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HISTORY OF THE FUTURES

THE EVOLUTION, CREDIBILITY, AND POLICY RELEVANCE OF THE EMISSION SCENARIOS INFORMING THE INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE (IPCC) 1990-2022

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History of the futures: The evolution, credibility & policy relevance of the emission scenarios informing the Intergovernmental Panel on Climate Change (IPCC) 1990-2022

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Geschiedenis van de toekomst:
De evolutie, geloofwaardigheid en beleidsrelevantie van
emissie scenario's die het IPCC informeren

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Abbreviations

AR	Assessment Report of the IPCC
AR1	First Assessment Report of the IPCC (published in 1990)
AR2	Second Assessment Report of the IPCC (published in 1995)
AR3	Third Assessment Report of the IPCC (published in 2001)
AR4	Fourth Assessment Report of the IPCC (published in 2007)
AR5	Fifth Assessment Report of the IPCC (published in 2013/2014)
AR6	Sixth Assessment Report of the IPCC (published in 2021/2022)
ASF	Atmospheric Stabilization Framework (model used for SA90 & IS92)
BaU	Business as Usual scenario (e.g., continuation of historical dynamics)
CA	Copenhagen Accord (2009)
CAT	Climate Action Tracker
CMP	Conference of the Parties serving as the meeting of the Parties to the Kyoto Protocol
CMA	Conference of the Parties serving as the meeting of the Parties to the Paris Agreement
CP	Copenhagen Pledges (2009; non-binding pledges in the UNFCCC context)
DA	Doha Amendment to the Kyoto Protocol (2012)
CBDR-RC	Common But Differentiated Responsibilities and Respective Capabilities
CCS	Carbon Capture and Storage
CDR	Carbon Dioxide Removal
CH_4	Methane
CO_2	Carbon dioxide
COP	Conference of the Parties to the UNFCCC
GDP	Gross Domestic Product
GHG	Greenhouse gas
GWP	Global warming potential
GST	Global Stocktake
HDC	Highly Developed Countries
IAM	Integrated Assessment Model
IEA	International Energy Agency
IMAGE	Integrated Model for the Assessment of the Greenhouse Effect (today developed by PBL)
IMF	International Monetary Fund
INDC	Intended Nationally Determined Contribution of the Paris Agreement
IPCC	Intergovernmental Panel on Climate Change
IS92	IPCC Scenarios 1992 (2^{nd} generation of IPCC scenarios; the updated SA90)
KP	Kyoto Protocol (1997)
LDCs	Least Developed Countries
LULUCF	Land Use, Land-Use Change and Forestry
MDCs	Medium Developed Countries
MP	Montreal Protocol (1987)
NDC	Nationally Determined Contribution of the Paris Agreement
NETs	Negative Emissions Technologies
NICs	Newly Industrialized Countries
OECD	Organisation for Economic Co-operation and Development
PBL	Netherlands Environmental Assessment Agency
PA	Paris Agreement (2015)
PCS	Paris-Compliant Scenario (similar to “PCP” Paris-Compliant Pathway)
RCP	The Representative Concentration Pathways (2011): 4^{th} scenario generation informing the IPCC
SA90	Scientific Assessments 1990 (1^{st} generation of IPCC scenarios)
SBSTA	Subsidiary Body for Scientific and Technological Advice
SBI	Subsidiary Body for Implementation
SDGs	Sustainable Development Goals
SPA	Shared Policy Assumptions (2014): 4^{th} scenario generation informing the IPCC

SPI	Science-Policy Interface
SRES	Special Report on Emission Scenarios (3rd generation of IPCC scenarios, published in 2000)
SSP	Shared Socioeconomic Pathways (2017): 4th scenario generation informing the IPCC
SSP-RCP	The SSP-RCP combinations (2019): SSP narratives combined with RCP radiative forcing levels
SR15	The four 1.5°C pathways in the 1.5 Special Report
STS	Sociology of science and Technology Studies
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
WB	World Bank
WGs	Working Groups of the IPCC
WG1	Working Group I of the IPCC (Physical Science)
WG2	Working Group II of the IPCC (Adaptation)
WG3	Working Group III of the IPCC (Mitigation)
WMO	World Meteorological Organization

How often do you stop to think about the way that society is organized and may evolve (similar or completely different) in the future? (Always? Sometimes? Never?)[1]

1 Introduction

1.1 Climate scenarios form a critical tool to support climate change research and policymaking

Climate change uniquely challenges humanity (Santos et al., 2022). The solution (in terms of mitigation and adaptation) requires a fundamental shift in almost all parts of human society. At the same time, this needs to be done against a background of social dilemmas related to different costs and benefits across societal groups and countries as well as across time, large uncertainties, and essential inequality in responsibility and capability to respond. An effective response requires contributions from science and policymaking (Morseletto, 2017). The development of an international climate change regime in 1992, the United Nations Framework Convention on Climate Change (UNFCCC, 1992), was closely interwoven with the story and development of scientific institutions, like the Intergovernmental Panel on Climate Change (IPCC) established in 1988, to assess the challenges and produce usable knowledge for political decision-makers (Bodansky, 1993; Demeritt, 2010).

A critical aspect of climate change policymaking, and thus research, is that we must address an uncertain future, exploring possible future trajectories. To ensure reliable and valid information for science and policymaking (O'Neill et al., 2016; van Beek et al., 2020), we need regular assessments of possible futures and the effectiveness of response strategies (Hulme and Dessai, 2008a). Four generations of emission scenarios informing the Intergovernmental Panel on Climate Change (IPCC) have therefore comprised a backbone in the analyses of future climate change and aim to inform policy (IPCC, 2022a, 2022b; Moss et al., 2010; J. T. S. Pedersen et al., 2022; van Beek et al., 2020). The scenarios explore possible changes regarding socioeconomic conditions, emissions, climate change, and impacts over time. (IPCC, 1990a; Riahi et al., 2017). So-called Integrated Assessment Models (IAMs) produce these scenarios, providing information to analyze consequences and needed preparedness for mitigating climate change and adapting (Riahi et al., 2017) to avoid catastrophic futures (Anderson, 2010; Poli, 2017). Key scenario users include scientific and non-scientific users, e.g., national policymakers and intergovernmental party delegates of the Conferences of the Parties (COPs) under the Climate Convention (UNFCCC).

Critical questions exist regarding the effectiveness of scenarios in informing policy. Therefore, this thesis studies the relationship between emission scenarios, the policy objectives they support, and how they could improve to be more relevant for policy and policy implementers. It includes assessing aspects related to the science-policy interface, such as how scientific knowledge is produced and why, focusing on the evolution of emission scenario generations

[1] Inspired by Taylor (2017)

since 1990. The policy-science interface bridges the thesis' relevance for academic knowledge and climate policy. The thesis presents the first assessment of scientific emission scenario critiques to understand how and why they have evolved (chapter 3). In addition, it compares historical drivers and emissions with scenario projections to assess if scenarios are updated and relevant for research and informing policy (chapters 4-5), which has not been done since 2006 (van Vuuren and O'Neill, 2006). The third novelty of the thesis is that it explores the policymaker perspective of emission scenarios (chapter 6), which is poorly communicated in the literature. This all aims to improve the policy relevance of emissions scenarios for facilitating intergovernmental treaties and designing national policies (less explored in the literature).

The introduction chapter presents the thesis' problem definition, including the social, policy, and academic challenges (1.2), the thesis' research questions (1.3), and the thesis structure (1.4).

1.2 Problem definition

1.2.1 Societal challenge

1.2.1.1 Climate change

Climate change is currently the most prominent global environmental challenge. As of 2022, IPCC has concluded that human activities are the most crucial cause of the climate change experienced in the last 150 years (IPCC, 2021a). Anthropogenic carbon dioxide (CO_2) is the essential greenhouse gas (GHG) that causes the most significant anthropogenic contribution to radiative forcing[2] and global mean surface temperature increases (IPCC, 2021a, 2014a). Its emission originates mainly from burning fossil fuels (oil, coal, and natural gas) and deforestation (IPCC, 2022b). Methane (CH_4) and nitrous oxide (N_2O) are also greenhouse gases influencing anthropogenic climate change (hereafter climate change) (Cloy and Smith, 2018).

Since the 1960s, fossil fuel consumption and land-use changes have caused a rapid accumulation of GHG concentrations in the Earth's atmosphere (IPCC, 2021a). Recent data indicate that the concentration of GHGs in the atmosphere is currently the highest in the last 800 thousand years. The average concentration of CO_2 reached 400 parts per million (ppm) in 2016, which is 40% higher than in the preindustrial era (EEA, 2017).Figure 1-1 presents developments in atmospheric GHGs since prehistorical times, after year zero (covering human impacts), and projections of plausible future changes depending on human actions. The latter is provided by emission and climate scenarios informing the IPCC (Gidden et al., 2019b).

[2] Radiative forcing quantifies changes in energy flows caused by changes in natural and anthropogenic substances and processes that alter the Earth's energy balance IPCC (2021).

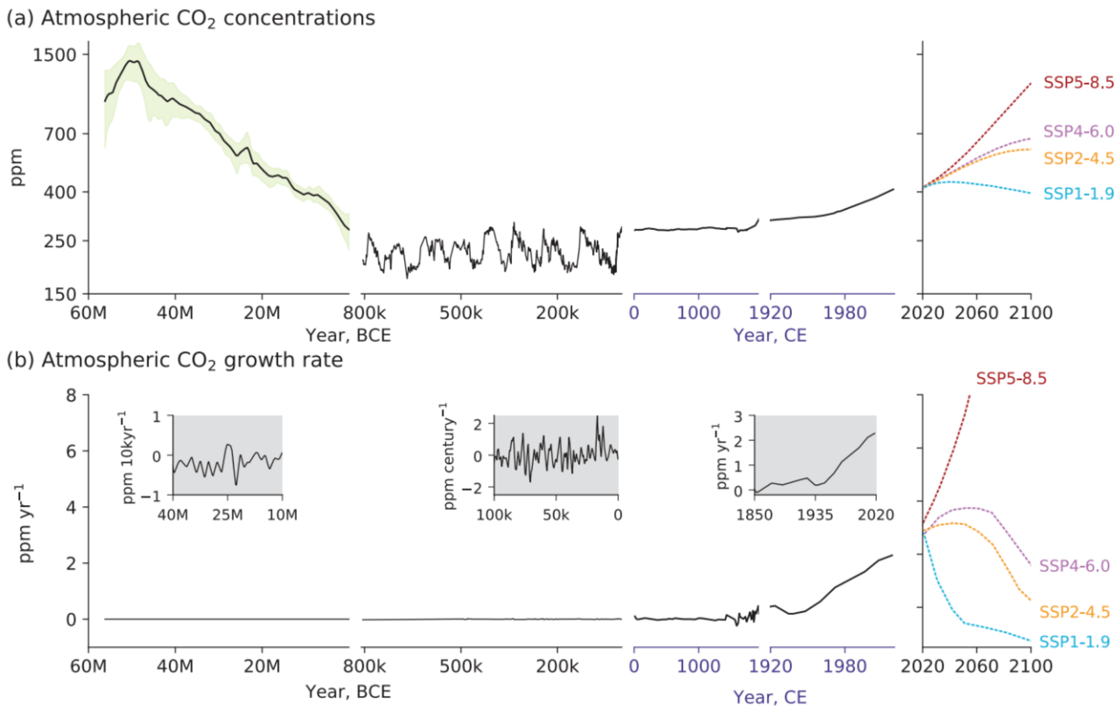

Figure 1-1. Atmospheric CO_2 concentrations (a) and growth rates (b) for the past 60 million years (Myr), including future projections for 2020-2100.
Source: IPCC (2021a).

The increase in the global average temperature is the primary manifestation of climate change. The previous decade was the warmest ever recorded. Between 2012-2021, the global average surface temperature was 1.11-1.14 °C warmer compared to preindustrial levels (1850-1900). Temperature changes are not equally distributed. Over land areas, the increases were almost double (1.59 °C) compared to over the ocean (0.88 °C) (APA, 2019; IPCC, 2021a). In some areas, like Europe and the poles, land temperatures increased faster than in ecosystems like the Amazon (Carvalho et al., 2020; EEA, 2022; IPCC, 2021a). In addition, climate impacts are not equally distributed (IPCC, 2022c, 2022b). More severe impacts and fewer capabilities to cope with them generally make poorer countries significantly more vulnerable to climate change than richer countries (IPCC, 2022c; ND-GAIN, 2020).

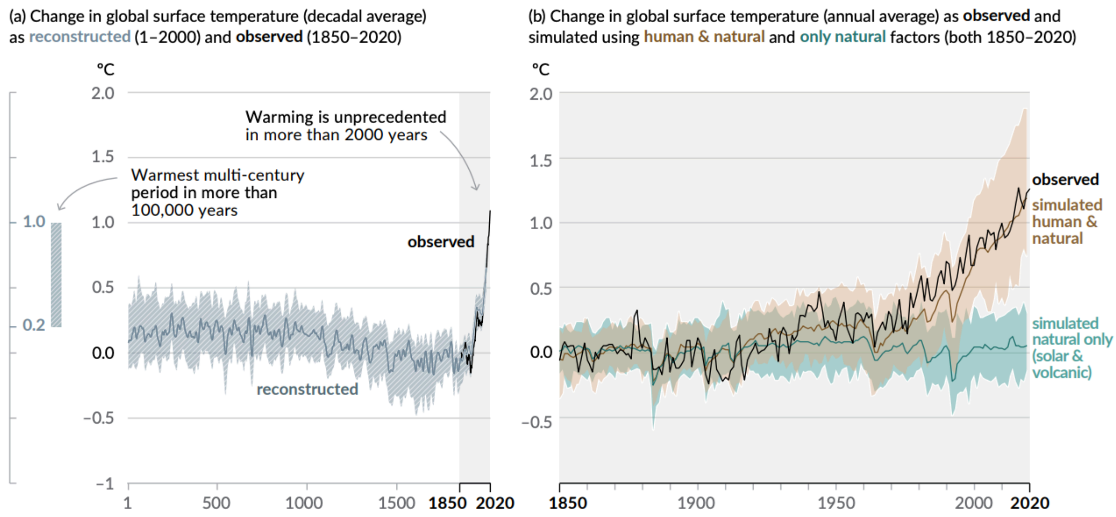

Figure 1-2. Changes in global surface temperature relative to 1850–1900.
Source: IPCC Working Group I Summary for Policymakers (2021a).

It is possible to make projections of future emissions. This is done based on expected trends in energy use and land use. The outcomes of such scenarios vary from continued emissions growth to some form of reversal, as indicated in Figure 1 (we will discuss these projections in much more detail further in this introduction). In the past, emissions have increased, driven by a growth of economic activity. Some future scenarios show a similar trend. Still, reducing emissions by significantly changing current and dominant socioeconomic systems and lifestyles is possible. This is termed climate mitigation or emissions reduction (IPCC, 2022b). Research indicates that CO_2 emissions will have to go to zero within 2-5 decades to comply with the objectives of the Paris Agreement (aiming to avoid significant and possibly dangerous climate change). If politicians do not manage to implement efficient mitigation policies, the impact of floods (sea level rise) and droughts (e.g., forest fires) is projected to increase significantly (IPCC, 2022b). Continuing historical (mitigation) trends, global temperatures could reach about 2.6-3.2 °C by 2100 (SSP2-4.5, SSP4-6.0) (Carvalho et al., 2020; UNEP, 2022). Fulfilling the 2015 Paris Agreement on Climate Change's objective of staying well below 2 °C and preferably at 1.5 °C by 2100 will still cause increasing climate impacts, however less frequent and severe, than a continuation of the current societal dynamics (IPCC, 2022b, 2022a).

It is possible to reduce emissions in various ways, like reducing the use of fossil fuels by reducing energy demand (and using carbon-free technologies), introducing technologies that can capture GHG emissions, stopping deforestation and moving to afforestation, and reducing non-CO2 emissions. These actions are referred to as climate mitigation. In addition to mitigation, it is also possible to respond to climate change thru adaptation, such as raising dikes and growing different crops (IPCC, 2022c). IPCC warns that there are limits to adaptation, making rapid mitigation necessary (IPCC, 2022a). Recently, some geoengineering options have also been considered possible response strategies (Burns, 2010). However, the IPCC considers these strategies dangerous and untested (IPCC, 2012). In essence, scenarios can support evaluating the effectiveness of all possible response strategies, despite seldom including geoengineering (Riahi et al., 2017).

Emission budgets are relevant to climate change mitigation because they communicate the limits of carbon emissions (concentrations) associated with trespassing various temperature limits leading to dangerous global warming (IPCC, 2018a; Matthews et al., 2020, 2009). Staying likely (66% chance) below 1.5 °C requires staying within a carbon budget of 360 Gt CO_2 from 2021 onwards (in other words, equal to 11.5 years of current emissions). The corresponding budget for 2 °C is 1100 Gt CO_2 or 33 years of current emissions (IPCC, 2021a).

1.2.2 Policy responses

Governments adopted the United Nations Framework Convention on Climate Change (UNFCCC) in 1992 to avoid dangerous climate change (UNFCCC, 1992). The UNFCCC sets out several critical principles for international climate policy, such as anticipating action and recognizing that countries have different responsibilities and capabilities (UNFCCC/COP, 2015a, 1997).

Since 1992, the Conferences of Parties (COPs) have been organized to translate the UNFCCC into more precise policy measures. Initially, the international climate policy aimed for a globally binding agreement (UNFCCC, 1992). This process led to the pledges of industrialized countries in the Kyoto Protocol (and the second Kyoto commitment period agreed upon via the Doha Amendment) to reduce their emissions in 2008-2012 (and 2013-2020) compared to 1990 levels. The Kyoto Protocol (KP) did not lead to an emission peak for the industrialized Annex-I countries, the US (Republican government) did not ratify the Protocol, and Canada withdrew prematurely from the agreement. Subsequent negotiations on a binding agreement finally stalled.

The most recent follow-up agreement to the UNFCCC treaty is the Paris Agreement (PA) (IPCC, 2022b; UNFCCC/COP, 2015). It indicates that the goal should be to "Holding the increase in the global average temperature to well below 2 °C above preindustrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above preindustrial levels, recognizing that this would significantly reduce the risks and impacts of climate change" (UNFCCC/COP, 2015a). These goals are, however, formulated at the global scale, while action needs to happen at the national scale. The Paris Agreement requires countries to formulate voluntary policies and pledges (NDCs) at the national scale in line with the global goal (UNFCCC, 2021a).
At the moment, however, action by countries is insufficient to reach the global goals – both in terms of current policies and the self-defined 2030 National Determined Contribution (NDC) targets of the Paris Agreement (IPCC, 2022b). Countries are asked to raise their ambitions in the coming years as part of the global stocktake process. In addition to assessing the possibilities at the national scale (and the associated costs), this directly and indirectly also requires assessing what would be a fair distribution of the reductions across various parties (COP/UNFCCC, 2021; UNFCCC/COP, 2015). A critical aspect of the debate is that the historical responsibilities for climate change differ. Since 1850, the United States of America (US) (25%) and the European Union (EU) (17%) have been responsible for the most significant number of historical global cumulative fossil fuel and industry CO_2 emissions (Ritchie and Roser, 2018). Figure 1-3 shows CO_2 emissions from fossil fuel and industry (IPCC, 2014a) and primary energy consumption for the four major global emitters (G4): China, the US, the EU, and India. A rapid industrialization process in China increased emissions higher than the US and EU during the past two decades. India surpassed Japan around 2005, entering the top four major global emitters (G4).

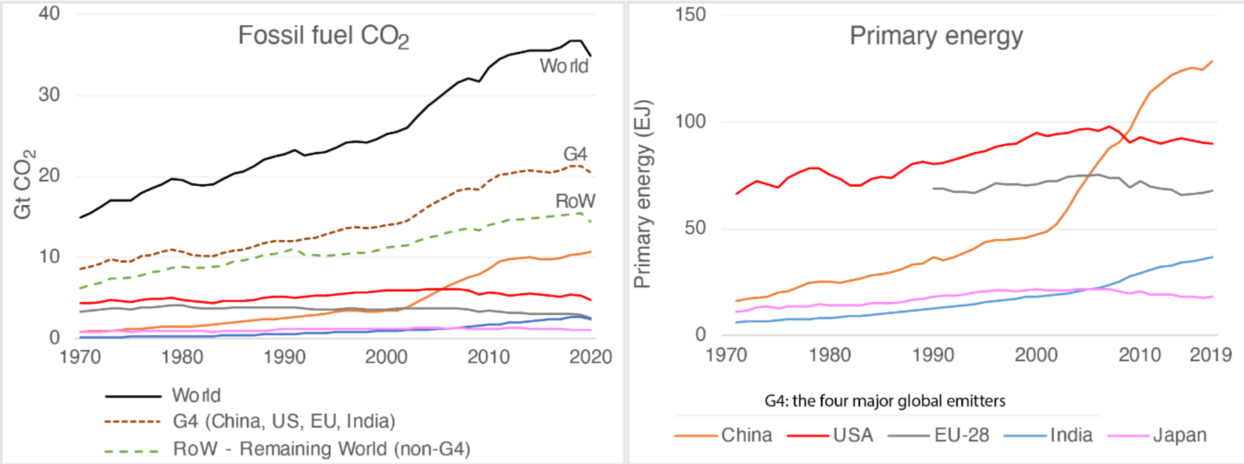

Figure 1-3. Global & national fossil fuel and industry CO_2 (left) and primary energy supply (right) 1970-2020.
Data sources: Global Carbon Project (GCP) (2021a) and International Energy Agency (IEA) (2022a)

The four countries/regions represent an interesting showcase for global mitigation. They reflect very different cumulative emission patterns per capita over the last 30 years and the impact of contrasting political and economic systems. Together, the four major emitter parties (G4) have contributed to around 60% of global emissions over the past 100-200 years. However, it hides underlying differences between countries, including socioeconomic circumstances. India and China have a large population and a relatively recent industrialization process (non-Annex I). USA and EU27 experience much lower population growth, higher per capita emissions, and a mature industrialization process (Annex I). The countries also differ in governance regimes (Repucci and Slipowitz, 2022).

1.2.3 The use of scenarios to support climate policy

Scenarios thus play a critical role in supporting the policy process. They are used:

- To explore possible future emissions, climate change, and impacts and
- To explore possible response strategies
- To evaluate the effectiveness of current policies and pledges.

The scenarios are developed by Integrated Assessments Models (IAMs) and expressed in words (assumptions and narratives about how human societies and the World may evolve) and numbers (e.g., energy consumption and emission levels) (O'Neill et al., 2017; Pepperet al., 1992). The first three generations were developed inside IPCC by WG3. They include the "1990 IPCC First Scientific Assessment" (SA90) (IPCC, 1990a), the "1992 IPCC Scenarios" (IS92 series) (Leggett et al., 1992), and the 2000 "Special Report on Emissions Scenarios" (SRES) (Nakicenovic and Swart, 2000a). The scientific community outside the IPCC developed the fourth and most recent generation (Moss et al., 2010a). It is comprised of the "Representative Concentration Pathways" (RCPs) (van Vuuren et al., 2011a) and the "Shared Socioeconomic Pathways" (SSPs) (O'Neill et al., 2014; Riahi et al., 2017). The framework also includes policy assumptions via the Shared Policy Assumptions (SPAs) (Kriegler et al., 2014).

In the fourth scenario generation, two emission scenarios reflect the Paris goals of 2 °C (SSP1-1.9) and 1.5 °C (SSP1-2.6) (Gidden et al., 2019a). They are often referred to as Paris-Compliant Scenarios (PCSs). The SSP-RCP names refer to five storylines (SSP1-5) and (RCP) radiative forcing levels of 1.9 and 2 w/m^2 by 2100, respectively. Radiative forcing expresses the change in energy flux in the atmosphere[3] affected by human and natural causes (IPCC, 2021). At the other end of the scenario range, two scenarios explore high emissions and radiative forcings (SSP5-8.5, SSP3-7.0). High-end scenarios are relevant to assess the full range of possible climate change, its impacts, and investments in plausible response strategies for long time horizons. Medium scenarios (e.g., SSP4-3.4, SSP2-4.5, and SSP4-6.0) are often based on assumptions that have matched the historical global emissions pathway well or the effect of current policies (Carvalho et al., 2020) or pledges. The RCP/SSP scenarios support evaluating current policies and national pledges (i.e., the Nationally Determined Contributions (NDCs) of the Paris Agreement). In addition, other short-term emission scenarios evaluate in more detail the gaps between current policy and Paris Compliant Pathways (CAT, 2022, UNEP, 2022). Therefore, the full range of emission scenarios remains important as inputs to scenario-based analysis assessing possible climate change and impacts (Lawrence et al., 2020; J. S. T. Pedersen et al., 2020).

1.2.3.1 Knowledge gaps

First, the academic literature does not reveal how and why scenario generations have evolved and changed over time. Filling this gap may inform the reasons for emission scenario changes in the past and aspects to consider for future scenario developments.

Second, the uncertainty about future climate change is widely discussed, including the credibility and salience of emissions scenarios as inputs to climate models. With long-term data (1990-2020) available, the thesis compares how the diversity of scenario ranges (ex-post) holds against historical trends. Filling this gap is crucial from a policy perspective because the IPCC scenario ranges are often interpreted as boundary conditions (minimum and maximum projections) in UNFCCC negotiations and associated national and international climate policies.

Third, we know little about emission scenarios' actual use and relevance in policymaking. Scientific evidence (including emission scenarios) aims to inform policy, but we know little about what information policymakers need and request to implement anticipative actions. Despite continuous scientific interest in the policy relevance of scenarios as a policy tool, the literature has not yet revealed the policymaker's perspective on emission scenarios and their usability in policymaking. Scenario relevance (salience) discussions have been primarily between scientists (Hausfather and Peters, 2020; Schneider, 2001). Some policymakers have been included in scenario developments (Kok et al., 2019a, 2007; O'Neill et al., 2019; Patel et al., 2007), and a few evaluations of scenario users were identified (Braunreiter and Blumer, 2018). However, it is uncertain how scenario relevance has been addressed and what needs have been communicated in the science-policy interface processes.

1.3 Research questions and limits

In this thesis, I aim to look at the use of scenarios by the climate community and draw lessons for new generations of scenarios. For this, I first intend to analyze the evolution of scenarios and changes since 1990, providing the first comprehensive review of emission scenario critiques (e.g.,

[3] Net zero radiative forcings characterize the planetary equilibrium temperature. Any net gain of energy will cause planetary warming. Positive radiative forcing means Earth receives more incoming energy from sunlight than it radiates to space. Negative radiative forcing is equal to planetary cooling, meaning that Earth loses more energy to space than it receives from the sun.

evaluations and assessments), aiming to inform plausible future scenario updates (or development of new scenarios). Second, I intend to analyze the relationships between historical developments and scenario projections (emissions and emission drivers) to assess the scenario's credibility. Additionally, I intend to analyze the long-term contribution of different drivers to projected CO_2 emissions to assess the contributions of various key drivers. Third, I explore the policymaker perspectives to support a better understanding of the role emission scenarios play in policymaking, aiming to contribute to improving scenarios and their policy relevance.
It should be noted that climate policy is a relatively young area of public policymaking, and so far, it has not been very successful in terms of mitigating emissions (Geden, 2016; Huitema et al., 2011; IPCC, 2022a). It is uncertain how policymakers see the potential of emission scenarios in the national and international policy processes. With the thesis, I intend to make an initial step toward understanding the policymaker's perspective on how scenarios may become more policy relevant. The overall reason for conducting the research is to improve scenarios (scientific knowledge) to increase their relevance in policymaking. The linkages between science and climate policy are based on the increasing need for information from the IPCC and UNEP (IPCC, 2005d) to provide evidence-based policies (Huitema et al., 2011) and negotiations within the UNFCCC (UNFCCC, 2021b) also involving technical-scientific policy advisors (UNFCCC, 2020a). Notably, since the future is uncertain scenario may aim to support **well-informed decisions** rather than evidence-based policymaking.

1.3.1 Research questions

Based on the problem analysis, the following questions will guide the research scope and define the main four steps in structuring the results and discussion sections:

The overarching question of this thesis is:

How have scenarios, their credibility, and policy relevance evolved over the past 30 years, and how can they be improved to serve present needs?

To answer the overarching question, the central line of inquiry leads to a series of sub-questions:

RQ1. How have emission scenarios evolved between 1990-2020, and which critiques have they raised?

RQ.2. How do these scenarios compare to historical global and regional emissions and key socioeconomic development trends?

RQ.3. How do UNFCCC policymakers perceive emissions scenarios and their relevance for policy designs?

RQ.4. How can the current emission scenarios be improved to better inform mitigation (and adaptation) policy, i.e., handling the boundaries between knowledge and actions in the climate change science-policy interface?

The research questions are related to the evaluation criteria of credibility, saliency, and legitimacy, suggested to explore the boundaries between knowledge and actions in the science-policy interface (Cash et al., 2003; Hulme and Dessai, 2008a), assessing the scenario design development (legitimacy), projections and interconnectedness of variables (credibility), and their user relevance (salience). Credibility focuses on the technical components and scientific adequacy. Legitimacy concerns the scenario designs development process and transparency, construction, and distribution, while salience focuses on scenario relevance to decision-makers' needs.

The thesis presents a three-fold framework for assessing the scenarios and, as the fourth aspect, discusses plausible future scenario lessons to soften the boundaries between scientific knowledge and policy action. The first three questions concern the role of (scientific) critiques and perspectives regarding the evolution of the scenario design; how the scenarios retrospectively relate to historical trends (e.g., has the future turned out as envisaged?); and do they sufficiently inform 'good' decisions or UNFCCC negotiations (decision-maker communication)? The fourth RQ aims to synthesize the results of the first three RQs, presenting lessons for further scenario analyses. It focuses on information that might support evaluating scenario variables and scenarios' future role in climate change decision-making, potentially improving scenario credibility (content) and salience (user communication).

In essence, the thesis analyzes and compares the four scenario sets used in the IPCC context and their capability to project future emissions. It seeks to support possible scenario updates before and after the seventh IPCC assessment cycle (AR7) to maintain the scenarios' relevance for science and policymaking, contributing with strategic suggestions on when and how to review the current use of global emission scenarios informing the IPCC. Chapters 4 and 5 (J. S. T. Pedersen et al., 2020; Pedersen et al., 2021) already informed the 6th IPCC Assessment cycle (AR6), e.g., the historical credibility of scenario ranges, complications regarding regional diversity in emissions growth (IPCC, 2022b, 2021a), and the relevance of high emission reference scenarios (IPCC, 2022b).

1.3.1.1 The RQs connection to the science-policy interface

Efforts to mobilize science for sustainability are more likely to be effective when they manage knowledge-action boundaries by enhancing scientific information's salience, credibility, and legitimacy (Cash et al., 2003). From a scientific perspective, emission scenarios should be plausible in economic structures, demographics (O'Neill et al., 2017), and energy systems (Bauer et al., 2017). From a policy perspective, the scenario design and scenario communication (RQ1) and the credibility of projections (RQ2) are crucial for their relevance to designing reliable policies. Since emission scenarios also aim to inform policy, it is crucial to understand how policymakers (rather than researchers) understand scenarios, their needs, and requests for improving the scenarios' policy relevance (RQ3).
Research is considered policy-relevant when it guides informed decisions or develops effective policies, providing actionable information that policymakers can use to design and implement policies that achieve desired outcomes (Haynes et al., 2018). It depends on factors like quality, applicability to real-world problems, the efficiency of science-policy communication, and to which degree policymakers use the information provided (Pielke, 2007; Rosenthal et al., 2014).

It is necessary to take several steps to understand the nature and subsequent development of the emission scenario generations. Aside from guiding the empirical inquiry, these questions provide the structural backbone of the analysis. Figure 1-4 illustrates how the research questions follow a circular investigation of interconnected scenario roles within the science-policy interface. The first step in evaluating the relevance of the emission scenario tool is to review how the design and series of scenarios have evolved. The second is to assess the credibility of scenario content, i.e., the scenarios' ability to project the future (including the emission range), and the third is to evaluate how policymakers connect to the tool. Fourth, I synthesize the results of RQ1-3 into strategy suggestions for scenario improvements for science and policy.

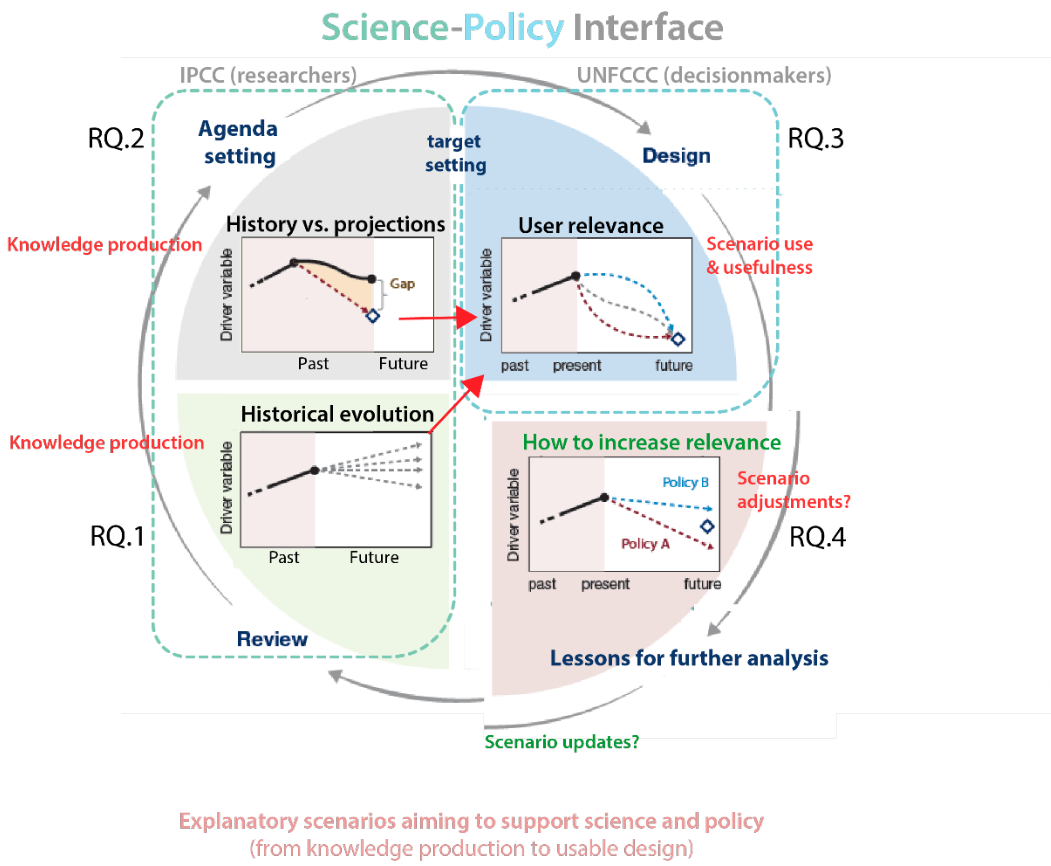

Figure 1-4. Research diagram and flow: Research questions (black text), scenario themes, and analytical concepts (red text).

The Figure 1-4 diagram reflects two issues calling for further consideration. The science-policy communication does not only comprise a linear model from science to policy (Beck et al., 2014; Chen, 2022), and the role of model-based scenarios is merely agenda setting. In reality, science-policy interaction entails a dynamic two-way interaction, including co-creation (see more in subsection 2.4. Models aim to inform policy (van Beek et al., 2020), while their role in actual policy is less specific. However, they have played roles related to agenda-setting and target-setting (van Beek et al., 2022). In recent years political requests for exploring mitigation pathways have added political focus on the usefulness of models (Kriegler et al., 2017b), which has become more apparent with the IPCC focus moving toward a more solution-oriented mode (Beck and Mahony, 2017; Tollefson, 2015).

The scenarios have received many critiques over the years, shaping design developments and scientific content. RQ1 focuses on the evolution of emission scenario critiques (and responses) and how they have shaped the scientific-technical content, development process, and user relevance. RQ1 aims to understand how the scenarios have been developed, by whom, and through which processes. This involves analyzing the critiques topics and how these have affected future scenarios and their developments. The relatively large number of critiques indicates the scenario's importance in science and policy and its potential in agenda setting. Thus, it is essential to assess the scenarios' emissions regularly ranges against historical trends (RQ2), evaluating the credibility of scenario ranges to inform science and policy sufficiently. RQ2 aims to characterize, analyze, and categorize the **scientific content** of the scenarios for cross-comparisons regarding quantitative model results and qualitative narratives/storylines. Furthermore, to analyze the **consistency** of the scenario generations against historical trends and their ability to project future emissions and assess the deeper causes, development, and relevance of specific emissions drivers (e.g., GDP, population, energy, technology), globally as well as regionally, and their relation to observed historical developments between 1990-2018. RQ1 and RQ2 (design evolution and content validation) have relevance for answering RQ3. RQ3 concerns the scenarios' salience (their usability in policymaking), aiming to analyze **policymakers' perception** of emission scenarios and how they access emission scenarios' policy relevance for designing national policies and facilitating UNFCCC treaties. Finally, RQ4 initiates a discussion of results focusing on plausible **lessons for further scenario analysis** for modelers (and policymakers) to support scenario updates or future scenario development (IPCC AR7 and beyond) and their relevance for decision-makers and UNFCCC COPs in reaching the Paris Agreement. The question concerns how the current models or GHG projections can be improved to provide more accurate and reliable information to inform climate mitigation policies. It acknowledges that there are often boundaries between scientific knowledge and policy actions, and it seeks to understand how these boundaries can be better navigated or bridged. In other words, the question concerns how to better translate scientific knowledge into actionable policies to effectively tackle climate change.

1.4 Summary of approaches and methods

The initial research, Chapters 3-5, focuses on analyzing empirical evidence, i.e., historical data and existing scenario knowledge (variables and data). The second half, chapters 6 (results) and 7 (discussion) analyze and discuss the nature of scenarios as social constructions shaped by cultural and social perceptions. It focuses on multiple realities, asserting that values/norms in designing emission scenarios and other types of policy-relevant knowledge are socially constructed by different categories of actors and perspectives rather than universal and absolute values/norms (Brand and Brunnengräber, 2012; Cass, 2016; Gergen, 1985). The thesis' discussion aims at integrating relevant perspectives to interpret the scenarios and their variables in the light of their usability in policy and for policymakers.

When I focus on scientists, I focus on the critiques and responses leading to changes in the models and scenario approaches. When I focus on decision-makers, I include both their self-reported familiarity (knowledge) with emission scenarios and perceptions of the usability to guide policy designs, across a sample (n=57) of a population (N=299) of UNFCCC national focal points. The population is a small, well-defined group distributed between global North (22%) and South (78%) party representatives. The sample comprised 33% global North and 67% global South representatives (Chapter 6).

The discussion focuses on specific scenario variable details, the reality behind these details (e.g., subjective meanings), and the plausible consequences for (informing) policy. Here I use the concepts of anticipative action and the science-policy interface. Scenarios belong to the field of anticipative action (Hastrup and Skrydstrup, 2013) and are developed as boundary objects within the science-policy interface (den Elzen et al., 2005; Hulme and Dessai, 2008a). Scenarios aim to inform policy (Moss et al., 2010a; van Beek et al., 2020), thus within the science-policy interface, modelers and researchers must be capable of developing knowledge, which policymakers listen to in designing policies (Haas, 2004). It also considers the issues negotiated within the UNFCCC, where it is difficult to reach an agreement about mitigation actions without addressing environmental justice (Dooley et al., 2021; Lahn, 2020, 2018).

The research design drew upon both qualitative and quantitative methods. Specific methods are described in the chapters with more detail in the thesis' Supplementary Information (SI) and the published SIs to the published papers. Therefore, the thesis does not provide a methods chapter.

Table 1-1. Overview of objectives and applied methods

Objective	Methods	Tools/sources	Focus
1 Analyze the scientific evaluations and processes behind the scenarios informing the IPCC	Literature search and review of peer-reviewed and grey literature emission scenario critiques and modeler responses	Primary scenario literature; bibliographies; SCOPUS, Google, and Google Scholar database searches	Identifying and categorizing key emission scenario aspects
2 Characterize, analyze, and categorize the scientific content of the scenarios for cross-comparisons	Comparison and categorization of individual illustrative scenarios across the four scenario generations	Analyze and compare 1) storylines/assumptions and 2) cumulative emissions via primary literature and scenario databases.	Cross-scenario series grouping of scenario families by narratives and cumulative total CO_2 emissions
3 Analyze the consistency of the scenario generations against historical trends and their ability to project future emissions and assess the deeper causes, development, and relevance of specific emissions drivers	Analyze and compare drivers and emissions Compare historical trends with projections	Weighted moving averages of and correlations Compound Annual Growth Rates (CAGR)	Analyzing the long-term historical relationships between key emission drivers and emissions Key emission drivers (population, GDP, primary energy) and emissions (CO_2 from fossil fuels & industry)
4 Analyze policymakers' perception of emission scenarios and how they access emission scenarios' salience (relevance) in designing national policies and facilitating UNFCCC treaties	Semi-structured interviews Participant observation & informal interviews Survey	Modelers/experts, IPCC authors, policymakers, and policy advisors Ministers and delegates at COP25 (Madrid, 2019), COP26 (Glasgow, 2021) UNFCCC delegates (n=57) from a population of National Focal Points (N=299)	Policy relevance and implications Knowledge about emission scenarios, perception of relevance for policy designs, perception of scenario improvements to increase policy relevance
5 Discuss and recommend possible strategy suggestions and approaches to support scenario updates or future scenario development	Synthesis & meta-analysis		Plausible strategy suggestions for scenario improvements

1.4.1 Ethical Issues and Considerations

When using analytical terms like GDP growth and climate justice, it is crucial to discern between the constructionists (how scenarios are developed and by whom), how it may appear normative at times (e.g., the nature of the assumption used in the scenarios), and how it is used in practice (e.g., in governments, UNFCCC negotiations, NDCs, and science), i.e., observe how it is used without judging if it is correct or not. In terms of producing scientific knowledge, 100% objectivity is not feasible but situated within specific social, cultural, and historical contexts, influenced by the subjective experiences and biases of the individuals involved (Haraway, 1988; Sjørslev, 2015). However, the criteria of how knowledge is produced may be based on what is considered correct and incorrect within a scientific field (Foucault, 1975, 1972). Thus, scenarios may include assumptions that are selected, implying some kind of normative selection. I aim to assess whether, scenarios and selected narrative variables are made from a somewhat discursive cultural truths (e.g., well established in some global regions). Since scenarios are primarily (but not solely)[4] developed in global North institutions (Riahi et al., 2017), they risk becoming part of a power-knowledge dialectic or an institutionalized power (Foucault, 1980, 1972) that produces a normative view of the world that is different from other regional perspectives. I additionally considered my own ethical position (Haraway, 1988), aiming to realize my position and, as a researcher, strive to stay objective, e.g., toward the role of the fossil industry and policy delays (which is easy to judge from a personal perspective) and assess climate justice from various cultural perspectives rather than a normative perspective.

The research follows ethical principles when working with respondents and clients. The most important ethical considerations are confidentiality, anonymity, privacy, consent, hidden intentions, and involuntary participation. For the survey and interviews, informants were briefed and debriefed. I mentioned the possibility of telling me if they said anything they did not want to be published, including contact information, in case they regretted having conveyed it post-interview or survey. I used concrete examples and principles to inform and ensure confidentiality and anonymity towards respondents and techniques to avoid deceiving respondents (e.g., clearly stating if a question or topic could be sensitive during the interview). I assessed how to ensure that respondents react most naturally. For example, I intentionally presented themes in a specific order. I made a briefing based on considerations to avoid influencing respondents' spontaneous responses, e.g., considering elements that could affect other answers before the survey/interview was completed.

Because of the nature of intergovernmental negotiations, the information provided is potentially sensitive. Thus, the survey participants' identities and nationalities are excluded from the manuscript and Supplementary information. The Institute of Social Sciences of the University of Lisbon, Portugal (ICS-ULisboa) provided guidelines for study procedures. ICS-ULisboa and the Faculty of Sciences of the University of Lisbon (FC-ULisboa) approved the study protocol. I followed the research ethics of the International Statistical Institute (ISI) regarding the survey and analyses of answers and how to handle and store data, and ethical guidelines via The Nuremberg Code, WMA Declaration of Helsinki, Utrecht University, and The European Commission's DCF regulation for data collection and storage (EC, 2023)

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1.5 Thesis structure

The first two chapters, leading up to the analysis, provide an overview of the thesis foundation via an analytical and conceptual framework guiding the thesis discussions (Chapter 2). The analyses comprise four chapters (3-6). Chapter 3 (Paper 1) analyses how scientists have perceived the scenarios over time and how the scenario content (assumptions, ranges), methodology, and development processes changed because of, e.g., scientific critiques. Chapter 4 (Paper 2) introduces the historical development of emissions (fossil fuel and industry CO_2) and key emissions drivers (population, GDP, energy transition) and how they compare with projections in the four generations of IPCC emissions scenarios. Chapter 5 (Paper 3) discusses the relevance of high emission scenario RCP8.5 and high emissions scenarios in light of recent RCP8.5 critiques. Chapter 6 (Paper 4) analyzes the policymaker perspective and discusses the differences in knowledge bases related to emission scenarios within the UNFCCC parties. Discussion of plausible scenario lessons and strategy suggestions for further scientifical improvements and

[4] For instance, modeling institutions from China, India, and Brazil cooperate in scenario developments (see section 2.4.1.2).

policy relevance is addressed in Discussion Chapter 7. Finally, the Summary and conclusions presents a synthesis of the results by chapter and in an integrated way (Chapter 8).

The Supplementary Information (SI) provides additional material about databases, calculations, and methods (e.g., persons interviewed, survey questions, and coding). Chapter SI 1 provides more detail about the evolution of the emission scenario generations in shifting historical contexts (summarized in Chapter 4). Chapter SI 2 presents comparisons of eight short-term policy scenario assessment institutions published right after the Paris Agreement (2015-2016), related to comparisons presented in Carvalho et al. (2020). Chapter SI 3 provides more detail on the literature debates and their contexts (analyzed in Chapter 3), while the literature sources are available in the scenario critique paper’s SI. Chapters SI 4-7 comprise the databases, scenario categorization, equations, and data analysis used for Chapters 4 and 5. Chapters SI 8-10 provide information related to interviews and surveys. SI Chapter 11 presents a table of landmarks in the evolution of the climate science-policy interface and the UNFCCC climate regime.

2 Analytical Framework

This chapter introduces three fundamental concepts of this thesis: the concept of anticipative systems and action (2.2), emission scenarios (2.3), and the use of these scenarios as part of the science-policy interface (2.4).

2.1 Concepts, empirical framework, and theoretical approach

Dealing with climate change is complex: it involves many actors and interests, complex causal relationships, and critical uncertainties. Effective climate policy, therefore, requires scientific support. Since climate change extends far into the future, it is vital to connect present-day decisions to possible future consequences to formulate mitigation strategies (anticipative actions). The long-term emission scenarios informing the IPCC represent a scientific tool to assess the relationship between present mitigation policies, the specific details of the energy and socioeconomic futures, and future emissions (Riahi et al., 2017; UNEP, 2022). They provide a tool to support assessments of future climate change (IPCC, WG1), impacts (IPCC WG2), and mitigation (IPCC WG3). In addition, these scenarios combined with short-term emission scenarios are also used to evaluate and compare current national mitigation policies, NDC targets 2030 (and mid-century net zero targets[5]), and Paris-Compliant Pathways (CAT, 2023a; UNEP, 2022). Scenario analysis thus aims to support anticipative thinking, scientific analyzes of mitigation and response strategies (IPCC, 2022a, 2022b), and national and intergovernmental policymaking, e.g., being part of the knowledge base of the UNFCCC library (UNFCCC, 2021b, 2008).

Table 2-1. Key concepts used in the thesis

Central concepts	Key points	Main references
Anticipation action	Connecting present actions to future consequences. A governance principle to avoid future catastrophes Challenges: - Models vs. real life - Delayed action	Hastrup & Skydstrup (2013) Anderson (2010) Pezzulo et al. (1998) Poli (2017) Rosen (1985) Rosenblueth et al. (1950)
Emission scenarios	Long-term emission scenarios: A tool to model long-term futures to inform responses Short-term policy scenarios: A tool to assess the progress of the Paris Agreement Scenarios can be evaluated within the science-policy interface via the following criteria: Credibility, legitimacy, and saliency Challenges: Scenarios are human constructs primarily developed in the global North	IPCC (1990a), Leggett et al. (1992), Swart & Nakicenovic (2000a) Van Vuuren et al. (2011a) Riahi et al. (2017) Gidden et al. (2019a) IPCC (2018a) Cash et al. (2003)
Science-Policy Interface	Intergovernmental Science-policy institutions International climate treaties - Kyoto Protocol (KP) - Paris Agreement (PA)	UN (1972), Chen (2022) UNFCCC/COP (1992, 1997, 2012, 2015) Gupta (2014, 2010)

[5] These targets were introduced in the IPCC Special Report on 1.5-pathways (IPCC, 2018).

Boundary objects - Multiple users of scenarios - Science-policy interaction models Paris Compliant Scenarios (Climate Justice) - Historical Common But Differentiated Responsibilities (CBDR) - Respective Capabilities (RC) Challenges: - Policymaker vs. scientist perspectives - Trust	Gupta et al. (2018) Okereke et al. (2016) UN (2015a) Guston (2001) Star (2010) Sundqvist et al. (2018)

In this thesis, I evaluate the use of scenarios, particularly the scenarios series informing the IPCC assessment reports1 with emission scenarios and perceptions of usability to guide policy designs and processes.

2.2 Anticipation

The concept of anticipation became a focus area in the 1980s based on the idea that many things in life are anticipatory (Rosen et al., 2012). Therefore, decision-making should be anticipative (Anderson, 2010). It was initially based on theoretical frameworks from philosophy, biology, and psychology (Pezzulo et al., 1998). Today, various anticipation perspectives exist in related disciplines like public policy, futures studies, social-ecological systems, environmental policy and governance, transition studies, science and technology studies, and innovation literature (Muiderman et al., 2020a; Poli, 2010a).

Anticipation involves causality, evaluating actions based on their goal (Herbart, 1824; Pezzulo et al., 1998) or their movements towards a goal (Rizzolatti, 1997), e.g., acting in the present to avoid, adapt to, or shape uncertain futures (Anderson, 2010; Muiderman et al., 2020b). Anticipative actions are purposeful (goal-directed) as opposed to random and purposeless actions (no clear goal) (Rosenblueth et al., 1943). Proactive and goal-oriented steps (Castelfranchi, 1998; Tulving, 1983) are based on beliefs or expectations about future states (Hastrup and Skrydstrup, 2013; Huron, 2008), often shaped by models (Hastrup, 2012). An anticipatory system (AS) contains a ‘predictive’ model of itself, allowing it to change state according to the model’s predictions (Rosenblueth et al., 1943). In other words, AS contains a model of a system (MS) with which it interacts. This predictive model presents information about the future states of MS (Pezzulo et al., 1998; Rosen, 1985). The capability to formulate predictions and use them for their purposes distinguishes an anticipatory system from a merely reactive one (Hastrup, 2012).

2.2.1 Connecting the Present to the Future

In the case of specific future existential threats, anticipative thinking is essential to avoid future catastrophes (Anderson, 2010; Rosen, 2012). Examples include the uncertain futures of global issues like pandemics, biodiversity loss, and terrorism (Anderson, 2010; Ciotti et al., 2020; Otero et al., 2020). Decision-making must also be anticipatory in response to the threat of climatic change. However, here anticipation is not easy as climate mitigation involves various sectors (like the energy sector) while climate impacts are related to a whole range of issues, including food security (IPCC, 2019a; Manhice et al., 2022), health (Costello et al., 2009), and cause economic losses in multiple areas (WMO, 2021).

It is, therefore, vital for climate change to connect the present to the future (Anderson, 2010; Rosen, 2012) to assess climate-related impacts and response strategies (anticipative actions) for both mitigation (GHG emission reduction) and adaptation (adjusting to changing conditions). Emission scenarios can provide a tool to evaluate the relationship between present actions and future emission levels (Riahi et al., 2017; UNEP, 2022), informing decision-making on the need for anticipative mitigation actions (IPCC, 2022a, 2018b; van Beek et al., 2020).

2.2.2 Anticipation as a governance mechanism

Anticipation processes are thus a key governance mechanism for dealing with uncertain futures and guiding policy actions. The ability to imagine and (via anticipative action) accordingly govern the future has become a core aspect of sustainability research and practices. This includes foresight practices, like scenarios, visioning processes, and games (Muiderman, 2022a). Anticipation has become a decision-making method of collecting information and data about essential societal aspects (Pedersen and Manhice, 2020; Shove et al., 2012) or behavior (Bourguignon, 2016). A large part of the work of the IPCC, as the most prominent institution on climate change, is also directly oriented towards anticipation (Tollefson, 2015; UN, 1973; WMO/UNEP, 1988).

However, interpreting anticipation in the sense of *predicting* the future is impossible. Given the large uncertainties and the possibility of human anticipative actions, the future is essentially unknowable (Riahi et al., 2017). This means that various viewpoints must be considered in envisaging the future (Roxburgh, 2009). Social science scholars have argued for understanding anticipation as a site of political negotiation (Anderson, 2010; Hastrup, 2012). Scientific knowledge must be understood in relation to power, articulated through and by individuals, creating a power-knowledge dialectic (Foucault, 1980). The struggle for and against policy regulation between decision-makers, industries, and researchers (Oreskes and Conway, 2010) shows this clearly. Parties use future expectations as part of the negotiations by either depicting continuous growth or the threats of future disasters and, for instance, replicate these images in the media to influence other actors (Appadurai, 1990), sometimes creating an increased public acceptance of regulatory actions (Henley, 2019). The degree of public acceptance of policy regulation could be seen as a “political operating space” for regulatory practice in a specific policy context.
The impact of anticipation is directly related to the threat, the ability to act, and the imminence. For instance, short-term anticipative actions towards terror and pandemics appear to have had more public and political backup than environmental and climate change policy regulations. The threat of pandemics and terror seem more apparent, and the relationship between actions and prevention is more transparent than in the more abstract case of climate change (with a long-term impact). While scientific knowledge has played a crucial role in understanding and acting on climate change as a political issue (Lahn, 2018), despite increasing scientific assessments and tools, the world has not yet reached an emissions peak (GCP, 2021a; Geden, 2016; Gütschow et al., 2021).

Anticipation theory is a plausible approach to climate justice, considering the future consequences of present actions and decisions. Anticipation theory literature sources (Anderson, 2010) is a basic premise concerning future climate change and scenario literature. Some sources communicate that climate change is not just an environmental issue but also a social justice issue (Anderson, 2010; van den Berg et al., 2020), which is also reflected in intergovernmental fora (IPCC, 2003, 1996; Paavola and Adger, 2002; UNFCCC/COP, 2022). Thus, overall, anticipation theory provides a framework for approaching climate justice that considers the complex and interrelated social, economic, and ecological dimensions of climate change.

2.3 Model-based scenario analysis

Scenario planning represents a key tool for anticipative actions (Akhmetzyanova, 2016; Anderson, 2010; Poli, 2017). The development of future anthropogenic greenhouse gas emissions (and thus climate change) heavily depends on uncertain socioeconomic development and political decisions in various contexts. These uncertainties can be explored through multiple emission scenarios. IPCC describes emission scenarios as plausible future greenhouse gas and aerosol emissions development pathways. Despite their common name (emission scenarios), they also include detailed descriptions of underlying socioeconomic activities such as population and economic growth, energy use, and land use. The emissions scenarios are used directly to inform climate policy but also serve as input for climate change calculations. Four generations of model-based scenarios have been used to inform the IPCC assessment reports (see further). These scenarios are among the most prominent scenarios in the scientific literature and policy assessment (O'Neill et al., 2020; Wilkinson and Eidinow, 2008).

Scenarios are qualitative descriptions of alternative futures. They are not forecasts or *predictions* of most likely futures but descriptions (or *projections*) of alternative futures that are plausible but not necessarily probable. They are typically based on different sets of assumptions about how various factors might evolve over time. Scenarios are used to explore the range of possible outcomes and to understand the potential consequences of different decisions or events (Riahi et al., 2017; Rogelj et al., 2019). In this thesis, scenarios, and pathways are sometimes used interchangeably in the results chapters, as is the case of IPCC reports (IPCC, 2023a, 2022a). In the literature, scenarios are sometimes used to describe the SSP narratives, while pathways are used in relation to the more abstract RCP emissions and radiative forcing pathways. I sometimes use the term *projections*, which are quantitative estimates of future trends based on data and assumptions. *Projections* are typically based on statistical models or other analytical tools. They are sometimes used to generate numerical future outcomes based on current trends. Scenarios, pathways, and projections are similar terms, aiming to inform science and may be relevant to inform decisions about resource allocation, policy development, and investment planning. Forecasts often include predicting likely futures based on frequency distributions (Webster et al., 2003).

Scenario planning allows various types of data to be processed for thinking and elaborating on the future. Some emission scenarios project anticipative actions implementing mitigation goals set by the global climate regime (UNFCCC, 1992; UNFCCC/COP, 2015a), while other scenarios overshoot policy targets (Gidden et al., 2019a). Given the involvement of both human development, technology, and earth system impacts, the scenario approach bridges the social and natural sciences, comprising sociological narratives and mathematical quantifications, describing and modeling how the world may evolve in different directions with different consequences (O'Neill et al., 2017; Riahi et al., 2017). So-called Integrated Assessment Models (IAMs) are used to construct scenarios and integrate information from various disciplines. It should be noted that proper validation of such models is impossible given the lack of repeatable experimentation (Oreskes et al., 1994; Rosen, 1985). Such models can only be evaluated in relative terms, realizing that they are constructions (Hastrup and Skrydstrup, 2013) and given the usefulness for their intended purpose (Oreskes et al., 1994).

IPCC originally developed its emissions scenarios (Girod et al., 2009; Moss et al., 2010a; Pielke and Ritchie, 2020). IPCC Working Group III (WG3) generated three series: the SA90 (IPCC, 1990a), the IS92 series (Leggett et al., 1992), and the SRES (Nakicenovic and Swart, 2000a). In recent years, the scientific community, independent of the IPCC, developed the current RCP-SSP scenarios (Moss et al., 2010; Riahi et al., 2017; van Vuuren et al., 2011a). The replacement of each scenario set by a new one was typically motivated by a combination of new scientific insights (Nakicenovic and Swart, 2000a; Parikh, 1992a) and a changed political context (IPCC, 1996, 1991; Moss et al., 2010a).

Figure 2-1 compares visualizations of the first scenario generation (SA90) and fourth emission scenario generation (SSP-RCP combinations). Interestingly, the communication of scenarios is merely unchanged. The four generations of scenarios form a key binding element between the three IPCC Working Groups (WGs) on 1) climate science, 2) impacts, vulnerability, and adaptation, and 3) mitigation strategies. In addition to the community scenarios, a large body of emission scenario work exists published by individual research groups. While IPCC also assesses this work, this is outside the scope of this study.

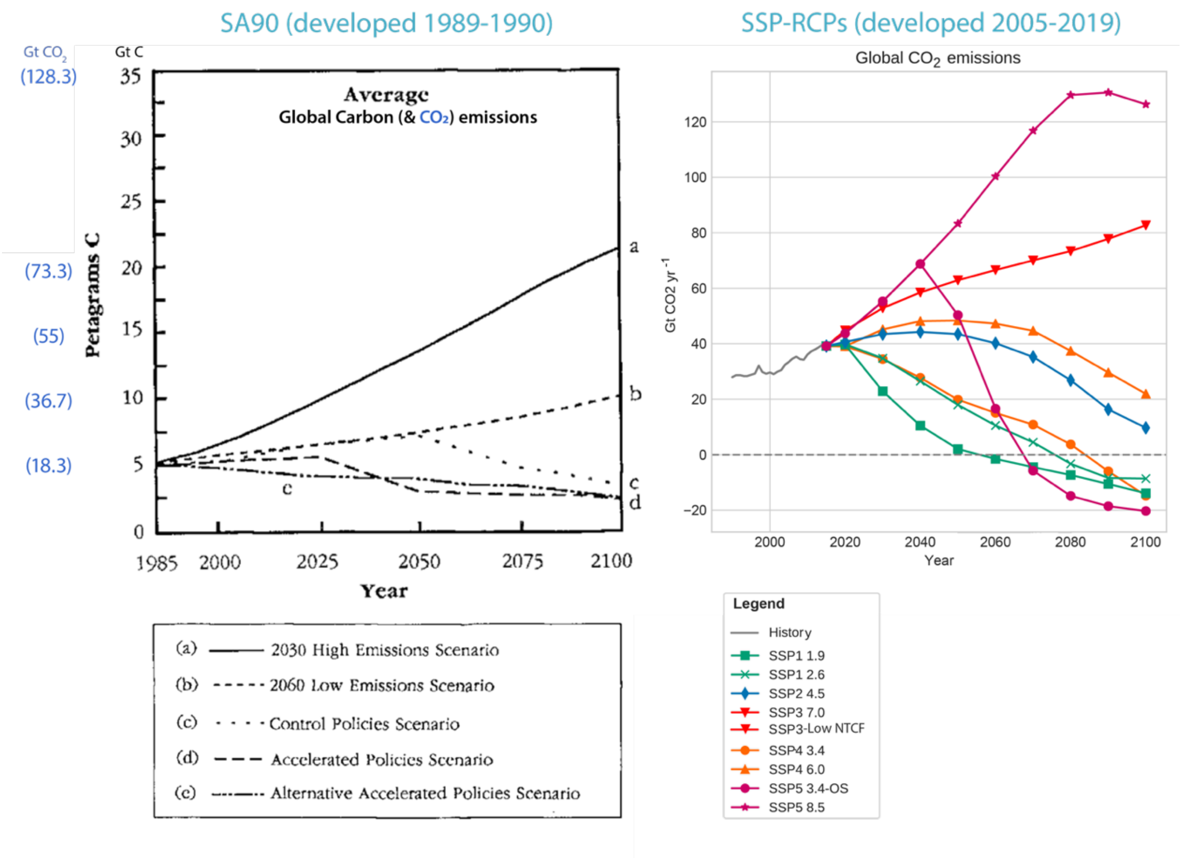

Figure 2-1. Communications or visualizations of the first (1990) and most recent (2019) emission scenario series informing the IPCC. a: 1st (SA90), b: 4th (SSP-RCP).
Based on graphics from IPCC (1990) and Gidden et al. (2019).

It is possible to examine the effectiveness of scenarios by assessing the criteria of saliency (relevance), credibility (accuracy), and legitimacy (development process and transparency) (Cash et al., 2003; Hulme and Dessai, 2008b). In this thesis, we evaluate the scenarios from different perspectives. For instance, the reasons behind the evolution of emission scenarios and their improvements and changes can be accessed via literature critiques 1990-2022 (Chapter 3). Credibility relates to the accuracy of scenario content (assumptions and numbers). Understanding the socioeconomic assumptions of the scenarios and how they relate to the real world is crucial to understanding the need for scenario updates: for example, how scenarios relate to historical data (Chapters 4-5). The salience of knowledge is assessed from a policymaker's perspective in Chapter 6.

2.3.1 State of the Art of emission scenarios informing the IPCC

Scenarios are regularly debated. Such debates include evaluations about the use (or overuse) of specific scenarios (Hausfather and Peters, 2020; Pielke and Ritchie, 2020) and the choices of climate scientists and energy modelers regarding how to describe or present plausible futures (Castles and Henderson, 2003b; Parikh, 1992a; Jr. Pielke et al., 2008). One recurring type of criticism involves their performance, notably that projected emissions may be too conservative (Peters et al., 2013; Jr. Pielke et al., 2008) or exaggerated (Castles and Henderson, 2003b). A detailed comparison of the emissions scenarios with observed emissions over the last 30 years (GCP, 2021) and an analysis of global/regional discrepancies (GCP, 2019; Peters et al., 2011) may improve the understanding of how short-term and long-term drivers determine emissions (van Vuuren et al., 2010). The number of critiques indicates that scenarios are not neutral or 100% objective. This means scenarios include selected assumptions, implying plausible normative selection that may conform to certain time-specific cultural or social norms. Furthermore, models created by a few researchers may have a potentially global impact on science and policy. The emission scenarios informing the IPCC were developed by global North modeling institutions (Riahi et al., 2017), with some support from Chinese and Indian modeling groups (JGCRI, 2017). This may create a global North-friendly bias in the assumptions.

Although the scholarly literature has reviewed the role of IPCC, it has not reviewed and assessed the collection of emission scenario critiques and their impacts on scenario development. Filling these knowledge gaps would improve the basis for assessing future climate change and impacts based on the current emissions and climate change scenarios (SSP-RCP) (Moss et al., 2010a; O'Neill et al., 2016). It is, moreover, informing a discussion on the need for rewriting or designing a new set of emissions scenarios that may be needed now. The international climate governance landscape has changed because of the Paris Agreement (Peters et al., 2017), technological (IEA, 2019), and socioeconomic developments (Hausfather and Peters, 2020), and COVID and the war on Ukraine (Santos et al., 2022). Additionally, the policy relevance of emission and climate scenarios are often debated by researchers (and modelers) (Cline, 1991; Hausfather and Peters, 2020; Schenk and Lensink, 2007; Schneider, 2001), while the literature presents very little detail about the policymakers' and politicians' relationship to scenarios (Kok et al., 2019b, 2007; Patel et al., 2007). We know little about scenarios' role in guiding UNFCCC negotiations and international policymaking (e.g., argumentations and trade-offs). However, this is highly relevant for assessing and improving the processes for anticipating climate change, as stated in the UN Sustainable Development Goals (SDG13) and improving intergovernmental conventions for sustainable and long-lasting international partnerships (SDG17) (UN, 2015b).

2.3.2 The concept of long-term emission scenarios

Scenarios are typically expressed both in words (assumptions and storylines) and numbers (model quantifications) (Raskin et al., 2005; van Vuuren et al., 2012).

- A "Storyline" is a physically self-consistent unfolding of past events (Shepherd et al., 2018) or pathway descriptions of plausible future societal evolutions (O'Neill et al., 2017; Riahi et al., 2017). These qualitative elements provide the logic underlying the quantitative scenario elements.
- The storylines are used to run quantitative simulations and categorize simulation results into types of futures, creating numbers. Typically, this is done for variables related to economic and population growth, energy systems, land use, and emissions. In most cases, scenarios are explorative, meaning no probabilities are assessed. Instead, the emphasis is placed on understanding the driving factors involved and the plausibility of those sometimes-interconnected factors (Schweizer and O'Neill, 2014). No *a priori* probability of the storyline is assessed (O'Neill et al., 2017). This contrasts with forecasts and scenarios based on frequency distributions (Schneider, 2001). Some variables are challenging to project quantitatively, like the quality of institutions, political stability, and environmental awareness.

Figure 2-2 illustrates how quantitative analyses require assumptions for variables such as population, economic growth, or technology advances that can serve as inputs to models of energy use, land use, emissions, and other outcomes (O'Neill et al., 2017; Riahi et al., 2017).

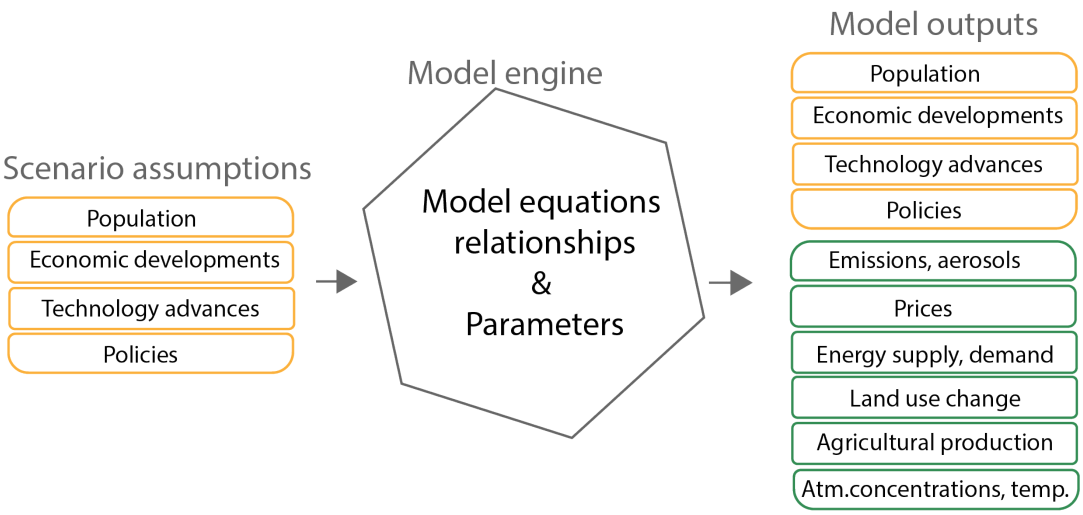

Figure 2-2. Conceptual diagram of a generic emission scenario model and a few key variables

IAMs producing socioeconomic (e.g., GDP) and energy pathways, resulting in emission pathways, have four fundamental components (Riahi et al., 2017):

1. **Scenario drivers**: the critical input assumptions. Those that come from outside the model, e.g., population, economic growth, technology characterizations, resource capabilities, societal/political value preferences (often economy vs. sustainable development), and policies.

2. **The model structure**: the fundamental relationships between the input drivers and the model outputs (emissions, aerosols, pollutants). They comprise the quantitative model's equations.

3. **Model parameters**: the set of data that transforms a model's equations into exact relationships, i.e., the parameters define specific model behaviors. Some are interdependent parameters, e.g., high education leads to low population and technological developments. Some of the model parameters are set. Others define the interrelationship between variables, e.g., that low education leads to high population growth and low technology advances, e.g., the high use of traditional biomass in SSP3, compared to other scenarios (see variables in the SSP Database: Riahi et al., 2017).

4. **The model outputs**: the variables and values produced by the model, e.g., energy and land use data, GHG and air pollutant emissions

Typically, scenarios are developed as a set providing contrasting, plausible, and selected narratives about how the future might unfold (Raskin et al., 2005). A few storylines are chosen, constraining the infinite possibilities and ways to conceptualize the future (Schweizer and Kriegler, 2012). The scenario range is crucial, and the embedded uncertainty about the future is a key reason to explore multiple possible scenarios translated into emission trajectories. Here, scenario models can project low emission scenarios reaching the Paris targets, intermediate trajectories consistent with current expectations or historical trends, and high-impact cases (Gidden et al., 2019b; Moss et al., 2010; van Vuuren et al., 2011). The latter is essential for adaptation policy (Lawrence et al., 2020; Pedersen et al., 2020).

There er multiple ways of telling these stories. Low emission trajectories are often explained by value change from economic to sustainable public and policy focus (Nakicenovic and Swart, 2000a; Riahi et al., 2017). Alternative low-emission storylines not included in the long-term scenarios informing the IPCC comprise discontinuity narratives (Raskin and Swart, 2020), like ecosystem breakdowns (Pereira et al., 2021) and the global North concept of degrowth (Lenzen et al., 2022), which is hardly represented in the global South. Intermediate scenarios can be narrated and quantified based on historical dynamics and trends (Riahi et al., 2017). Short-term societal variabilities, like economic crises, may not affect long-term trends (van Vuuren et al., 2010) as described in the scenario narratives (Riahi et al., 2017), e.g., outlined via the Central Limit Theorem (CLT)[6] (Gordin, 1969). The CTL of historical data is one of several combinations that lead to medium growth of emissions. Others may represent medium policy ambitions or population declines combined with increased per capita consumption.

2.3.3 Three types of scenarios connect IPCC Assessment Reports

The outcome of a) emission scenarios are used as input for b) climate change scenarios, which are subsequently used as input for c) impact scenarios (IPCC, 1990d, 1990c). These three types of

[6] CLT is a fundamental concept in statistics and probability theory, stating that, under certain conditions, the sum or average of a large number of independent and identically distributed random variables will be approximately normally distributed, regardless of the shape of the original distribution. In other words, if you take repeated random samples from any population with a finite mean and standard deviation, the distribution of the sample means will approach a normal distribution as the sample size increases.

long-term scenarios cut through the three IPCC working groups (WGs). The interconnection between them is illustrated in Figure 2-3.

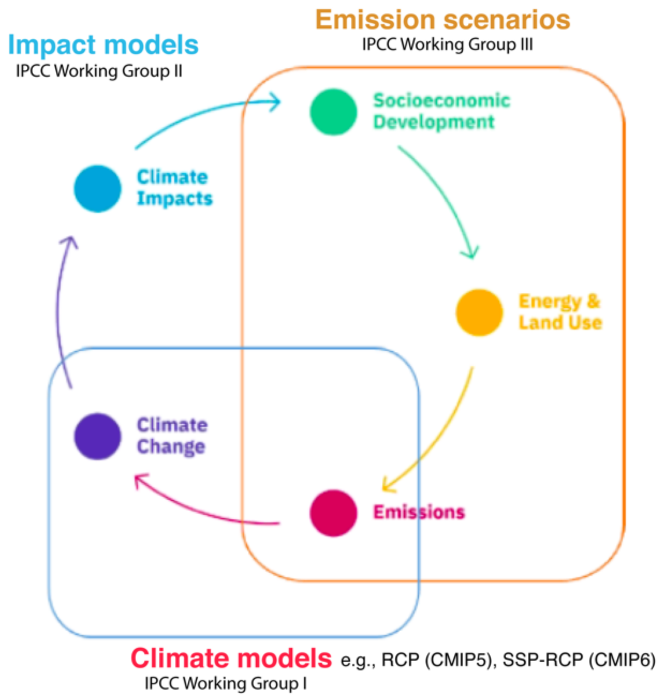

Figure 2-3. The Interconnections between the three types of scenarios and how scientific papers using emission scenarios, climate scenarios, and impact scenarios inform WG3, WG1, and WG2 of the IPCC

These different scenario types are instrumental for analyses of future climate change, impact assessment, and mitigation strategies. Because impact scenarios are based on the two others, they are often analyzed later, meaning that the impact scenario literature has sometimes been implemented later in the IPCC WG2 assessments (see Figure 3-2). It should also be noted that uncertainty piles up through the system, e.g., human development and climate policy, climate system uncertainty, and resilience of impacted systems.
This also means that the quality of scenario projections in the first step, e.g., relationships between drivers and emissions, has considerable consequences for the accuracy of climate change analyses and impact assessments. Thus, validating emission scenario ranges is relevant (Chapters 4-5) for sufficiently informing science and decision-making. In addition, it is crucial to evaluate the historical (and future) relationships between drivers and emissions to adjust assumptions and calibrate models.

2.3.4 Relationship with chapters in this thesis

Emissions scenarios should be plausible in economic structures, demographics (O'Neill et al., 2017), and energy systems (Bauer et al., 2017). One way to evaluate this is by comparing history with scenarios, and it has not been assessed since 2006 using 1990-2000 data (van Vuuren and O'Neill, 2006). Thus, the thesis evaluates the credibility of past projections 1990-2018 for the four scenario generations (Chapters 4-5). One development challenge (legitimacy) that is potentially related to the scenario content (and credibility) is the strong connection of models to primarily global North institutions (Riahi et al., 2017), potentially reproducing specific cultural perceptions about the relationships between policy, societal aspects, and future emissions and dominant discursive frameworks. Thus, the thesis will review the scientific perspectives on scenarios over time (Chapter 3), assess the relationships between global South and North emissions and drivers (Chapters 4-5), and discuss how these connect to scenario variables and assumptions (Chapter 7).

Another challenge is the uncertainty of how conceptualizations of the future drive present actions and their implications for realizing sustainability transformations (Muiderman et al., 2020a). Two critical issues in anticipation are how the anticipative models connect to real life (Hastrup, 2012; Rosenblueth et al., 1943), which relates to how they include relevant aspects in the anticipative models to connect the present with plausible futures. Here model assumptions about purposeful (Rosenblueth and Wiener, 1950) climate actions may or may not appear purposeful for real-life actors (e.g., UNFCCC parties). Thus, the thesis will explore and discuss several connections between the UNFCCC policy context and Paris-Compliant scenario assumptions, e.g., related to climate justice (Chapter 7).

2.4 The Science-Policy Interface

It is crucial to bridge the gap between knowledge and action to achieve sustainability through scientific evidence. This can be done by enhancing the information's credibility, legitimacy, and salience (Cash et al., 2003; Hulme and Dessai, 2008a). Here it is essential to establish institutional mechanisms that promote effective communication, translation, and mediation across boundaries. Doing so can create a more effective and efficient system toward sustainability (Cash et al., 2003).
This section describes the science-policy interface, the process by which science and policy communities work together to inform decision-making. IAMs have become a standard method for imagining plausible futures to inform decision-making (IPCC, 1990a; Moss et al., 2010a). They cut across various scientific disciplines and prominent norm-setting institutions like the scientific Intergovernmental Panel on Climate Change's Assessment reports and the United Nations Environment Program's Global Environmental Outlook (Muiderman, 2022), and the political United Nations Framework Convention on Climate Change's Conferences of the Parties (COPs) (UNFCCC, 2020a).

Since IAMs aim to inform policymaking, the section focuses on science-policy interactions, knowledge production, and climate justice. These are considered a context for improving the quality of scientific knowledge communication to support decision-making processes. These processes include various interaction forms, where scientists transmit knowledge to policymakers, where policymakers request specific policy-relevant scientific knowledge, and sometimes co-production processes, where knowledge, tools, or policies are co-created (boundary objects). The section discusses the concept of boundary objects and how it applies to emission scenarios developed with input from multiple fields and disciplines and interpreted differently by various groups, including scientists, governmental technicians, policy advisors, and policy enablers. Boundary objects may simultaneously project contrasting interpretations, which can support conceptualizing what science wants to do with the tool, what it comprises and expresses, and how and who uses it. Finally, the section highlights the importance of climate justice within the UNFCCC and how it guides transition pathways. Justice principles sometimes guide transition scenarios. Thus, they are relevant to assess scenario salience, connecting the context-dependent and value-laden processes of how governments and interest groups negotiate competing options.

2.4.1 The science-policy interface

At the international level, there are many examples of how science is used to inform policymaking, for instance, as part of the Montreal Protocol (MP) to protect the ozone layer (IISD, 2022; Kohler, 2020; UN, 1989), the UN Sustainable Development Goals (SDGs) (Fritz et al., 2019), and the Paris Agreement (UNEP, 2022). The scientific and policy communities have worked together for at least 50 years (since the Stockholm Convention (UN, 1973)) on international human rights and environmental issues such as stratospheric ozone depletion and climate change, including international assessments providing a scientific basis for informed international and national decision-making (Kohler, 2020; Watson, 2005). The Science-Policy Interface (SPI) in the environmental field has developed from the past global institutions of SPIs under the Montreal Protocol to a landscape of subsidiary SPIs, with agendas set by parties to a treaty and stand-alone SPIs with their designated governing bodies (IISD, 2022; Kohler, 2020).

The science-policy interface can be defined as "social processes which encompass relations between scientists and other actors in the policy process, and which allow for exchanges, co-evolution, and joint construction of knowledge intending to enrich decision-making" (van den Hove, 2007). It focuses on solving similar issues, potentially triggering an effective science-policy interface (Burton et al., 2019), and may inform intervention, influence research, and guide funding (Fuller et al., 2011). The IPCC and UNEP are essentially for fostering communication and cooperation between researchers and decision-makers (Gustafsson and Lidskog, 2018) and closing the gap between scientific knowledge and policy goals (Burton et al., 2019).

2.4.1.1 Science-policy interaction

Figure 2-4 presents a simplified overview of a science-policy process cycle and science and policy actors' responsibilities in producing and implementing evidence-based climate policies. Scientists produce knowledge (1) assessed and synthesized in IPCC reports (2), aiming to inform intergovernmental and national decision-making (3) and policy implementation (4). Finally, the UNFCCC, IPCC, and science assess the implementation efforts (den Elzen et al., 2019; UNFCCC, 2021c), again informing science (Carvalho et al., 2020).

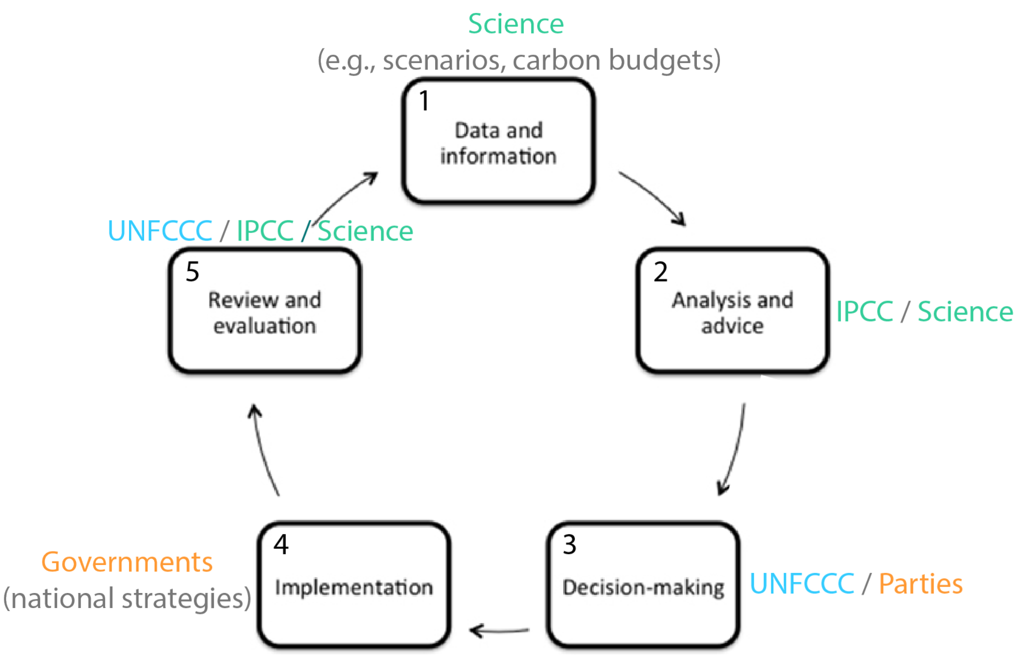

Figure 2-4. Science policy cycle and key actors (Science, UN organs, and governments). The figure is a modified version of McConney et al. (2016).

The information, implementation, and evaluation processes regarding global mitigation involve the use of carbon budget assessments (Friedlingstein et al., 2022), short-term (UNEP, 2022), and long-term scenarios (Rogelj et al., 2019; van den Berg et al., 2020). Notably, scientific recommendations may change as new insights and uncovered grounds are covered.

Scientific knowledge may improve the quality of decision-making processes (Geden, 2016; Strydom et al., 2010). It requires that scientific knowledge is communicated in a policy-relevant way (salience), collected and analyzed using proper scientific methods (credibility) and developed via correct procedures and processes (legitimacy) (Hulme and Dessai, 2008a; Siwale, 2018). Researchers often use detailed and, therefore, non-transparent assumptions and methods, whereas policymakers require to-the-point information for decision-making (Burton et al., 2019; Santos et al., 2022; Sarkki et al., 2014). This exemplifies the importance of communicating scientific insights to decision-makers (non-specialists) in an easy-to-understand way rather than detailed technical knowledge. In 1991, researchers made a traffic-light assessment of temperature limits: Green (<1 °C) limited damage; orange (1-2 °C) extensive damage; and red (social and economic disruption) (Vellinga and Swart, 1991). It was received as a recommendation for staying below 2 °C, guiding policy objectives (Morseletto et al., 2017). Despite this, intergovernmental negotiations took 25 years to implement the scientific knowledge about the 2 °C and 1.5 °C limits into the Paris Agreement's temperature goals (Dimitrov, 2016; Morseletto et al., 2017). Part of the complications relates to the general challenge of integrating and reaching a consensus over scientific evidence. Not until 2009, 18 years after the scientific 'recommendation' or political translation of the scientific traffic light projections, all countries agreed that anthropogenic GHGs cause climate change (UNFCCC/COP, 2009).

2.4.1.2 Epistemological Challenges and possible bias in the scenario literature

There are various limitations to the knowledge we produce. It is not without importance where we are coming from, grew up, where our research is situated and in which time period. Politically motivated funding is guiding research, e.g., resulting in a "following" role in policymaking of some scientists. Thus, science in, e.g., the US, India, China, and the EU may take different pathways depending on the funding topics offered and the region's political and public debate. Scholarship on climate change is mainly produced in the global North, with some countries in the global South also contributing. When this is assessed in the IPCC documents, this bias gets exaggerated as scanning the IPCC bibliographies shows persistent North-South inequalities in IPCC authors, balanced towards the global North (Corbera et al., 2015; Hughes and Paterson, 2017a; IPCC, 2022b, 2021) and because choices are often made to exclude certain kinds of science (e.g., nor peer-reviewed science, indigenous knowledge, or because some issues are seen as 'relevant') (Corbera et al., 2015; Hughes and Paterson, 2017). Additionally, scenario developments are concentrated in global North institutes (Riahi et al., 2017), with the inclusion of Chinese, Brazilian, and Indian modeling teams (CD-LINKS, 2019; ENGAGE, 2022; PLB, 2019; WCRP, 2020). As interest between North and South is different (e.g., responsibility and impacts), this difference in research capacity is essential. In addition, most scenario developers are economists or engineers - looking at the world from a certain perspective (expert interviews) and generally exclude anthropologists, political scientists, and legal scholars.

Producing policy-relevant knowledge is challenging. First, policy relevance is not stable over time, and it may differ for different policymakers and between various policy contexts. Second, different policy questions require different scientific information. This can lead to differences between, for instance, policymakers working on strategic questions vs. specific policy implementation; or those working on mitigation vs. adaptation.

Historically, differentiated perspectives on climate change exist. The global warming effect was discovered almost 200 years ago (Arrhenius, 1906; Fourier, 1824; Tyndall, 1863), fully described during the previous century (Plass, 1956), and has led to scientific consensus (Oreskes, 2004a) since at least 1988 (WMO/EC/UNEP, 1989). However, differentiating viewpoints exist on what is essential regarding climate change policy among scientists, companies, politicians, policymakers, and other social actors.

The contemporary political perspective or consensus may reflect societal knowledge production. During the 1970s and 1980s, the fossil energy industry was causing climate change (Duarte Santos, 2021; Santos et al., 2022) and simultaneously promoting climate denial (Dunlap, 2013; Dunlap and Jacques, 2013; Santos et al., 2022). Such discrediting of climate change science may have caused epistemological challenges related to the goals and preconditions of knowledge and affected how knowledge was generated (Egger and Yu, 2022), e.g., as opposition to climate denial by researchers (Oreskes, 2004b; Oreskes and Conway, 2010) or opposition to mainstream climate science by so-called climate deniers (NIPCC, 2011) or IPCC skeptics (Castles and Henderson, 2003a). The passive role of politicians in mitigating climate challenges led to scientific frustration (Anderson and Bows, 2011; Geden, 2016). Scientists are discussing whether they can act as 'honest brokers' or need to take a more active role. This also means that researchers have been accused of exaggerating climate assessments to push and accelerate policy actions (Risbey, 2008) as, for instance, happened during the Climategate debate (McKie and Thorpe, 2021).

2.4.1.3 The policy relevance of scenarios is not self-evident

It is easy to reproduce a scientific understanding within scientific communities that emission scenarios are relevant to or used in policymaking. However, policymakers consider multiple aspects in designing (climate mitigation) policies. Scenarios are central to scientific knowledge about future climate change and response strategies. They aim to inform policymaking but do not necessarily play "a key role" in designing climate policy. Interests expressed by the public and stakeholders (e.g., fossil energy (Dunlap and Jacques, 2013) and cement companies (Martini, 2022)) sometimes contradict certain policy types or design elements, as well as other government objectives such as the general public's practices and lifestyle (e.g., tourism, consumption), and affordability, job creation, and competitiveness of trade-exposed emissions-intensive sectors that are often seen to go against climate objectives (Jaccard, 2016; Lodhia and Martin, 2012). Sometimes, private sector interests intersect with the public interest (Lodhia and Martin, 2012) or state interests. This needs to be addressed seriously in the scenario and mitigation policy science regarding emission scenarios' actual policy usability and relevance. In essence, emissions scenarios are not the only key to understanding climate change and designing climate policy.

2.4.2 Emission scenarios as boundary objects

The boundary object concept originated in the field of the sociology of science and technology studies (STS) (Star and Griesemer, 1989a; Trompette and Vinck, 2009), referring to objects with different localized meanings and usage in various groups where meaning can be established across social boundaries (Morseletto, 2017; Star, 2010). Model-based scenarios have multiple users and are developed via input from various fields and disciplines. Thus, they are often interpreted as boundary objects (Girod and Mieg, 2008; Hulme and Dessai, 2008a). A boundary object can be, e.g., an artifact, discourse, product, instrument, or tool (e.g., a map, policy roadmap, scenario) used differently by various groups, professions, or co-created via different disciplines (Star, 2010), like scientists, governmental technicians, policy advisors, and policy enablers (designing and negotiating policies). They may simultaneously project contrasting interpretations (Franco-Torres et al., 2020).

Regarding scenarios,' boundary object' may support conceptualizing what science wants to do with the tool, what it comprises and expresses, and how and who uses it (Gustafsson and Lidskog, 2018; Guston, 2001). Scientific tools informing decision-making, like scenarios, cannot emerge solely as a scientific product (Hulme and Dessai, 2008b). The three generations of IPCC scenarios were developed via intergovernmental processes within the IPCC panel, discussing purposes and shaping scenario content and development processes (IPCC, 1996, 1991, 1989a). As the panel recommended, modelers consulted societal institutions to develop the third and fourth scenario generations (IPCC, 2007a; Nakicenovic and Swart, 2000). In addition, several national and regional scenario extensions were developed via stakeholder and policymaker co-creation (Kok et al., 2019b, 2007; Patel et al., 2007).

Generally, researchers are divided on cooperation between the policy and science fields. In the literature, such a split is expressed as a co-productive *one-world* versus a separated *two-world* (Sundqvist et al., 2018). Based on this scientific discussion, Chapter 6 examines policymakers' perceptions of including policymakers in scenario developments. In addition, the historical development of scenarios is assessed in Chapters 3-5, implicitly inspired by the below presented science-policy interactions. As illustrated in Figure 2-5, scientific knowledge to support policymaking can be developed through various science-policy processes between scientifical knowledge producers and political knowledge users (Chen, 2022).

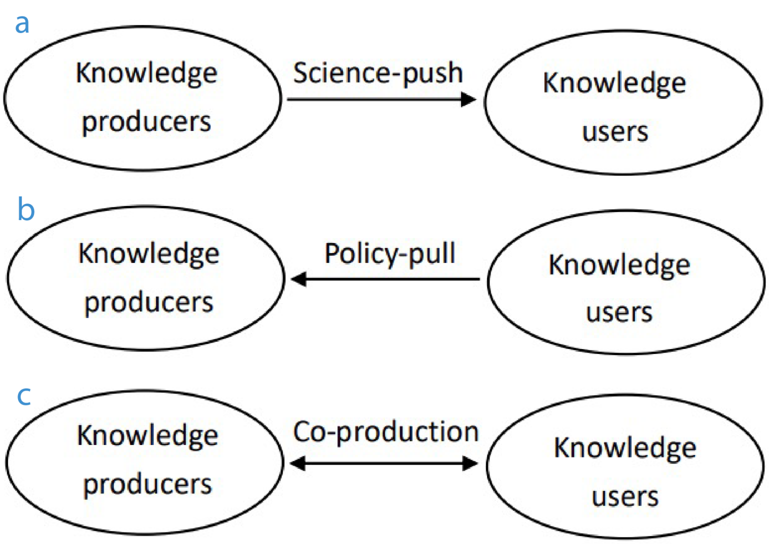

Figure 2-5. Science-Policy process models.
Three classic processes of science-policy interactions. The figure is modified from Chen (2022).

Figure 2-5a exemplifies a science-push process, where knowledge-oriented scientists transmit knowledge to policymakers. Ideally, researchers aim to objectively inform science, society, and policy (van Beek et al., 2020). One example is the net-zero GHG strategies and deadlines presented in the IPCC 1.5 pathways (IPCC, 2018a), implemented in several national NDC targets (Frayer, 2021; Rogelj et al., 2021; The Economist, 2022). Complications may arise if scientists cross the line of objectively informing policymakers (Radaelli, 1995). An example is the "Climate-gate" controversy following the IPCC AR4 report (IAC, 2010; Risbey, 2008) (IAC, 2010b), resulting in mistrust towards the IPCC for pushing policy actions (IAC, 2010; Kintisch, 2010). Notably, the distinction between objective and subjective is not clear-cut. Researchers may unintentionally produce biased knowledge or leave out important information in scenarios because of their scientific, social, or cultural embeddedness rather than deliberate 'miscommunication' (Haraway, 1988; Sjørslev, 2015). For example, introducing net zero may not be neutral/objective as it opens the doors for postponing action.

Figure 2-5b presents another linear science-policy relationship, the policy-pull or demand-driven process, where policymakers (or stakeholders) request specific policy-relevant scientific knowledge (Chen, 2022). Scientists generally work on funded research, and research funding is almost always geared toward specific policy goals. An example is the UNFCCC COP request for 1.5-pathways (Kriegler et al., 2017b), later developed and published in the IPCC 1.5 Special Report (IPCC, 2018a). Other policy-demand processes comprise politically defined funding, like the EU's Horizon 2020 program (EC, 2015), pulling researchers to address specific topics (Chen, 2022). Conversely, under Trump, research priorities shifted away from environmental and other risk-related research, emphasizing deregulation and reducing what they perceived as burdensome regulations on industries, including those related to environmental protection (Gibbens, 2019).

Figure 2-5c presents co-production processes, expressing situations where knowledge, tools, or policies are co-created (boundary objects). Sometimes, policymakers are invited to participate in scenario developments (Patel et al., 2007). Co-creation may also emerge gradually via the interplay between science and policy negotiations over time, exemplified by the 1.5 °C target (Morseletto et al., 2017) and the translation of actions needed to reach it. This may also create a bias toward the interests of those policymakers and stakeholders invited to participate in such scenario-building processes.

2.4.2.1 Paris Compliant Scenarios and Just Transition

Achieving the energy transition necessary to meet the Paris goals may have winners and losers. To ensure a just transition, it is crucial to consider a wide range of information on transition pathways at various scales: international, intra-national, and inter-generational. Historically, the concept of climate justice is essential within the UNFCCC, e.g., national responsibilities and capabilities (UNFCCC, 1992; UNFCCC/COP, 1997). Opposing studies have addressed mitigation implications regarding timing for intergenerational equity (Nordhaus, 2007; Stern, 2007). Clear optimum global solutions (Incropera, 2015; Rittel and Webber, 1973; Sun and Yang, 2016) emphasize difficulties associated with long-time scales concerning several social generations (IPCC, 2023), bringing in questions of intertemporal choices, time discount rates, and the social price of carbon (Nordhaus, 2017, 2007; Stern, 2007).

Box 2-1. Country groups in the UNFCCC based on obligations and capabilities

The United Nations Framework Convention on Climate Change (UNFCCC) divides countries into different groups (annexes) based on their specific obligations and responsibilities in addressing climate change:

- Annex I: The countries listed in Annex I of the UNFCCC are the so-called industrialized or developed. *The term developed refers to economic and technological advances, but not sustainable development.* These countries have historically (post-1990) been the most significant emitters of greenhouse gases and have assumed the primary responsibility for mitigating climate change. They are expected to take the lead in reducing their emissions and providing financial and technological support to developing countries. Annex I countries include members of the Organisation for Economic Cooperation and Development (OECD) and countries with economies in transition.
    - Annex II: a subgroup of countries listed within Annex I. Annex II countries are the high-income developed countries expected to provide financial resources and support for climate change mitigation and adaptation efforts in developing countries. These countries have a greater capacity to provide financial assistance, technology transfer, and capacity-building measures due to their higher levels of economic development.
- Non-Annex I: countries consist of developing countries that are not expected to have the same level of responsibility for mitigating climate change as Annex I countries. These countries generally have lower levels of greenhouse gas emissions and are often characterized by their relatively lower levels of economic development.

It's worth noting that the categorization of countries into annexes under the UNFCCC has not evolved much over time. Thus, I made new classifications for categorizing the survey participants (country representatives) for Chapter 6 (Pedersen, 2022): https://osf.io/5qctp/. However, the country's responsibilities have evolved from top-down binding targets to bottom-up volunteer and non-binding national targets. Paris Agreement introduced a different framework, compared to the Kyoto Protocol, for differentiating countries based on their circumstances and capabilities (UNFCCC/COP, 2015a). The KP relied solely on top-down negotiated Annex-I and Annex-II mitigation targets (Oberthür and Ott, 1999a; UNFCCC/COP, 1997).

In the UNFCCC terminology, the so-called developed Annex-I parties (42 industrialized countries and economies in transition) are considered historically responsible for climate change and therefore obliged to reduce emissions under the Kyoto Protocol (and the Doha Amendment) (UNFCCC/COP, 2012, 1997). With high financial and technological capabilities, developed countries (Annex-I and II parties) are called upon to support developing countries financially under the Paris Agreement (UNFCCC/COP, 2015a). The countries labeled developing non-Annex-I comprise 151 parties. Given the massive pollution caused by Annex-I high-income countries, companies, and people, it is noted that the term developed is inappropriate.
Countries' historical responsibility for climate change and their financial capabilities to mitigate and adapt is embedded in intergovernmental negotiations (Bhardwaj et al., 2018; Oberthür et al., 1999). The Common but Differentiated Responsibilities and Respective Capabilities (CBDR-RC) comprise two fundamental justice principles aiming to operationalize equity (UNFCCC, 1992;

UNFCCC/TWN, 2019). These principles have not always guided decisions (Evans et al., 2021) or practical implementation of decisions (Timperley, 2021). The CBDR principle comprises at least five sub-categories: human development, economic capacity, resilience to climate impacts, governance capacity, and technology and innovation capacity (Klinsky et al., 2016). The underlying ethical considerations concern international and intercommunity equity (Klinsky et al., 2016; Vojnovic, 1995), addressing historical polluting countries (Evans, 2021) and industrial producers (Frumhoff et al., 2015) like the fossil industry (Gabbatiss and Tandon, 2021; McCright and Dunlap, 2003).

The Convention (UNFCCC) initially asked Annex-I to adopt policies and measures on mitigation and report annual GHG inventories by sources and removals by sinks (UNFCCC, 1992) based on IPCC methodologies (IPCC, 2019, 2006a). Reporting depends on capabilities and report preparation funding, meaning that non-Annex I Parties are obliged to submit their inventories and mitigation and adaptation actions less frequently (UNFCCC, 2022a), reflected in the UNFCCC inventories database (UNFCCC, 2022b).
The CBDR principle is not fixed in terms of its definition, formulation, legal nature, and practice and has contributed to a climate negotiation standstill (Deleuil, 2012). Its definition is multiple and translated differently in the Kyoto Protocol (KP) and Paris Agreement (PA). The PA changed the translation or definition of "differentiation" to be more dynamic, flexible, and politically acceptable (Klinsky et al., 2016), which may complicate analyses of effort sharing in Paris-Compliant scenarios. The KP had top-down negotiated targets, while PA presented a bottom-up approach where parties decide mitigation targets via their nationally determined contributions (NDCs) (UNFCCC/COP, 2015a, 1997). The respective capabilities principle of the PA refers to those that can help others mitigate and adapt to climate change encouraging primarily Annex-I (UNFCCC/COP, 2015a), while the CBDR is more explicitly represented by Annex-I countries' obligations to compensate several non-Annex-I for climate change loss and damages (UNFCCC/COP, 2022).

Box 2-2. Examples of climate justice asymmetries with relevance for scenarios

Climate change is viewed as an intra-generational and inter-generational global challenge addressed by ethical principles aiming to inspire and guide real-world responses. They are sensitive and heavily negotiated within the UNFCCC (UNFCCC, 1992; UNFCCC/COP, 2022) but primarily raised by non-Annex-I parties (Dimitrov, 2016, 2010). Often, attention have been centered around the North-South economic aspects of justice, e.g., addressing the CBDR-RC principles, historic responsibility and country capabilities (UNFCCC, 1992; Voigt and Ferreira, 2016), Other crucial issues may concern gender, generations, consumer vs producer emissions (emissions export) (Peters et al., 2012).

Justice asymmetries are often related to inter- and intra-generational injustice (Leichenko and Silva, 2014; Rozanova et al., 2006), caused by the delay in mitigating the GHG emissions produced by current generations and anticipating the negative impacts for future generations (Santos et al., 2022).

- One justice concern seeks to tackle the asymmetries between individuals in developing and developed countries (international justice) and inside each country (intra-national justice), concerning capacities, contributions, and institutional responsibilities in GHG emissions, mitigation, and adaptation responsibilities (Santos et al., 2022; UNFCCC, 1992; UNFCCC/COP, 2015a).

- A second asymmetry concerns vulnerability to climate impacts, primarily people living in developing countries (OECD, 2018; Santos et al., 2022) with low adaptation capabilities (ND-GAIN, 2020; UNFCCC/COP, 2021).

- Concerning intergenerational injustice, most existing people were not born in 1990 (UN, 2018).

- Intra-generational often focuses on age and gender. In developing countries, poor people and women are most vulnerable to harmful climate impacts (Nellemann et al., 2011), with girls and women often experiencing more challenges from climate change impacts. This intensifies existing gender inequalities, threatening female livelihoods, health, and safety. One reason for this is that worldwide, women have less access to but depend more on natural resources (UNWomen, 2022).

In essence, Climate change disproportionately affects vulnerable and marginalized communities (Muiderman, 2022b) and the asymmetries are argued to increase poverty, gender vulnerability, hunger, malnutrition, health, insecurity, and climate change-induced migration of vulnerable populations (Daoudy et al., 2022; Dellmuth et al., 2018; IPCC, 2022b; Terry, 2009). **Scenarios** are yet to embrace consensus on socially, culturally, and politically diverse future images into the narratives (Muiderman, 2022b), justifying an increased focus on the inclusion of equity, fairness, and the distribution of burdens and benefits in scenario development and policy recommendations is crucial. Thus, a manual on climate change ethics might be relevant for guiding decision-making, e.g., on how to distribute investments between mitigation and adaptation and how to balance the costs and benefits of mitigation measures (and non-climate benefits) of emissions reductions- guiding a just transition away from a fossil-fuel-based global economy (Santos et al., 2022).

There is a broad and growing literature on climate justice, arguing that the concept of climate justice is essential for the elaboration and implementation within the UNFCCC (Gupta, 2014; Lahn, 2018; Newell et al., 2021; Okereke and Coventry, 2016; Warlenius, 2018). Within intergovernmental fora (the IPCC and UNFCCC), the concept of climate justice is critical. Climate justice principles are fundamental in the global South (Parikh, 1992a) and frequently discussed within UNFCCC COPs, however with less interest among global North parties (Dimitrov, 2010; UNFCCC/COP, 2022b). IPCC trust is built through the collective expertise, rigorous methodologies, and consensus-building processes employed by the scientific community (IPCC, 2023b). Understanding the science, scenarios, and behind-lying variables used to provide future climate change analyses is a premise for trusting IPCC assessment reports and the scientific knowledge produced in the community (IPCC, 1996; Parikh, 1992a), especially for global South policymakers (IPCC, 2023a).
In the science community, justice principles sometimes guide transition scenarios (Li and Duan, 2020; van den Berg et al., 2020). Most scenarios do not have explicit assumptions regarding global equity, environmental justice, or intra-regional income distribution (IPCC, 2023). The IPCC considers itself neutral concerning the assumptions underlying the scenarios in the assessed literature for the AR6, acknowledging that they do not cover all possible futures (IPCC, 2023). The

IPCC WG3 scenario database comprises 3131 emission scenarios, of which about 1200 were considered sufficient for climate analyses (IIASA, 2022; IPCC, 2022a). About 50% of the modeled global emission scenarios assume cost-effective approaches, relying on global least-cost mitigation/abatement options. The remaining 50% focus on existing policies and regional and sectoral differentiated actions (IPCC, 2023, 2022a).

In essence, expanding the knowledge base to incorporate multifaceted aspects is imperative for informed decision-making. Decision-makers may require comprehensive information that surpasses the capabilities of existing models and analytical tools. To effectively define energy transformation pathways, it is essential to consider a range of factors, like holistic insights into general well-being, encompassing sustainability, equity, justice, and job creation (Santos et al., 2022). Other missing scenarios or missing scenario variables (i.e., information beyond what is communicated in the existing scenario series) represent issues essential to narrating feasible and just Paris-compliant (energy) transformation scenarios. Examples comprise environmental degradation (Otero et al., 2020), connections to SDGs (O'Neill et al., 2020), lifestyle and lifestyle change (Girod et al., 2013), the role of governance and institutions (Andrijevic et al., 2020; Hegre et al., 2016), and more balanced global South-North scenario developments (IPCC 1996, 2003), including climate justice (Parikh, 1992a).

In conclusion, to assess scenario salience, it is crucial to explore the context-dependent and value-laden processes of how competing options are negotiated by governments and interest groups (Greenhalgh and Russell, 2009). It appears essential that scenarios reflect the global policy context to be broadly accepted and salient. Chapter 7 synthesizes the thesis results. Here I will explore the emission scenarios' connection to real-life policymaking, also addressing climate justice and regional differences concerning global mitigation.

2.4.3 Relationship with this thesis

Scientific advisories aim to support evidence-based decision-making, injecting competent and critical intelligence into the regulatory system. However, policy processes do not frequently agree on science use (Jasanoff, 2011, 1990). Science has tried to support decision-makers on what is dangerous climate change, while it is up to policymakers to make the final conclusions and decisions (Gupta and van Asselt, 2006; Morseletto et al., 2017; Rijsberman and Swart, 1990).

Scientists need to learn about policymakers' requirements and needs, and policymakers need to understand the capacity and content of science (Dunn et al., 2018). A challenge is that sometimes those fields comprise different motivations and goals. Scientists tend to be motivated and focused on producing research publications in specific areas. In contrast, policymakers are typically concerned with several societal areas, quickly moving from one to another on the policy agenda. The values of the two groups can also conflict since climate scientists are working with long-term timescales (e.g., 30-80 years) and are usually interested in detailed research that is public and transparent, whereas policymakers require information for decision-making within short time frames, e.g., election cycles (e.g., four years) (Burton et al., 2019; Santos et al., 2022; Sarkki et al., 2014). At the same time, scientists often work with a high complexity of knowledge, not easily communicated (Oreskes and Conway, 2010), while policymakers usually prefer to-the-point and solution-orientated information with low complexity, e.g., without uncertainty assessments (Morseletto et al., 2017; Shaw, 2009). In addition, disappointment in policy actions or distrust in policymakers is outspoken in the climate research community (Anderson and Peters, 2016; Geden, 2016, 2015), making (scenario) co-creation with policymakers sensitive

(Beck and Mahony, 2017; Lövbrand, 2011). Thus, the thesis explores and compares the scientific perspectives (Chapter 3) and policymaker perspectives (Chapter 6) on emission scenarios, their content, policy relevance, and the views on co-creation.

3 Literature critiques and emission scenario evolution 1990-2022

Title

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

(2022)

Authors

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3.1 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.

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

3.2 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 assessment, and finally, 3) mitigation analysis. Thus, these scenarios play a key role in linking different climate research disciplines (IPCC, 2014b, 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, 2015a), and referred to in national climate pledges (UNFCCC, 2021e) 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., 2010a), different worldviews (Parikh, 1992a; 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, 2000a), and the additional Post-SRES including intervention (IPCC, 2001b). The most recent emissions scenarios were developed outside the IPCC (Moss et al., 2010a), i.e., the "Representative Concentration Pathways" (RCPs) (van Vuuren et al., 2011a) 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, 2021a). 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., 2010a; van Vuuren and O'Neill, 2006). This paper aims to objectively 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.

3.3 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., 2002a), or judged the scenarios (e.g., Parikh, 1992a). Others evaluated the scenarios (e.g., Manne et al., 2005) based on initial critiques (Castles and Henderson, 2003b). 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, 2001b), primary scenario literature, and their bibliographies (e.g., Nakicenovic and Swart, 2000a), SCOPUS, Google, and Google Scholar database searches. The search terms included all combinations presented in Figure 3-1. 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 3-1), their evolution, and contribution (Tables SI 3 and 4).

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 3-1). 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 Figure 3-5.

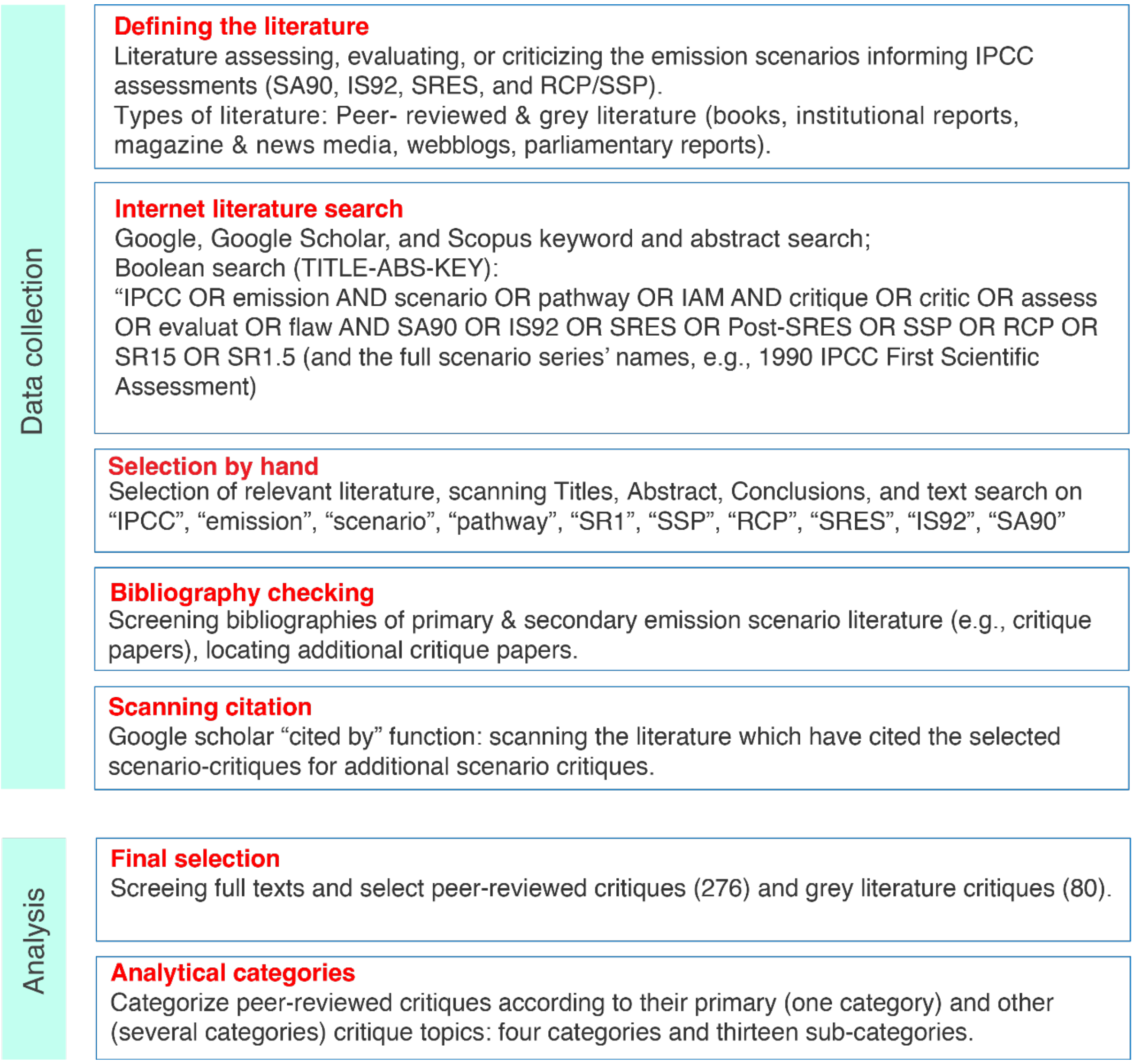


Figure 3-1. Methodology. Literature search, data collection/paper selection, and categorization/analysis of critique topics.

Table 3-1. 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

3.4 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., 2010a). 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, 2014c, 1989b). 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, 1989a). The second (IS92) and third (SRES) series were designed under explicit intergovernmental mandates (Leggett et al., 1992; Nakicenovic and Swart, 2000a) adopted in IPCC sessions. Between 2003-2006, 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, 2006b) rather than generate new data (Moss et al., 2010a).

3.4.1 The four generations

The SA90s informed IPCC AR1 (IPCC, 1990a). They were developed between 1989-1990, led by the United States Environmental Protection Agency (USEPA) and the Dutch Environment Ministry (IPCC, 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, 2007a). 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, 1990d).[i] 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[ii] 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, 1999a). 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, 1990c). Several delegations, including the US[iii], 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., 1995a; 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 1996-1999 (IPCC, 1996; Nakicenovic and Swart, 2000a). 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 was more detailed (IPCC, 2006b, 2005a, 1996, 1991, 1989a) and described a significant expansion of the development and author team - including economic stakeholder institutions, experts from various disciplines, and world regions (IPCC, 1996, 1995a). 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, 2000a). The scenarios were grouped according to their cumulative CO_2 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, 2000a), changing low-emissions assumptions and quantifications (Pedersen et al., 2021).

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., 2011a), the Shared Policy Assumptions (SPA), describing climate policy developments (Kriegler et al., 2014a), 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, 2018b) requested by the parties to the Climate Convention (UNFCCC) to guide the Paris Agreement goals (IPCC, 2018a; Kriegler et al., 2017). IPCC sessions encouraged the inclusion of organizations with scenario experiences in development processes (IPCC, 2006b). **The RCPs** informed AR5 (2013-2014). **With** more elaborated socioeconomic assumptions, the SSP-RCP combinations informed AR6 (IPCC, 2021a). 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, 2007b; Weyant et al., 2009).

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.

3.4.2 The IPCC context

Figure 3-2 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 until AR4 (2007).

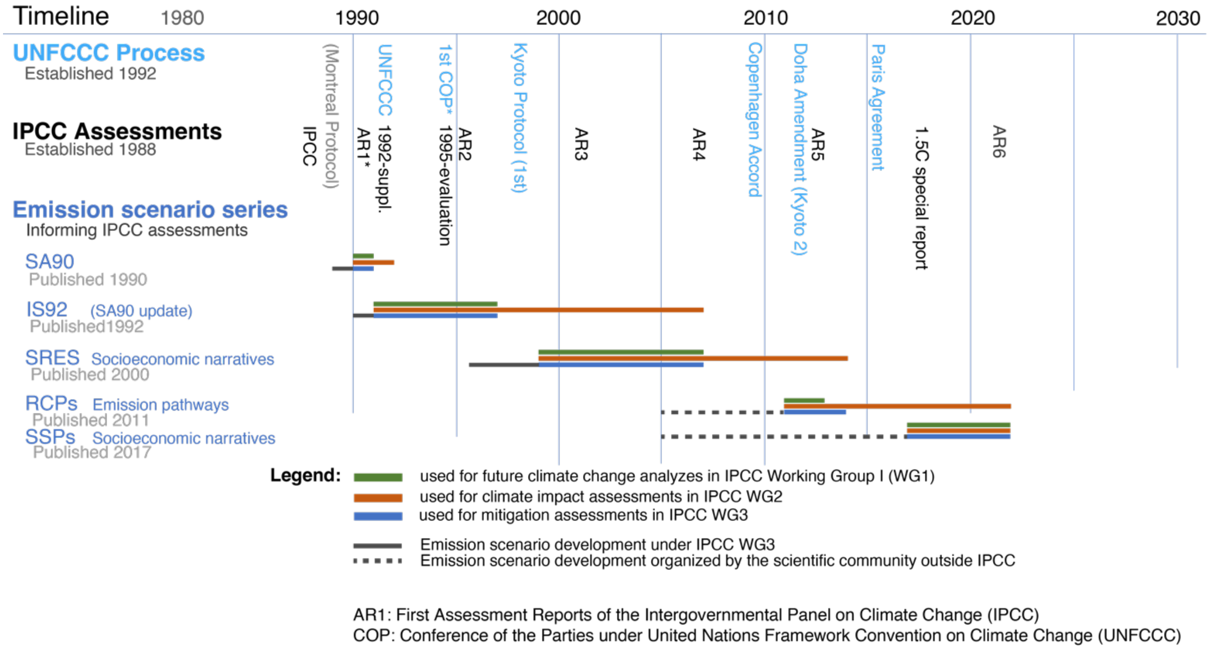
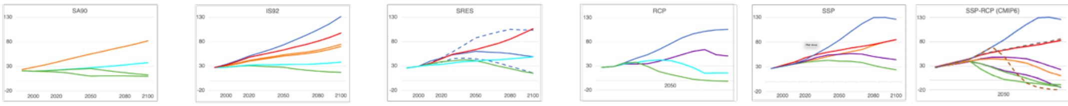


Figure 3-2. Historical overview of UNFCCC, IPCC, and emission scenarios informing IPCC. United Nations Framework Convention on Climate Change (UNFCCC) history and key processes, Intergovernmental Panel on Climate Change establishment and assessment reports (IPCC ARs), and the four generations of emission scenario series and their inclusion in scenario-based literature informing IPCC ARs three Working Groups. Data sources: IPCC ARs 1990-2021.

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.

Figure 3-3 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 (Figure 3-3b). 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.

	Developed under IPCC mandates			Developed outside IPCC mandates		
Scenario series	SA90	IS92	SRES	RCP	SSP	SSP-RCP
Number of scenarios	4 marker scenarios	6 scenarios	4 narratives (+2 illustrative)	4 pathways	5 narratives (+21 mitigation)*	7 (+2 exp.)**
Development year	1990	1992	2000	2011	2017	2018
Total CO_2 ranges						
Reduced regional inequality***	0	0	2 (2)	-	2 (9)	4 (4)
Mitigation scenarios	2	0	0	1	0 (21)	5 (2)

Key variables: Range of projections (yearly average growth rates)

Period	1985-2100	1990-2100	1990-2100	2005-2100	2010-2100	2015-2100
Population	0.7	0.2-1.1	0.3-0.9		0.2-0.7	
GDP (MER)	1.5-2.9	1.1-3.0	2.2-3.0		-	
GDP (PPP)	-	-	-		1.7-3.1	
Total Primary Energy	0.3-1.5	0.4-1.8	0.3-1.7		0.6-1.5	
Cumulative Total CO_2 1990-2100 (Gt C)	440-1600	775-2200	775-2550	500-2100	290-2425	340-2400

* The SSPs are based on 5 narratives: They include the 5 baseline scenarios (+ 21 mitigation scenarios based on the RCPs)
** The SSP-RCP scenarios are climate model experiments used in CMIP6 (Phase 6 of the Climate Model Intercomparison Project).
The emissions SSP-RCP outcomes are related to the SSP socio-economic scenarios (2017): 2 baseline and 5 mitigation scenarios were selected + 2 experimental scenarios.
*** Convergenge scenarios express future worlds that move towards less inequality between world regions (e.g., reduction in regional differences in per capita income, increased interaction)

Figure 3-3. 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 (2005c).

3.5 Overall critique topics and timeline

We identified 280 peer-reviewed emissions scenario critiques and responses, and 80 selected grey literature publications (Figure 3-4). Critiques intensified with the publication of the SRES, with 93% of peer-reviewed critiques published after 2000.

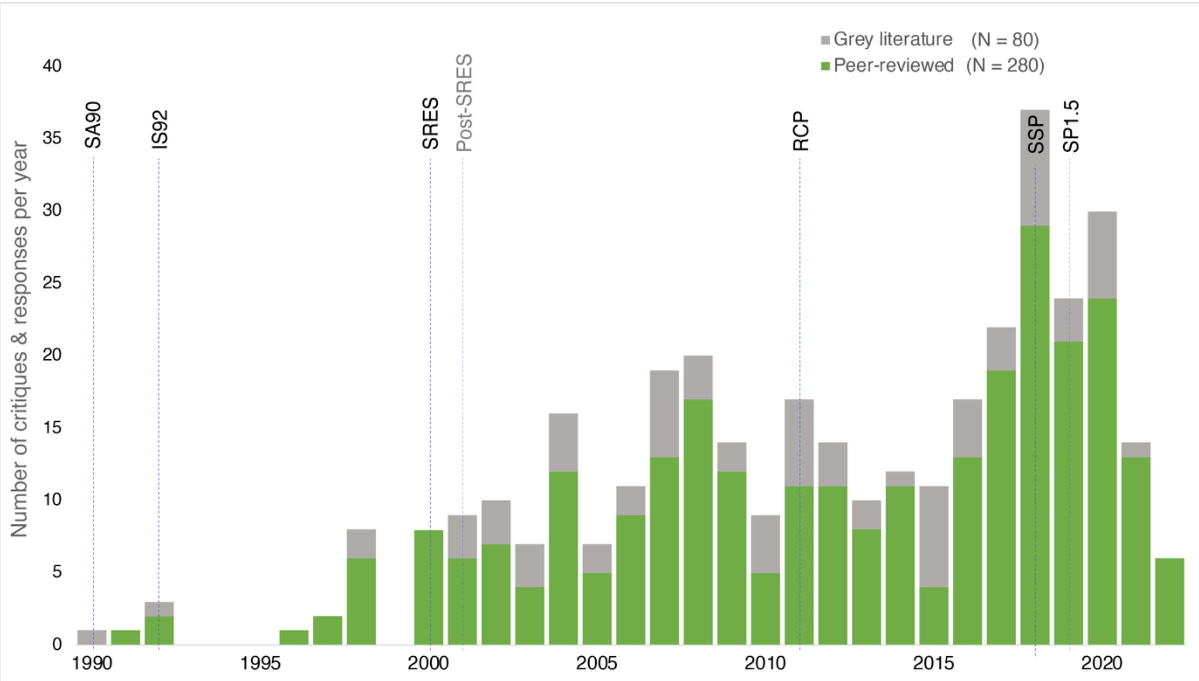


Figure 3-4. Historical development and weight of scenario critique 1990-2022: Peer-reviewed (green) and grey literature (grey) critiques of emissions scenarios in the IPCC context.

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 2021. Still, we believe that the first scenario set received little critique. During the 1990s, several critiques addressed model methodology (e.g., Oreskes et al., 1994a). In the past decade, several critiques addressed IAMs (Bellamy and Healey, 2018) without addressing the IPCC scenarios and are thus not included.

Figure 5a shows that most peer-reviewed critiques addressed assumptions (40%), 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 either primary or secondary topics, while 66%, 56%, and 33% addressed scenario ranges, methods, and user relevance, respectively. Policy relevance and implications were crosscutting issues often related as secondary topics to assumptions and/or range critiques. Method critiques were primarily addressed as a scientific issue rather than a politically heated topic and were seldom replicated in public media.

Figure 3-5. 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 1990–2021 assessing SA90, IS92, SRES, SSP-RCPs, or SR1.5 emission scenario series (See SI excel, Sheet 1).

Several critique topics have persisted for three decades, like assumptions on energy and emission ranges (Figure 5b). Over time, more scientific attention was drawn to scenarios (Figure 3-4). 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), and missing scenarios critiques.

3.6 Key scenario critiques

This section presents the critiques in more detail.

3.6.1 Assumptions

3.6.1.1 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, 1992b). 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, 2000a; 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, 1992b) became a governing negotiation issue (Gupta and Hisschemöller, 1997; Okereke and Coventry, 2016) based on economic interests (Hecht and Tirpak, 1995; Oberthür and Ott, 1999a) 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, 2003b, 2003a). 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, 2021a)), historical PPP could not have been used in the SRES. Expert meetings and IPCC AR4 assessed PPP vs. MER-based scenarios (IPCC, 2007c, 2005d). Successive research concluded that economic metrics had no significant influence on emissions ranges (Dixon and Rimmer, 2005; Holtsmark and Alfsen, 2005; IPCC, 2007c, 2005d; 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, 2005b).

3.6.1.2 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 narrative (Gidden et al., 2019b; IPCC, 2018b). 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 (COP/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 260-1080 Gt CO_2 between 2020-2100 (IPCC, 2018b).

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 (Anderson, 2015; Fuss et al., 2014; Smith et al., 2016) and SP1.5 low-emission scenarios (Beck and Mahony, 2018b; 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 (3.6.4.2). 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 target (Tanaka and O'Neill, 2018; van Vuuren et al., 2017).

3.6.1.3 Energy system assumptions

Energy technologies and transitions are central mitigation drivers and inform policy responses. During RCP preparations (IPCC, 2007b), researchers debated SRES energy assumptions (R. Pielke et al., 2008; Richels et al., 2008; Smil, 2008) and technology transitions without policy intervention (R. Pielke et al., 2008; Smil, 2008). They argued that modelers underestimated the technological challenges of stabilizing GHG concentrations (R. 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, 2001a), concluding that it would not limit carbon emissions by 2100 (IPCC, 2001b). Between 2008-2017, 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).

3.6.2 Range of emission scenarios

3.6.2.1 Emission ranges: Too-high or too-low

Emissions ranges are essential for assessing needs for mitigation (low emission scenarios) and adaptation (high impact cases). 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 1999-2012, the World experienced a high emissions growth period (Pedersen et al., 2021), making researchers think 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; R. Pielke et al., 2008) or too high (Burgess et al., 2020; Castles and Henderson, 2003b; Christensen et al., 2018; Sanderson et al., 2011). These critiques of 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 (J. S. T. 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 (J. S. T. 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, 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).

3.6.2.2 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., 2021a; 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, 2018b). SSP developers welcomed some missing scenario aspects to complete the SSPs, welcoming some of the missing scenarios (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, 2014b). 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 Management (SRM) (Wigley, 2006), aiming to modify Earth's shortwave radiative budget (IPCC, 2018b). 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, 2018b) with side effects and ethical implications (IPCC, 2014c).

3.6.3 Methodological issues

3.6.3.1 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, 1992a) and stereotyped (western) discourses (Sardar, 1993; Thompson, 1984b), limited insights (Castles and Henderson, 2003a), 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, 1999a). (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, 2005b) following scenario expert meeting recommendations (IPCC, 2007d, 2007b, 2005e, 2005d). 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 decision-making (Cradock-Henry et al., 2018; Workman et al., 2020), and assess the feasibility of mitigation pathway solutions (Anderson and Jewell, 2019; Weber et al., 2018a). 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).

3.6.3.2 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, 2000a). 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).

3.6.3.3 Transparency

Users' understanding of scenarios, numbers, and narratives is essential for user trust and relevance (Chapter 6) 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 (R. 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).

3.6.3.4 Higher resolution for impact assessments

National detail is essential for policymakers' 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 decision-making 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).

3.6.4 Policy relevance and implications

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

3.6.4.1 Policy relevance

The earliest known scenario critique argued for extending emissions projections beyond 2100 to improve decision-making (Cline, 1991), which was included in the SSP-RCPs twenty-five years later (IPCC, 2007b). More recently, researchers argue that the translation of scenarios and scientific evidence into effective decision-making 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 (Schenk and Lensink, 2007). On the other hand, to ensure robust decision-making (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; J. S. T. Pedersen et al., 2020), including state and non-state viewpoints (Weber et al., 2018a; Workman et al., 2020), identifying local policy interventions (David Tàbara et al., 2018), 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).

3.6.4.2 Policy implications

Several previously elaborated critiques addressed the scenarios' potential policy implications, like energy assumptions (Nel and Cooper, 2009; R. Pielke et al., 2008), regional GDP (Castles and Henderson, 2003a; Parikh, 1992a), 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, 2003a; 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, 2005a), the media (Economist, 2004, 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, 2018b, 2018a). 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).

3.6.4.3 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 decision-making, 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 decision-making (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., 2002a), 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, 2005d; Webster et al., 2002a). 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, 2005c). AR4 compared what-if, probabilistic, and best-guess scenarios (IPCC, 2007c), while AR5 comprised results from 31 models and 1184 scenarios (IPCC, 2014d). 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 decision-making (Allen, 2003; Schneider, 2001; Webster et al., 2002b) 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).

3.7 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.

3.7.1 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., 1995a; Parikh, 1992a) guiding intergovernmental mandates (IPCC, 1996). Since 2000, the scenarios have evolved primarily via scientific critiques and assessments (IPCC, 2007b; 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, 2007c) and probability assessments (IPCC, 2014d). Seemingly the post-SRES scenarios were less visible as these 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, 2003b) 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, 2003b; IPCC, 1996; Parikh, 1992a). For the fourth generation (SSP-RCP), the IPCC panel recommended (IPCC, 2005b) including a wider variety and the number of non-governmental stakeholders, e.g., research communities, scenario user groups, and multilateral organizations (IPCC, 2007b).

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).

3.7.2 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, 2003b), global technology developments (R. 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.

3.7.3 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).

3.8 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.

3.8.1 Author contributions (Sample CrediT)

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.

3.8.2 Data availability

Supplementary information is available in the online version of the paper. See also SI Chapters 8-12.

4 Scenarios against historical trends 1990-2020 & historical relationships between drivers and CO_2 emissions

Title

An assessment of the performance of scenarios against historical global emissions for IPCC reports

(2021)

Authors

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4.1 Abstract

Long-term emissions scenarios have served as the primary basis for assessing future climate change and response strategies. Therefore, it is important to regularly reassess the relevance of emissions scenarios in light of changing global circumstances and compare them with long-term developments, to determine if they are still plausible, considering the newest insights. Four scenario series, SA90, IS92, SRES, and RCP/SSP, were central in the scenario-based literature informing the five Assessment Reports of the Intergovernmental Panel on Climate Change (IPCC) and the sixth assessment cycle. Here we analyze the historical trends of carbon dioxide (CO2) emissions from fossil fuel combustion and industry and emissions drivers between 1960 and 2017. We then compare the emission scenario series with historical trends for the period 1990-2017/2018. The results show that historical trends are quite consistent with medium scenarios in each series. As a result, they can be regarded as valid inputs for past and future analyses of climate change and impacts. Global CO2 emissions 1960-2018 (and 1990-2018) comprised six (and three) overall subperiods of emissions growth significantly higher and lower than average. Historically, CO2 emissions (in absolute numbers and growth rate) are tightly coupled with primary energy and indirectly with GDP. Global emissions generally followed a medium-high pathway, captured by "middle-of-the-road" scenario narratives in the earlier series, and by combinations of "global-sustainability" and "middle-of-the-road" narratives in the most recent series (SRES and SSP-baselines). Historical non-OECD trends were best captured by "rapid-growth" and "regional-competition" scenarios, while OECD trends were close to regional-sustainability and global-sustainability scenarios. Areas where the emissions scenarios captured the historical trends less well are renewable and nuclear primary energy supply. The fact that the actual historical development is consistent with rapid-growth narratives in the non-OECD regions might have important implications for future greenhouse gas emissions and associated climatic change.

Keywords: Emissions scenarios; Intergovernmental Panel on Climate Change; emission scenarios against historical trends; socioeconomic trends; global; non-OECD/OECD

4.2 Introduction and background

Emissions scenarios form a key tool in the scenario-based literature, informing the Intergovernmental Panel on Climate Change's (IPCC) assessments (IPCC, 1990a; Moss et al., 2010). The history of IPCC assessments now covers several generations of emissions scenarios. These include 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, 2000a). They also include more recent emissions scenarios developed outside the IPCC (Moss et al., 2010a), i.e., the "Representative Concentration Pathways" (RCPs) (van Vuuren et al., 2011a) and the "Shared Socioeconomic Pathways" (SSPs) (O'Neill et al., 2014; Riahi et al., 2017).

These emission scenarios aim to explore possible trajectories. They include those trajectories that are consistent with current expectations, as well as more uncertain developments that show trajectories that would meet specific goals (IPCC, 2014d) or explore possible high impact futures (Moss et al., 2010; Riahi et al., 2017; van Vuuren et al., 2011a). They are not predictions – as the future is fundamentally uncertain. This uncertainty is a key reason to explore multiple scenarios.

Simultaneously, emissions scenarios should be plausible in economic structures, demographics (O'Neill et al., 2017), and energy systems (Bauer et al., 2017).

Therefore, it is important to regularly reassess the relevance of emissions scenarios in light of changing global circumstances (Peters et al., 2013; Richels et al., 2008; van Vuuren et al., 2010); to compare them with long-term developments; determine if they are still plausible; consider the newest insights. One way to do so is to compare observed emission trends with emission scenarios to inform and update the outlook of various futures being realized. These comparisons can provide information on whether scenario updates are needed and compare emission trajectories against goals, such as the 2015 Paris Agreement on Climate Change.

More than ten years ago, Van Vuuren and O'Neill (2006) conducted the first quantitative evaluation of the emissions scenarios by comparing the socioeconomic drivers and greenhouse gas (GHG) emissions projected in the SRES set with historical data for the 1990-2000 period. Later, researchers argued that the observed growth in fossil-fuel and industry CO_2 emissions was higher than in most fossil-fuel intensive SRES scenarios. The researchers argued that this high-growth was caused by a turnaround of earlier declining trends in the energy intensity (Raupach et al., 2007) and unforeseen local shifts in emissions caused by unanticipated GDP growth in Asia and Eastern Europe (Pretis and Roser, 2017). Additionally, some questioned if the high end of emissions ranges were too low (Peters et al., 2013).
From a policy perspective, these arguments are critical because the scenario ranges are often used in the context of the United Nations Framework Convention on Climate Change (UNFCCC) negotiations and associated national and international climate policies. However, short-term observations are not necessarily good indicators of long-term future emission trajectories. Evaluating the reasons for the differences requires distinguishing between short-term developments and the long-term trends on which the emissions scenarios are based (Manning et al., 2010; van Vuuren et al., 2010). In 2020, we have almost thirty years of historical data available for a longer-term assessment of the scenario sets.

This paper evaluates the four generations of emission scenario sets against historical trends in CO_2 emissions and socioeconomic developments. We assess whether projections are within the emission scenario ranges during the examined period and analyze the historical relationship between emission development and socioeconomic drivers. More specifically, we address the following research questions: (1) How do actual fossil fuel and industry CO_2 emissions relate to emissions drivers over a long-term period (1960-2017)? (2) How do emissions scenarios, used by IPCC in successive assessments, compare to actual emissions and drivers from 1990 to the present?

Addressing these questions contributes to a better understanding of the emissions scenarios' abilities to capture historical developments and informs the ongoing debate on the role and usefulness of emissions scenarios as a central part of the knowledge basis for assessing future climate change. The key added value over previous studies is the coverage of all four emission scenario sets and historical development analysis over a more extended period.

The paper is organized as follows: Section 2 presents the methodology and data sets used for our analysis. Section 3 compares and categorizes emissions scenarios across sets in narrative families (3.1), analyzes the historical relationship between emissions and emissions drivers 1960-2017 (3.2), and compares historical trends against scenarios (3.3). Section 4 discusses how the results relate to earlier scenario debates and the potential implications for future emissions scenario developments.

4.3 Material and methods

We performed a detailed comparison of CO_2 emissions and socioeconomic variables for all emission scenario sets used for assessments for IPCC Assessment Reports (from now on, emission scenarios will be mainly referred to as scenarios). We selected five key variables, i.e., CO_2 from fossil fuel and industry, population, GDP, total, and fossil primary energy. The variables were chosen because they are key scenario results in all four sets. Developments in population, economic growth, and technology (e.g., fossil/non-fossil) are used as input for determining energy use and emissions (O'Neill et al., 2017; Riahi et al., 2017) and are central in the Kaya identity for the total CO_2 emissions level (Kaya and Yokobori, 1997; Nakicenovic and Swart, 2000a). Moreover, CO_2 from fossil fuels and industry account for ~65% of global greenhouse gas emissions (IPCC, 2014c).

First, we compare and categorize the assumptions underlying the scenario sets (SA90, IS92, SRES, and SSPs) in scenario families (based on van Vuuren et al., 2012) to group scenarios and facilitate comparison of individual scenarios across the sets. Additionally, we group scenarios by "low" (<1099 GtC), "medium-low"(1100-1429 GtC), "medium-high" (1430-1799 GtC), and "high" (>1800 GtC) emissions pathways based on total cumulative total CO_2 emissions between 1990-2100 (IPCC, 2000a) - to facilitate comparison of long-term developments across sets.

We calculated weighted moving averages based on eight-year estimates using equal weight filtering to compare and analyze long-term emissions trends with emission drivers. This method reduces the noise from inter-annual growth rates by "smoothing" the time sets to highlight the underlying trend (Hyndman, 2009). Additionally, we identified twelve sub-periods of low/high CO_2 emission growth rates as sub-periods of high growth rates (>1%) and sub-periods of medium-low growth (1% or lower). Finally, we analyzed linear correlations between emissions and drivers for absolute numbers and growth rates. We used the compound annual growth rate for calculating average yearly growth rates.

We focus on "marker scenarios" (e.g., SSP baseline (SSP-BL) and SRES marker/illustrative scenarios) when we compare scenarios with historical trends. The RCPs are included in the emissions comparison, only, since they are not connected directly to specific socioeconomic drivers (van Vuuren et al., 2011). But they are essential for emissions evaluations since there is no one-to-one match between the SSPs and RCPs in the SSP-RCP structure (O'Neill et al., 2016; Riahi et al., 2017; van Vuuren et al., 2011a).

First, we compare observed emissions with scenarios to inform and update the outlook of various futures being realized. Second, we compare the quantifications underlying the assumptions of the IS92, SRES, and SSP-BLs with the historical development of selected emission drivers and CO_2 emissions (sufficient data for all key variables were not accessible for the oldest, SA90 set).

We base the socioeconomic comparisons on growth rates rather than absolute numbers because absolute start-year values differ within and across scenario databases. The scenarios generally report emissions at intervals of 5, 10, or 25 years. Thus, the method of "compound annual growth rates" (CAGR) was used since it calculates the beginning and end value, providing a consistent growth rate comparison between projections and historical developments. A sensitivity analysis suggests that CAGR is robust, compared to "average annual growth rates" (AAGR) - an often-used method (Peters et al., 2013). The inclusion of OECD/non-OECD countries differs between sets. As such, we recalculate estimates of historical emissions and drivers according to the scenario database non-OECD and OECD categories to perform valid comparisons of regional scenarios (see supplementary material).

The databases used for analyses are presented in Table 4-1.

Period	Variable	Data source
1751-2018	$CO2_2$ fossil & Industry (global budget)	Global Carbon Budget (GCP, 2019)
1959-2018	CO2 fossil & Industry (national budgets)	GCP (2019)
1960-2018	Global population	World Bank (WB, 2021b)
1960-2018	GDP MER (Market Exchange Rates; constant US$2010)	World Bank (2019)
1990-2018	GDP PPP (purchasing power parity; constant international$2011)	World Bank (2019)
1965-2018	Primary Energy Consumption (PEC)	BP (2018a)
1971-2017	Primary Energy Supply (PES)	International Energy Agency (IEA, 2018; 2020)
1985-2100	SA90	IPCC (1990a)
1985-2100	IS92	Pepper et al. (1992)
1990-2100	SRES	Nakicenovic & Swart (2000a)
2005-2100	SSP/RCP	Riahi et al. (2017)/van Vuuren et al. (2011a)

Table 4-1. Databases for emissions, emissions drivers, and scenarios

Historical estimates between 1990-2017 were used for all variables to compare growth rates with scenarios since this was the IEA's latest recorded year. Historical primary energy estimates differ over time because the IEA statistical methods changed in 2005 (OECD/IEA, 2005). Therefore, primary energy values also differ between scenario databases and between models. From the SSP database, we converted SSP nuclear primary energy (via the "partial substitution" method, multiplied by 1/0.33), which is according to present IEA methodology (OECD/IEA, 2005) to provide fair comparisons between historical and scenario databases. We then recalculated *total and non-fossil* estimates to allow for meaningful comparisons between energy projections and historical estimates. Because of the uncertainty of the actual assumptions used by the developers of IS92 and SRES - 20 to 30 years ago - we use the original data. We perform regional cross-scenario comparisons for the non-OECD and OECD categories, as reported in the IS92, SRES (OECD90), and SSP databases (OECD90+EU member states and candidates).

4.4 Results

4.4.1 Categorizing emissions scenarios: Assumptions underlying the sets

Storylines were developed for the SRES and additionally for the SSPs. The SA90 and IS92 assumptions and quantifications can effectively be related to specific, more extensive narrative descriptions of the later sets. Despite the two earliest sets having more simplified assumptions, we categorize all emission scenarios in five scenario-families based on storylines to compare scenarios across all four sets (Table 4-2).

SCENARIO NARRATIVE FAMILIES	SCENARIO SETS			
	SA90	IS92	SRES	SSP
“Global sustainability” (Low to medium-low cumulative emissions) *	SA90-C: Control policies (low) SA90-D: Accelerated policies (low)	IS92c (low)	B1: global solutions (low)	SSP1 (medium-low)
“Regional sustainability” (low to medium-low)	SA90-B: Low emissions (low)	IS92d (low)	B2: local solutions (medium-low)	
“Middle of the road” (medium-high)	SA90-A: High emissions (medium-high)	IS92a IS92b: OECD efficiency (medium-high)		SSP2: Middle of the road (medium-high)
“Regional competition” (medium-high to high)		IS92f (High)	A2: Self-reliance (High)	SSP3: Regional rivalry (medium-high) SSP4: A divided road (medium-low)
“Rapid growth” (high to low)		IS92-E (high)	A1FI: Fossil intensive (high) A1B: Balanced energy (medium-high) A1T: Energy transition (low)	SSP5: Fossil-fueled (High)

*Cumulative total CO_2 emissions 1990-2100.

Table 4-2. Five main storyline families underlying the SA90, IS92, SRES, and SSP-baseline scenario sets.

Scenarios are additionally classified according to their cumulative total CO_2 emissions trajectory 1990-2100 (low, medium-low, medium-high, high) based on IPCC (2000a). Scenarios with an emissions trajectory different from the general scenarios in their family (grey text) are located twice and also in the family that customarily has similar trajectories (grey text in brackets). The categorization of scenario families is based on van Vuuren et al. (2012), and the categorization of cumulative emissions is based on values introduced in IPCC (2000a). See also Supplementary Information.

The general storylines of the scenario-families do not necessarily reflect the long-term emission trajectory. The global sustainability scenarios have a peak-and-decline shaped trajectory, where emissions peak during the century and decline towards 2100. Four other scenarios have a peak-and-decline pathway (two SRES rapid-growth, the SA90 regional sustainability, and an SSP regional-competition (SSP4)). To make the differences between individual scenario quantifications transparent, we added the cumulative emissions category (Table 2).

The storyline focus of the scenario sets has changed over time: from energy mix and efficiency (SA90) to population, income, and fossil fuel resources (IS92), to ''regional vs. global'' and ''economic vs. environmental'' (SRES) (Girod et al., 2009). Most recently, there has been a shift to energy system demand and supply characteristics as a function of a set of demographic and economic drivers broader than previous scenarios, providing a more solid basis for complementary mitigation and adaptation analyses with the SSP/RCP (Riahi et al., 2017).

At one end of the emissions range, a family of optimistic scenarios explores worlds in which governments join forces, e.g., through adopting environmental or other sustainable development policies to promote global advances in low-carbon technologies. At the same time, poverty and inequality are reduced (Global sustainability). As further discussed below, IS92 and SRES explicitly exclude specific climate or mitigation policies because of their terms of reference (IPCC intergovernmental mandates). At the other end of the emissions range, scenarios include rapid global economic growth based on fossil fuels and reduced inequality (rapid growth) or examine countries that upgrade their use of cheap fossil fuels, pursuing national economic growth (regional competition).

Box 4-1. Overview of long-term scenario narratives and families 1990-2019

Assumptions underlying the four generations of emission scenarios informing the IPCC (1990-2019)

Developing the SA90 scenarios in the late 1980s, modelers made assumptions about possible future socioeconomic developments and associated GHG emissions (Bolin, 2007; IPCC, 1990a). The developers provided no narratives other than lower, average, and higher economic growth and different climate policy levels. Scenarios involved one "baseline", one "low emissions", and two "intervention" scenarios (including mitigation policies). In the following sets, the emissions ranges were increased to include scenarios with high cumulative emissions trajectories (IPCC, 1991; Leggett et al., 1992; Nakicenovic and Swart, 2000a). The second (IS92) and third (SRES) generation comprise only baseline and no intervention scenarios (Leggett et al., 1992; Nakicenovic and Swart, 2000a).

In the first generation (SA90), elaboration of the regional level scenarios was less well developed (IPCC, 1990a); thus, global (in-)equality considerations were less explicit. Inequality later became one of the governing principles of the SRES and SSP assumptions (Nakicenovic and Swart, 2000a; O'Neill et al., 2014). The "rapid-growth" and "global-sustainability" families generally describe future worlds with increasing global equality. In general, they represent the highest and lowest cumulative emissions pathways, respectively (IPCC, 1990a; Nakicenovic and Swart, 2000; Pepper et al., 1992; Riahi et al., 2017).

Global sustainability scenarios: The scenarios quantify a peak and decline in emissions from about 6 GtC/year in 1990 to a range of 3-7 GtC/year by 2100. They assume a shift in values from economic growth to sustainable development (e.g., climate or environmental policy assumptions). No intervention scenarios (climate policy assumptions) were included in IS92 and SRES. After the SA90s, policy assumptions were excluded in the IPCC mandate for IS92 (IPCC, 1991; Leggett et al., 1992) and SRES (IPCC, 1996; Nakicenovic and Swart, 2000a). Thus both IS92 and SRES evolved in the absence of climate policy assumptions (Leggett et al., 1992; Nakicenovic and Swart, 2000a). However, low emissions scenarios were included, based on other assumptions, such as side effects of non-climate/environmental policies (Alcamo et al., 1995a) and technological development

(Nakicenovic and Swart, 2000a). Emissions by 2100 range from 3 to 7 GtC/year (Annual growth rates: -0.4 to 0.3%).

Regional sustainability: Scenarios in this family assume moderate technology innovation in high-income regions and quantify global slow emissions growth throughout the century. In these scenarios, emissions increase between 10 and 14 GtC/year by 2100 (Annual growth rates: 0.6-0.7%).

Middle-of-the-road: These scenarios follow similar assumptions and medium-high emission pathways. The original Business-as-Usual (BaU) scenario in the SA90 was criticized at IPCC sessions, and thus this label was officially excluded in the successive scenario terminologies (IPCC, 1991). However, this type of scenario was represented in the IS92 via two scenarios (Leggett et al., 1992) and in the SSPs, labeled 'Middle-of-the-road'. The SRES set does not have such a scenario narrative. This family's scenarios increase from about 6 GtC/year in 1990 to about 20 GtC/year in 2100 (Annual growth rates: 0.8-1.3%).

Regional competition: In general, these scenarios assume low environmental regulation, high population, weak economic growth, and slow technological change. Three scenarios (SSP3, A2, and IS92f) fit this description best. They project an increase in the range of 22-28 GtC/year by 2100 (Annual growth rates: 1.2-1.7%). One SSP scenario (SSP4) assumes continued global inequality with energy transitions in high-income regions, thus quantifying a peak-and-decline emissions pathway to 12 GtC/year by 2100 (Annual growth rates: 0.7%).

Rapid growth: These scenarios assume rapid economic growth. In most rapid growth scenarios, growth is provided via a fossil-fuel intensive energy sector and quantifies emissions in the range of 30-35 GtC/year by 2100 (Annual growth rates: 1.5-1.8%). As mentioned earlier, two of the SRES rapid-growth scenarios quantify high economic growth but medium-high and low cumulative emissions because of various degrees of energy transitions. They quantify annual growth rates in the range of -0.3 to 0.7%.

4.4.2 Historical trends for emissions and main emissions drivers

CO_2 emissions from fossil fuels and industry grew by about 1750% between 1900 and 2018, with an average annual rate of 2.5%. The yearly emissions growth during the IPCC period was 1.7%.

We divide CO_2 emissions over the period 1960-2020 (1990-2020) into twelve (seven) sub-periods of lower and higher growth (Fig. 1, Panel A). In total, we find 12 subperiods of higher and lower emission growth between 1960 and 2020 (including recent projections of 2019 and 2020). When we leave out very short-term events (1-2 years), we see that the entire period contains six periods of reversed higher and lower emissions growth. The IPCC period includes two high (1988-1991 and 1999-2012), two medium-low growth sub-periods (1992-1998 and 2013-2020). As such, emission growth in the last decade is also significantly below the long-term average.

In essence, the periods since the establishment of IPCC (in 1988) show very different average annual growth rates, emphasizing the importance of distinguishing between short-term and long-term trends (van Vuuren et al., 2010) - e.g., sub-periods of high and low emissions growth. Since the emissions scenarios (and their models) do not capture short-term variability, but long-term developments (Manning et al., 2010; van Vuuren et al., 2010), it makes sense to evaluate the scenario projections against long-term historical developments.

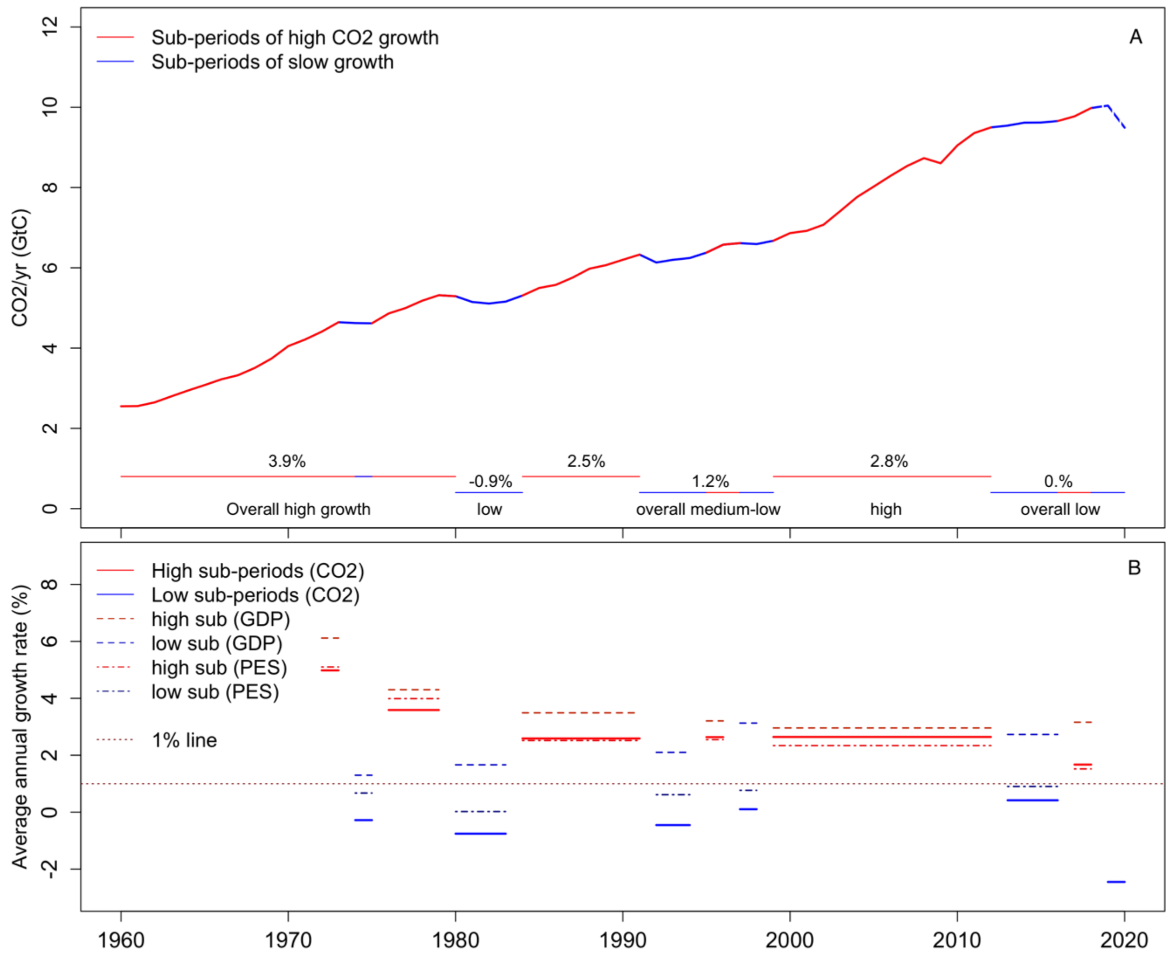


Fig. 1. Development in global CO_2 emissions from fossil fuels and industry 1960-2017.

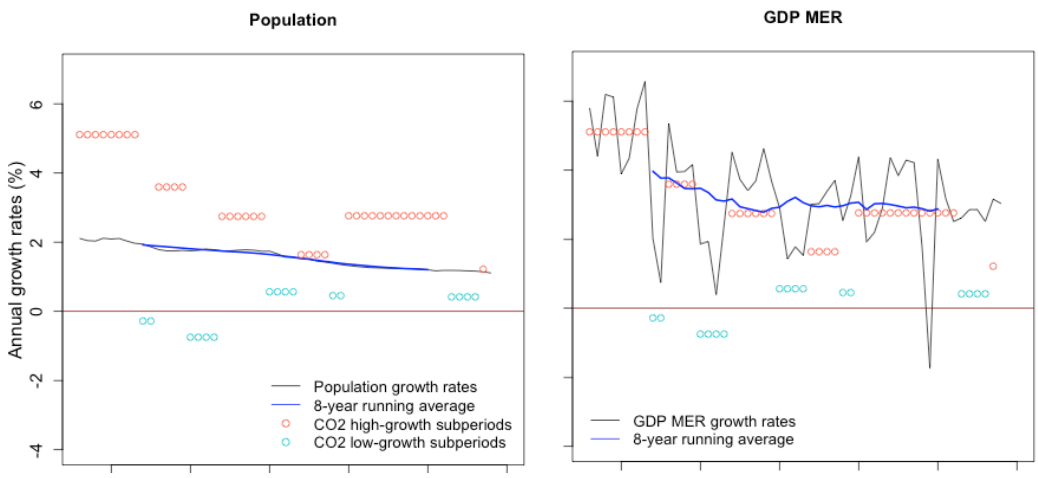
Panel A: Emissions per year with six high-growth sub-periods (red) – years with annual growth rates >1% - and five slow-growth sub-periods (blue) - years with growth rates equal to or below 1%. Panel B: average annual growth rates for high and low-growth sub-periods of CO_2 compared to sub-period growth rates of GDP and primary energy supply (PES). PES for the 2017-2018 period (Panel B) is based on 2017, while GDP are based on 2017 and CO2 includes most recent projections for 2019 (0.6%) (GCP, 2019) and 2020 (-5.5%) (le Quéré et al., 2020). Data source: GCP (2019), WB (WB, 2019), and IEA (2018; 2020).

Additionally, it is challenging to disentangle short-term influences (about five years) and long-term drivers (several decades or a century) influencing emissions. Our comparison of higher and lower emissions growth periods (Fig. 1 Panel B) illustrates that the average sub-period growth rates for CO_2, GDP, and primary energy supply (PES) followed approximately similar higher and lower growth patterns until the 1992-1994 period. Population growth didn't correlate well with CO_2 (see Figure 4-1).
Financial crises do not appear to have had a lasting effect on global emissions. Interestingly, we see that GDP growth rates, after the 1992-1994 period, have been relatively stable with low

variability between higher and lower emission growth periods. However, PES continues following the reverse in higher and lower emissions growth. As such, primary energy appears as a more reliant short-term indicator of emissions growth.
The latest period (2013-2018) has medium-low emissions combined with stable economic growth. The 2013-2016 drop marks a shift from historical patterns, showing a stationary situation or slower growth in emissions that was not forced by financial crises in major world regions like in 2008/2009, 1998/1999, and earlier. It may be a result of at least three fundamental changes: emerging climate policies (Burck et al., 2018; OECD, 2019), falling prices of renewable energy technologies (IRENA, 2019b; Observ'ER, 2019), and expansion of fracking (International Energy Agency, 2019). The not yet estimated 2019 emission growth is expected to be low (0.6%) (Friedlingstein et al., 2019), and a temporary drop between -4 and -7% is expected for 2020, due to the effect of the Covid-19 pandemic on economic activities (le Quéré et al., 2020). It may lead to an overall growth rate of around 1.5% between 1990 and 2020. It is, however, too early to state the long-term consequences of the Covid-19 pandemic as well as plausible structural changes.

The share of fossil primary energy has remained almost unchanged, around 82%, since 1990. At the same time, levels of both non-fossil and fossil fuel consumption have increased by 60% between 1990-2017 (International Energy Agency, 2020). There is no convincing evidence yet that the world has already started a sustained global energy transition leading to decreasing fossil growth.

All examined emissions drivers have been continuously growing throughout the examined (and IPCC) period. However, our comparison of developments in interannual growth rates shows a different picture. As illustrated in Figure 4-1, world population growth rates declined continuously. Global average GDP growth has stabilized with a small decrease, while CO_2 and primary energy supply (PES) followed similar up and down patterns.



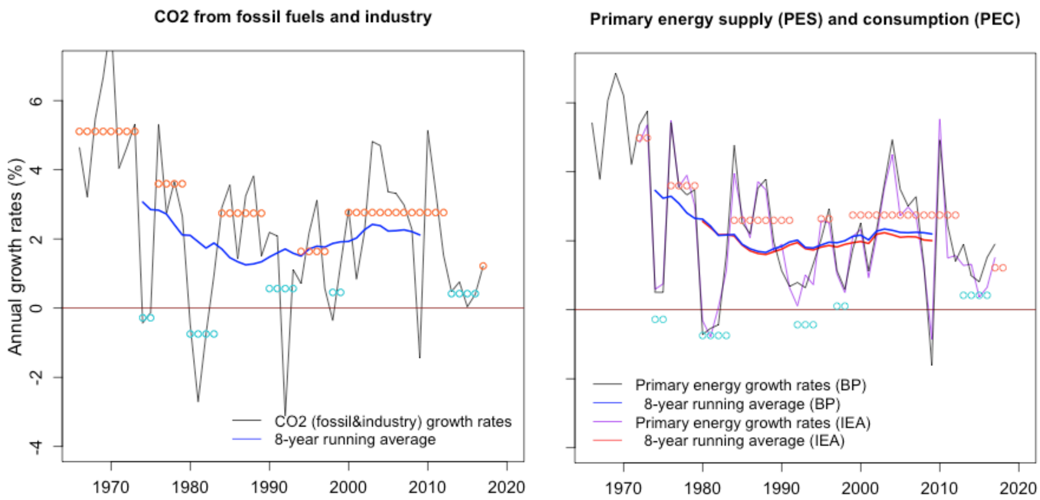


Figure 4-1. Global growth rates 1966-2018 (black & purple lines)
for Population (top left), GDP (top right), CO_2 (bottom left), and Primary energy (bottom right) with weighted eight-year average (blue and red lines). Sub-periods of low (blue circles) and high CO_2 growth (red circles). Data source: WB (2021b, 2019), GCP (2019), IEA (2018), and BP (2018a).

In conclusion, the historical shifts in emissions trends (GCP, 2019) makes it difficult to interpret trends based on a couple of years (Manning et al., 2010; van Vuuren et al., 2010), which has been done in the literature before (Raupach et al., 2007). In this context, we evaluate the historical and current emission pathway compared to, and in the light of, the following scenario sets used to inform IPCC assessment reports.

4.4.3 Emissions scenarios against historical trends

During the period analyzed, historical global emissions generally developed within the range of pathways described by the IS92, SRES, and SSP-BL sets. Emissions exceeded the SA90 range post-2000 (Figure 4-2). However, our 1985-2020 period's assessment shows that the SA90 middle-of-the-road projects an emissions growth (1.7%) lower than the historical trend for the same period (1.8%).

We locate an emission trajectory similar to scenarios that project a medium-high century-long emissions pathway for the examined period. Middle-of-the-road scenarios best capture this. Considering the projected emissions growth in 2019 (0.6%) (Friedlingstein et al., 2019), current emissions are close to middle-of-the-road, global sustainability, and the SRES rapid-growth scenario assuming high non-fossil energy transition.

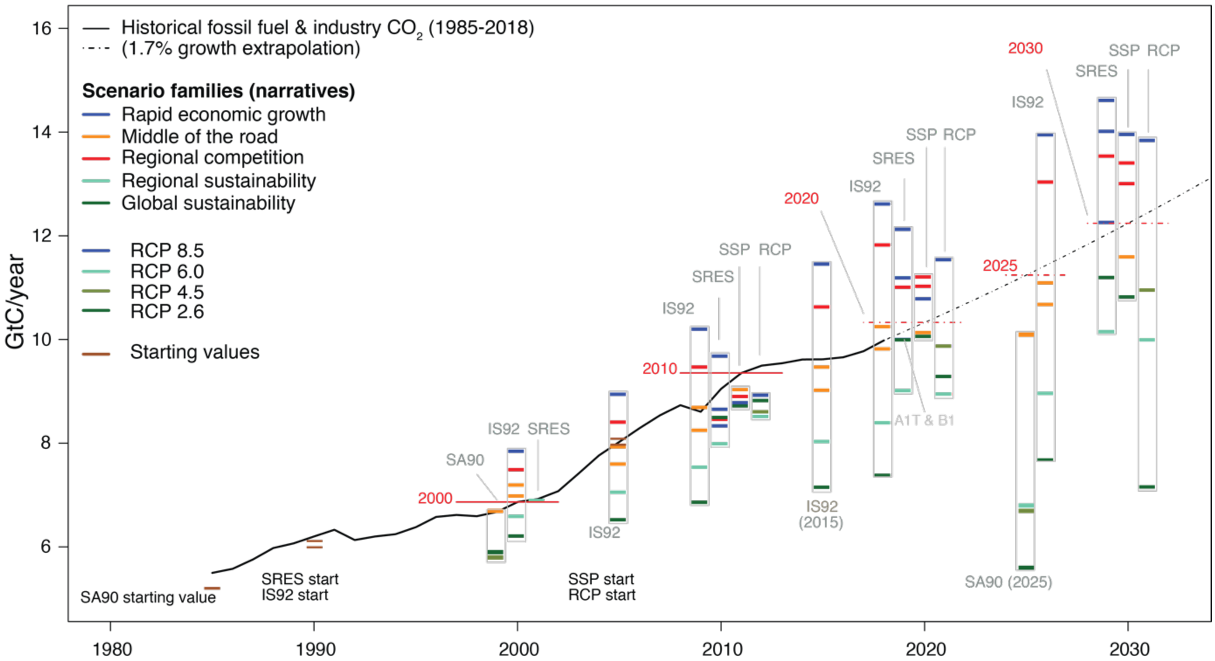


Figure 4-2. Observed CO_2 emissions trend over the past three decades (black line) compared with emission scenarios SA90, IS92, SRES, RCPs, and SSP-BL.

The black dotted line shows extrapolation beyond 2017 of the 1.7% growth rates for 1990-2018 historical emissions. 'Rapid growth' (includes IS92e/SRES-A1B/SSP5), 'Middle of the road' (SA90-A/IS92a/b/SSP2), 'Regional competition' (IS92f/SRES-A2/SSP3/SSP4), 'Regional sustainability' (SA90-B/IS92d/SRES-B2), 'Global sustainability' (SA90-C/D/IS92c/SRES-B1/SSP1). Data sources: IPCC (1990a), Pepper et al. (1992), Nakicenovic & Swart (2000a), Riahi et al. (2017), van Vuuren (2011a), GCP (2019).

The historical emissions trajectory followed a low to medium-low to medium-high emissions pathway between 1992 and 1998, which was similar to the middle-of-the-road scenarios, as well as SRES and SSP global-sustainability scenarios. Between 1999 and 2012, emissions followed a trajectory between medium-high and high emission pathways, which was between IS92 middle-of-the-road and regional-competition scenarios. From 2013 to 2016, historical growth was below 1% annually, which made the observed CO_2 emissions pathway return to the center of the ranges of the scenario sets – back to being close to middle-of-the-road and global-sustainability scenarios.

We note that the lower ends of the scenario ranges have moved up – and not down – for the successive sets. This may be because the later sets accounted for the realized emissions, and the fact that SA90 was the only set including "marker" scenarios with explicit policy. The differences in the uncertainty emissions range between the scenario sets are to be expected. The SA90 has a broader uncertainty range since it projects a more extended period (33 years) and includes mitigation scenarios. We note that, in general, the uncertainty range has declined depending on the number of years they cover with IS92 (covering 28 years), SRES (20 years), and SSP (15 years). However, the uncertainty range for SA90 is lower due to the more 'positive' projections (not including high-emission scenarios).

4.4.3.1 Emissions and socioeconomic scenarios against the historical trend

The actual global development in CO_2 from fossil fuels & industry and the four key emissions drivers examined during the past three decades are, in general, quite close to the middle-of-the-road scenarios in the IS92 set. For the SRES and SSP sets, it looks different. Here global-sustainability scenarios are comparable to emissions growth and the most direct driver, fossil primary energy growth (Figure 4-3).

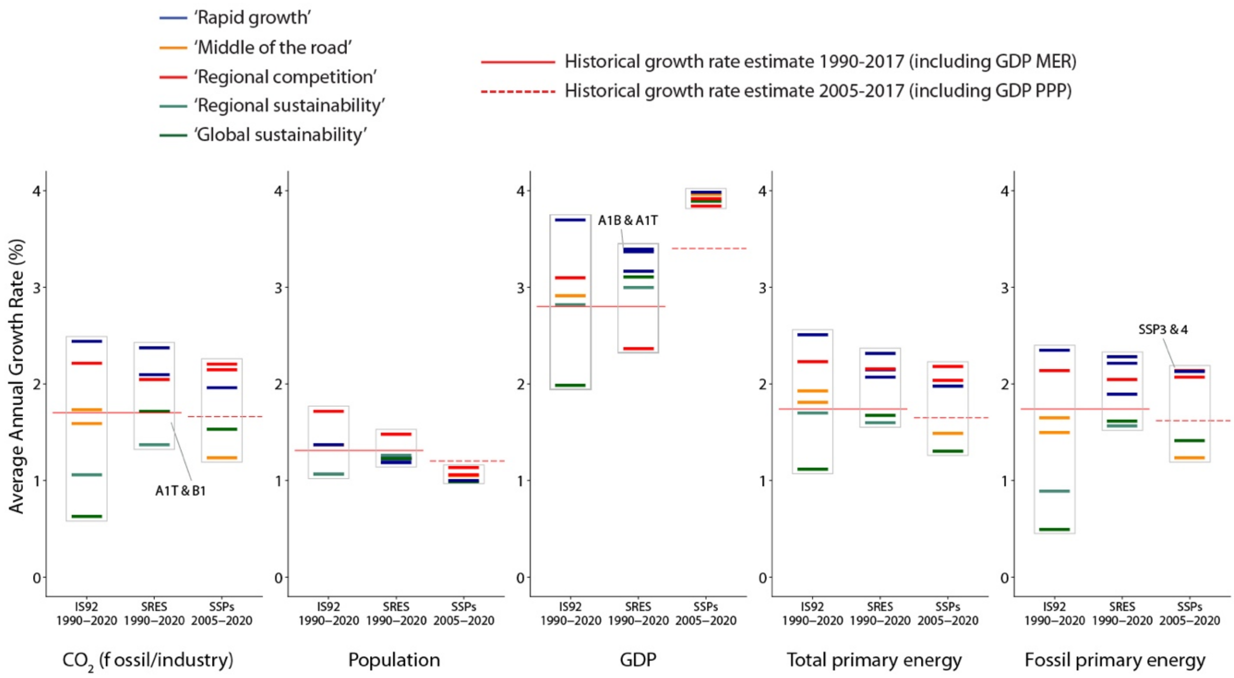


Figure 4-3. Global growth rate projections 1990-2020 for IS92, SRES & SSP-baseline scenarios compared to historical trends until 2017.

Scenarios are categorized in narrative families: 'Rapid growth' (IS92e, SRES-A1, SSP5), 'Middle of the road' (IS92a/b, SSP2), 'Regional competition' (IS92f, SRES-A2, SSP3/4), 'Regional sustainability' (IS92d, SRES-B2), 'Global sustainability' (IS92c, SRES-B1, SSP1). Data source: IPCC (1990a), Pepper et al. (1992), Nakicenovic & Swart (2000a), Riahi et al. (2017), GCP (2019), IEA (2020), WB (2021b, 2019; 2019).

Historical energy and economic growth are best captured by IS92 middle-of-the-road and regional-sustainability, while SRES global- and regional-sustainability are close. SSP middle-of-the-road and global-sustainably are below but most comparable to historical energy growth.

In essence, the scenarios compare well with the historical trends for underlying variables for the global population, GDP, and PES. There are two exceptions: the SSP population and GDP growth, where historical increases are above and below scenario ranges, respectively. Although historical population growth was below the SSP-BL range, the global historical trend is still within the United Nations population scenario range (United Nations Statistics Division, 2020). When including the entire SSP range (including the SSP mitigation scenarios), historical population growth is well within the SSP range. The historical GDP growth is within the SSP range, considering the 1990-2020-period, while historical population growth is still above the SSP-BL range.

4.4.3.1.1 Non-fossil energy scenarios

Historically, both fossil and non-fossil energy grew by 1.7% per year between 1990 and 2017. During this period, the IS92 set overestimated non-fossil growth, while SRES almost also did the same. The SSP-BL range (0.8-2.7%) was consistent with the historical growth trend between 2005 and 2017 (1.8%) (Figure 4-4).

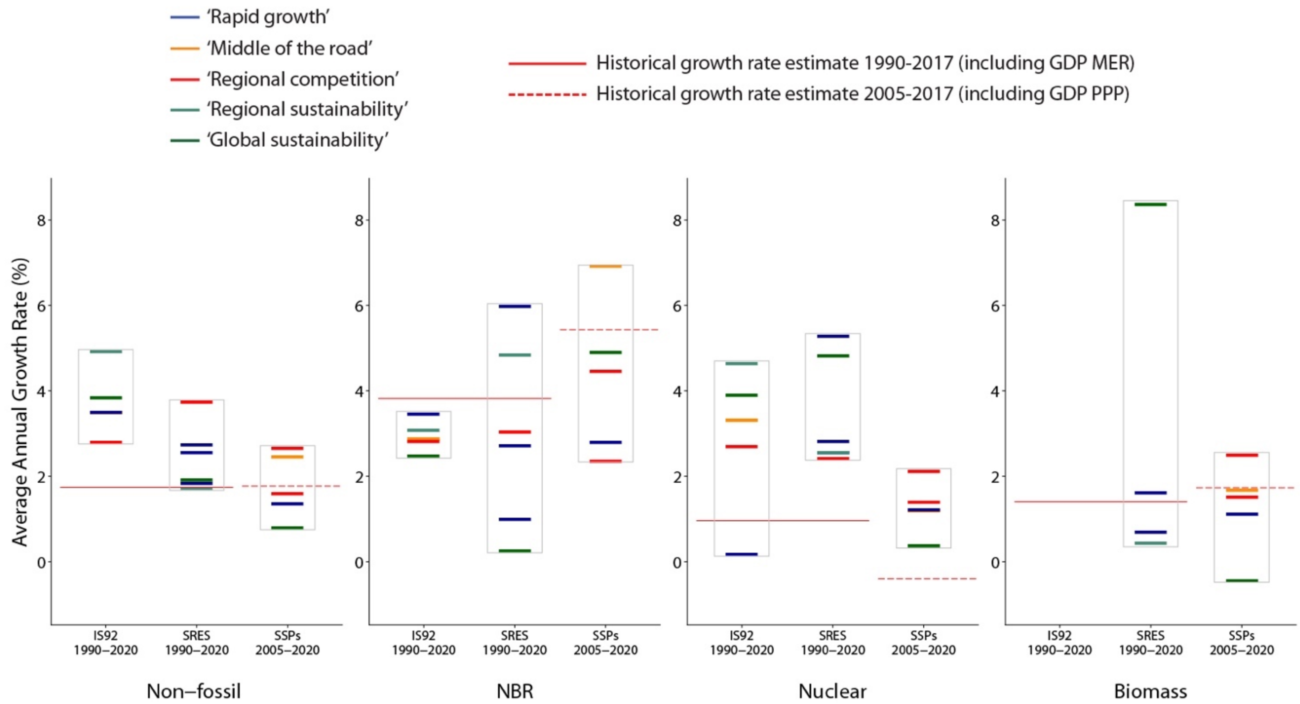


Figure 4-4. Growth rates of historical and scenario non-fossil estimates including sub-categories biomass, nuclear, and non-biomass renewables (NBR) for IS92 and SRES 1990-2020 and SSP-BLs 2005-2020.

No biomass growth rates are shown for IS92 and some SRES rapid growth and regional competition scenario families because their 1990-estimates were zero. Data source: (1990a), Pepper et al. (1992), Nakicenovic & Swart (2000a), Riahi et al. (2017), IEA (2020).

It appears as if nuclear energy has decreased faster than expected in most scenarios, thus further analyses of trends, outlooks, and energy policies are recommended to evaluate if there is a need for adjusted nuclear energy assumptions in future scenario updates. This depends on factors such as the Post-Paris Agreement negotiations and the future role of nuclear in policies, which is still unclear.

Additionally, it is too early to state if there are reasons to adjust SSP-BL "non-biomass renewables" assumptions. Renewable energy is maturing quickly and is becoming price competitive with fossil fuels in several regions (IRENA, 2019a; Metayer et al., 2015; Observ'ER, 2019). They may be ready to play a defining role in a near-term future promoted by climate policies and market forces. Such developments may indicate that renewable energy scenarios could move in a different direction than expected in the SSP-BLs.

4.4.3.1.2 Non-OECD and OECD scenarios

IS92 and SRES scenarios underestimated emissions growth in non-OECD countries, and they track the high end of the SSP range. The opposite counts for OECD countries, where historical emissions follow the low end of IS92, below SRES, and middle of SSP range (Figure 4-5).

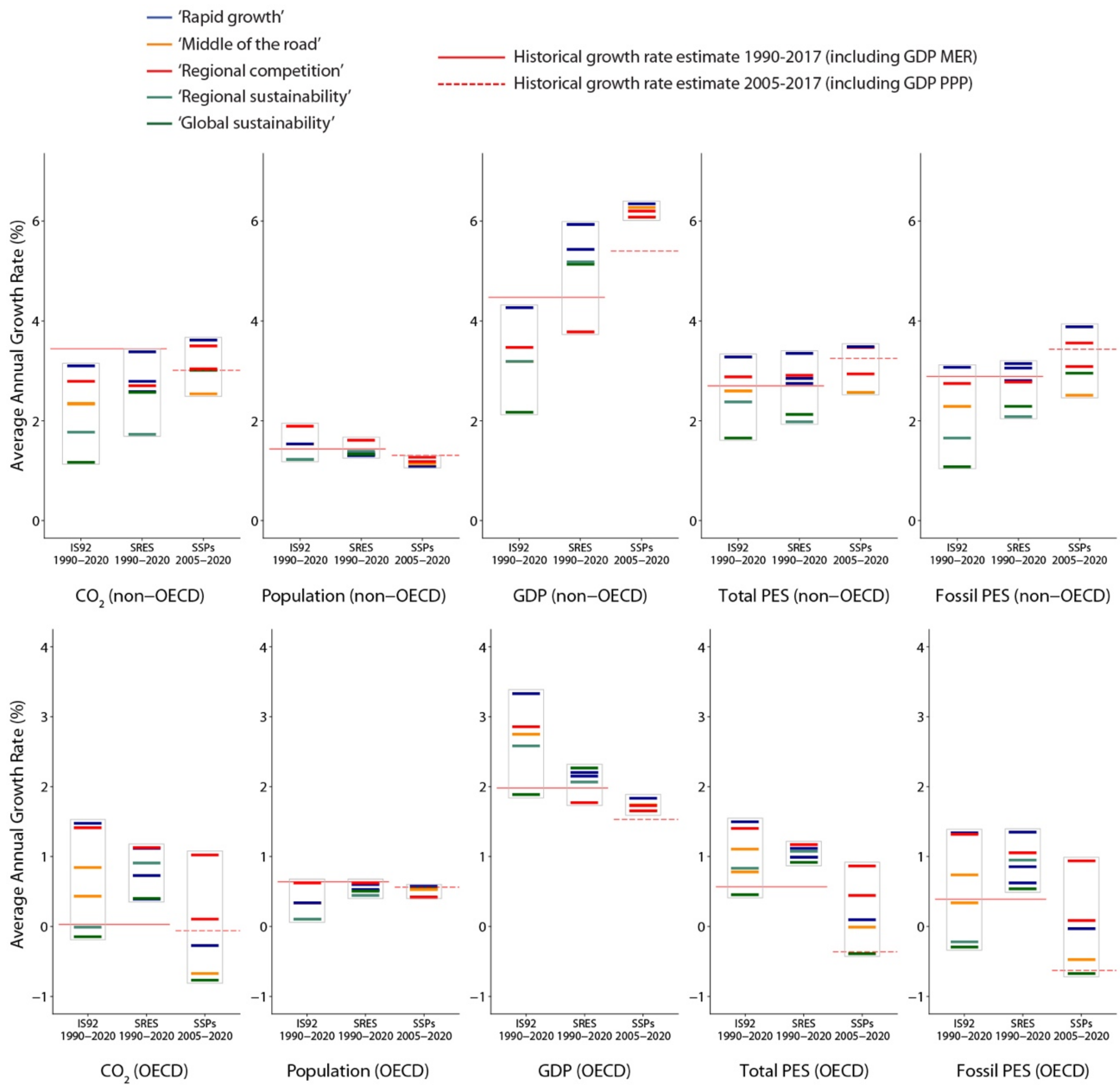


Figure 4-5. Non-OECD and OECD growth rates of historical and scenario CO2 emissions (fossil fuels and industry) population, GDP, total primary energy, and fossil primary energy 1990-2020.

Top panel: non-OECD. Bottom panel: OECD. The definitions of OECD and non-OECD differ between the IS92/SRES and SSP databases (e.g., IS92/SRES OECD is based on "OECD90" and thus including fewer countries than the SSP OECD category including "OECD90 + EU member states and candidates"). Historical estimates were calculated according to SSP definitions and IS92 definitions for emissions, population, and GDP. The representation of countries in the energy database was considered too small, and thus the IEA database definition was used. Data source: Pepper et al. (1992), Nakicenovic & Swart (2000a), Riahi et al. (2017), GCP (2019), IEA (2020), WB (2021b, 2019; 2019).

In general, rapid-growth and regional-competition scenarios are closest to the historical non-OECD trend, while regional and global-sustainability scenarios are close to those of the OECD. The SSP3 regional-competition scenario was close to non-OECD energy and emissions variables, while the SSP1 global-sustainability scenario was, in general, equivalent to OECD variables. At the same time, the SSP2 middle-of-the-road scenario was also quite close. We note that the SSP ranges for both non-OECD and OECD were above historical GDP 2005-2017. Additionally, historical total and fossil primary energy growth track the low ends of SSP ranges.

Overall, the four sets capture the direction of global socioeconomic development well. In particular, the IS92 and SSP middle-of-the-road, and the SSP and SRES global sustainability scenario were quite precise in both emissions and energy scenarios. Since there are still two to three more years of the various annual estimates to calculate complete growth rates for the 1990-2020 period, changes may happen. A drop in annual 2020 emissions, given the impact of the Covid-19 pandemic (le Quéré et al., 2020), may lead to lower overall historical growth estimates.

4.5 Discussion

Climate change extends far into the future, making emissions scenarios and associated development in emissions and drivers essential for a broad range of analyses of climatic change mitigation, impacts, and adaptation. Regular evaluations of these scenarios are crucial, as new information about technological and socioeconomic developments becomes available over time, and scenario methods and tools change (Allen, 2003; van Vuuren et al., 2010). This paper compares observed emission trends with emission scenarios over a more extended period than has been done before and addresses the performance of subsequent sets of scenarios developed for IPCC assessment.
Since a complete assessment of all variables would exceed one paper's scope, we focused on the most critical greenhouse gas emissions (CO_2 from energy and industry) and the central drivers.

Overall, our analysis shows that long-term global emission development is relatively close to the middle of the scenario ranges. Still, some significant deviations were noted for indicators at a more detailed level. Below, we briefly discuss some of the results.

4.5.1 How do the projected emissions hold up against historical trends?

During the various periods of relatively rapid or slow growth, the emissions scenarios were critiqued in the literature as having either an upward bias in emissions projections (Castles and Henderson, 2003b; Gray, 1998) or a downward bias(Le Quéré et al., 2009; Peters et al., 2013; Raupach et al., 2007). However, we note that sub-periods of high and low emissions growth have counterbalanced each other in the past, keeping the long-term trend well within the ranges of IS92, SRES, and SSP-BL sets. All in all, there is very little support for earlier claims that future emissions would be systematically overestimated at the global level, except for the 1st set (SA90). In a century-long window, the SA90 "middle-of-the-road" scenario has slightly higher emissions growth projections (1.3%) than its equivalent middle-of-the-road scenarios in the IS92 (1.1%) and SSP-BLs (1.2%) (Leggett et al., 1992; Riahi et al., 2017). Whether the relatively good correlation between medium scenarios and the historical data will also continue in the future is uncertain. Global emission growth between 2010 and 2018 is significantly below the long-term average, and as a result, the trend during this period is at the low end of the SSP-BL range. In 2019 emission growth was low (0.6%) (GCP, 2019), and a temporary drop is expected for 2020 due to the effect of the Covid-19 pandemic on economic activities (le Quéré et al., 2020).

4.5.2 Differences between OECD and non-OECD regions

Our results suggest that the emissions scenario sets capture fairly well global socioeconomic developments but show differences notably for regional projections. The magnitude of non-OECD emissions and fossil primary energy growth 1990-2017 is higher than in the IS92 and SRES sets. There could be several reasons for this, including higher economic growth in non-OECD countries and/or a shift stronger than expected of industrial activity from OECD to non-OECD countries. In this context, it should be noted that the choice of the accounting method for greenhouse gas emissions can have fundamental effects. Following international rules, the assumptions for all emission scenario sets were developed to track emissions within national territories (Leggett et al., 1992; Nakicenovic and Swart, 2000a; Riahi et al., 2017), rather than emissions related to consumption (Peters et al., 2012). Figure 4-6 illustrates how OECD consumption-related emissions are significantly higher than their territorial, production-related emissions.

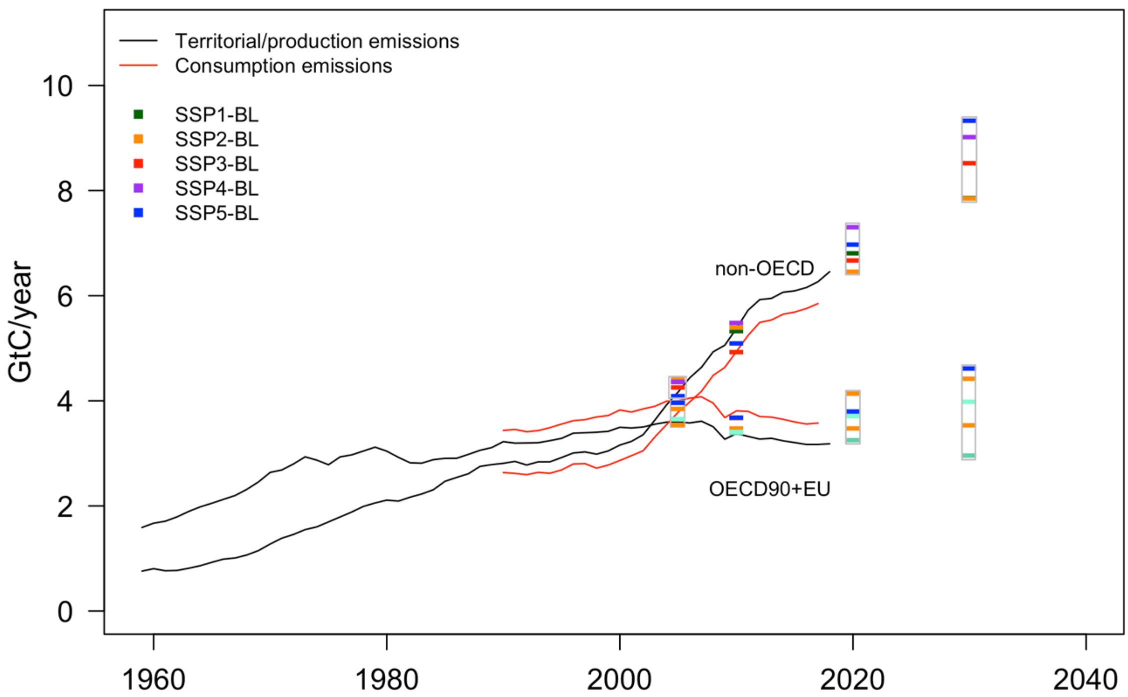


Figure 4-6. Historical developments in CO_2 emissions 1959-2018 compared to SSP scenarios. Territorial/production emissions (black) and consumption emissions (red) for non-OECD and OECD90+EU (SSP definition). Data source: GCP (2019), Riahi et al. (2017).

Emissions from the manufacture of traded goods and services are increasing, leading to rising shares of global CO_2 from producing countries (Peters et al., 2012), particularly China and India. In contrast, EU-28 and North America "consume more than they produce" in terms of emissions (GCP, 2019) – consumption-related emissions per capita for the US and EU-28 are 1.3 and 1.4 tCO_2/person higher, respectively, compared to their terrestrial production-related emissions (GCP, 2019; WB, 2021b). The scenario studies do not explicitly deal with trade (other than energy carriers). Arguably, the scenarios indirectly, or implicitly, include shifts in production from OECD to non-OECD regions, via the calibration to historical trends (before publication year of the scenario sets) and the underlying assumptions for regional developments. As a result, it is challenging to assess whether the shifting industrial activity is the leading cause of the growth in non-OECD countries being more rapid than projected. Nevertheless, under international rules, emissions from production in one region to satisfy consumption in another remain attributed to the producing regions.

Our analyzes provide evidence that, in particular, the earlier scenarios captured regional trends less well but did not reveal the causes behind that. There is no evidence of potential regional modeling bias. Still, the results may put a new focus on the significance of considering a broad set of issues determining future developments, also beyond the processes and indicators included in the models used. Potential regional biases in scenario development (such as a biased 'northern' perspective) have been widely discussed in the literature (Parikh, 1992a; Shukla, 2004) and in and IPCC sessions (IPCC, 2006b, 1996). These also include arguments to include more 'developing' country expertise. This has shaped the SRES' terms of reference (IPCC, 1996; Nakicenovic and Swart, 2000a) and inspired the RCP/SSP development principles (IPCC, 2006b, 2005d). Different stakeholders have been included in scenario preparations and discussions, contributing to diverse perspectives (IPCC, 2007b, 2005d). In essence, it appears increasingly essential to intensify knowledge about socioeconomic developments, the functionality of institutions, and policy implementation in non-OECD countries (Ajulor, 2018), because it is very different from those in many high-income countries from which region the models originated. This appears essential both to strengthen future scenarios and to inform future climate change response choices.

4.5.3 Representation of income variables

Changes in indicator characteristics, like their definition or choice of units, may affect projections. In the SA90, IS92, and SRES, economic growth was reported in US dollars based on conversions using market-exchange rates (MER). The SSPs use purchasing power parities (PPP). As a consequence of the choice of indicator, the SRES was critiqued for overestimating economic growth and, therefore, also emissions growth in the rapid-growth and global-sustainability families (Castles and Henderson, 2003a, 2003b; Henderson, 2006, 2005). The critique was picked up by both governmental (Tol, 2005) and media debates (Economist, 2003b), although hardly any useful PPP-based databases (World Bank, 2019) nor PPP-based analyzes existed at the time that could have been used in the SRES models (IPCC, 2007c). Critics argued that PPP compares the actual welfare levels across regions more accurately (Holtsmark and Alfsen, 2005; van Vuuren and Alfsen, 2006). They argued that using MER to reach global economic convergence would lead to overstated economic growth projections in low-income regions. They argued that this would result in disproportionate aggregated growth in energy demand and emission levels, which would not represent the actual high and low end of the emissions range in a reliable manner (Castles and Henderson, 2003a, 2003b). Our results show that the emission growth in the SRES scenarios was lower than the historical data for the non-OECD, but this is not the case for economic growth. Comparing MER and PPP growth rates for the 1990-2018 period, global growth measured in PPP (3.4%) is higher compared to MER (2.8%). This is because of a rapidly growing GDP in low-income regions and the higher difference between MER and PPP metrics in low-income countries, compared to most OECD countries. For regional growth, the differences are, by definition, smaller.

While the critique itself (Castles and Henderson, 2003a) was not peer-reviewed, it initiated a heated debate (IPCC, 2007c; Montague, 2018; van Vuuren and Alfsen, 2006). Research showed that differences between these two methods did not significantly affect emissions projections (Holtsmark and Alfsen, 2005; Manne et al., 2005; van Vuuren and Alfsen, 2006). One critic accepted that his analysis was wrong (Montague, 2018).

4.5.4 Limitations of models

In essence, the "performance” of the scenario sets, compared with actual emissions at the global level, is within the ranges. But does this automatically mean that this will also be the case in the future? One can be right for the wrong reasons (equifinality). Furthermore, the future is unknown, and societal changes can happen unexpectedly, most recently exemplified by the Covid-19 pandemic. Additionally, the assessment in this paper focuses on key input and output of emissions scenarios. An analysis focusing more directly on performance and differences of the models used may provide other perspectives and suggestions for future improvements, complementing the presented results. The models can be right for high-level quantitative indicators, but this does not mean that they correctly capture the underlying story.

Our assessment of inputs and outputs of emission scenarios shows a high correlation between historical emission development and the scenario studies' medium values. In this context, we note that the IS92 set also captures global trends reasonably well. However, there was considerably less experience in modeling and scenario development at the time, and only a few modeling teams participated in the scenario development activities. At the same time, projections have become arguably more difficult given the gradual emergence of an additional factor, namely climate policy. This also means that even though the sets generally capture historical developments**,** this gives little proof of equally strong performance in the future. Nevertheless, we note that scenarios were never meant to predict future trends, but rather to explore different possible outcomes. In that sense, all models have limitations - they cannot represent all possible quantified outcomes of a scenario narrative (IPCC, 2014a, 2007a) because they are 'idealizations' or 'simplification' of reality. They use current knowledge and scientific data; however, as knowledge progresses and more scientific data becomes progressively available, the models based on that knowledge and data are subject to change.

4.6 Conclusions

Due to the high relevance of emission scenarios as input for future climate change analyses that informed and shaped IPCC assessments for 30 years, it is relevant to regularly reassess the scenarios to inform future scenario development and the policy debate. Focusing on key variables (CO_2 from energy and industry, population, GDP, energy system characteristics), we have compared long-term historical developments of key socioeconomic drivers and greenhouse gas emissions and compared historical trends against scenario projections from 1990 to the present.

Our results show that the scenarios did not systematically overestimate or underestimate actual global emissions, as suggested earlier in the literature. History shows that it has been difficult to foresee shifts between and magnitude of medium-low and high emissions periods. The global historical emission trajectory was close to high-emissions scenarios from 1999 to 2012, which led to critiques in the literature and policy discussions, arguing that the upper scenario ranges were too low. Between 1990-1998 and 2013-2019, historical emissions were close to medium-high emissions trajectories. Over the period 1960-2020 (1990-2020), we identified twelve (seven) sub-periods of lower and higher growth (short-term periods). It illustrates that it is difficult to interpret trends based on a limited number of years of data. Good practice requires a distinction between long-term and short-term trends.

Overall, historical global emissions followed a medium-high emissions pathway for the three latest sets (IS92, SRES, RCP/SSP), well within those scenario ranges, however just above the high-emission scenario of the first set (SA90). Historically, CO_2 emissions are tightly coupled directly with primary energy use, and indirectly with GDP: despite short-term variabilities in global CO_2 emissions are mainly caused by a combination of slow changes in long-term drivers.
Most scenarios overestimated OECD CO_2 emissions growth but underestimated non-OECD CO_2 emissions. The SSP-BLs overestimated OECD GDP and underestimated non-OECD GDP growth and was at the margins of primary energy growth for both regions. The past global developments result from a combination of contrasting storylines in different areas at different times, such as the relatively low economic and emissions growth in the OECD region and higher growth in the non-OECD region, notably China and India. This can have implications for present policymaking and possible improvement of assumptions regarding the "outsourcing" or export of emissions in future scenario exercises.

4.6.1 Recommendations for future work in the area of global emission scenarios

First, the recent development of national and international climate policy makes it increasingly problematic to compare the IPCC scenarios (which did not include climate policy by definition) with historical trends. However, we recommend that they can still be relevant as counterfactual baselines for climate change, impact, or response analysis.
Second, because the implementation of climate policies related to the Paris Agreement of 2015 may mean an active break with past trends, exploring policy options in further work on the latest scenario set (SSPs) in a long-term perspective becomes increasingly relevant. Third, it may be worthwhile to analyze discontinuous futures related to historical and future crises (as illustrated by the current Covid-19 situation) and possible societal transformations, which have not been addressed explicitly in any of the scenario sets used. Fourth, our analyses lead to the recommendation to re-evaluate SSP assumptions on particular developments in "non-biomass renewables" and "nuclear" primary energy – to judge if associated scenario adjustments would be desirable in future updates. Fifth, the fast-growing emissions in non-OECD regions provide a reminder that non-OECD emissions and outsourcing of emissions may play an increasingly important role in the global emissions, an issue very relevant for future policy choices and scenario development. Technically, it may be pertinent to consider more specific regions other than non-OECD/OECD or non-Annex/Annex1. These regions now include both high-income and low-income countries, different from the times that the first scenario sets were developed. Sixth, in the research underlying this paper, we focused on the emission scenarios and their drivers, not on the characteristics of the integrated assessment models used to quantify the storylines. Future research could evaluate to what extent these models are (still) suitable to assess the relationship between emissions and their socioeconomic drivers in a comprehensive and meaningful way. Seventh, future scenario work is recommended to include evaluating the total lifecycle emissions of large-scale application of new wind, solar, biomass energy technologies, fracking (including methane leakage), and land-use change.

4.6.2 Author contributions (Sample CrediT)

Jiesper Tristan Strandsbjerg Pedersen: Conceptualization, Formal analysis, Methodology, Writing - Original Draft, Software, Visualization, Project administration, Validation; **Filipe Duarte Santos**: Conceptualization, Resources; Supervision, Writing - Review & Editing, Validation; **Detlef van Vuuren**: Conceptualization, Methodology, Writing - Review & Editing, Validation; **Joyeeta Gupta**: Supervision, Writing - Review & Editing; **Ricardo Encarnação Coelho**: Investigation, Review & Editing, Validation; **Bruno A. Aparício**: Software, Visualization, Review & Editing; **Rob Swart**: Conceptualization, Methodology, Formal analysis, Methodology, Supervision, Validation, Writing - Review & Editing.

4.6.3 Data availability

Supplementary information is available in the online version of the paper (only with access – the paper is not open access). See also SI Chapters 4-7.

5 The relevance of high emission scenarios

Title

Variability in historical emissions trends suggests a need for a wide range of global scenarios and regional analyses

(2020)

Known outcome:

a. Cited in IPCC Working group I: Science (Chapter 1) (IPCC, 2021a)
b. Cited in IPCC Working group III: Mitigation (Chapter 2, 3) (IPCC, 2022b)

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5.1 Abstract

Long-term developments in carbon dioxide emissions have tracked the middle of projected emission scenario ranges over the past three decades. If this tendency continues, it seems increasingly less likely that future emissions will follow current high emission scenarios. However, in the past, periods of slow and fast global emissions growth was observed, which have led to previous critiques of scenarios being too low or too high. In the light of such unpredictability and since scenarios are meant to explore plausible futures, we here argue that a broad range of emission scenarios continue to be considered input in scenario-based analyses of future climate change. Furthermore, we find substantial regional differences in emissions trends. Territorial emissions in OECD countries fall on the low side of emission scenario ranges, whereas non-OECD territorial emissions fell closer to the medium or high-end. Since non-OECD emissions will become increasingly important, we recommend further exploring the relationships between regional and global emissions to support scenario assumptions and climate policymaking.

5.2 Introduction

Climate change extends into the distant future (IPCC, 2014c; Raskin et al., 2005). Thus, in climate change research, emission scenarios play a crucial role, given the importance of evaluating the long-term consequences of near-term decisions and exploring plausible emission trajectories (Moss et al., 2010a; van Vuuren et al., 2010). These emission scenarios are used as input for scenario-based literature assessing plausible future climatic changes, risks, and responses to inform policy decisions (Moss et al., 2010a).
Recently, the relevance of the high emission scenario RCP8.5 of the Representative Concentration Pathways (RCP) was questioned concerning its role in the analyses of present and future emissions and climate change as it supposedly reflects very high emissions given current information (Hausfather and Peters, 2020; Pielke and Ritchie, 2020; Tollefson, 2020). We find it essential to evaluate the subsequent scenario series used in climate change research (since the 1990s) to understand their evolution and current emissions developments to provide policymakers with relevant and valid scientific evidence and ensure that valuable information is not excluded.
The emission scenarios aim to explore possible trajectories, including those consistent with current expectations of the most likely trend and more uncertain developments. The latter include both low emission scenarios that could lead to specific climate policy goals and high scenarios that explore the upper range of possible futures and high impacts (Moss et al., 2010; Riahi et al., 2017; van Vuuren et al., 2011a). It is important to regularly reassess these emission scenarios in light of changing circumstances (Peters et al., 2013; Richels et al., 2008; van Vuuren et al., 2010). The (policy) relevance of specific emission scenarios has often been debated (Peters et al., 2013; R. Pielke et al., 2008): for instance, the assumptions of low-end emission scenarios have been questioned as not being feasible (Fuss et al., 2014; R. Pielke et al., 2008), while high emission scenarios were questioned as being too low(Le Quéré et al., 2009; Peters et al., 2013; Raupach et al., 2007). The latter assessments were formulated during periods of rapid economic and emission growth that have regularly occurred over the current and previous centuries (GCP, 2019; World Bank, 2019). Thus, history shows that it is difficult to assess long-term trends based on just a few years of data (Manning et al., 2010; van Vuuren et al., 2010).

Overall, over the last 30 years emissions have fluctuated around the middle of the scenario range – as possibly intended – but also making current high emission scenarios less likely.

Simultanously, history has also shown high variabilities in growth rates and future departures from long-term trends cannot be excluded. These findings emphasize that it is problematic to operate with best-guess scenarios only, since they have historically had short shelf lives. Therefore, it is still relevant to base future climate projections on a wide range of emission scenarios. Moreover, future studies that explore regional relationships in emissions developments are needed and recommended for policymaking.

5.3 Historically, global emissions have tracked the middle-of-the-scenario ranges

Here, we focus on the emission scenarios used in scenario-based literature informing the Intergovernmental Panel on Climate Change's (IPCC) assessment reports(Moss et al., 2010a). We compare the emission scenarios with recent trends in carbon dioxide (CO2) emissions from fossil-fuel combustion, cement production, and gas flaring (GCP, 2019). CO_2 emissions are the most significant contributor to long-term climate change (IPCC, 2014c) and thus provide a good reference to regularly assess the implications of developments of emissions and their socioeconomic drivers with the emission scenarios (GCP, 2019; Peters et al., 2013) used as the basis for science and policy assessments. The IPCC process has resulted in four generations of emission scenarios (Moss et al., 2010a). Three were developed under the mandate of the IPCC: Scientific Assessment 1990 (SA90) (IPCC, 1990a), 1992 IPCC Scenarios (IS92) (Leggett et al., 1992), and the Special Report on Emission scenarios (SRES)(Nakicenovic and Swart, 2000a). The fourth comprises the Representative Concentration Pathways (RCPs) (van Vuuren et al., 2011a) and Shared Socioeconomic Pathways (SSPs) (Riahi et al., 2017), which informed Phase 5 and 6 of the Climate Model Intercomparison Project (CMIP5/CMIP6) (O'Neill et al., 2016). The RCPs have been used in scenario-based literature informing the IPCC Fifth Assessment Report (AR5), while the SSP/RCP combination will be used for the IPCC Sixth Assessment Report (AR6). CMIP6 made a selection of the SSP/RCP combinations (O'Neill et al., 2016) that will be highlighted in AR6. These are therefore shown separately, labeled as SSP CMIP6, in the figures.

Comparing the global average emissions growth rate in these scenarios with historical emissions shows that historical emissions roughly fall around the middle-of-the-scenario ranges (Figure 5-1).

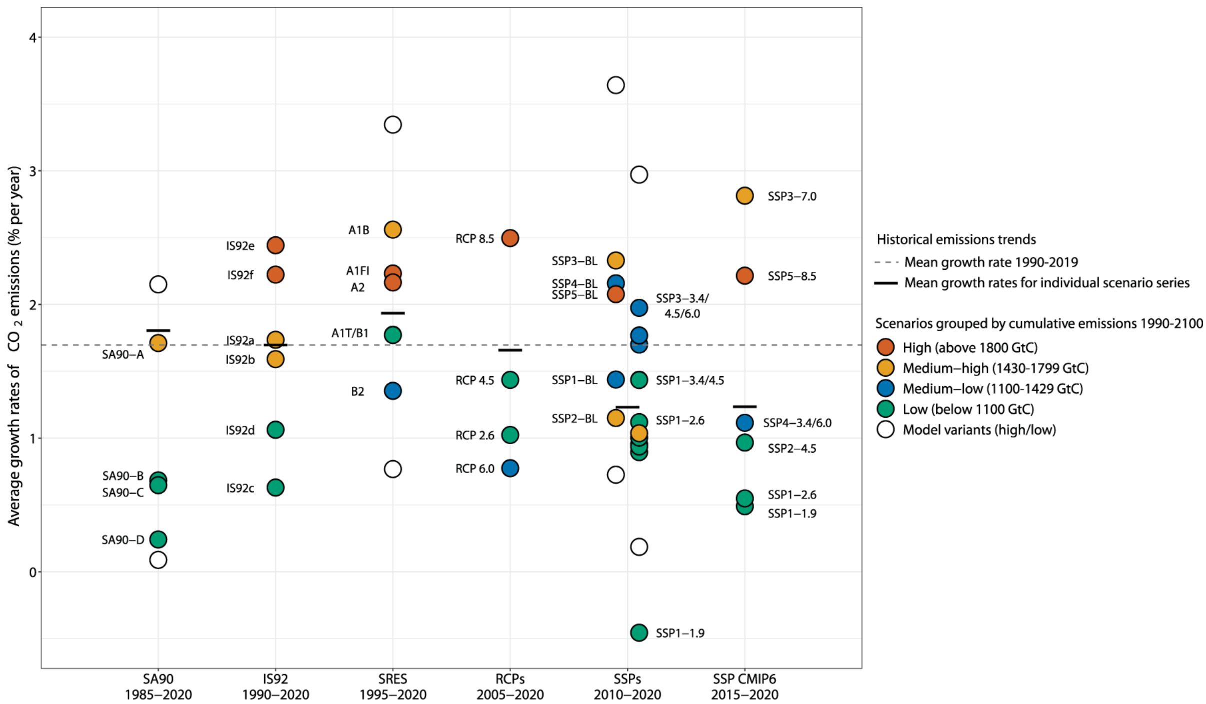

Figure 5-1. Global growth rates of historical and scenario CO_2 emissions from fossil fuels and industry.

The average scenario growth rates of emissions are calculated for individual marker/illustrative scenarios (filled circles) and low/high model variants (open circles) covering the actual projected period for each series (IPCC, 1990a; Leggett et al., 1992; Nakicenovic and Swart, 2000; Riahi et al., 2017; van Vuuren et al., 2011) compared to growth rates of historical emissions (GCP, 2019) for the equivalent periods (short black lines) and the IPCC period 1990-2019 (dashed grey horizontal line). Individual growth rate lines (short black lines) cover SA90 (34 years), IS92 (29 years), SRES (24 years), RCPs (14 years), SSP-baselines (left) & SSP-mitigation (right) (9 years), and SSP CMIP6 (4 years) (O'Neill et al., 2016; Riahi et al., 2017). Scenarios are grouped into four cumulative emissions categories (Total CO_2 emissions 1990-2100) (IPCC, 2000a): low (vermillion), medium-low (bluish-green), medium-high (orange), and high (blue) emissions – the color-coding is optimized for readers with color blindness (Wong, 2011). For some of the scenarios, the growth rates (1985-2020) do not necessarily reflect the century-long emission trajectory of the scenarios (e.g., several scenarios have a peak-and-decline shaped trajectory, such as SA90-B, IS92c, SRES-A1B/T/B1, RCP4.5, SSP1, and SSP4). The scenario databases commonly report emissions at intervals of 5, 10, or 25 years. The Compound Annual Growth Rates (CAGR) method was used since it calculates the beginning and end value, providing a consistent growth rate comparison between projections and historical developments. Projected scenario estimates for the years 1990, 2020 (SA90), and 1995 (SRES) were calculated using linear interpolation, which is considered robust (Peters et al., 2013). (See Supplementary Information Figure 1 and Tables 1-2, 4-9).

The historical global emissions are roughly aligned with SA90-A, IS92a, RCP4.5, SSP2 and SSP1-2.6, and SSP4-3.4/6.0 (CMIP6) (Figure 5-1). Overall, the scenario range forms an almost symmetrical bracket around the historical emission trend for each scenario exercise. It should be noted that the IS92, SRES, SSP-baselines, and several RCPs do not include new climate policies – and thus they represent possible reference cases to assess policies. Notably, RCP6.0 has the lowest growth rate in the RCP series for the 2005-2020, while it's the second highest between 2005-2100.

Global CO_2 emissions have increased by 40% (from 6.2 GtC in 1990 to 10 GtC in 2018), with an average annual growth rate of 1.7%. The period covers three sub-periods of overall medium-low growth (1992-1998: 0.6%), high growth (1999-2012: 2.6%), and overall medium-low growth (2013-2018: 0.8%). In 2019, emission growth was relatively low (0.6%)(GCP, 2019), and a temporary drop (between -3 and -7%) is expected for 2020 due to the Covid-19 pandemic's effect on economic activities (le Quéré et al., 2020; Liu et al., 2020).

Since 2000, the most recent historical high-growth period began just after the SRES publication. Several publications noted that emissions were tracking the high-end emission scenarios (Le Quéré et al., 2009; Peters et al., 2013; Raupach et al., 2007). However, we find that on average, emission growth over the last three decades has fallen between the medium and high emission scenarios. The high growth period ended around the SSP publication, explaining the significantly lower historical growth rate averages assumed in the SSPs. As a result, the historical trend is at the low end of the SSP baseline range. This slow growth may be attributed to a combination of slow historical global economic growth rates (World Bank, 2019) (which were also below the SSP-Baseline range(Riahi et al., 2017)), rapid technological development of some renewable resources (IRENA, 2019b; Observ'ER, 2019) (partly a result of policies), increasing natural gas use (driven by new production routes (Cremonese et al., 2019)), and climate policy implementation(International Energy Agency, 2019; United Nations Environment Programme, 2019).
In essence, the long-term historical developments (~20-30 years) suggest that the world has followed an emission pathway in the middle of IS92, SRES, RCP, and SSP scenario ranges. Simultaneously, shorter-term trends show high variability, emphasizing the importance of maintaining a broad emission range for future emission scenarios.

5.4 Implications for defining BAU or best-guess scenarios

Over the historical period, emissions have thus tracked the middle of emission scenario ranges, slowly moving to a slow growth period in the last few years. It seems logical to conclude that it is more likely than eight years ago (Peters et al., 2013) that emissions (and global warming) will follow a trajectory much lower than RCP8.5 (Hausfather and Peters, 2020). Together with RCP4.5 and RCP6.0, RCP8.5 was initially published as one of a set of three possible baseline scenarios, describing a low-end, median, and high-end baseline trend (in the absence of climate policy), respectively. It was stated that it was, at the high-end, close to the 90th percentile of emission scenarios published at that time(van Vuuren et al., 2011a).
However, some researchers in the community that uses emission scenarios as input quickly picked up RCP8.5 as a business-as-usual scenario (BAU). In the primary literature, the BAU term was only used in the SA90 series for a scenario without policy assumptions (SA90-A) (IPCC, 1990a). Historically, the BAU concept and policy assumptions were excluded from scenario developments by the IPCC terms of reference in 1991 (IPCC, 1991; Pepper et al., 1992). After this, the developers have created scenarios with similar assumptions as SA90-A. Such scenarios have been described as continued historical trends (IS92a) (Leggett et al., 1992), dynamics-as-usual (SRES-B2)(Riahi et al., 2017) or middle-of-the-road (SSP2) (Riahi et al., 2017). These were not intended as a best-guess or BAU scenario.
A BAU choice or a best-guess scenario is complicated and subjective since it reflects assumptions that may change from decade to decade as new societal trends make in-roads and plausibly affect emissions trends. The high focus on RCP8.5 from the scientific community (Pielke and Ritchie, 2020) may have been a consequence of the 1999-2012 high-emission period (GCP, 2019)

and the scenario-assessments discussing a plausible too-low emission range (Le Quéré et al., 2009; Peters et al., 2013; Raupach et al., 2007). The appraisal that RCP8.5 should not be described as 'the' BAU scenario (Hausfather and Peters, 2020; Pielke and Ritchie, 2020) is thus entirely in line with its initial intention as a relatively unlikely, but still plausible high emission case(van Vuuren et al., 2011a).

Politicians or policymakers do not always consider uncertainty ranges(Tulkens and Tulkens, 2011) and sometimes request best-guess estimates from researchers. However, historically best-guess scenarios have had limited shelf lives: Between 2007 and 2013, a best-guess scenario could have been RCP8.5 (Peters et al., 2013; Raupach et al., 2007), and during the 1990s – before the last high growth period – the IS92a (medium-high) was an often preferred reference scenario for mitigation and stabilization studies (Alcamo et al., 1995a; Intergovernmental Panel on Climate Change, 2001). To inform decisions with a long lead time for planning and implementation, information about the full range of uncertainty is relevant (Hinkel et al., 2019; Oppenheimer et al., n.d.) for decision-makers to be aware of uncertainties and make decisions that are robust or adaptive to such uncertainties.

In essence, best-guess scenarios may not be the best way to reduce complexity and simplify the interpretation of scenarios for policymakers. The recommendation of attaching a set of best-estimate or probabilities to future emission scenarios to assess future climate change(Hausfather and Peters, 2020) may provide a false sense of certainty to decision-makers and additionally costly adjustments if the world evolves in unanticipated ways (Lawrence et al., 2020).

5.5 Implications for low- and high-end emission scenarios

The RCP8.5 does not describe a continuation of current trends but a scenario for analyzing low-probability high-impact events. In the light of recent scientific discussions, is RCP8.5 still relevant for this purpose? By definition, if emissions track the middle-of-the-scenario range, both the low and high-end scenarios will become less likely over time. For instance, the lower bounds of the emission scenario series during the 1990-2020 period have moved up in the successive sets from SA90 to SSPs, arguably adapting to rising historical estimates over time (IPCC, 1990a; Leggett et al., 1992; Nakicenovic and Swart, 2000; Riahi et al., 2017).

A lesson from our historical analysis is that there are unpredictable changes in global economic conditions (and technological advances) that have a relatively immediate impact on emission trends. Thus, it is wise to have modest expectations when we estimate the emission range, given the reversal of different global trends at different times (as illustrated in Figure 5-2a). Therefore, the key question is whether the factors that have caused the recent historical change of a high emission growth period (1999-2012) to a medium-low growth period (2013-present) are structural and different from when they were assessed in the past. One may expect some of the factors leading to slower emission growth(GCP, 2019) (recent medium-low energy growth (International Energy Agency, 2020), emerging climate policies(Rogelj et al., 2016b; United Nations Environment Programme, 2019), and decreasing costs of renewables (IRENA, 2019b; Observ'ER, 2019)) to be structural(Hausfather and Peters, 2020). Thus, both medium-low and low emission scenarios remain plausible and should be regularly reassessed since they relate to important policy goals. But does it automatically mean that emission trends could not pick up speed again?

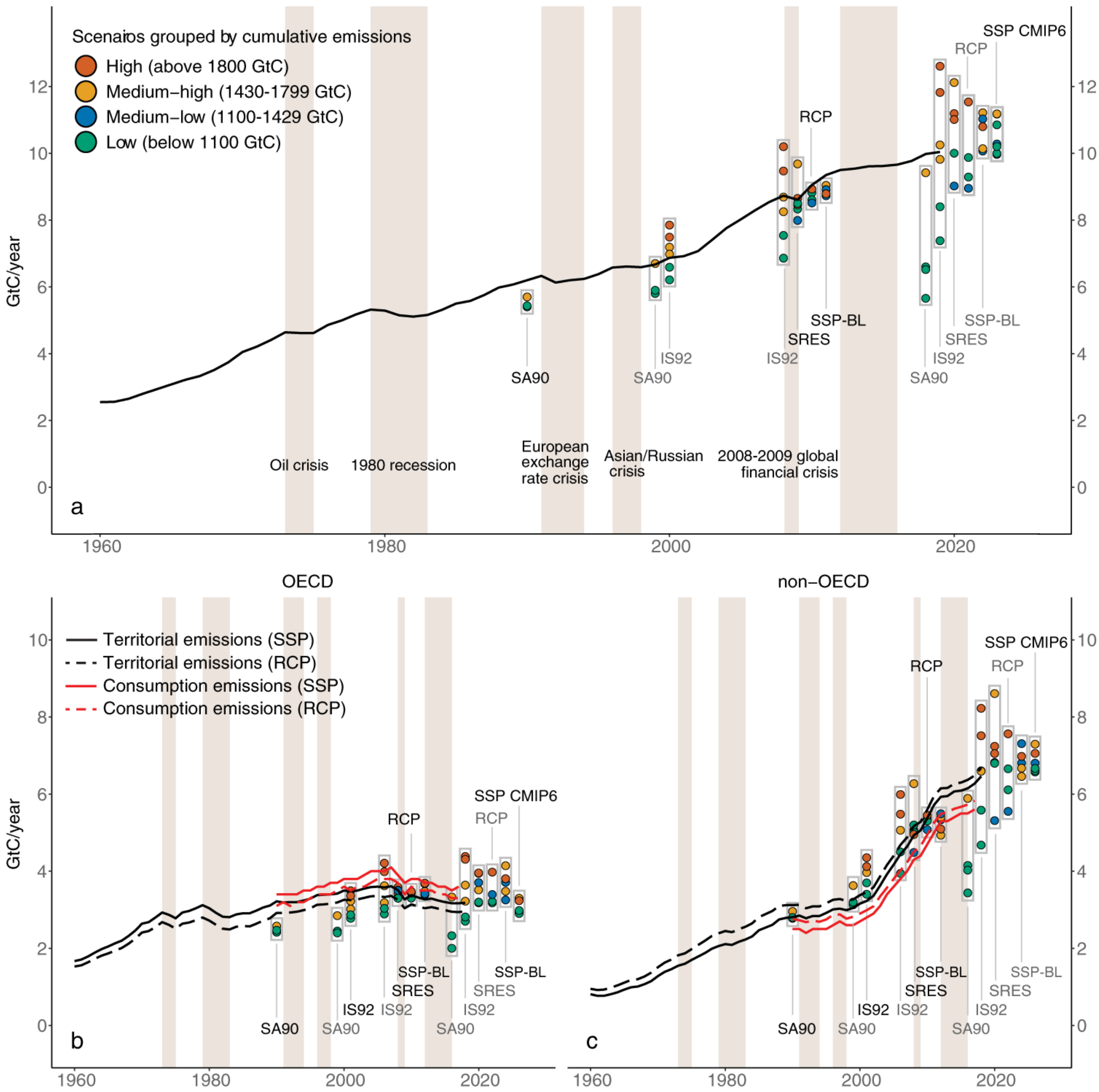

Figure 5-2. Global, non-OECD and OECD historical CO_2 emissions (1959-2018) compared to SA90, IS92, SRES, RCP, SSP-BL, and SSP (CMIP6) emission scenarios.

a, Global emissions with low to medium-low growth periods of ≤1% annual growth (grey shaded areas) and periods of global emissions growth above 1% (white areas). b, OECD territorial/production (black) and consumption (red) emissions (GCP, 2019) compared to scenario projections. c, non-OECD territorial/production (black) and consumption emissions (red) compared to scenario projections. Historical data are presented by solid lines (SSP definitions(Riahi et al., 2017)) and dashed lines (RCP definitions (van Vuuren et al., 2011a)). The definitions of OECD and non-OECD differ between the SA90 (IPCC, 1990a), IS92 (Leggett et al., 1992), SRES (Nakicenovic and Swart, 2000a), RCP and SSP databases (e.g., RCP OECD is based on OECD90 (32 countries) and thus including fewer countries than the SSP OECD category, including OECD90+EU member states and candidates (44)). Scenarios are grouped into four cumulative emissions categories (Total CO_2 emissions 1990-2100): low (vermillion), medium-low (bluish-green), medium-high (orange), and high (blue) emissions. (Furthermore, see growth rate comparisons in Supplementary Information Figure 2).

At odds with the results of the growth rate comparisons, according to recent research, historical cumulative emissions 2005-2020 track RCP8.5 emissions closely(Schwalm et al., 2020). We find that total historical cumulative CO_2 emissions for both the 1990-2020 period (288 GtC) and 2005-2020 (168 GtC) are close to the projections in medium-high emission scenario IS92a and SSP3-7.0, and high emission scenarios SRES-A2, SRES-A1FI, RCP8.5, SSP5, and SSP5-8.5 (Supplementary Information Table 3). High emission scenarios are still of importance to account for possible extreme outcomes.

There are several possible ways in which the future can unfold. Governments in various countries could actively continue using fossil-fuel, regardless of the Paris Agreement's international ambitions. Some political leaders in key countries (e.g., the United States and Brazil) support CO_2 intensive economic growth, while fossil fuels are still heavily subsidized in EU member states(Coady et al., 2017), despite climate policies. Digitalization could lead to increased efficiency(Grubler et al., 2018), but could also increase energy use via new energy-requiring activities. The energy poverty and availability of fossil fuel resources in low-income countries could increase fossil rather than renewable energy investments, supported by investments from high-income countries (Doukas et al., 2017; Rawoot, 2020). New developments in energy extraction in the African (Crooks, 2018) and Polar regions could lead to a drop in fossil fuel extraction costs and enhanced energy-intensive economic growth. Also, the global population's persistent growth together with increasing per capita consumption and energy use play an important role, albeit from a low base in economies that have currently low incomes and historically low emissions. Population growth could track the UN high scenario (15.5 billion by 2100) (United Nations Department of Economic and Social Affairs Population Division, 2019) instead of 12 billion in RCP8.5 (van Vuuren et al., 2011a), and economic growth could be underestimated in the RCPs/SSPs (Christensen et al., 2018).
Moreover, it is difficult to foresee the aftermath of the Covid-19 pandemic. There has been a clear drop in energy use and strong voices arguing for green recovery packages. However, low fossil fuel prices may reduce renewable energy investments seeing fast economic recovery without sustainability conditions, which may slow down climate policy(Tollefson, 2020). Finally, recent insights into climate – greenhouse gas feedbacks suggest that earth-system emissions in response to climate change could be higher than those currently included in the models (Hausfather and Betts, 2020).

Given these plausible future developments, both low and high emission scenarios are still possible. To provide support for meaningful decision-making, via scenario-based literature, also the outer ends of the plausible emission scenario range with associated low and high climate impacts remain relevant to inform mitigation and adaptation challenges.

5.6 Global emission trends hide very different regional dynamics and key linkages

To better understand possible future global emissions, it is crucial to consider regional emissions and their drivers. The historical global average hides underlying regional trends, making it important to look at regional emission trends such as those from OECD and non-OECD regions. Assessing the slow growth periods, global emission growth (Figure 5-2a: vertical grey shaded areas) was determined mainly by OECD member countries during the 1970s and 1980s (Figure 5-2b and c). In comparison, the slow growth during the 1990s characterized both OECD and non-OECD trends. During the last slow growth period, both global and non-OECD emissions' slope broke to a less steep curve simultaneously from 2013 onwards, while the OECD emissions stabilized or decreased a couple of years earlier (from 2010).

Since 1990, emission growth has been dominated by countries with no emissions limitation targets (UNFCCC/COP, 1997) and low per capita emissions (Le Quéré et al., 2009; Parikh, 1992a; UNFCCC/COP, 1997), and by the USA and Canada, which did not ratify the Kyoto Protocol, with resulting increase in emissions till 2008 (GCP, 2019). As such, it is relevant to consider if regional emissions have grown faster or slower than projected and if new assumptions may strengthen future projections. While the historical trend is closer to the medium-low and low-end of the scenario range in OECD countries, it is closer to the medium-high and high-end of the scenario range in non-OECD countries (Figure 2b and c).

These observations mainly tell us something relative: that non-OECD scenarios may have been a bit too low and OECD scenarios too high compared to reality (territorial emissions). And thus, non-OECD is getting more important in the future. The recent trend in OECD countries is partly caused by increasing renewable investments (International Energy Agency, 2020), increased energy efficiency, and climate policy (United Nations Environment Programme, 2019), but also by the trend of exporting (mostly fossil fuel-related) energy investments (Doukas et al., 2017) and industrial production to non-OECD regions (Peters et al., 2012). Accounting for the industrial energy-export (GCP, 2019), OECD consumption-related emissions tracked medium-high and high emission scenarios closely. While some of the factors such as policy and energy efficiency also play a role in non-OECD countries, they have not led to a downward shift in emission trends. Historically, the more prosperous countries were expected to reduce their emissions to allow for fossil driven developments in low-income countries, under the climate change regime (UNFCCC/COP, 1997). Additionally, a bulk of the remaining global fossil fuel reserves are located in the global south, which has attracted exploitive energy corporations based in high-income countries such as the United States, Asian, and climate policy leading EU member states (Build, 2018; Crooks, 2018; Doukas et al., 2017). If such authoritative trends continue, this may support continued global inequality, e.g., as described in the SSP3 and SSP4 storylines. SSP4 represents high adaptation challenges in low-income countries, and SSP3 high mitigation and adaptation challenges.

One may note that emissions from non-OECD countries could represent a key to future emissions developments. In particular, since the non-OECD group contains a larger number of countries, people and landmass compared to the OECD group and are on an earlier stage of economic development, their future development may lead to greater energy use.
Retrospectively, the SA90 and IS92 scenarios had low growth rates for developing countries (Parikh, 1992a), compared to the global convergence scenarios of the SRES (and SSP) series. Continued fossil investments in low-income countries (Doukas et al., 2017) may cause stranded assets (Bos and Gupta, 2019; Mercure et al., 2018) but also long-term structural inertia. Hence, a substantial driver of growing energy demand in the future may be continuing economic convergence between the global North and South - with rapid economic growth in large economies like India and China. To curb global emissions, it appears crucial to analyze national responsibilities both within and outside national borders. As such, consumption and energy investments represent two areas of plausible interest for policymaking and UNFCCC negotiations.

5.7 Conclusion and future outlooks

We conclude that it is still realistic to assume that global emissions can track high emission scenarios. One may argue that although fast emission growth has become undoubtedly less likely, high-end scenarios such as RCP8.5 are not yet impossible and still relevant. In particular, to assess the full range of possible climate change impacts for investments with long time horizons. Therefore, the full range of emission scenarios remains important as inputs to scenario-based analysis assessing possible climate impacts, particularly for investments with long time horizons. But for this, RCP8.5 should be described as a low-possibility, high-impact case, and not as a business-as-usual case. Best-guess scenarios tend to have a short shelf life and using only those may lead to a mistaken sense of certainty for scenario-based assessments and policy decisions. Medium scenarios may represent best-guesses, and thus IS92a may present an example of a best-guess scenario that has matched the historical global emissions pathway well. However, IS92a has been less successful in capturing historical developments in regional emissions. Regarding mitigation analyses, the choice of a high or medium baseline is less relevant since, especially in the short-term, the gap between any baseline scenario and 2° or 1.5° C scenarios is still very large, requiring global emissions to be urgently reduced.

The essence of emission scenario development is to explore a range of possible pathways and their relevance. The long history of inaccurate predictions concerning oil prices or energy use demonstrates that it has been, and it will remain challenging to foresee shifts in economic and technological development paths at the global and regional levels. Hence, providing a wide range of scenarios with distinct regional characteristics remains a fundamental approach to inform policy meaningfully. If high-emission scenarios would ever be realized, this may particularly result from developments in non-OECD emissions as they are linked to consumption in the OECD countries, the still large quantities of fossil fuel reserves available in the South and associated national and international energy investments. Even if territorial emissions in OECD countries would decrease, the implications of economic interconnections between high- and low-income countries for global emissions should be further investigated, e.g., in new scenario analysis.

5.7.1 Author contributions

All authors contributed to the planning of the paper. JP and DV led the work. BA and JP prepared the figures and the associated analysis. JP did the mean annual growth rates, interpolations, and cumulative emissions calculations. JP and DV processed the primary structure, and writing and all authors JP, DV, BA, RS, JG, and FS contributed to data interpretation, revisions, and paper writing. RS supported scenario analyzes, JG regional analyzes, and FS emissions and socioeconomic trends.

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5.7.2 Additional information

Supplementary information is available in the online version of the paper (www.nature.com/articles/s43247-020-00045-y). See additionally SI Chapters 4-7.

6 The Policymakers' Perspective: simpler communication, more national detail, and capacity building

Journal

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Title

Bridging Science-Policy and Closing the South-North Knowledge Divide: Surveying the Policy Relevance of Emission Scenarios

Authors

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6.1 Abstract: Technical and non-technical

Abstract: Climate change extends into the far future (IPCC, 2023a). Thus, for three decades, model-based scenarios have comprised a backbone of future climate change science, aiming to inform policies (Moss et al., 2010b; van Beek et al., 2020). The science-policy interface asserts that effective climate policy links scientific knowledge and policy action. Researchers have focused on improving scenario content and credibility, development methods and legitimacy, and discussing the scenarios' policy relevance and salience (Hulme and Dessai, 2008b; Pedersen et al., 2022) without communicating the actual policymaker experiences and needs. Moreover, the scientific community within the Intergovernmental Panel on Climate Change (IPCC) requested more insight into how policymakers understand and use scenarios (IPCC, 2023d). Here, we survey national focal points of the United Nations Framework Convention on Climate Change (UNFCCC), assessing their knowledge of emissions scenarios, policy usability, and plausible scenario improvements. The population (N=299) and sample (n=57, response rate 21%) comprised policymakers, scientists, and government officials engaged in UNFCCC activities and connected to national policymaking. It may not be generalizable to the larger population. We show that the examined UNFCCC policymakers request more uncomplicated scenario communication and more policy-relevant detail. The results show a regional divide in knowledge, with representatives from least-developed countries having a significantly lower understanding of scenarios. Thus, capacity building may also play a key role in improving scenario salience.

Keywords: Emission scenarios; policymaker perspectives; policy relevance; science-policy communication; climate justice; United Nations Framework Convention on Climate Change (UNFCCC); Intergovernmental Panel on Climate Change (IPCC)

Non-technical abstract: Emission scenarios are descriptions of different possible futures. They can all happen, but since they show different outcomes, the actual realized future may look like one of the scenarios. They show how the global society can develop in terms of energy use, economic growth, population, lifestyles, political ambition, and focus (e.g., on economic growth or sustainable development). These describe the future levels of greenhouse gas emissions by 2100 and how warm the planet may get. The scenarios are created via words (storyline descriptions of the global society and political foci) and numbers (mathematical calculations and translations of the storylines). Scenarios are the only existing tool to track the progress of the Paris Agreement (the short-term policy scenarios analyzing national targets for the Paris Agreement). Other emission scenarios represent the backbone of future climate research (long-term emission scenarios informing the Intergovernmental Panel on Climate Change, used as input for climate scenarios). The latter is used as input for impact scenarios (assessing future damage to nature and human societies and how they are vulnerable to changes in the climate, e.g., more extreme and frequent droughts and storms). Too little attention has been paid to the needs and views of scenario users in discussions about how to develop scientific knowledge (scenarios), which policymakers understand and will use in designing policies. The survey informing the paper included 57 UNFCCC delegates. The research shows that scenario developers need to better support policymakers, e.g., provide more uncomplicated communication of scenarios to non-scientists and provide more national detail about how to reduce emissions via policy (e.g., the plausible cost and effect of various emission reductions actions). It is recommended that the scientific community producing scenarios engage in ongoing science-policy dialogue to improve scenario communication, implement policy-relevant information in scenarios, and support training and capacity building in the global South to support the use of scenario knowledge in low- and middle-income countries.

6.2 Introduction

While the scenarios' salience is often discussed by scientists (Hausfather and Peters, 2020; Schenk and Lensink, 2007; Schneider, 2001), the actual policy relevance is not evident (Jaccard, 2016; Lodhia and Martin, 2012), and the literature has hardly communicated the policymakers' perspectives on scenarios. Here, we surveyed if policymakers are familiar with the scenario concept, if they find scenarios useful to guide decisions, seeking to evaluate the practical policy relevance of emission scenarios and explore avenues for enhancing their effectiveness by surveying the perspectives of UNFCCC national focal points. It aligns with ongoing discussions on the usability of scientific knowledge in policymaking (Cash et al., 2003; White et al., 2010) and the value of scenario information for addressing climate change challenges (Masson-Delmotte et al., 2023).

The history of the IPCC shows that it is essential to pay attention to the three criteria of credibility, legitimacy, and salience to link knowledge and action effectively for environmental assessment (Clark et al., 2006) and sustainable development (Cash et al., 2002, 2003; Haas, 2004; White et al., 2010). Credibility concerns the information's trustworthiness, quality, and reliability (Cash et al., 2003; Haas, 2004), e.g., data accuracy (Cash et al., 2003; Pedersen et al., 2021), that the scenario developments (Beck and Mahony, 2017) and contents are transparent and non-biased(Cash et al., 2003), and non-scientific users trust the product (Cash et al., 2002; Robertson, 2021). IPCC initially aimed to be a reputable source of scientific data (WMO/UNEP, 1988). Credibility was at the center of attention for the first assessment reports(Cash et al., 2002), emphasizing creating organizational structures and processes to ensure the credibility of(Agrawala, 1998) and provide trusted information (Cash et al., 2002). Credibility alone was insufficient to bridge the knowledge-action gap. Global South researchers and IPCC delegates raised concerns about the scenario legitimacy and the fairness of the information-producing process, i.e., the lack of representation of global South perspectives (IPCC, 1996; Parikh, 1992a). Legitimacy concerns knowledge development (Cash et al., 2003) and involves the fairness, equity, and inclusiveness of the process. Legitimate information is produced through processes that minimize potential biases and include participation from those who are affected by the decisions being made, with representation of diverse perspectives and interests in the decision-making process(Cash et al., 2003), ideally leading to acceptance outside the modeling community(Haas, 2004). Within the IPCC the critique highlighted a need to consider a larger range of values, concerns, and viewpoints of various actors (Agrawala, 1998). Legitimacy concerns knowledge development, e.g., processes minimizing biases and equal inclusion (Cash et al., 2003). The critique led the IPCC to mandate significant changes in the author team for developing the 3rd scenario generation, informing the IPCC (IPCC, 1996; Nakicenovic and Swart, 2000a). Successive credibility and legitimacy critiques moved scenario development of the 4th generation(Gidden et al., 2019a) outside the IPCC(IPCC, 2006c). Finally, salient assessments are geared to real-world decisions(Clark et al., 2006), how well the information aligns with the priorities, needs, and concerns of decision-makers, delivered timely, and provides advice that can be converted into policies by decision-makers (Cash et al., 2003; Haas, 2004; White et al., 2010). Scenario salience has been discussed in different ways. For instance, the implicit assumptions in the information provided (e.g., supply-side focus) but also the role of a set of possible development versus[20,38] the most likely scenario (Hausfather and Peters, 2020). On the other hand, scenarios may not address the currently valuable questions or present a broad enough variety of perspectives (Masson-Delmotte et al., 2023). One way to increase salience is to communicate scenarios in less complicated ways to policymakers (O'Neill et al., 2020; Schenk and Lensink, 2007).

Emission scenarios explore a range of plausible future developments in greenhouse gas emissions (GHGs) under different future societal conditions (Riahi et al., 2017). They serve as input for scenario-based literature assessing plausible future climatic changes (climate scenarios), which again serve as input for impact scenarios, assessing risks and responses (Lawrence et al., 2020; J. S. T. Pedersen et al., 2020). The scenario literature includes both long-term scenarios focused on different views of the future and more short-term scenarios that assessed national mitigation policies and targets related to the Copenhagen pledges and Nationally Determined Contributions (NDCs)(CAT, 2023a; UNEP, 2022) under the Paris Agreement (UNFCCC/COP, 2015a). The global scenarios also play a major role beyond the global scale: they are used (via downscaling tools) to also inform national governments and sectors (e.g., the Network for Greening the Financial System (NGFS) scenarios (NGFS, 2021) and the use of scenarios in the Science-based Targets setting(Science Based Targets, 2023)).

Given the role of scenarios in the climate negotiations, the IPCC reports and even, indirectly, national level policy advise, we surveyed National Focal Point delegates of the United Nations Framework Convention on Climate Change (UNFCCC) (UNFCCC, 2020a) about their familiarity with scenarios and the perceived usefulness of emission scenarios to provide insights into the specific requirements, challenges, and expectations of those directly involved in shaping climate-related policies. UNFCCC national focal points play a key role as intermediaries between the international negotiations and their countries, facilitating information exchange and coordinating activities within their countries. Unlike country delegations at COPs, the national focal points are committed year-round to UNFCCC processes, offering unique insights into national policy contexts. By examining the knowledge, perceptions, and needs of these delegates, the research aligns with IPCC scenario expert requests, aiming to understand the role of scenarios in informing decision-making in both international and national policymaking contexts (Masson-Delmotte et al., 2023). The familiarity and views of the focal points on scenarios is useful – even independent of the question what role scenarios should ideally play in decision-making. Despite a limited population and sample size, the survey provides first hand perspectives from dedicated UNFCCC delegates on the challenges and expectations surrounding scenario knowledge in policymaking.

6.3 The sample

The survey achieved a response rate of 21%. Fifty-seven of 299 UNFCCC national focal points(UNFCCC, 2020a) participated (emails were successfully sent to 278 focal points). The participants were between 24-72 years (M = 44). On average, the respondents find it highly important to mitigate climate change (4.8 out of 5). Participants UNFCCC experience ranged between 1 and 30 years (M=8 years). Seventy percent had UNFCCC negotiation experience, and 86% had experience with national policymaking. They self-identified their principal occupational roles as policymaker (77%), researcher (11%), or stakeholder/other (12%). Regarding their role in policymaking, participants classified themselves as either leading (35%), coordinating (14%), advisory (35%), informing (4%), following (4%), or having no role (9%). We categorized participants in leading and coordinating roles as "policy enablers" directly engaged in the policymaking process, while the remaining were classified as "policy contributors."

The sample comprises 65% from non-Annex-I countries and 35% from Annex-I countries, statistically different from the population (80%/20%) with higher Annex-I representation. The world has changed since the creation of the UNFCCC annex structure, distinguishing between developed and developing countries. Thus, we differentiated participants based on income levels and UN-defined country development categories for analytical purposes. Among the respondents, 28% represented countries classified as Least Developed Countries (LDCs), 33% represented Medium Developed Countries (MDCs), and 39% Highly Developed Countries (HDCs). LDCs comprise UN classifications of least developed countries (UNDESA, 2023), MDC middle-income countries (excluding UN-classified LDCs), and HDC high-income countries according to World Bank classifications (World Bank, 2022). In comparison, the global distribution of these categories stands at 23%, 46%, and 31%, respectively (Pedersen, 2022). Notably, considering environmental sustainability, we recognize that the term developed is inappropriate since HDCs contribute most to pollution and greenhouse gas emissions (GHGs).

Given the relatively modest population and sample size, drawing broad generalizations to the entire UNFCCC delegate population implies challenges. The findings primarily pertain to the subset of delegates actively engaged in both annual COP meetings and inter-sessional UNFCCC meetings and negotiations in Bonn.

6.3.1 Informants' familiarity with the scenario tool

We examined the participants' self-reported familiarity with the emission scenario tool to create a foundation for the analysis, i.e., participants who are familiar with the scenario tool are more reliable in evaluating its policy relevance and plausible improvements. Figure 6-1 shows the distribution of delegates with low (yellow) and high (green) awareness of the emission scenario concept. On average the participants have high familiarity (4 out of 6). A little more than 70% of the examined policymakers recognize the concept of emission scenarios (answers 4-6). Of these, about 40% have heard about them (answer 4), and about 30% know them very well (answers 5-6).

There is, however, a large regional dimension. On average, the examined LDCs (3.8) and MDCs (3.6) have a familiarity expressing knowing them little and well, while HDC participants (4.5) know them between well and very well. Only 27% of LDCs and 7% of MDCs, while more than half of HDC (57%) representatives know emission scenarios very well. The difference between LDCs/MDCs and HDC participations regarding emission scenario familiarity is significant at a 10% level (0.006).

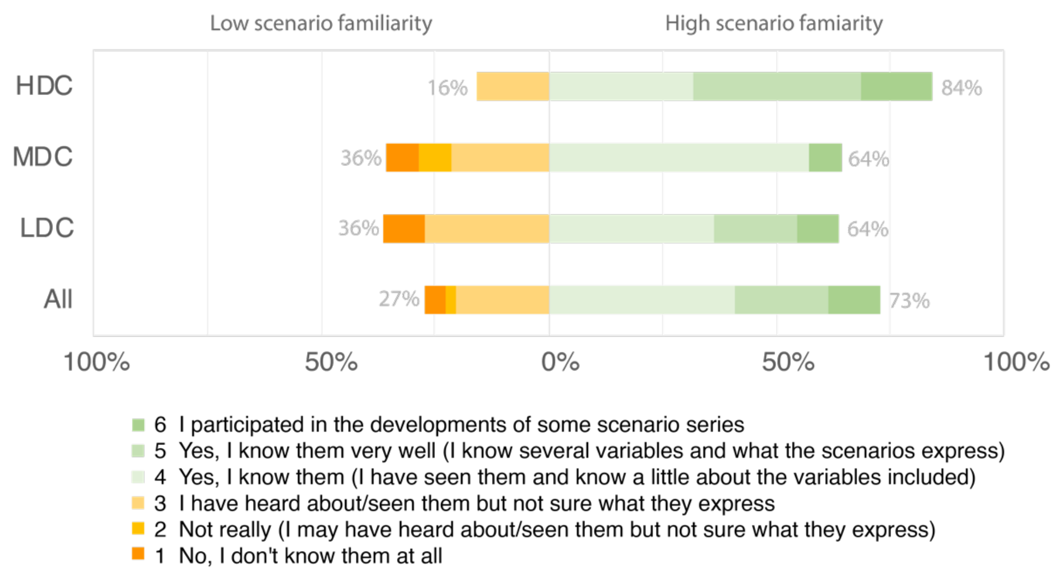

Figure 6-1. Familiarity with the emission scenario concept.

The share of UNFCCC national focal points having a high awareness (green colors) and low awareness (yellow colors) grouped by Highly Developed Country (HDC), Medium Developed Country (MDC), and Least Developed Country representatives (LDC), and all examined delegates (All), n=57 (N=299).

About 25% of the examined delegates have low knowledge about emission scenarios. They have either heard about them but are unsure what they express (20%) or don't know them (7%) (answer 1). Low familiarity is displayed by a higher share (36%) of Medium and Least Developed Country (LDC/MDC) representatives than Highly Developed Country (HDC) representatives (17%). Also, the open-ended questions reflect two different knowledge bases. Typically, HDC participants use advanced terms related to scenario models (e.g., IAMs, variables, downscaling) and variables (e.g., CDR, AFOLU, BECCS). They have more advanced requests for scenario improvements, like "The issues of climate change and biodiversity need to be equally covered in scenarios" (HDC policy advisor). MDC and LDC survey participants describe scenarios in more general terms, like "display scenarios in a simpler and more understandable way" (MDC African Policy enabler) and make them "transmittable to a national policy context" (LDC, Small Island policy enabler).

6.4 Emission scenario salience

Policy relevance (or salience) pertains to information's usability for policymakers and decision-makers in guiding decisions or achieving political goals(Cash et al., 2003; Haas, 2004; Haynes et al., 2018). Since UNFCCC delegates often engage in national policymaking and both global scenarios and local scenario extensions assess and inform about national policies(CAT, 2023a; Kebede et al., 2018), we investigated policy relevance by asking the informants how they perceive various scientific tools' usefulness in designing national mitigation policies and facilitating UNFCCC treaties.
In national policymaking, governments may benefit from scenarios to set emission reduction targets, develop mitigation and adaptation strategies, and assess the potential impacts of policy measures(EU, 2020a). Within the UNFCCC, emission scenarios inform assessments of safe emissions limits related to potential future impacts of various emissions pathways(SBSTA/SBI, 2015). Global scenarios may support negotiators in setting global emission reduction targets and how to achieve them. In contrast, several short-term scenarios provide transparency and insight into the policies and achievability of national commitment.

Figure 6-2 shows the connection between the degree of scenario knowledge and the perceived policy relevance of emission scenarios for all delegates (Panel a) and grouped by country development level (Panel b). The participants with high scenario familiarity may have more comprehensive backgrounds for evaluating salience. They also evaluate emission scenarios as more useful in international and national processes compared to those with low familiarity.

Scenarios might be less salient to decision-makers from less developed countries. Highly Developed (or High-Income) country (HDC) representatives find emission scenarios more useful for designing national mitigation policies compared to medium and least-developed countries (MDC/LDC) and more relevant nationally than facilitating international climate treaties. On average, MDC/LDC representatives perceive emission scenarios as between 3 and 4 ("in-between" and "some degree" useful) in a national context. In contrast, for facilitating international treaties, they are, on average, considered between 4 to 5 ("some degree" to "high degree") useful.

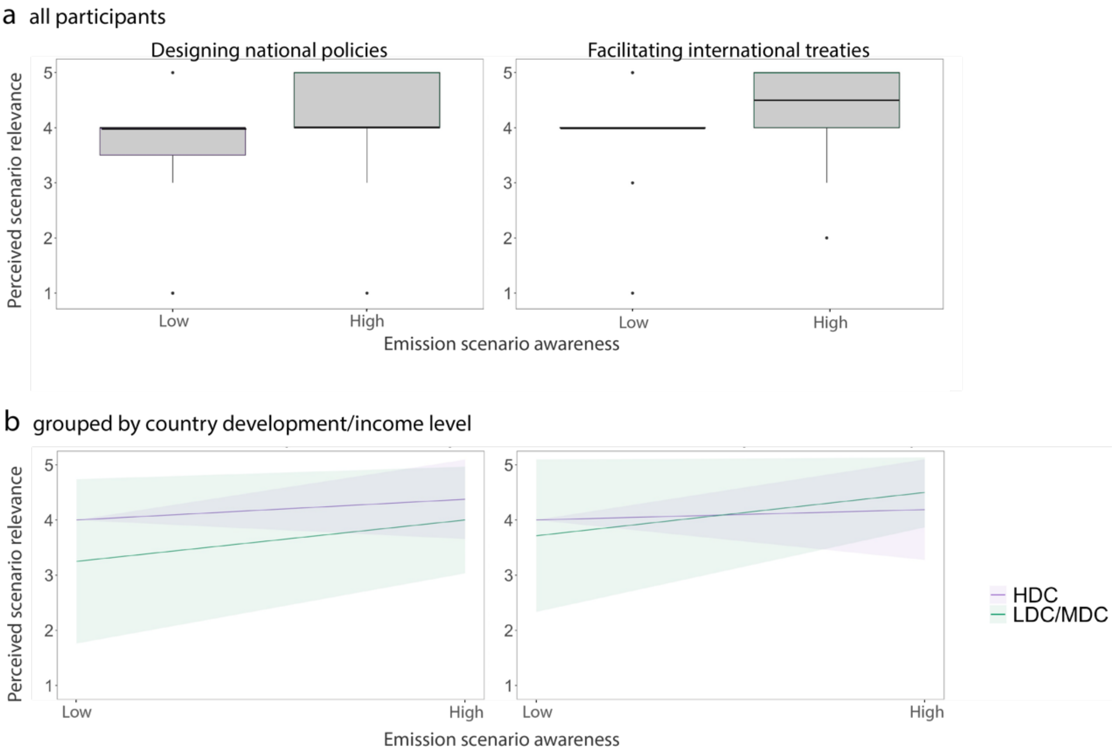

Figure 6-2. Policy relevance of emission scenarios in facilitating national policy (left) and UNFCCC treaties (right) as perceived by UNFCCC delegates.
Panel a: results are comprised based on answers from all participants and grouped by their awareness about the scenario instrument; panel b: answers grouped by country development level representation (22 HDC (Highly developed) and 35 MDC/LDC (medium and least developed). Median (line) and variability/standard deviation (colored area). The box plot shows the 'middle 50%' of the answers (grey box), and the median (horizontal black line) represents the middle answer. In comparison, the box-ends represent the 25% quartile and 75% quartile (comprising 50% of the data responses). Each of the whiskers (vertical black lines) extends up to about 1.5 times the box size (the whiskers extend to the most extreme responses, which are within the range of the upper and lower ends of the box plus or minus 1.5 times the interquartile range (IQR - the box length). Outliers (dots) express low or high responses outside the whisker ranges. In Panel b, the lines correspond to the median value within an informant group, with lower and upper shaded boundaries corresponding to the 2.5 and 97.5 percentiles, respectively. Low awareness (Score 1-3: "I have heard about them but not sure what they express" to "I do not know them"), High awareness (score 4-6: "I know emissions scenarios a little," to "I participated in developing scenarios").

Overall, considering all participants (HDC, MDC, and LDC), the data show statistically significant correlations between self-reported knowledge and perceived usability of emission scenarios in national and UNFCCC contexts. Regarding policymaking relevance in the national context, scenario awareness is statistically significant at the 5% level (p: 0.039), while in the UNFCCC context, it is statistically significant at the 10% level (0.095). The HDCs find emission scenarios significantly more policy-relevant for facilitating international treaties than MDC/LDCs on a 10% level (0.058). One explanation could be that detailed scenario knowledge is less important in international negotiations than in more detailed national policy designs. Another reason may be that HDCs have more academic capacities to analyze and use scenarios (Corbera et al., 2015; IPCC, 2022a). MDC/LDC representatives with high scenario awareness find emission scenarios more relevant for the international context than those less familiar, with a statistical significance to the 10% level (0.07). However, they do not find scenarios significantly more policy-relevant in a national context than those less familiar (0.15). There is no significant difference between HDC representatives with high and low awareness in both national and intergovernmental contexts. While associations are found when comparing scenario awareness within the development level categories, fewer relationships are statistically significant at this more detailed level than when the entire sample is considered (partly due to the reduced population and sample sizes). Additionally, generalizing to the broader UNFCCC delegate population and the diverse global policymaker group is not feasible due to the limited sample size. Nevertheless, the surveyed individuals are a committed and consistently all-year around engaged subset of UNFCCC delegates whose perceptions are considered valuable to examine regarding the salience of communicated scenario knowledge.

Considering the literature informing the IPC, most recent long-term emission scenarios, the most recent long-term emission scenarios series comprise three series. The Representative Concentration Pathways (RCPs) were published in 2011 (van Vuuren et al., 2011a) and informed AR5 (IPCC, 2014d). The Special Report on the 1.5 Pathways (SR1.5) was published in 2018 (IPCC, 2018a) at the request of the UNFCCC (Kriegler et al., 2017b). The Shared Socioeconomic Pathways combined with the RCPs (SSP-RCPs) published in 2019 (Gidden et al., 2019a) informed the AR6 (IPCC, 2023a). In addition, short-term scenarios, such as the Climate Action Tracker (CAT) and United Nations Environment Programme (UNEP) scenarios(CAT, 2023a; UNEP, 2022), evaluate the effect of current policies and the Nationally Determined Contributions (NDCs) of the Paris Agreement(UNFCCC/COP, 2015a) and the gaps between these national policy strategies and the Paris goals. According to the policymakers with a high scenario awareness, the RCPs, SR1.5, and UNEP scenarios have been the most relevant for designing national mitigation policies (see SI Chapter 2). The open-ended questions supplement that several participants find: "The UNEP emissions Gap report and the IPCC report and their presented scenarios have been used for the Paris Agreement for the mitigation and climate goals” (Europe, HDC).

However, to what degree policymakers consider emissions scenarios as key to understanding climate change responses and how they use them to design climate policy is not evident. Assessing the literature, they appear to play a role in some selected leading jurisdictions, like the EU and US agencies (EU, 2019; Fawcett et al., 2015, 2009), while scenario analyses are less apparent in South America and Africa.

It is plausible that middle- and least-developed policymakers do not use scenarios as frequently as HDC policymakers. One reason might be that they lack institutional, academic, and technological capacities, e.g., policymaking does not benefit from the same technical support as in some HDC countries. Unlike HDC, MDC/LDC representatives frequently request more scientific or technical staff via open questions. "We require the input or presence of technical experts to assist in creating relevant tools, methodologies, and policies to address climate change issues” (Small Island MDC). MDC and LDC representatives state a lack of computer power and human resources to process the highly demanding scenario data. They request expert knowledge to understand how the models work, which variables they communicate, and analyze the data for policy. They frequently request scientific capacity building and provide scenario training. “Support capacity building & technology Transfers & financial support for research, climate change observations, and modeling” (LDC, Small Island state policy enabler). “Provide capacity building and training when presenting the scenarios” (MDC, African policy enabler).

6.5 Enhancing Salience: Tailored Communication and Capacity Building

The policy relevance of emission scenarios has been widely discussed (Pedersen et al., 2022). Here, we examined the national focal points' perception of possible scenario improvements discussed in the literature over the past two decades, e.g., simpler communication (Schenk and Lensink, 2007), best-guess scenarios, and the role of scenarios (Hausfather and Peters, 2020; Schneider, 2001), and science-policy co-creation (Beck and Mahony, 2017; Sundqvist et al., 2018).

Figure 6-3 compares the relationship between the policymakers' scenario awareness and perception of five plausible scenario improvements. The top rows of Figure 6-3a & b present three proxies for scenario communication, examining if there is a need for reduced scenario complexity in how scenarios are communicated, their applicability in policy design making, and if the scenario output data needs to be easier to access and process. Figure 6-3a bottom presents scenario changes related to the role of scenarios ("include a best-guess scenario" or a most likely scenario in scenario series) and scenario development process ("include policymakers in scenario development processes").

Both LDC, MDC, and HDC representatives request simpler communication of emission scenarios and what the various scenarios communicate. It is more important for LCD/MDC representatives that scenarios become easier to implement and contain less complex output data. Thus, high complexity appears to constrain salience according to (the examined) MDC/LDC policymakers. On the contrary, HDC representatives do not find complex output data to constrain salience. Generally, the examined policymakers are less interested in the science-policy co-creation of scenarios, i.e., policymaker inclusion.
Interestingly, delegates with low scenario awareness favor policymaker inclusion, while the examined delegates with high awareness, to a lesser degree, find policymaker inclusions to increase the scenarios' policy relevance. Via the open-ended questions, some participants state that some policymakers are not interested in mitigation. A best-guess scenario appears less relevant for HDCs with high scenario awareness but relevant for MDC/LDC representatives.

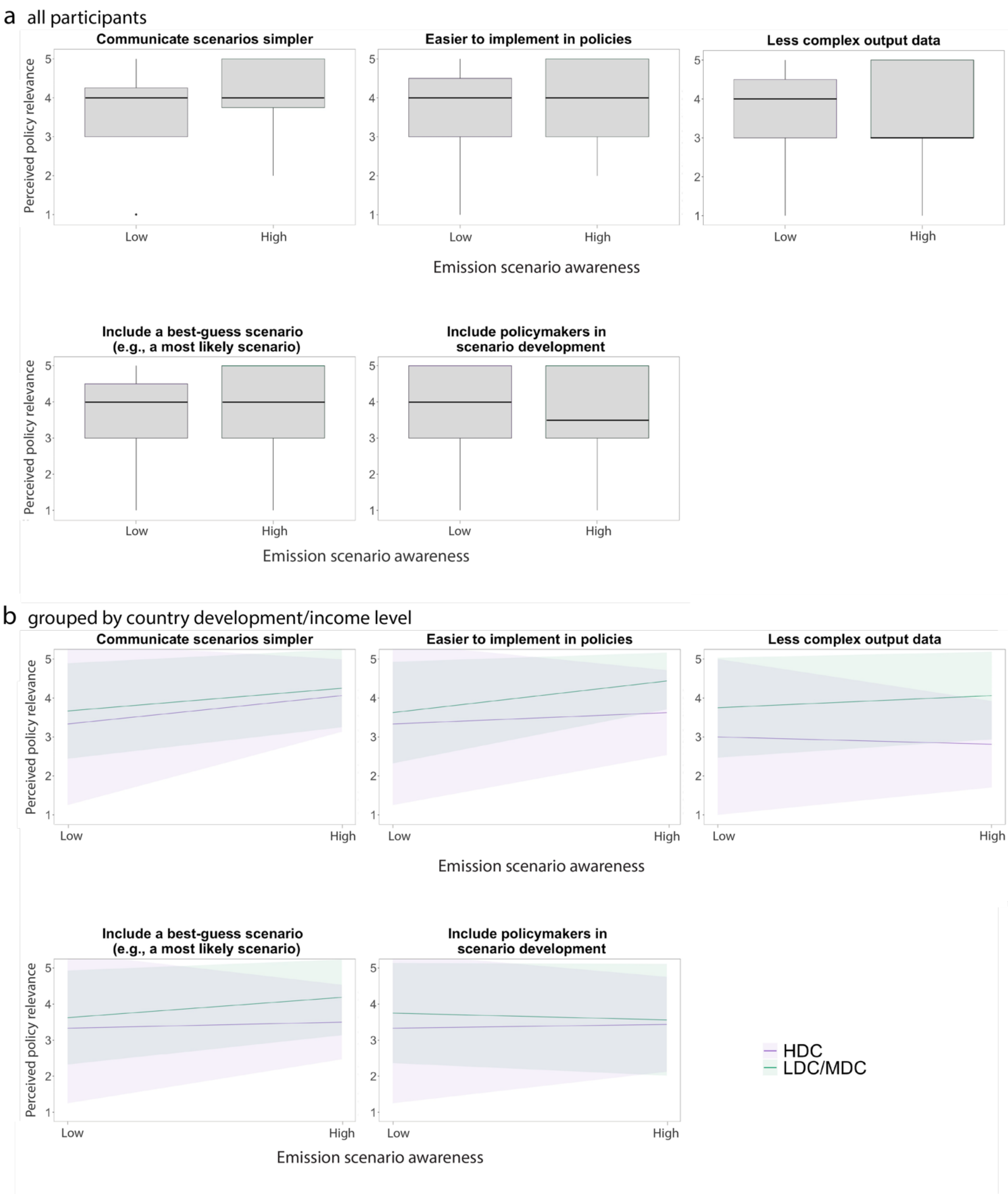

Figure 6-3. Improved policy relevance of emission scenarios perceived by non-Annex-I (solid lines) and Annex-I policymakers.
Low and high reflect the informants' awareness of emission scenarios (horizontal axis). The vertical axis reflects informants' opinion if specific scenario changes would increase the policy relevance of emission scenarios. a: Results based on answers from all participants, b Grouped by country development and income levels (representatives of high, medium, and least developed countries). Lines correspond to the median value within an informant group, with lower and upper shaded boundaries corresponding to the 2.5 and 97.5 percentiles, respectively.

Fifty-one percent of the participants have an advisory or informing role, while 49% have a coordinating or leading role in policymaking. These are from now on referred to as "policy supporter" and "policy enabler," respectively. Asking if scenarios should be easier to implement in policies is a broad question that does not add much information on how to improve scenarios. However, it indicates needs, e.g., if policymakers find it challenging to use scenarios for policy designs, which is the case in several MDCs/LDCs. Open questions supplemented the multiple-choice questions. Here, participants communicated two potentially opposing requests for improving the emission scenarios' policy relevance: more straightforward communication and adding more detail. Eleven participants commented on science-policy communication. Four of these stated that scenarios were too complex, e.g., "reduce the complexity of scenarios" (LDC, small island policy advisor).
Ten requested "communication of emission scenarios to policymakers should be more simple" (HDC, EU policy advisor), e.g., comprising "reader-friendly and use simpler language" (MDC, Middle Eastern policy enabler). These policymakers address how scientific information is communicated. "The challenge is to communicate complex science to make it understandable for everyone" (HDC, EU policy advisor). "They [scenarios] can be used more and become more relevant if they are better understood and simpler information is used to explain them" (MDC, Latin American policy advisor). Nine (seven LDCs and two MDCs) request capacity building and training for policymakers and technical staff. "Present [scenarios] in a more simplistic language and include capacity building and training when presenting them" (MDC, African policy advisor). "Our country is a developing country and, at this moment, lacks the technical capacity and experts to create scientific knowledge on the diverse areas of climate change. We require the input or presence of technical experts to assist in creating relevant tools, methodologies, and policies to address climate change issues" (MDC, small island policy enabler). It includes "Exchanges of learnings" (LDC, Asian policy enabler) and "Support to setting up inventories in our country" (LDC, African policy enabler). "More capacity building especially to understand the climate model" (LDC, Asian policy enabler). In addition, one stated that "we used the SRES [published in 2000], to create our national carbon neutral scenarios, because the SSPs data were to complex" (HDC, EU policy enabler). Researchers recently introduced new ways of communicating model-based scenarios (https://futuremodelsmanual.com/), and modelers announced a need for simplified communication (e.g., infographics and simpler IAMs) and better accessibility via informative and user-friendly online databases developed via stakeholder inclusion(O'Neill et al., 2020).

Almost half of the examined policymakers (25) requested more scenario detail. Twenty-one (35%) requested more national detail (3 LDCs, 7 MDCs, and 11 HDCs). Some were general requests, like present and future mitigation options, cost estimates, missing scenarios, and relation to other policy objectives like biodiversity and considering the complexity of intergovernmental climate policy. National detail requests focused on adding information to support adaptation and mitigation actions: "Much of the scientific knowledge is for global scenarios, especially for developed countries. Developing countries need localized scientific knowledge so national policies can be appropriately developed using information relevant to the national scenarios" (LDC, small island state policy enabler). "The scenarios policy relevance will improve If they provide data that can be applied to the national policymaking process" (MDC, Small Island policy enabler). There were requests for missing scenario aspects regarding appropriate and effective mitigation options: "Unpacking Paris-compatible scenarios to identify the socioeconomic changes that need to happen now and (where applicable) missing options. E.g., the need for timely phase-out of internal combustion engine passenger vehicles is now quite well understood in policy circles. This is not the case for other things such as domestic heating systems driven by natural gas or heating oil" (HDC, European policy advisor). "It is more useful to use modeling to check what policy mix would deliver specific emission reduction level at what cost to the sectors and the society within the country. Emission scenarios work at a higher level, especially aggregating global emissions, but they do not directly drive policymaking" (HDC, European policy advisor). "National policymaking is based mostly on economic analysis of current and future costs of actions, the burden on society, and the anticipated level of public and private investments required. Science would be helpful if focused on those economic aspects" (HDC European policy advisor). Additionally, "the policy relevance will improve if analyzed scenarios correlate with economic and political data" (Latin America, HDC).

Scenario salience may improve in the areas of understanding scenarios better and how to use them in policymaking (for policymakers and their technical staff), provided via communicating less complex scenario data and data that can be transferred to national policymaking.

6.5.1 Capacity Building

Capacity building is mainly requested by LDC participants. The survey results reflect a need for improving institutional and technological capacities in LDCs and partly MDCs. Figure 6-4 shows that HDC and MDC policy enablers find their countries' mitigation policies to be implementable. On the contrary, LDC policy enablers perceive their technological and institutional capacities as potential barriers to successful policy implementation.

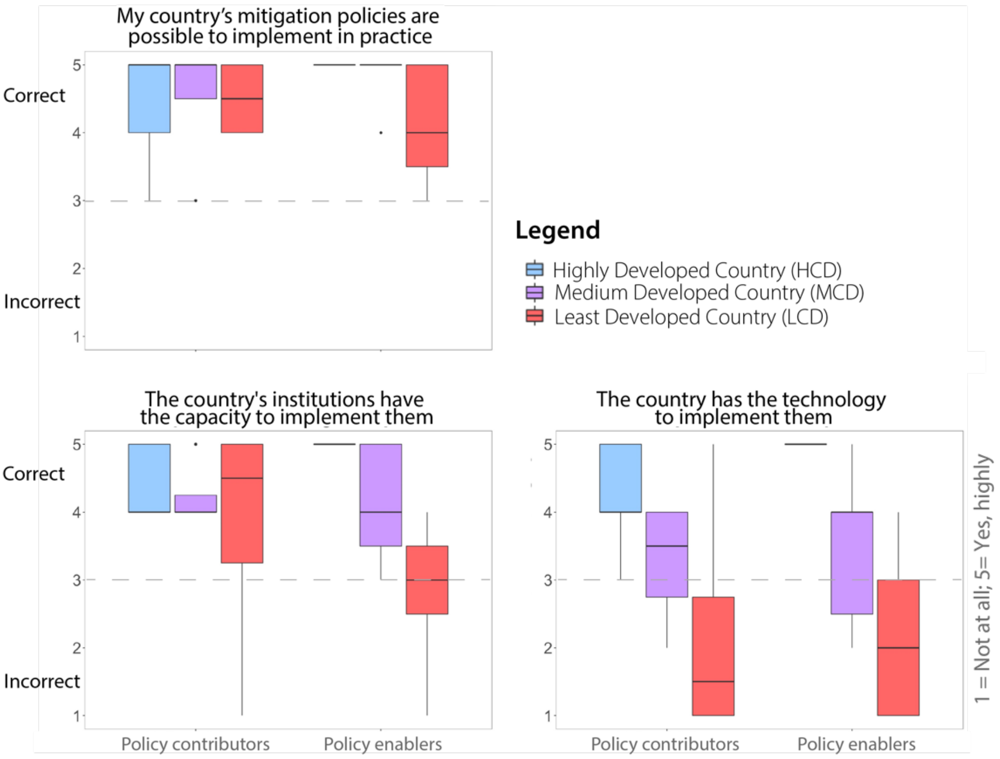

Figure 6-4. Policy implementation perceived by UNFCCC National Focal Point delegates.

The examined policymakers' perspectives on policy implementation and the institutional and technological capacities to implement mitigation policies. Responses are grouped by country development level (Least, medium, and highly developed) and policy role (Policy advisor and Policy enabler). Policy advisors comprise informants having a self-reported informative, following, or advising role, and policy enablers a coordinating or leading role in policymaking.

Real-life capacity building is outside the scope of scenarios. However, it is relevant for scenario assumptions and variables. Institutional capacity is not yet included in the RCP-SPA-SSPs and may improve scenario credibility(Andrijevic et al., 2020; Pedersen et al., 2022). Since scenarios are primarily developed in the global North(CAT, 2023a; Riahi et al., 2017) they may unintentionally overlook other regional perspectives (IPCC, 2023d; Parikh, 1992a).
The increased national importance reported by HDC informants may be attributed to their greater institutional and knowledge capacities. Additionally, it could be influenced by the extent to which scenarios accurately encompass the diversity of national contexts. This facet is less well-developed for regions in the global South.

6.6 Discussion

Scenario credibility and legitimacy have increased over time(Girod et al., 2009; Pedersen et al., 2022). Still, there is room for developing salience via renewed detail, communication, and capacity building. In addition, strengthened global south aspects may increase legitimacy and credibility. Our results show that exploring the complexities of scenario utilization and policymakers' requirements involves looking beyond knowledge gaps and considering institutional capabilities and context-specific climate change analysis.

To support bridging gaps between scientists and policymakers, we discuss three boundaries (and potential barriers) concerning scenario salience: scenarios' ability to reflect policy objectives, science-policy interaction and communication, and unequal institutional capacities. First, for scientific knowledge to be relevant, the knowledge produced needs to be connected to policy objectives. Second, policymakers need to understand the communicated knowledge, which needs to be useful for policy purposes. Third, decision-makers need to have access to and be able to use the scenario knowledge provided. This emphasizes regular science-policy dialogues or policymaker studies regarding policy-relevant communication and detail but also supporting the technical assistance available for policymakers.

6.6.1 Scenario Content and Policy Objectives

Salience pertains to the scientific analysis' usability in achieving political goals (Cash et al., 2003; Clark et al., 2006; Haas, 2004). Scientific information is considered policy-relevant when it addresses the specific needs of policymakers and stakeholders and provide insights that can be effectively utilized in the decision-making process (Cash et al., 2003), e.g., provided on time and contains valuable information that guides informed decisions or develops effective policies (Cash et al., 2003; Haas, 2004; White et al., 2010). It depends on various factors, like the research quality (credibility), its applicability to real-world problems (legitimacy/salience), and to which degree policymakers use the information provided (salience) (Pielke, 2007; Rosenthal et al., 2014). Scenarios aim to provide an empirical foundation and forward-looking insight (Riahi et al., 2017), valuable for decision-makers to make informed decisions, develop effective anticipatory actions(Hastrup and Skrydstrup, 2013), and negotiate international agreements (Moss et al., 2010b; O'Neill et al., 2020).

One boundary challenge in the science-policy interface concerns decision-makers not getting the information they need and scientists producing information that is not used (Cash et al., 2002).

Thus, it is relevant to specify scenario types, specific purposes, and the policy objectives scenarios aim to support. Based on contemporary literature (UNEP, 2022) and survey answers, we identify at least three essential objectives and issues relevant to current anticipatory decision-making: mitigation objectives (e.g., temperature goals), long-term socioeconomic drivers' effect on emission levels (Riahi et al., 2017), and the need for adaptation (Lawrence et al., 2020; J. S. T. Pedersen et al., 2020).

Current emission scenarios partly fulfill those three policy objectives. The short-term policy scenarios partly inform the first policy objective, i.e., assessing current policy pathways (CAT, 2023a; UNEP, 2022). However, they do not provide information about how to close the gap, "Informing national policies & strategies" (LDC Small Island policy enabler). Several of the examined Policymakers request more detailed information on achieving or practically implementing Paris-compliant or overshoot scenarios. Neither short-term nor long-term scenarios provide clear-cut understandings of efficient mitigation actions or century-long policy roadmaps for implementing the Paris Agreement.
For the second policy objective, the long-term scenarios informing the IPCC aim to evaluate specific energy and socioeconomic futures. Here, the examined policymakers request simpler communication and more specific details (e.g., mitigation options and their effectiveness). These are not yet provided by these scenarios to support the development of mitigation strategies (O'Neill et al., 2017; Riahi et al., 2017). Concerning the third, the long-term scenarios informing the IPCC provide high-impact scenarios (e.g., SSP3-7.0 and SSP5-8.5) relevant as input for vulnerability analyses to inform adaptation policies (J. S. T. Pedersen et al., 2020) relevant to inform adaptation strategies. Here, national HDC assessment institutes develop information for strategy based on scenarios (Star et al., 2016). Global South analyses are less abundant (IPCC, 2022c).

6.6.2 Co-creation and Communication Barriers

Insights from the dynamics of scientific advice in policymaking emphasize the intertwining of spheres (Burton et al., 2019; Cash et al., 2003; Guston, 2001; White et al., 2010), e.g., how bureaucrats use technical information in shaping and implementing policies (Lipsky, 2010). Boundary objects, such as scenarios, assemble between two different social worlds (Cash et al., 2002). Without losing their identity, they may enhance connections between scientific knowledge and policy actions by creating salient, credible, and legitimate information for multiple audiences (Cash et al., 2002, 2003; White et al., 2010). Scenarios have served scientific users to analyze future mitigation, climate change, and impacts (IPCC, 2023a). It does not mean the same information is useful for policy. To improve salience in the policy field, the examined policymakers requested specific new scenario details on mitigation actions and scenarios to be communicated less complex.

Linking knowledge and action highlights fostering effective interaction (Guston, 2001; White et al., 2010), such as science-policy dialogue (SBSTA/SBI, 2015) and co-creation (Kok et al., 2007). The examined policymakers are, on average, not in favor of co-developing scenarios. Similarly, some researchers believe in keeping the science and policy fields separate, meaning they are cautious about collaborative efforts (Sundqvist et al., 2018), such as scenario development (Beck and Mahony, 2017; Lövbrand, 2011). Others favor science-policy collaboration (Sundqvist et al., 2018). Several local scenario extensions are co-created (Kebede et al., 2018; Kok et al., 2019b) and several scenario modeling projects include stakeholder participation in various exercises (CD-LINKS, 2019; ENGAGE, 2022; Kok et al., 2007; Nakicenovic and Swart, 2000a; PLB, 2019; WCRP,

2020). However, it is not known whether these have supported user relevance. To overcome critique regarding scenario co-creation (Beck and Mahony, 2017), science-policy collaboration may focus on communicating scenarios and exchanging ideas for scenario content to support a "better coordination between public entities and academia and greater promotion of the need for informed decision-making" (HDC South American Policy Advisor).
Developer-user collaboration has the potential to enhance the involvement of end-users in defining data requirements, which may increase the likelihood of producing salient information. It may improve credibility by incorporating various types of expertise and enhance legitimacy by granting multiple stakeholders more transparent access to the information production process (Cash et al., 2003).

Such dialogues aim to bridge boundaries, such as revealing key differences between the science and policy fields. Differences may relate to methodologies (Oreskes and Conway, 2010), time perspectives(Burton et al., 2019; Santos et al., 2022), motivations and goals (Morseletto et al., 2017; Shaw, 2009), and purposes (Cash et al., 2002). One concern is that scientists may not have access to policymakers or be unfamiliar with the policymaking process(NASEM, 2017), e.g., policy processes do not frequently reach a consensus over science use (Jasanoff, 2011, 1998). In addition, scientific blind spots may imply a barrier. From a scientific perspective, scenarios aim to inform policymaking (Moss et al., 2010b). Thus, it might be easy to reproduce an understanding within the scientific field (Bourdieu, 1977) that emission scenarios are used in policymaking. However, several researchers argue that they do not necessarily play a 'key role' in designing policies (Jaccard, 2016; Lodhia and Martin, 2012).
On the contrary, policymakers may not understand the information provided or interpret it in line with their interest (Jasanoff, 2011, 1998). Decision-makers' knowledge deficits (Suldovsky, 2017) may be caused by the overwhelming amount of science on climate change (IPCC, 2023a) and that IPCC reports, predominantly crafted by scientists, prioritize technical accuracy (IPCC, 2022a, 2022c), which may limit broader readership and practical use (Bardach and Patashnik, 2023; Haas, 2004).
A rational-optimist perspective suggests that reliable knowledge supports a collective understanding of complex problems (e.g., clarifying the plausible effectiveness of interventions and reducing stakeholder disagreements), resulting in better policy outcomes(Head, 2022). However, this may not always be true since policy debates comprise several knowledge forms, values, and interests, e.g., policy actors might mobilize evidence selectively to influence the perceived credibility of favored policy options, like energy and funding interests (Head, 2022; McCright and Dunlap, 2003; McGrath, 2021; Pedersen, 2021).

Since actors on different sides of the science-policy boundary may perceive and value salience, credibility, and legitimacy differently(Cash et al., 2002), we suggest ongoing dialogues to enhance mutual understandings. These may focus on which type of scenario content to develop to serve policymaker needs and how to tailor scenario communication to specific users.
In addition, we suggest communicating scenario series (and scientific knowledge) separately and in non-technical terms for policymakers with clear links for policy implementation. Modelers already aim to communicate emission scenarios more straightforwardly by reducing complexity, e.g., infographics (O'Neill et al., 2020) or via non-technical manuals (https://futuremodelsmanual.com/). Here, modelers need to be selective in the displayed information. This can involve co-created user-friendly databases tailored to policymaker needs. Tailoring scenario information to policymaker needs involves presenting data, insights, and projections in a relevant and useful way for policymakers, e.g., ensuring that information aligns

with the policymakers' objectives, priorities, and decision-making processes, e.g., facilitating understanding of the potential implications of different scenarios on policy outcomes.
To meet the policymaker demand for “national detail”, we recommend country scenarios provided via the short-term policy scenarios (e.g., CAT policy assessments) to move from assessing existing policies and targets to also illustrate various national policy mixes needed to reach country targets and national Paris Compliant pathways. These may guide national policies, ambitions, and effort sharing. Such scenario roadmaps may identify plausible actions and support monitoring policy progress.
Furthermore, we suggest long-term global scenarios to support UNFCCC negotiations with examples of specific global climate policy roadmaps fulfilling the Paris Agreement. Salience may depend on the flexibility of the RCP-SPA-SSP scenario design for future scenario elaborations to accommodate specific policy considerations and alternative policy pathways. More detailed policy roadmaps to the individual scenarios in future elaborations may aim to contribute to discussions of effort-sharing and mitigation options across regions and sectors.

6.6.3 Capacity building: Unequal Regional Knowledge

Based on the survey results, salience not only depends on science-policy dialogues and communication, but also on institutional (and academic) capacities. It is not evident but plausible that the examined MDC and LDC policymakers find scenarios less salient and use scenarios less frequently compared to HDC policymakers. The survey results show the lowest scenario knowledge among LDC representatives, reflecting unequal knowledge and human capacity distribution. This may not be surprising since IPCC authorships are concentrated in the global North (Corbera et al., 2015; IPCC, 2022a).

A potentially higher national salience in HDCs might be a result of higher institutional and knowledge capacities. The issue might also be that those PMs considering scenarios more important may belong to the same knowledge communities or nations that create these scenarios. If policymakers have technical experts using scenarios, it may motivate them to learn about and apply them. A fundamental difference in knowledge capacities evolves from the fact that scenario developments are concentrated in HDC and Annex-I countries(IEA, 2021a; WCRP, 2020), increasing the possibilities of policymakers connecting to modelers in those countries.

Another explanation may be that scenarios may not adequately represent the diverse national contexts within the global South (Masson-Delmotte et al., 2023). Information deficits may extend beyond a lack of knowledge, stemming from unequal access to resources and capacities for scenario knowledge generation and processing. A global South request for epistemic sovereignty, is evident in the survey (and in IPCC intergovernmental discussions (Masson-Delmotte et al., 2023)). Empowering global South regions to control their knowledge systems and scenarios may lead to a more equitable and inclusive approach, increasing salience of already existing scenario knowledge. Regarding legitimacy, scenarios and IPCC reports may become irrelevant for some countries (IPCC, 2023d; Ketcham, 2022) if narratives do not cover Global South aspects and challenges. Integrating global South perspectives into narratives may enhance scenario legitimacy (Masson-Delmotte et al., 2023) and additionally reinforce scenario credibility, e.g., via higher accuracy of regional emission projections. Weaving regional governance and institutional capacity differences into scenario narratives (Andrijevic et al., 2020) may enhance credibility, e.g., improving accuracy of regional emission projections (J. S. T. Pedersen et al., 2020).

Capacity building, scenario training, collaborative knowledge-sharing initiatives, and efforts to enhance technical capabilities appear valuable in countries with identified deficits. The Kyoto Protocol, Doha Agreement, and Paris Agreement acknowledge that individual countries have different “Respective Capabilities” (RE) (UNFCCC/COP, 2015a, 2012, 1997). The UNFCCC principle of different historical responsibilities, “Common But Differentiated Responsibilities” (CBDR) (UNFCCC, 1992) also shaped the Kyoto Protocol. Such principles have been assessed in scenarios regarding effort sharing(Li and Duan, 2020; van den Berg et al., 2020) and may support intergovernmental negotiations despite being a sensitive political issue.
Regarding capacity building, the UNFCCC annex structure lays the foundation for the three Paris Agreement financing pillars, ‘binding’ Annex-I parties (42 of 60 HDCs) to support mitigation, adaptation, and loss and damages in non-Annex-I (UNFCCC/COP, 2021). A fourth financial pillar may support research, systemic observations, modeling, and providing more training to technicians involved in emissions scenario analyses to improve evidence-based decision-making globally – or may operate under the IPCC.
Several modelers find capacity building necessary to foster interdisciplinary scientific collaboration and allow users to understand better scenario approaches (O’Neill et al., 2020). With international support, it may be feasible that national researchers in countries that are less advanced in this area would be supported to develop their own scenarios. Many Annex-I countries (and a few non-Annex-I) are already doing this, e.g., translating scientific insights into policy-relevant results(Klaassen et al., 2004). Despite efforts to include global South perspectives throughout the IPCC’s history (IPCC, 2005c, 1996) and modeling institutions cooperation with stakeholders (CD-LINKS, 2019; ENGAGE, 2022; PLB, 2019), scenario narratives and knowledge capacities can still be improved.

6.7 Conclusion

There are large differences in awareness about scenarios among UNFCCC national focal point representatives from different regions. Approximately 70% of the examined policymakers know the emission scenario concept, with 40% having heard about it and 30% knowing it very well. HDC representatives show higher awareness (53% knowing scenarios very well) compared to MDCs (38%) and LDCs (13%). About 25% of delegates have low knowledge, particularly prevalent in MDCs and LDCs (36% low awareness) compared to HDCs (17%).

Policymakers’ awareness significantly correlates with the perceived salience of emission scenarios. Statistically significant correlations exist between self-reported knowledge and emission scenarios’ perceived usability in national and UNFCCC contexts. HDC representatives find scenarios more useful for designing national mitigation policies than MDC/LDC representatives. On average, MDC/LDC representatives perceive emission scenarios as moderately useful nationally and somewhat useful internationally.

Policymakers, especially from MDCs/LDCs, request simpler communication and less complex output data for emission scenarios. There is a general interest in more national detail and adaptation of scenarios to local policymaking contexts. Policymaker inclusion in scenario development processes is less emphasized, particularly by those with high awareness. The importance of addressing institutional capacity and providing training for policymakers and technical staff is highlighted.

The requests for simpler scenarios and more detail appear contradictory. On the one hand, emission scenarios need to be communicated simpler to be understandable for policymakers. On the other hand, the examined policymakers request scenarios to contain more variables, increasing their complexity. However, the request for more national detail, despite becoming more complex, scenarios can still be communicated simpler, including what is most relevant for policymakers (and other users). Today, no policy roadmaps are connected to scenarios. Scenarios may increase their policy relevance if they clearly focus on policymaker needs and explain how they can support policy objectives, e.g., communicating various policy mixes for national and global mitigation.

Delving deeper into the dynamics of scenario use and policymaker needs goes beyond focusing on knowledge deficits also to consider institutional capacities. HDC policy enablers perceive their countries' mitigation policies as implementable, while LDC policy enablers identify technological and institutional capacities as potential barriers. Including more global south perspectives and insight may not only improve credibility of emission projections, but also scenario legitimacy. The perceived higher national salience among HDCs may be attributed to superior institutional and knowledge capacities, raising concerns about the diversity of perspectives in scenario development.

The paper's key recommendations imply strengthening scenario communication if one wants to make use of scenarios in the climate negotiations more equal. This can also include focusing on capacity building in several MDC/LDC regions. The results indicate that policymakers focus on scenario tools for negotiations and national policy. This emphasizes a gap between policymaker perspectives and how researchers have approached scenario developments in the past, focusing primarily on content and methods (Pedersen et al., 2022). Tailoring scenario communication to the knowledge level of policymakers, providing localized data, and addressing institutional capacity are requested for enhancing scenario salience. The results indicate a need for ongoing capacity building, especially in MDCs and LDCs, to improve understanding and use of emission scenarios in policymaking. It appears essential to strengthen scientific communication of scenarios to a broader audience that, to a higher degree, includes practical policy communication with clear links for policy implementation to policymakers (and the public) and that the UNFCCC and HDC parties strengthen the knowledge base and use of scientific tools in MDC and LDC countries. We show that the examined policymakers focus on understanding and using scientific tools for negotiations and national policy. This contrasts with the scenario literature, where scientists focus on issues related to the quality of content and methods. Scenarios' policy relevance may improve when policymakers are provided ways to communicate their needs, requests, and (scenario) challenges to scientific developers. Scientific institutions and the IPCC have already facilitated such processes but could also include the UNFCCC. With changing policy contexts and objectives, it is essential to investigate policymaker demands regularly. Thus, the requirements for effective scenarios may change over time and vary according to policymakers' needs and perspectives.

Notably, the study's findings may be limited by the narrow focus on UNFCCC national focal points and uncertainty regarding a relatively small sample size (and a biased share of EU representatives in the HDC group). Thus, the results may not be generalizable to other policymakers, and further research in national contexts is recommended to validate them. A larger and more diverse population could be targeted in future surveys, including asking what knowledge policymakers use when they design policies and why or why not they use scenarios.

6.8 Methods

6.8.1 Key study objects and survey aim

The study focuses on emission scenarios, a crucial scientific tool cutting across the three IPCC Working Groups (WGs) (Gidden et al., 2019; IPCC, 2018), and short-term policy scenarios assessing mitigation policy (CAT, 2021; UNEP, 2021a). Since 1990, the four generations of emission scenario generations within the IPCC (Moss et al., 2010a) are grounded in the work of WG3 (climate mitigation) and used by scientists in WG1 (climate science) and WG2 (impacts and adaptation) as essential bases for analyzing future climatic changes. Emission scenarios assess ranges of future greenhouse gas emissions (GHGs) and climate mitigation assessments(IPCC, 2014c, 1990a; UNEP, 2021a), serving as input for climate and impact scenarios (Carvalho et al., 2020; IPCC, 2021). Since 2011, a new type of emission scenario has emerged, aiming to assess the plausible effect of the national pledges expressed within the UNFCCC. First, these scenarios assessed the non-binding Copenhagen pledges (UNEP, 2010; UNFCCC/COP, 2009) and later the National Determined Contributions (NDCs) under the Paris Agreement (UNEP, 2021a).

The survey themes aim to explore and analyze policymakers' self-reported knowledge about and perceptions of the usability of emission scenarios (relevance for) designing national policies and facilitating international treaties within the UNFCCC. Emission scenarios' usability is compared with climate and impact scenarios (Moss et al., 2010a) and three other scientific tools to support policymaking (policy roadmap, economic assessment of mitigation costs versus costs of no action, and climate-impact costs). Furthermore, we examined policymakers' perceptions of scientifically discussed scenario changes to improve their policy relevance, as discussed in the literature (Pedersen et al., 2022).
Regarding scenario familiarity, we asked the participants about their knowledge of emission scenarios (Honestly, how well do you know the scientific tool of emission scenarios?). The reasoning was to provide a starting point for the analysis, identifying the participants' emission scenario knowledge base. In the analysis, we termed this "emission scenario awareness" as either high or low. Low awareness comprises "I have heard about them but not sure what they express" to "not knowing them" (answers 1-3). High familiarity constitutes knowing emissions scenarios "a little" to "a high degree" to "participated in developing scenarios" (answers 4-6).

6.8.2 Research design and methods

The analysis is based on a quantitative survey. The survey used a five-point (11), six-point (1), and seven-point Likert scale (3), open-ended questions (9), and social variables (e.g., age, policy role, and intergovernmental experience. Pre-interviews were made to improve the survey design, e.g., the overall scope, covering challenges and aspects relevant to policymakers and researchers. The questions were tested by researchers (3) and delegates (2) to ensure non-ambiguous, simple, and neutral questions were communicated in easy-to-understand language to improve reliability (answer consistency). We have obtained informed consent from all participants. The survey is replicable. The Survey data is available in the Open Science Framework repository (https://osf.io/5qctp/). The quantitative data was processed in R and Excel, and the open-ended questions were analyzed via ATLAS.ti. We analyzed if the sample means were statistically different (between Annex groups) via sample t-tests (Two-Sample Assuming Equal Variances and Unequal Variances). Both algorithms were included. Significant differences were defined via Equal Variances when the ratio of standard deviations was below 2:1. Correlational analyses were performed using R. The "cor.test" command calculated the correlation coefficient and conducted the test of significance simultaneously using Pearson's product-moment correlation. The open-ended answers were coded into three overall scenario communication categories (simpler communication), reduced complexity, capacity building (training, technology, human resources), and more scenario detail (national detail, mitigation, missing scenarios). They were coded for quantitative analysis to count the most common responses (to adjust for repetitions, each category could not be counted more than once per respondent). All quotes in the paper are based on survey answers unless otherwise expressed. Sometimes, we modify quotations to increase readability without compromising the meaning.

Finally, the survey themes and questions were designed based on literature reviews of scenario critiques, semi-structured interviews with modelers and scenario developers (6), researchers and IPCC authors (5), and national policymakers (5). Some of the interviewed policymakers also had experience in research (3). Of the 16 interviewees, nine and five had UNFCCC and IPCC intergovernmental experiences, respectively. The unformal interviewees comprised ministers and UNFCCC delegates from Europe, Africa, Asia, North America, and South America, including Small Island states.

6.8.3 Population and Sample

We surveyed a population of 299 national focal points. These focal points were identified from a list of 299 party members from 196 parties during COP25(UNFCCC, 2020a). The COVID-19 COP delays provided a unique opportunity to access these typically busy policymakers. The selection of national focal points was carefully considered and justified by their official role, representativeness, stability in representation, the likelihood of persisting views on policymaking needs, and practical considerations. The approach allowed the survey to gather valuable insights from a clearly defined population and into the perceptions and utilization of emission scenarios within the UNFCCC policymaking process and related to national policymaking. First, National focal points are officially designated by their respective parties within the UNFCCC framework, making them highly relevant for understanding how parties interact and engage with knowledge and expertise. Second, the entire population of UNFCCC delegates has grown yearly with a potentially ever-changing composition of stakeholders(McGrath, 2021). The focal point representation is expected to be more stable, e.g., with commitments to participate in several annual meetings (e.g., in Bonn). We assume the views found here are likely to persist across years if the needs of policymakers aren't addressed within the design of subsequent emissions scenarios. Third, unlike the entire population of UNFCCC delegates, which can change significantly from year to year and across meetings, Focal point representation tends to be stable over time due to commitments to participate in annual meetings, offering insights that are likely to persist over time. Third, surveying national focal points provides a manageable and targeted approach to gather insights from key individuals responsible for coordinating their parties' engagement. On the contrary, surveying the entire population of UNFCCC delegates would be logistically challenging and resource-intensive, given the dynamic nature of delegate participation and the absence of contact information.

The participants(Pedersen, 2022; UNFCCC, 2020a) were invited via email, including 2 reminder emails between October 2020 and November 2021. Twenty-one emails were not delivered. Fifty-seven answered the survey partially or entirely, resulting in a response rate of 21%. Specific implications relate to the small population. The response rate is considered relatively high, considering the busy schedules of UNFCCC delegates. However, the small group of informants analyzed creates certain limitations of the analysis, like their ability to generalize results to the large group of UNFCCC delegates currently active in UNFCCC work and the entire group of policymakers worldwide. Despite the small sample and population, the data provide insights into the knowledge gaps between Global North and South regarding scenario awareness and what aspects of scenarios are missing to make them more relevant for mitigation policy.

Respondents included 38 participants from least, semi, and newly industrializing (or developing) non-Annex-I countries (63%) and 23 from industrialized (or developed) Annex-I countries(UNFCCC, 1992) (37%), representative of the examined population. The population comprised 240 non-Annex-I focal points (80%) and 59 (20%) Annex-I focal points. The UNFCCC parties comprise 151 non-Annex-I (78%) and 42 Annex-I (22%), making the sample's country representation of countries slightly biased towards Annex-I representation. The share of Annex-I focal points in the population is lower than the sample Annex-I share to a statistically significant degree (P=0.0045), meaning that a larger percentage of Annex-I focal points joined the survey. We acknowledge that since the sample and population are relatively small, our statistical findings may not precisely represent the entire population of UNFCCC and national policymakers. Still, we believe the sample is representative enough of UNFCCC focal points regarding country representation and that our results highlight UNFCCC focal point perspectives. Of the Annex-I representatives, seventeen informants represented High-income countries and two Middle-income countries.

The world has changed since the UNFCCC's establishment in 1992. Thus, it is relevant to distinguish between income levels and countries' present respective financial capabilities to implement mitigation actions and prepare for UNFCCC negotiations, e.g., human resources and institutional capacity. For the analysis, we grouped informants into three groups: LDC (UNFCCC definition, Medium Developed Countries (MDC, WB Middle-Income excluding UN LDCs), and Highly Developed Countries (HDC; WB High-Income), presented in Table 6-1. Distinguishing between Income levels, our sample comprises 16 representatives from Least Developed Countries (LDC; UN definition), 19 from Medium Developed Countries (MDC, World Bank defined "Middle-Income countries" excluding UN LDCs), and 22 from Highly Developed Countries (HDC; World Bank "High-Income Countries")(Pedersen, 2022; WB, 2023). Most HDCs represent EU member states (82%), while Oceania, North, and Latin America represented 18% of HDC informants. Using this definition, the distribution of countries within the UNFCCC comprises 46 LDCs, 90 MDCs, and 60 HDCs of the UNFCCC parties.

Table 6-1. Analytical classifications of participants grouped by income level of the countries they represent

* Three informants representing non-Annex-I countries are located in the HDC category

The paper's Classification	No. of participants	Share of sample	UNFCCC focal point population	Definition	Annex group belonging
LDC	16	28%	25%	UN LDC definition	non-Annex-I
MDC	19	33%	46%	WB Middle-Income (excl. UN LDCs)	non-Annex-I
HDC	22	39%	29%	WB High-Income Countries	non-Annex-I & Annex-I*
Total	57	100%			

According to UN definitions, the UNFCCC outlines 42 Annex-I countries as highly developed and 193 non-Annex-I developing countries, as defined in 1992(UNFCCC, 1992). In 2022, Annex-I comprised 40 high-income and two middle-income countries(Pedersen, 2022; WB, 2023). The UN defines 46 countries as least developed Countries (LDCs)(UNDESA, 2023), while the World Bank in 2022(World Bank, 2022) describes 28 countries as low-income, 108 as middle-income, and 76 as high-income(Pedersen, 2022; WB, 2023).

Despite some MDCs' high technological capacity (e.g., China), the grouping reflects the UNFCCC principle of Respective Capabilities (RE) rather than the Common But Differentiated Responsibilities (CBDR). However, fast-growing economies like ASEAN, China, and India are starting to have high historical emissions responsibilities. Given the massive pollution caused by high-income countries, companies, and people, we note that the term developed is highly inappropriate. Our Least-developed country (LDC) definition is equivalent to the UN definition. In contrast, our medium-developed country (MDC) and highly developed country (HDC) are equal to the WB middle-income (excluding UN LDC) and high-income definitions. We keep the UN definition of the LDC group since it is a well-established group in COP negotiations and because delegates often refer to themselves as belonging to this group. It is essential to distinguish between income levels since LDCs are more vulnerable to climate change, have fewer capacities to implement mitigation actions than MDCs and HDCs, and have not been responsible for the bulk of greenhouse gas emissions.

The average age was 44 years. The participants identified their primary work role as either policymaker (77%), researcher (11%), or stakeholder/other (12%) (Table 6-2). Seventy percent expressed experience as a formal UNFCCC negotiator, and 83% had experience with national policymaking.

Table 6-2. Primary work role

Category	Policymaker	Researcher	Stakeholder
All	44	6	7
	77%	11%	12%
LDC	15	2	0
	26%	4%	0%
MDC	16	1	2
	28%	2%	4%
HDC	12	3	4
	21%	5%	7%

Table 6-3. Participants role in policymaking based on question categories

Role in Policymaking	Count	Share	Categories for analysis
Lead	20	35%	Policy enabler
Coordinating	8	14%	28
Advisory	20	35%	Policy advisor
Informing	2	4%	29
Following	2	4%	
"No role" or "other role"	5	9%	
	57	100%	

Most HDC participants represented European countries (17), with fewer responses from Latin America (3), the United States (1), and Australia (2). However, this is a logical consequence of the methodological choice of examining the national focal point population.

Table 6-4. Informants grouped by Region and Country Income Level

Income level	Region	Count	Share of total	Count
LDC	Africa	10	18%	
	Asia	3	5%	
	Island state	2	4%	
	Latin Am	1	2%	16
MDC	Asia	6	11%	
33%	Island state	5	9%	
	Latin America	4	7%	
	EU	2	4%	
	Africa	1	2%	
	Middle East	1	2%	19
HDC	Europe/EU	15	26%	
39%	Latin America	3	5%	
	AUS/New Zealand	2	4%	
	Europe (non-EU)	1	2%	
	North America	1	2%	22
Total		57	100%	57

6.8.4 Definitions: Emission Scenario Awareness and Policy Relevance

Emission scenarios are hypothetical trajectories of future greenhouse gas emissions based on assumptions about factors such as population growth, economic development, and technological advances. Aiming to inform scientists and policymakers to explore the potential consequences of different policy choices and identify strategies, their policy relevance refers to the degree to which future greenhouse gas emissions projections and their potential impacts on the climate system can inform policy decisions related to climate change mitigation and adaptation.

We determine "emission scenario familiariy" by the self-reported level of informants' knowledge and awareness with the tool of emission scenarios. This concept encapsulates individuals' degree of information and awareness with emission scenarios, providing a comprehensive perspective that includes both knowledge and awareness. Emission scenario familiarity refers to being well-acquainted or knowledgeable about the content of scenarios(Anderson, 2012; Johnson and Russo, 1984), encompassing variables, narratives, and potential future greenhouse gas (GHG) emission trajectories. An individual with a heightened awareness of emission scenarios is likely to understand better diverse pathways, including the influencing factors such as economic growth, population dynamics, technological advancements, risks, and mitigation opportunities. This understanding is crucial for making well-informed decisions. The variable categorizes participants' comprehension of the emission scenario tool into low or high awareness. Low awareness ranges from "I have heard about them but not sure what they express" to "not knowing them" (answers 1-3), while high awareness includes knowing emission scenarios "a little" to "to a high degree" and even "participated in developing scenarios" (answers 4-6) (see Question 3 in SI Chapter 4.2).

Research is considered policy-relevant when it guides informed decisions or develops effective policies, providing actionable information that policymakers can use to design and implement policies that achieve desired outcomes(Haynes et al., 2018). Saliency means information is provided on time and contains valuable information for making public policy by decision-makers, e.g., provides advice that can be converted into laws or decisions by decision-makers (Cash et al., 2003; Haas, 2004; White et al., 2010). Salience pertains to information's usability for policymakers and decision-makers in achieving political goals(Cash et al., 2003; Haas, 2004). Policy relevance depends on various factors, like the quality of the research, its applicability to real-world problems, and to which degree policymakers use the information provided, also implying the efficiency of science-policy communication (Pielke, 2007; Rosenthal et al., 2014). (Science Based Targets, 2023)

6.8.5 Data availability

The datasets generated during and/or analyzed during the current study are available in the Open Science Framework (OSF) repository, https://osf.io/5qctp/ (Pedersen, 2022). The online dataset details country grouping, sources, answer scores, and open-question answers. Additional data analyses, figures, and datasets generated during and/or analyzed during the current study are available in SI and from the corresponding author at reasonable request. Identities and nationalities are anonymized. Besides that, no data availability restrictions exist. The survey is accessible on the SurveyXact platform (https://www.survey-xact.dk).

6.8.6 Code availability

Statistical analyses were conducted using the R statistical computing platform. Codes or algorithms used during the current study are available from the corresponding author upon reasonable request.

6.8.7 Ethical statement

The information provided is potentially sensitive because of the nature of intergovernmental negotiations. Thus, the survey participants' identities and nationalities are excluded from the manuscript and Supplementary information. The Social Science Institute of the University of Lisbon, Portugal (ICS-UL) provided guidelines for study procedures. ICS-UL and the Faculty of Science, University of Lisbon (FC-UL) approved the study protocol. More detail about the different stages of the research is available from the corresponding author on reasonable request.

6.8.8 Author contributions (Sample CRediT)

Jiesper Tristan Strandsbjerg Pedersen: Conceptualization, Formal analysis, Research Design, Executing Research (Survey, Interviews), Methodology, Writing - Original Draft, Software, Visualization, Data curation, Project administration, Investigation Validation, Funding acquisition; **Carla Gomes**: Supervision, Writing - Review & Editing, Validation; **Filipe Duarte Santos**: Resources; Supervision, Writing - Review & Editing, Validation Funding acquisition; **Detlef van Vuuren**: Supervision, Writing - Review & Editing, Validation; **Joyeeta Gupta**: Writing - Review & Editing; **Patrick O'Rourke**: Software, Visualization, Data curation, Review & Editing, Validation; **Rob Swart**: Formal analysis, Methodology, Supervision, Validation, Writing - Review & Editing.

7 Discussion: Lessons for further scenario analysis

How can current models or GHG projections be improved to provide more accurate and reliable information to inform climate mitigation policies, acknowledging the fact that there are often boundaries between scientific knowledge and policy actions? This chapter seeks to understand how these boundaries can be better navigated or bridged. In other words, the question concerns how to improve scenarios and better translate scientific knowledge into actionable policies to tackle climate change effectively.

7.1 Summary

Although emission scenario analysis has proven to be a credible tool to support policy, this does not guarantee future successful use. And policy relevance is not apparent in all regions and countries. Based on this thesis, in this discussion chapter, we propose eight possible improvements to increase the salience, credibility, and legitimacy of future scenarios and updates.

(A) Scenario communication

(1) Provide non-technical and policy-relevant scenario communication based on science-policy dialogues.
(2) Attach detailed policy roadmaps to scenarios.
(3) Provide funding for scenario development and use in the global South.

(B) Missing scenarios

(4) Take institutional capacity into account in analyzing future climate policies.
(5) Include consumption-based emissions in scenarios (and UNFCCC inventories).

(C) Scenario Assumptions

(6) Combine regional assessments of mitigation potential (including infrastructure) with scenario analysis.
(7) Specify the feasibility and challenges regarding policy strategies presented in scenarios.
(8) Broaden the range of mitigation scenarios (imaginative capacity).

These recommendations aim to improve the science-policy co-work by ensuring that decision-makers are well-informed about what scenarios express and how to combine mitigation strategies to reach targets. Strengthening the credibility of scenarios and providing clear communication to decision-makers can lead to improved policy pathways and, ultimately, to practical and evidence-based policies that address climate change. Additionally, considering regional differences and intra- and inter-generational justice (Rozanova et al., 2006) can provide alternative pathways and mitigation options that may lead to more equitable and sustainable outcomes.

7.2 Introduction

This chapter aims to provide insights and recommendations on how to improve current emission scenarios to better inform policymakers, particularly in the context of the Paris Agreement and upcoming IPCC AR7 and UNFCCC COPs. This is done based on the previous chapters. The recommendations are organized into three categories: scenario communication (7.1), missing scenarios (7.2), and the connection between scenario assumptions and real-world situations (7.3). Eight specific recommendations are made to enhance future emissions scenarios' credibility, salience, and legitimacy. The underlying rationale is that while model-based scenarios can provide valuable representations of the world, they require continuous evaluation and alignment with changing information needs. This chapter responds to the thesis' RQ4 by offering practical approaches to strengthen science-policy cooperation in developing emission scenarios.

7.3 Scenario communication

Chapter 6 shows that scientific knowledge may not always be directly useful for policymaking and may not always be understood sufficiently. As a result, Chapter 6 also shows that scenarios are not always used. The interviews and survey suggest that model-based scenarios are used less in the global South than in the global North. The latter (in the US and EU) is described in the literature (EU, 2019; Fawcett et al., 2015, 2009). These findings are essential since scenario planning aims to inform decision-making and result in anticipation (Moss et al., 2010a; van Beek et al., 2020). One challenge is that the science and policy fields represent very different normative concerns, knowledge, time perspectives, and methodological traditions (Chapter 2). Here, I provide three recommendations for improving scenario communication to support policy in the scenario community, IPCC, and UNFCCC.

7.3.1 Recommendation 1: Non-technical and policy-relevant scenario communication based on science-policy dialogues (salience)

7.3.1.1 Rationale

Chapter 3 has shown that so far, the needs and views of scenario users have only played a smaller role in scientific debates on how to develop "policy-relevant" scenarios. In addition, that scientists focus on the quality of scenario content and methods, assessing policy relevance from a scientific perspective. On the contrary Chapter 6 shows that the interviewed and surveyed policymakers want other types of information than scientists, e.g., less information with lower complexity, specific new details, and higher transparency between variables and parameters. The chapter presented recurring policymaker requests for uncomplicated communication, indicating that the scenario salience depends on simpler communication of the scenario narratives and numbers underlying the storylines. Additional information may not reduce transparency as long if the information presented to policymakers is selective and includes only the information valuable for policy.

These results are aligned with recent research, highlighted the need for new ways of communicating scenarios and their variables. The modeling community has discussed infographics (O'Neill et al., 2020) and presented alternative scenario communication (https://futuremodelsmanual.com/). In general, visual communication is becoming increasingly essential in general (Lilleker et al., 2019) and represents an efficient way of communicating complex knowledge in an easy-to-understand way (Shabak Alrwele, 2017; Siricharoen et al., 2015).

7.3.1.2 Recommendation (1)

It is recommended that modelers and the IPCC engage in continuous science-policy dialogues with UNFCCC delegates and national decision-makers to improve scenario communication and what is policy relevant knowledge, and perspectives reflecting the diversity of UNFCCC parties and global South regions. Such process may include surveys, interviews, and follow-up workshops in, e.g., 3-year cycles to identify policy-relevant scenario knowledge and communicate the most relevant information to decision-makers. Those dialogues may aim to facilitate that decision-makers across regions can clearly communicate their needs, requests, and (scenario) challenges, identifying policy-relevant scenario knowledge (and improve scenario legitimacy (transparency).

By differentiating between various scenario users, the scientific modeling community may increase scenario legitimacy and salience. To facilitate non-technical communication, I suggest improving existing RCP-SSP databases and creating easy-to-understand and simple scenario databases tailored to different scenario users. For example, presenting straightforward mitigation strategies elaborated by science, such as the emissions output and cost of changing diet or carbon-prices (which in reality has shown difficulties to define and agree on within the UNFCCC). This may increase transparency for non-scientists and inspire mitigation. The communication platform should contain several layers, with more complex information for scientific and advanced users. Additionally, engaging industrial stakeholders and other relevant scenario users, such as those related to Scope 3 emissions,[7] is essential and requires stakeholder- and policymaker-communication with clear links to mitigation and policy implementation.

7.3.2 Recommendation 2: Attach detailed policy roadmaps to scenarios (salience)

7.3.2.1 Rationale

Chapter 6 indicated that the examined policymakers requested more explicit information that could be directly used to inform the development of sufficient adaptation and mitigation policies (e.g., sectoral reductions). There are three policy objectives that scenarios can contribute to:

(1) Evaluating policy strategies and targets and how to close the gap
(2) Evaluating details of the energy and socioeconomic futures to inform mitigation and adaptation needs and responses.
(3) Using scenarios as input for impact/vulnerability analyses to inform adaptation policies.

The scenarios partly fulfill these objectives. Short-term policy scenarios assessing the Paris Agreement (PA) provide current best-guess pathways and emissions gaps (1st objective). The long-term scenarios informing the IPCC contribute to evaluating the energy and socioeconomic futures and interconnection between drivers and emissions (2nd objective) and provide high-impact scenarios to inform adaptation policies (3rd objective).

[7] Scope 1 and 2 emissions are often referred to as "direct emissions," while Scope 3 emissions are referred to as "indirect emissions that occur in the value chain of the reporting organization, including both upstream and downstream emissions.

The complexity of the scenarios makes direct interpretation difficult. Furthermore, scenario representations (e.g., the UNEP Gap reports and Climate Action Tracker) assess current policy pathways but does not explain how or via which mitigation actions countries can reach national and global targets. Historically, the long-term emission scenarios communicate only a small set of variables, like global and regional energy mix (Riahi et al., 2017) and policy assumptions (Fujimori et al., 2017; Gidden et al., 2019a; Huppmann et al., 2019; Kriegler et al., 2014). The scenario explorer now provides much more detailed information about scenario outcome variables, like wind energy and GDP. These databases can be customized specifically for specific policy objectives and policymaker needs on the international level. In general, the models typically report rather abstract policies. There has so far not been a role for, e.g., welfare and taxation, revealing room to introduce subsidies for, e.g., forests and renewable energy (presently transcending EU and US policy debates) (Fleming et al., 2023), and cutting subsidies for fossils (Matsumura and Adam, 2018).

7.3.2.2 Recommendation (2)

To address the need for more **national detail** and **cost-efficiency mitigation action analyses**, it would be necessary to further improve the interaction between modelers and policymakers to identify key policy objectives and the type of information that could support policymaking in achieving those goals., i.e., century-long policy-roadmaps. Providing policy roadmaps might be subject to criticism, e.g., for scenarios being policy prescriptive. However, it fulfills a policymaker's request for more national detail on mitigation actions. Details on integrated mitigation action combinations will be useful for national and intergovernmental policy processes. Adding more detail on specific mitigation policy actions could enhance scenario credibility and salience by demonstrating how to design long-term national policies with clear connections between policy strategies and proposed targets. Short-term scenarios can support better national policy designs by analyzing plausible national roadmaps to achieve national and global goals. This may involve examining the necessary economic investments in national sectors. Long-term scenarios can support better UNFCCC negotiations by describing various mitigation policy mixes, including decadal and century-long policy roadmaps underlying the SSP-SPA-RCPs.

7.3.3 **Recommendation 3:** A Fourth UNFCCC funding pillar to support production of scientific knowledge in the global South (salience)

7.3.3.1 Rationale

The disparities between the global North and South have been extensively analyzed in Chapters 2 and 4. Critical differences exist between climate change and climate policy (historical responsibility, capacity, equity, knowledge differences, and development needs). At the same time, to reach the Paris goals, climate action from the global South is urgently needed, considering fast growing emissions the past two decades (Chapter 4).
Furthermore, Chapter 6 shows a lower scenario familiarity for the examined LDC and MDC representatives compared to HDC representatives. In addition, the recent IPCC scenario workshop showed low confidence in scenario narratives from several global South parties (Masson-Delmotte et al., 2023). The fact that scientific knowledge is not developed equally worldwide (Corbera et al., 2015; IPCC, 2022a) may enhance such discontent. Since, IPCC assessment reports focus on the global North, and few scenario institutes are located outside the global North, policymakers in the global South may suffer from lower technical assistance. At the

moment, climate financing does not include knowledge development nor equally distributed local and regional analyzes supporting the understanding of mitigation and adaptation needs.

7.3.3.2 Recommendation (3)

A potentially higher national salience in HDCs might be a result of higher institutional and knowledge capacities. The issue might also be that those PMs considering scenarios more important may belong to the same knowledge communities or nations that create these scenarios. If policymakers have technical experts using scenarios, it may motivate them to learn about and apply them.

To effectively anticipate climate change, all countries must have access to sufficient scientific knowledge and resources to support informed policy decisions. This means promoting more equitable distribution of research efforts, particularly in underrepresented areas in the global South. An opportunity is to develop a fourth pillar of climate financing mechanism under the Paris Agreement of the UNFCCC (or financed via the IPCC). Part of the work may include the scientific community, UNFCCC, or IPCC providing scenario training to government officials and technicians in these regions. To bridge the knowledge and capacity gaps between the global North and South, the scientific community, IPCC, and UNFCCC may also support the development (and co-creation) of an increasing number of local-based scenario extensions in currently overlooked countries. By doing so, the scientific communities get an opportunity to generate more localized and context-specific data to inform scenario development and more effective policy responses and mitigation strategies. This approach may empower decision-makers and enable them to take meaningful action to address climate change.

7.4 Missing scenario variables

Chapter 3 revealed that emission scenarios have improved over time via scientific critiques, and here several literature sources advocate for missing scenarios. Subsection 7.4 presents two additional variables that would improve the credibility of policy assumptions (7.4.1.1) and more efficiently explore the interrelation between country emissions (7.4.1.2).

7.4.1 **Recommendation 4:** Include institutional capacity in assumptions (credibility)

7.4.1.1 Rationale

The reliability of mitigation scenario projections can be improved by considering institutional capacity and governance. Weak institutions comprise a plausible barrier to policy implementation in some jurisdictions.[8] Chapter 6 shows that LDC policy enablers perceive their institutional capacity as a potential barrier to successfully implementing adaptation and mitigation policies. In addition, several global South interviewees stated that it is crucial to account for governance and institutional capacity when analyzing the conditions for policy implementation in global South regions since they are often very different from global North institutions, whose perspectives scenario assumptions may be inspired by.

[8] Other barriers exist., e.g., high institutional capacity combined with low (governmental) willingness will comprise another barrier.

The literature points out that the current scenario series lack quantifications of governance scenarios. Future governance projections show that weak governance will persist in countries representing 30% of the global population under the regional rivalry SSP3 scenario (Andrijevic et al., 2020).

7.4.1.2 Recommendation (4)

It is recommended that future scenario studies explicitly account for governance and institutional capacity, particularly in global South regions, to achieve reliable and credible projections for mitigation policies. By including governance and institutional capacity in scenario narratives, may contribute to higher scenario credibility, e.g., in regional scenarios (Chapter 5). Including global South perspectives, in general, may improve overall legitimacy. And finally, if these aspects are not considered, scenarios might be less salient to decision makers from less developed countries (Chapter 6) (Masson-Delmotte et al., 2023).
Modelers may work cocreate with policymakers to examine policy variables, such as political stability, governmental willingness, the rule of law, control of corruption, and accountability. Including governance and institutional capacity in scenarios can strengthen institutions globally and provide indicators of how these institutions may be strengthened further to achieve more reliable and credible projections.
The technology barrier is widely recognized as a significant hurdle to achieving regional and global mitigation efforts, as discussed in successive UNFCCC COPs (UNFCCC/COP, 2021, 2015a). Meanwhile, the Paris Agreement does, to a lesser degree, address institutional capacity as a barrier to policy implementation (UNFCCC/COP, 2015a).

7.4.2 **Recommendation 5:** Include consumption-based emissions in scenarios (credibility)

7.4.2.1 Rationale

Chapter 5 shows how CO_2 emissions stabilize in OECD regions while they increase in non-OECD areas, mainly in Asia (J. S. T. Pedersen et al., 2020; Pedersen et al., 2021). Global primary energy demand is projected to increase by 50% up to 2050, led by non-OECD countries' growth (IEA, 2021c). Part of the increase in non-OECD regions is associated with producing goods for OECD regions. As a result, as found in Chapters 4 and 5, consumption emissions may increase the accuracy of emission projections. Understanding the emission transfers embodied in production is valuable for balancing regional and national carbon budgets in a globalized world (Peters et al., 2012).
Moreover, the IPCC finds that the energy-demand sector and demand-based mitigation solutions have higher potential for synergies than trade-offs with the Sustainable Development Goals (SDGs) (IPCC, 2018b). SR1.5 introduce a focus on demand rather than supply to assess GHG drivers, with assumptions about changing the way energy and products are produced (P3) and where changes in energy demand are associated with improvements in energy efficiency and practice change (IPCC, 2018b).
Table 7-1 shows the differences between territorial (top) and consumption emissions (bottom) for the four major global emitters, China, the US, the EU, India (G4), and the Rest of the World (RoW). The G4 is responsible for 57% of historical CO_2 territorial and 56% of consumption emissions. Consumption-based emissions are higher than territorial emissions in the EU, US, and high-income non-Annex-I countries. In contrast, the Chinese and Indian consumption emissions are lower than their territorial emissions.

Table 7-1. Comparing cumulative emissions across UNFCCC parties & categories: territorial vs. consumption-based CO_2 (Gt CO_2).
Parties with lower consumption-based CO_2 emissions than territorial (blue) parties with higher consumption CO_2 (red). Data source: GCP (2021)

	G4: 59% of global GHGs				**Rest of the World** (RoW): 41% of global GHGs			
Party	USA	EU27	China	India	Kyoto Parties**	High-income	Newly Industrializing	Middle & least-developed countries
Cumulative CO_2 1990-2020	Annex-I		non-Annex-I		Annex-I/B***	non-Annex-I		
Territorial CO_2	168	105	184	42	115	84	68	112
Global share	19%	12%	21%	5%	13%	10%	8%	13%
Consumption-based CO_2	175	123	160	39	108	94	66	112
Global share	20%	14%	18%	4%	12%	11%	8%	13%

* RoW is divided into "Row Kyoto" (Annex-I/B initial Kyoto Parties (UNFCCC/COP, 1997)) and "High-Income, "Newly industrializing," and "Other middle- and low-income" non-Annex-I countries. "RoW Newly Industrializing" includes Brazil and ASEAN countries (WPR, 2021). RoW LDC/DC included the remaining least developing and developing non-Annex-I countries (J. S. T. Pedersen, 2022).
** In this assessment, Kyoto parties are excluding the US and EU. "RoW Kyoto" includes countries with initial obligations under the Kyoto Protocol, including countries that withdrew (i.e., the US and Canada are technically not Kyoto parties).
*** Annex I parties are countries with a historical responsibility for climate change and a greater capacity to address it. Annex B parties are a subset of Annex I parties that have agreed to specific emissions reduction targets under the Kyoto Protocol.

Annual per capita CO_2 in 2020 was 15.2 tCO_2/cap (US), 6.4 (EU), 6.1 (Kyoto parties excl. US & EU), 7.4 (China), 1.8 (India), 10.3 (High-income non-Annex-I), 4.0 (Newly industrializing Countries), and 2.0 tCO_2/cap (non-Annex-I MDCs and LDCs excl. India & China).

While some international trade assumptions exist in the SSPs, they are not presented in the scenario databases (Riahi et al., 2017). Adding consumption-based statistics to the scenarios may additionally have an effect on negotiations and country targets. Sweden has included consumption-based emissions in its climate targets (Morgan, 2022; Regeringen.se, 2022), Denmark included them in national reporting tools (ENS, 2022), while several European municipalities have started a process of incorporating consumption in mitigation targets (Blakey and Wendler, 2021; Leahy, 2018), setting a new standard for Annex-I parties.

7.4.2.2 Recommendation (5)

It is recommended that researchers and modelers conduct further research on consumption-based emissions in scenarios to address the current trend of increasing CO_2 emissions in non-OECD countries and their relationships with high consumption in the EU, US, Asia, and high-income countries in Annex-I and non-Annex-I. Future updates to the SSPs could include consumption-based emissions to change the conditions of intergovernmental negotiations and the perceptions of national responsibilities.
Scenarios, including consumption, may provide a more comprehensive insight into the dynamics of emission flows between countries and how to mitigate them. Scientifically exploring the effects of potentially unpopular legislation, such as a meat tax or limits on individual consumption (https://fairlimits.nl/), may be necessary but sensitive.

It is further recommended that decision-makers target consumption as part of national mitigation strategies. Sweden's recent inclusion of consumption-based emissions in its climate targets serves as an example of political change. Shifting the focus to international trade and consumption carbon flows within the UNFCCC may provide greater political awareness of alternative mitigation options and revised mitigation obligations, especially in high-consuming countries. Notably, territorial emissions will still be necessary to guide the needs and volumes for energy transitions in producing countries.

7.5 Scenario assumptions' connection to real-life policy challenges

The final discussion section explores specific scenario assumptions' connection to the future, identifying the need to adjust and improve those variables to increase the reliability of future projections. Scenario assumptions are vital in connecting the present to possible and reliable futures via a series of interrelated variables (Riahi et al., 2017). Chapter 3 revealed that certain complications have been raised in the scenario literature regarding the connection between scenario assumptions and real-life, like NETs (Fuss et al., 2014), too optimistic GDP (Castles and Henderson, 2003), or decarbonization rates (R. Pielke et al., 2008). Some of these critiques continued, while future developments (now in the past) ended others. Chapter 4 rebutted the GDP convergence critique of the SRES (Castles and Henderson, 2003a). At the same time, actual global decarbonization of the economy has been faster than the SRES projections (SI Chapter 7, Figure SI 8), despite the critique of being too optimistic (R. Pielke et al., 2008). These show that over-optimistic or very imaginative scenarios may not be impossible. In other cases, assumptions or variables may need to be reassessed.

Section 7.5 presents three suggestions for further analyses on energy infrastructures, current policy strategies (decarbonization and afforestation), and variables related to century economic growth.

7.5.1 **Recommendation 6:** Combine regional assessments of mitigation potential (including infrastructure) with scenarios analysis

7.5.1.1 Rationale

When transition scenarios quantify emission reductions in various sectors, their narratives implicitly represent a particular view of the challenge to be solved, e.g., the causes, who is responsible, who solves it, by which means, and in which policy setting (Ellenbeck and Lilliestam, 2019). Since models are primarily developed in the global North (Riahi et al., 2017) and focus on the carbon intensities of fossil fuels, modelers (unintentionally) risk reproducing assumptions that do not reflect the differentiated global socioeconomic conditions and challenges across countries and regions. IPCC WG3 scenario models (IIASA, 2022) and cost assessments of mitigation tend to reproduce the idea that it is optimal to quickly phase out coal (Adrian et al., 2022a, 2022b). Figure 7-1a shows the median and ranges of about 3000 fossil scenarios of the IPCC AR6 WG3 Database grouped by Paris compliant (below 1.5 °C and 2 °C by 2100) and baseline scenarios (above 2 °C by 2100). Here all Paris-compliant pathways (PCPs) assume a rapid reduction of coal to near zero before 2050, while oil and gas are projected to decrease slower.

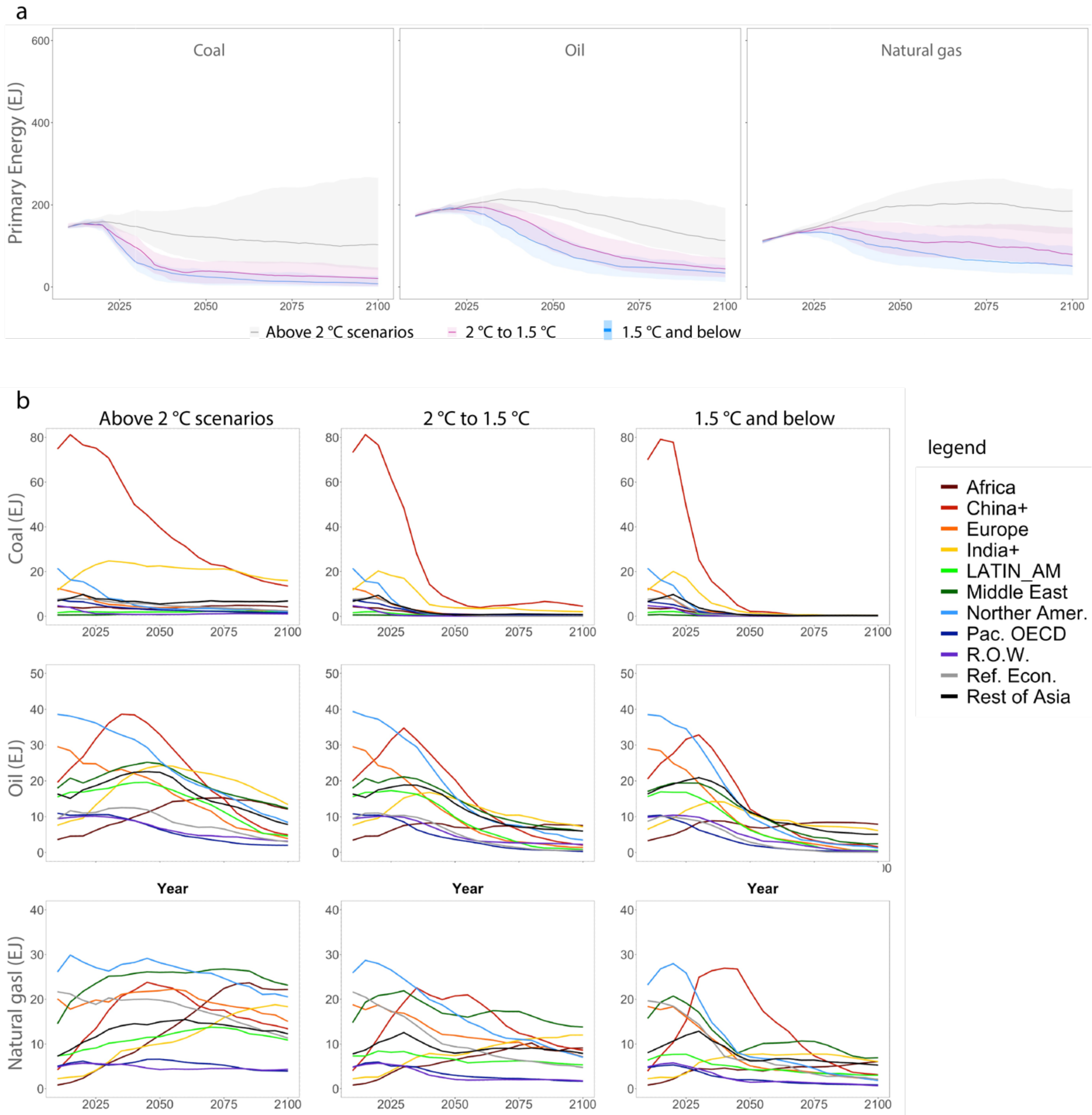

Figure 7-1. Global (a) and regional (b) oil, coal, and gas emission scenarios categorized by <1.5 °C (blue), <2 °C (purple), and >2 °C (grey).
Panel a illustrates the median (strong color) and range (light color) of the three types of scenarios. Patrick O'Rourke developed the graphic. Data source: IPCC AR6 WG3 database (Byers et al., 2022).

Figure 7-2b shows a high mitigation pressure on the two major non-Annex-I emitters, with coal diminishing rapidly in China (red line) and India (yellow line). Table 7-2 shows that Asian countries depend heavily on coal, particularly China and India. At the same time, mitigating oil and natural gas in Africa, the OECD, the Middle East, and Latin America would be more challenging, considering reliance on energy sources in the regional energy infrastructures.

Table 7-2. The shares of various fossil fuel sources of the total fossil primary energy consumption Data source: IEA (2022).

World Region	Share of fossil fuels in 2018 (%) Coal	Natural gas	Oil	Total fossil (EJ)	Total non-fossil (EJ)
Africa	26%	31%	43%	18	17
Asia	61%	12%	28%	180	31
Latin America	7%	33%	60%	18	9
Middle East	0%	57%	43%	18	0
OECD	20%	35%	45%	178	46

In essence, coal is the most carbon-intensive fossil fuel, and it is urgent to phase it out as quickly as possible. However, some parties, like India and Germany, are not entirely on board with this idea (Evans et al., 2021). The narratives surrounding transition scenarios have the ability to promote the mitigation challenges at hand and what policies are required to solve them (Ellenbeck and Lilliestam, 2019), which may be provided more clearly if models present differentiated national dependences on various fossil fuels for decision-makers.

7.5.1.2 Recommendation (6)

Mitigation potential is closely related to regional and national infrastructure. It is recommended to conduct analyses of differentiated regional energy infrastructures and sectoral emission reduction challenges to enhance the credibility and salience of scenarios for decision-making. Global economic institutions duplicate the narratives of transition scenarios. However, these risks overlook real-life complexities since they implicitly convey a specific viewpoint on the challenge at hand, e.g., emphasizing carbon intensities rather than the real-life challenges present and the policy settings required for its resolution. By including differentiated energy infrastructures, transition scenarios can explore how different fossil fuels can be phased out and in which regions, making them more representative of the political realities and national mitigation challenges. By conducting differentiated analyses of regional energy infrastructures and sectoral emission reduction challenges, decision-makers can better understand the mitigation potential of different regions and sectors and develop effective, credible, tailored strategies. The topic also touches on fairness aspects, e.g., causes and responsibility, often addressed in real-life COP negotiations. This recommendation, however, emphasizes on-ground mitigation potential.

7.5.2 Recommendation 7: Specify the feasibility and challenges regarding policy strategies presented in scenarios

7.5.2.1 Rationale

As stated in Chapter 2, anticipation divides active actions into two classes: purposeful (goal-directed) or purposeless (random, no clear goal) (Rosenblueth et al., 1943). Assessing mitigation strategies in emissions scenarios is crucial for informing policy actions that reduce greenhouse gas emissions and limit global warming. Chapter 6 shows that the examined policymakers require transparent and cost-effective information about mitigation strategies to make informed decisions. New methodologies for policy scenarios have been recommended to increase legitimacy, e.g., highlighting ethical, legal, social, and economic issues relevant to decision-makers and including more stakeholder perspectives (Wright et al., 2020). The Shared Socioeconomic Pathways (SSPs) and Working Group 3 (WG3) scenario databases provide projections related to decarbonization and carbon sequestration via forests. They do not offer specific policy details relevant to defining policy actions. Real-life policy strategies presented in Nationally Determined Contributions (NDCs) reflect decarbonization (Government of China, 2021; Government of India, 2015) and afforestation as central policy strategies (EU, 2020b; US Government, 2021).

Scenarios can inspire mitigation strategies, but it is essential that they also efficiently support feasible policy actions. Clear scientific communication of mitigation strategies and their implementation challenges is critical in solving complications presented in NDCs. Decarbonization is possible, but renewable energy supply must increase faster than fossil fuel. However, simply increasing renewable energy supply may not necessarily reflect actual mitigation, and as Chapter 4 identifies, global fossil fuel primary energy grew at a similar speed as non-fossil energy (1.7%/yr) (Santos et al., 2022). Carbon sequestration targets present serious complications. Continued deforestation caused by logging and forest fires is a significant threat across world regions (Brack, 2019; Costa et al., 2020; GFW, 2021), while net zero targets are facing challenges, e.g., regarding their definitions and double counting (Brack and King, 2021; Rogelj et al., 2021).

7.5.2.2 Recommendation (7)

The SSPs examine the relationships between drivers and emissions. This could be further explored by assessing mitigation strategies in emissions scenarios to inform cost-effective policy actions that effectively reduce greenhouse gas emissions and limit global warming. It is recommended that modelers reassess the relationship between scenarios and policies and present more concrete and goal-orientated mitigation actions. It could imply presenting (e.g., UNEP, CAT, or SSPs) policy scenarios with goal-oriented mitigation actions to support feasible policy actions that address the complications presented in NDCs.

To inform policies that effectively reduce greenhouse gas emissions and air pollution, it is suggested to rethink how we model different scenarios and their connection to actual policy goals. This means being transparent about the limitations of systems that offset emissions and looking for a balance between renewable and fossil fuel energy production. Decision-makers need to understand the strengths and challenges of policy strategies for meeting short-term and long-term goals, such as the Paris Agreement objectives. To achieve this, researchers are recommended to study different policy mixes, like carbon taxes, emissions trading systems, and offsetting schemes, and clearly communicate how, e.g., carbon sequestration strategies are feasible considering increasing climate change impacts and more frequent climate-induced fires (Costa et al., 2020; EFFIS, 2022). This implies clearly communicating and highlighting the risks of policy-convenient strategies, like offsetting systems, which in several cases, allow countries and businesses to continue polluting. This recommendation builds on the idea that providing national detail can support decision-makers in making more effective policy decisions and making greenwashing more transparent.

7.5.3 Recommendation 8: Broaden the range of mitigation scenarios (imaginary capacity)

7.5.3.1 Rationale

Chapter 3 (literature review) presents two different critiques of scenarios, which could be labeled "unrealistic scenario assumptions" and "limited imaginative capacity of developers." Chapters 3 and 4 noted that the long-term scenarios used by the IPCC do not question economic growth or consider the impact of economic losses on GDP. Degrowth or regrowth may appear unrealistic to most researchers and economic institutions (Jackson, 2009), while economists and politicians commonly have growth as the desirable objective (Schneider et al., 2010). Some researchers argue that policymakers' preferences and worldviews may influence the inclusion of disruptive or discontinuity pathways (Raskin and Swart, 2020), like degrowth (Hickel et al., 2021b; Lenzen et al., 2022), environmental breakdowns (Caleiro et al., 2019; Otero et al., 2020), and economic losses resulting from climate change impacts (Taconet et al., 2020). However, as more scientific data becomes available, models based on that knowledge and data are subject to change. The IPCC has recently included more and more literature on degrowth, post-growth, and post-development subjects (IPCC, 2022a, 2014c), and recent scenario exercises have included degrowth scenarios (Lenzen et al., 2022).

7.5.3.2 Recommendations (8)

It is suggested to broaden the range of mitigation pathways to include discontinuity futures. Despite their political sensitivity, this means considering discontinuity pathways related to climate change risks, biodiversity degradation, and alternative mitigation perspectives, such as degrowth, regrowth, or population regulation. As all models have limitations, and scenario series cannot explore all possible futures, it is recommended to regularly review storyline and variable assumptions and the reasons behind selecting specific scenarios over others in scenario series. The scenario literature offers alternative storylines, including sustainable communities and ecocide (Asara et al., 2015; Caleiro et al., 2019). However, policymakers' preferences and worldviews may downplay disruptive or discontinuity pathways, which is why it is essential to inform decision-makers about the risks of inaction, including the impact of economic losses resulting from climate impacts on economic growth.

With the objective to strengthen the credibility of long-term economic growth projections and increase transparency and salience of scenarios, future research on economic growth and climate change could consider discontinuity pathways. This would provide details to policymakers to also assess and consider the economic consequences of mitigation options, inequality, and critical ecological tipping points in emission scenarios when evaluating the need for mitigation. Here modelers could explore variables related to century-long economic growth, economic and financial stability, and plausible degrowth scenarios that have gained scientific acceptance in recent years and could challenge the mainstream discourse of century-long economic growth. Ignoring these scenarios narrows the spectrum of mitigation policy strategies, particularly those related to consumption.

8 Summary & conclusions

8.1 Introduction and research questions

Since climate change extends into the future, projections form a crucial part of climate research. These projections help to identify possible consequences and risks of climate change and explore anticipatory action to avoid or reduce these risks. Since 1990, the Intergovernmental Panel on Climate Change (IPCC) and the scientific scenario-based literature informing the IPCC assessment reports have relied on four generations of emission scenarios to inform evidence-based decision-making. Given their importance, it is vital to frequently evaluate the scenario content and user relevance. This thesis used the evaluation criteria presented in the science-policy interface by Cash et al. (2003), assessing 1) the process of scenario design (legitimacy), the quality of the projections, including scenario critique (credibility), and their user relevance (salience). Legitimacy concerns the scenario designs development process and its transparency, construction, and distribution; credibility focuses on the technical components and scientific adequacy, while salience focuses on scenario relevance to the needs of decision-makers. The thesis presents a three-fold framework for assessing the scenarios and introduces recommendations for future scenario use and development in the climate change science-policy interface context.

The thesis focuses on four research questions:

RQ1. How have emission scenarios evolved between 1990-2020, and which critiques have they raised? (credibility and legitimacy)

RQ.2. How do these scenarios compare to historical global and regional emissions and key socioeconomic development trends? (credibility)

RQ.3. How do UNFCCC policymakers perceive emissions scenarios and their relevance for policy designs? (salience and legitimacy)

RQ.4. How can the current emission scenarios be improved to better inform mitigation policy, i.e., handling the boundaries between knowledge and actions in the climate change science-policy interface? (legitimacy, credibility, and salience)

These questions aim at covering critical knowledge gaps regarding (1) a comprehensive review of the emission scenario critiques and how they affected the evolution of the four examined scenario series informing the IPCC Assessment Reports since 1990, (2) assessing current needs for scenario updates via systematic comparisons with historical data, (3) taking the first steps to assess UNFCCC policymakers' perceptions of emission scenarios and policy needs to make the scenarios more policy relevant, and (4) providing recommendations for scenario analyses to manage boundaries between knowledge and action in ways that simultaneously enhance the salience, credibility, and legitimacy of the scenario information.

8.2 Results and findings

8.2.1 RQ1: How have emission scenarios evolved between 1990-2020, and which critiques have they raised?

It is relevant to assess how scenario series have changed over time to evaluate the legitimacy of the design and content. Developing scenarios is not straightforward. Choices have been made on possible future changes related to qualitative and quantitative factors like socioeconomic development, technology advances, and lifestyle, and focus areas and definitions. 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. The chapter assessed the evolution of emission scenario critiques and their responses.

The subsequent scenario generations used in IPCC assessments developed over time. The scenarios have been used extensively in IPCC assessments (and other work). In fact, in most cases, scenarios also became the key reference in other research areas. From a scientific perspective, the (maybe) most noteworthy limitation of the first sets of scenarios was that mitigation scenarios were excluded for the IS92 and SRES sets (1992-2011). The decision to place scenario development outside IPCC provided room to solve this. The mandate on scenarios within IPCC was clearly exposed to the political interests of the IPCC member states. For instance, the panel excluded the term BaU and mitigation scenarios between 1992-2000 (until the RCPs, published in 2011). 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. Moreover, the key science question at the time focused on the possible consequences of climate change. The scientific literature did fill this gap already with the publication of mitigation scenarios based on SRES (post-SRES). Because of reoccurring scenarios and IPCC critiques, the IPCC decided (between 2003-2005) to move scenario developments outside the IPCC. As the RCP/SSP developments moved outside the IPCC, the scenarios' scope expanded to include mitigation as a component of sustainable futures.

Contentwise, scenarios have developed from simple explorations to an extensive set of baseline and mitigation scenarios. Various alterations have been made in developing scenarios and their content that respond to the critique. The review shows that scenario assumptions, quantifications, methods, and processes (author teams) have changed over time, inspired by scientific critiques and political considerations. The current framework deals with 1) uncertainty due to baseline development, 2) different levels of climate change, 3) mitigation and adaptation, and 4) uncertainties in all stages. Scientists have proposed several changes – in principle, to provide scientists and decision-makers with a more comprehensive and robust set of information about the interconnectedness between crucial societal variables and emissions and the different policy options available to mitigate emissions. However, this comes at a cost of a rather complex (and thus possibly untransparent) system.

The scenarios were exposed to critique over time. Emission scenario critiques can be grouped into various primary and secondary focus topics, revealing that almost half of the critiques are about assumptions. The peer-reviewed critiques and responses (280) focused 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. There are clearly waves in scenario critique – related to topical issues at the time. In scenario critique, over time, new themes have emerged. Some continued, while others disappeared.

Some areas of critique have decreased or become less prominent, like a discussion on probability, development process, convergence assumptions, and economic metrics. The IAM community responded to some of the critiques with improvements taking 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. IPCC critique disappeared after 2011 (with scenarios developed outside the IPCC), while convergence & probability discussions (including best-guess scenarios) decreased and lay dormant between 2013-2020. Critique responses show that metrics, narratives, and author teams changed.

Several other topics have become more dominant over time (e.g., NETs, missing scenarios). These include aspects like policy relevance & implications of scenarios, transparency, Negative Emissions Technologies (NETs) assumptions, and missing scenarios. Critiques regarding policy relevance and transparency have emerged more recently, addressed as secondary topics in NETs critiques. In addition, missing scenario critiques became more frequent, and suggestions were made to add new aspects to the narratives, like institutional capacity, conflict, economic externalities, and discontinuity narratives. For the NETs critiques, SSP/RCP-developers provided more transparent IAM descriptions, explored alternative pathways (e.g., lifestyle, renewables), and defended NETs assumptions as necessary to meet the Paris target if policy actions do not speed up before 2050.

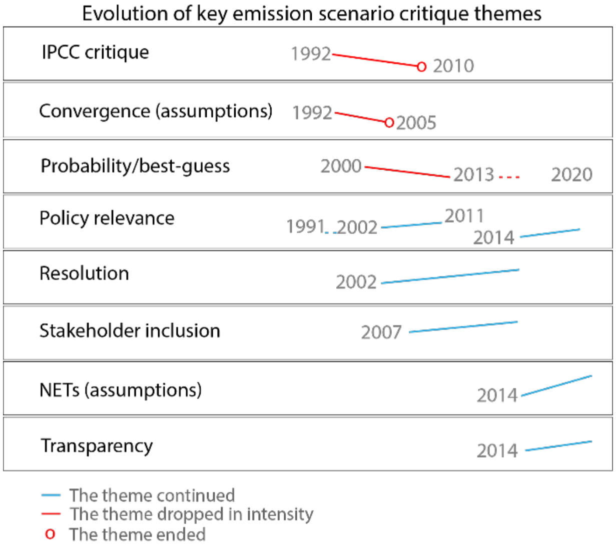

Figure 8-1. Evolution of seven key emission scenario critiques based on Chapter 3

Critique regarding the policy relevance of scenarios changed over time. Critiques regarding policy relevance emerged for the first time in 1991. Countries indicated that more detail was needed for scenarios to be useful (time extensions beyond 2100). Critiques were also formulated regarding the credibility of IPCC (2002-2011) (e.g., metrics critique) and the opinion that the author team is too narrow (1992-2003). Moreover, scientists' policy relevance discussions concerned probability discussions and more simple communication (2000-). Since AR5 and the RCP publications, policy implication critiques have focused mainly on NETs critiques and scenario assumption transparency (2014-). The latter is related to the trust/legitimacy and credibility of the information provided.

The scenario critiques also emphasize the importance of communication and transparency. Over time the scenario framework has become increasingly complicated. One part of the critique involves more uncomplicated scenario communication. It may be valuable to include user perspectives (e.g., policymakers, sectorial stakeholders) to develop effective scenario communication in the future. SSP developers announced a need for an increased focus on more straightforward communication (e.g., infographics and simpler IAMs) and better accessibility via developing an informative and user-friendly online database developed via stakeholder inclusion.

8.2.2 **RQ.2**: How do these scenarios (informing the IPCC) compare to historical global and regional emissions and key socioeconomic development trends?

It is relevant to regularly reassess the scenarios to inform future scenario development and the policy debate. Chapter 4 compared long-term historical developments of key socioeconomic drivers and GHG emissions; and historical trends against scenario projections from 1990 to the present. It focused on key emission scenario variables (CO_2 from energy and industry, population, GDP, and energy system characteristics).

Between 1960-2020 (1990-2020), it is possible to identify 12 (7) sub-periods of lower and higher growth (short-term periods of 1-2 years). When very short-term events (1-2 years) are excluded, the 1960-2020 period contains six periods of reversed higher (>1% per year) and lower emissions growth (1% per year or lower). The IPCC period (1990-2020) includes two high growth periods (1988-1991 and 1999-2012) and two medium-low growth sub-periods (1992-1998 and 2013-2020) where emissions on average grew 1% (or less) per year. In essence, the periods since the establishment of IPCC (1988) show very different average annual growth rates, emphasizing the importance of distinguishing between short-term and long-term trends. It illustrates that it is difficult to interpret trends based on a limited number of years of data, and good practice requires distinguishing between long-term trends and short-term variability. Short-term variability concerns fluctuations caused by, e.g., recession, covid, and wars, while these are often smothered in the long-term trends.

One set of critiques in the literature involves the systematic over-/underestimation of the scenarios compared to actual trends. The results show that this is not the case. The results show that the scenarios did not systematically overestimate or underestimate actual global emissions (Chapter 4), as suggested earlier in the literature (Chapter 3). The close connection between historical high emission growth and high-emissions scenarios between 1999-2012 (Chapter 4) led to critiques in the literature and policy discussions, arguing that the upper scenario ranges were too low (Chapter 3). Historical emissions were close to medium-high emissions trajectories between 1990-1998 and 2013-2019, which in both cases were accompanied by critiques of emission ranges being too high (Chapter 3). From the periods of high/low growth, it can be concluded that it is difficult to interpret trends based on a limited number of years of data. Over longer periods, the sets of scenarios perform very well – however, for sometimes 'wrong' reasons, like the different trends in emissions growth between OECD and non-OECD. Despite critiques, since IS92 (1992), the successive series were designed to cover more or less the range of the previous generations, reflecting a scientific consensus (van der Sluijs et al., 1998) about the inadequacy of the outer ends.

Interestingly, one can identify critiques that the scenarios underestimated emissions during past high growth periods and overestimated emissions during slow growth periods. For **instance,** the global historical emission trajectory was close to high-emissions scenarios from 1999 to 2012, which led to critiques in the literature and policy discussions, arguing that the upper scenario ranges were too low.

Overall, historical global emissions followed a medium-high emissions pathway for the three latest sets (IS92, SRES, RCP/SSP), well within those scenario ranges, however, just above the high-emission scenario of the first set (SA90). The historical emissions trajectory followed a low to medium-low to medium-high emissions pathway between 1992 and 1998, similar to the middle-of-the-road scenarios, as well as SRES and SSP global sustainability scenarios. Between 1999 and 2012, emissions followed a trajectory between medium-high and high emission pathways (between IS92 middle-of-the-road and regional-competition scenarios). From 2013 to

2016, historical growth was below 1% annually, which made the observed CO_2 emissions pathway return to the center of the ranges of the scenario sets – back to being close to middle-of-the-road and global-sustainability scenarios.

Medium/medium-high scenarios seem to track the historical emissions – and might have a higher probability of occurring due to the central limit theorem (there are more thinkable combinations that lead to medium growth). IS92a performed very well on the global level. Concerning regional (OECD/non-OECD) emission levels, IS92a has been less effective. Choosing between a high or medium baseline for mitigation analyses is, in the near-term, less relevant since the gap between those baseline scenarios and 2° or 1.5° scenarios is currently quite large.

The current high emission pathways (SSP3-7.0 and SSP5-8.5) are still relevant for a complete uncertainty range of plausible future emissions (Chapter 5). Regarding the scientific critique of RCP8.5, the thesis shows that it is still realistic to assume that global emissions can track high emission scenarios, considering both historical emissions growth rates and cumulative emissions. Although fast emission growth has undoubtedly become less likely, high-end scenarios such as RCP8.5 are not yet impossible. However, RCP8.5 should be described as a low-possibility, high-impact case, not a business-as-usual one. It should be noted that also policymakers request knowledge about worst-case scenarios to support adaptation policies (Chapter 6), i.e., high-impact cases.

Historically, CO_2 emissions are tightly coupled directly with primary energy use and indirectly with GDP. Despite global short-term variabilities, CO_2 emissions are mainly caused by a combination of slow changes in long-term drivers. Historically emissions and energy consumption increased annually between 1990-2020, while the share of non-fossil energy remained the same (~19%). When addressing renewable energy as a mitigation strategy, it is important to simultaneously address the decrease of fossil energy sources.

Globally, all SRES and SSP baselines, and five out of six IS92 scenarios, overestimated nuclear primary energy growth. Non-fossil primary energy growth was higher than projected in IS92 and SRES series, while it was middle of the range of SSP baselines. All IS92s and four out of five SSP baselines underestimated "non-biomass renewable" primary energy for the 1990-2020 and 2005-2020 periods, respectively.

Global middle-of-the-road scenarios closely follow historical emissions, which cover regional variability. Most scenarios (in particular the IS92 and SRES) overestimated OECD CO_2 emissions growth and underestimated non-OECD CO_2 emissions growth. The SSPs baselines captured the OECD/non-OECD emissions trends better than the previous series. However, they overestimated OECD GDP growth and population growth rates for both regions (and globally) and underestimated non-OECD GDP growth. Furthermore, the SSPs almost underestimated OECD primary energy and fossil energy growth. The historical developments mirror contrasting 'storylines 'in different areas at different times, such as the relatively low economic and emissions growth in the OECD region and higher growth in the non-OECD region, notably China and India. It may cause implications for present policymaking if scenarios are not updated, i.e., assumptions about the "outsourcing" or export of emissions may be relevant in future scenario exercises.

Exploring policy options in further work on the latest scenario set (SSPs) in a long-term perspective becomes increasingly relevant. Exploring different mitigation routes is getting increasingly relevant. One reason is that implementing climate policies related to the Paris Agreement of 2015 may mean an active break from past trends. Thus, it may be more relevant than examining baseline uncertainty (e.g., in future emissions and other emissions and climate change drivers) under dynamics as usual development. Exploring the potential impact of different mitigation policies, technologies, and behavioral changes and considering different combinations of mitigation strategies may support decision-makers to better understand the trade-offs between different policy options and make informed decisions about the most effective and feasible ways to mitigate climate change. In addition, it may also be useful to consider possible "discontinuity futures" that could arise due to historical or future crises, such as the COVID-19 pandemic, other societal transformations, or system tipping points that are not explicitly accounted for in existing scenario sets.

The scenario generations are still relevant as counterfactual baselines for climate change, impact, or response analysis, despite the lack of policy assumptions in the second and third scenario generations (IS92 and SRES). Chapter 4 focused on the emission scenarios and their drivers, not on the characteristics of the integrated assessment models used to quantify the storylines. Future research could evaluate to what extent these models are (still) suitable to assess the relationship between emissions and their socioeconomic drivers in a comprehensive and meaningful way.

It may be necessary to reassess SSP "population", GDP, "non-biomass renewables", and "nuclear" primary energy projections. Moreover, future updates could consider updating country categories, storylines, and emission projections. There are a number of variables that are less well represented in the SSP set compared to historical trends. These include scenario variables where historical trends were outside or on the borders of scenario ranges, like global population, GDP, non-biomass, and nuclear primary energy, and OECD emissions and primary fossil energy. The fast-growing emissions in non-OECD regions provide a reminder that non-OECD emissions and outsourcing of emissions may play an increasingly important role in global emissions, a relevant issue for future policy choices and scenario development. Furthermore, it may be relevant to evaluate further the total lifecycle emissions of large-scale applications of new wind, solar, and biomass energy technologies, fracking (including methane leakage), and land-use change, since it may reveal potential emissions areas, like the emissions associated with gas extraction and renewable manufacturing and disposal can be significant.

8.2.3 **RQ.3**: How do UNFCCC policymakers perceive emissions scenarios and their relevance for policy designs?

Since scenarios aim to inform policy, it is relevant to assess the perspectives of policy users to evaluate scenario salience from a policymaker's perspective. Salience concerns the relevance to the decision-makers' needs, e.g., being communicated in a clear and accessible manner policymakers understand and can act upon. Research is considered policy-relevant when it guides informed decisions or develops effective policies, providing actionable information that policymakers can use to design and implement policies that achieve desired outcomes. The chapter surveyed and analyzed perspectives of a group of policymakers' knowledge and perceptions of policy relevance and scenario improvements regarding emission scenarios based on a sample of 57 UNFCCC national focal points (N=299), a well-defined and comparable population with a connection to both international and national policy.

The survey on UNFCCC policymaker appreciation of emission scenarios included 38 participants from non-Annex-I countries (65%) and 19 from Annex-I countries (35%). The UNFCCC parties comprise 151 non-Annex-I (78%) and 42 Annex-I (22%) - excluding the EU and the Vatican - making the sample slightly biased towards Annex-I participation. The share of Annex-I focal points in the population is significantly lower than the sample Annex-I share (P=0.0045), meaning that a larger percentage of invited Annex-I focal points joined the survey. Since the World has developed since the UNFCCC categories were defined in 1992, the participants were grouped into three groups based on income levels for the analyses: 16 Least Developed Countries (LDC; UN definition), 19 Medium Developed Countries (MDC, World Bank defined "Middle-Income countries" excluding UN LDCs), and 22 Highly Developed Countries (HDC; World Bank defined "High-Income Countries"). It reflects the UNFCCC principle of "Respective Capabilities" (RE). The Annex-I comprise 37 high-income and five middle-income countries, while non-Annex-I comprises 28, 108, and 23 low, middle, and high-income countries. Keeping the UNFCCC LDC definition, the invited policymaker population represents 46 LDCs, 90 MDCs, and 60 HDCs of the UNFCCC parties.

Not all policymakers know about emission scenarios or how to use them. The results show that most of the examined policymakers have good to low knowledge, while more than 25% have insufficient scenario knowledge and need guidance to use scenarios. Almost 75% of the examined policymakers know more or less the concept of emission scenarios. Of these, about 40% have heard about them, and 30% know them very well. Only 16% of MDC/LDC and 57% of HDC representatives know emission scenarios very well. More than 25% of the examined delegates have very low or no knowledge about emission scenarios (36% of Medium and Least Developed Country (MDC/LDC) representatives and 17% of Highly Developed Country (HDC) representatives). It is not evident that policymakers understand the scenarios well enough to use them to design clear mitigation strategies. One could argue that scenarios could inform more concretely about policy-relevant topics, globally and nationally.

There is an unequal distribution of scenario knowledge between highly developed (HDC) and medium/least developed country (MDC/LDC) representatives. Least- (LDC) and medium-developed country (MDC) representatives have less insight into emission scenarios than highly developed country (HDC) representatives. Several examined LDC and MDC representatives request scenario training to cope with low scenario knowledge and few human capacities to use scenarios in policymaking. Thus, the scientific community in climate change can improve scenario communication by highlighting how scientific tools like emissions scenarios can and cannot support policymaking in non-Annex-I countries. A fourth UNFCCC financing pillar could support improved academic interest in, knowledge capacities, and distribution of knowledge, aiming to improve the efficiency of global South mitigation policies, supporting global mitigation.

Policymakers find emission scenarios to be, to some degree, relevant for designing national policies and facilitating international climate treaties. According to the least and medium-developed country representatives, they are less relevant for national policymaking. Paris-compliant scenarios are perceived as relevant, communicating processes toward policy goals. Policymakers also like that scenarios communicate economic growth. However, they face problems communicating policymaker-requested mitigation actions, e.g., to reach below 1.5 °C, facilitating the understanding of the problem, identifying the conditions that make action effective, and developing appropriate storylines that lead policymakers to identify with the scenarios.

A new focus on scientific communication of scenarios may improve scenario relevance if the communication is customized to policymakers' needs. The multiple-choice questions were supplemented by open-ended questions. Here participants communicated two potentially opposing requests for improving the emission scenarios' policy relevance: more straightforward communication and adding more detail. The policy relevance of emission scenarios may improve if they provide more national detail, informing efficient and long-term policy actions. Policymakers request a closer connection between scenarios and mitigation strategies. Emission scenarios do not provide clear-cut understandings of efficient mitigation actions and century-long policy roadmaps for implementing the Paris Agreement.

The examined policymakers request more simple and informative scenario communication to support policy design, including capacity building and training. The policymakers request more uncomplicated communication and reduced complexity. They want to know what the scenarios express (narratives and variables) and what they can be used for. Insufficient knowledge may risk constraining their use in current policy designs in both high-, middle-, and low-income countries. Scenario salience might be improved by communicating and presenting scenarios in a more basic language that policymakers understand and can act upon, including providing capacity building and training on how to use scenarios to policymakers and technicians, like communicating scientific knowledge in two versions: technical-scientific and non-technical. In addition, salience may improve when policymakers are provided ways to communicate their needs, requests, and (scenario) challenges to scientific developers. Scientific institutions and the IPCC have already facilitated such processes, but this could also be facilitated via the UNFCCC.

On the other hand, 44% of the examined policymakers request additional scenario information, such as national detail and cost-efficiency information about mitigation (and adaptation) actions and want scenarios to be more action-oriented with sector-specific targets. Thus, salience may improve by communicating knowledge relevant to policymakers and understanding policymaker needs. On a global level, policymakers request the long-term scenarios to become more action-oriented, e.g., information about the needed increase in renewable energy capacity and targets for particular sectors instead of theoretical indicators like emissions reductions or intensity changes. Several policymakers express that the global scenarios are not directly driving national policymaking and that national policymaking is concerned with economic analysis of current and future costs of actions and request information about needed mitigation investments. Essentially, they request scenarios explaining how to reach the Paris policy targets. Today's mitigation scenarios do not reveal recommendations for policy-mix actions needed.

The two types of requests do not necessarily contradict each other. On the one hand, emission scenarios need to be communicated more simply to be understandable for policymakers. On the other hand, they need to contain more variables, increasing their complexity. Further scenario sophistication often comes with a trade-off with transparency. Even though more scenario detail may provide higher complexity, scenarios can still be communicated more straightforwardly, including what is most relevant for policymakers (and other users). Including policy roadmaps in scenarios may increase the applicability of scenarios in policies. The policy relevance mainly requires that scenarios clearly focus on policymaker needs and explain how they can support policy objectives, e.g., communicating various policy-mix for national and global mitigation.

High scenario knowledge correlates negatively with increased science-policy co-creation. The more knowledge about emission scenarios, the more policymakers' support the separation between scientific scenario development and policymaker inclusion in the scenario development process (favoring separating science and policy cooperation). On the other hand, the interviewed modelers generally appear positive towards science-policy cooperation. It is recommended that science-policy co-creation focus on scenario communication rather than developing scenario content to avoid mistrust from decision-makers and scientists (the first is illustrated in the thesis, and the latter is exemplified in the literature underlying Chapter 3). It appears central that science facilitates policymaker requests and includes those wishes in scenarios to improve policy relevance (salience). These findings suggest improvements in scenario communication in two ways: improved scientific focus on understanding and using scenarios (in policymaking and for developing mitigation strategies) and reevaluating the scenario objectives where policymakers communicate their needs for scientific tools.

The study's findings may be limited by the narrow focus on UNFCCC national focal points and uncertainty regarding a relatively small sample size. Thus, the results may not be generalizable to other policymakers, and further research in national contexts is recommended to validate them.

8.2.4 **RQ4**: How can the current emission scenarios be improved to better inform mitigation policy, i.e., handling the boundaries between knowledge and actions in the climate change science-policy interface?

RQ4 explores navigating or bridging science-policy boundaries, i.e., identifying ways to improve scenarios and better translating scientific knowledge into actionable decision-making that effectively tackles climate change.

The emission scenarios' credibility and legitimacy have improved over the past three decades. Historically, projections were valid; the long-term scenarios did not systematically overestimate or underestimate actual global emissions, as suggested earlier in the literature, while transparency and customized communication to policymakers could improve the scenarios' legitimacy and salience. In addition, the models and their assumptions have changed over time, but the underlying logic is similar.

Salience regarding science-policy communication can be improved, focusing on policy-relevant information and serving low- and middle-income regions. Analysis of the scenario literature reveals that scientists focus on the quality of scenario content and methods, assessing policy relevance from a scientific perspective (Chapter 3). In contrast, the policymaker analysis shows that policymakers focus on understanding and using scientific tools for negotiations and national policy (Chapter 6). Too little attention has been paid to the needs and views of scenario users in discussions about how to develop "policy-relevant" scenarios. Furthermore, it may be relevant to strengthen scientific communication of scenarios to low- and middle-income regions with clear links for policy implementation. The knowledgebase regarding what scenarios express and how they can be used in policy is significantly lower among the examined MDC and LDC country representatives. Thus, there is a need for the UNFCCC and HDC parties to strengthen the knowledge base and use of scientific tools in MDC and LDC countries to support global mitigation by strengthening the quality of evidence-based policymaking

To increase scenario salience, it is relevant to regularly investigate policymaker demands and include stakeholder and policymaker foci and needs in emission scenario developments. Scientists may not have access to policymakers or may not be familiar with the policymaking process, e.g., the challenges of reaching a consensus over science use. Chapter 6 highlights potential institutional barriers that challenge effective scientific communication with policymakers. The relevance of scientific knowledge in policymaking depends not only on the credibility of knowledge but how it is communicated and if the 'simplified' knowledge communicated is absorbable to policymakers and applicable in policy designs and decisions. For the latter, the examined policymakers request more detail related to national and global mitigation actions and information on how to reach the Paris Agreement goals. Thus, the scenario knowledge produced and communicated to decision-makers can focus on the policymakers' requests for specific knowledge and aim to sufficiently support the policy objectives of contemporary times.

Emission scenarios can improve salience by focusing on contemporary policy objectives. The thesis identifies three policy objectives that scenarios can contribute to: (1) Evaluating policy strategies and targets and how to close the gap, (2) Evaluating details of the energy and socioeconomic futures to inform mitigation and adaptation needs and responses, and (3) Using scenarios as input for impact/vulnerability analyses to inform adaptation policies. The short-term policy scenarios partly accomplish the first policy objective, "The evaluation of policy strategies and targets," and how to close the gap. Since no policy road maps are attached to mitigation scenarios, neither the short-term nor long-term scenarios provide clear-cut understandings of efficient mitigation actions and century-long policy roadmaps for implementing the Paris Agreement. Emission scenarios provide insufficient national detail to inform efficient and long-term policy actions. The long-term scenarios support "policy objective 2" by "evaluating specific details of the energy and socioeconomic futures to inform mitigation (and adaptation) needs and responses" and "policy objective 3" by providing high-impact scenarios relevant as input for impact/vulnerability analyses to inform adaptation policies.

To ensure scenario credibility (and salience), it is vital that models represent the political reality in both the global North and South and the great diversity within those categories. The credibility of policy assumptions can be enhanced by analyzing and considering the institutional differences in, e.g., global South and North. In addition, for salience, policymakers' motivations for using models may diminish if models do not reflect the diversity in national conditions. For example, if models (unintentionally) reflect global North perspectives, global South users may find the models less useful. One example could be to make mitigation scenarios guided by the UNFCCC justice principles to navigate, categorize, and define parties' (moral) mitigation obligations and targets. Since the World has developed since the UNFCCC defined its party categories in 1992, it is relevant to also distinguish between income levels (and country capabilities related to national targets) and also consider the "Common But Differentiated Responsibilities" (CBDR) principle. It could be a valuable exercise for, e.g., the Climate Action Tracker (CAT) scenarios to incorporate country capabilities to assess appropriate targets (e.g., if they are strong enough considering capabilities and historical responsibilities) in their Paris Compliant Scenarios. Some scenario extensions of the long- and short-term scenarios already examine the UNFCCC process and party responsibilities, e.g., related to the analysis of effort sharing (Li and Duan, 2020; van den Berg et al., 2020). Notably, this implies a risk of being critiqued for being policy prescriptive.

8.3 Reflections and recommendations

8.3.1 Thesis reflections and retrospective considerations

Coming to the end of my thesis, I have noticed that scenarios, according to the examined policymakers, have played a role in supporting policy. However, there is a significant difference in the use and appreciation of scenarios among user/country groups. Second, there have been different themes of criticism. Some of the criticism also led to changes in scenario practice, while others did not or may take longer to implement. Third, although scenarios are meant to explore futures, the medium scenarios of the scenario generations have been relatively accurate in tracking emission developments. However, this is not equal to scenarios that will be accurate in the future, advocating for continued scenario adjustments.

There are also limitations to my research. Among the most important limitations are the factors listed below:

- The research has been mostly empirical. This means that we did not attempt to contribute to the main theories on science-policy interactions.
- The survey could have explored more closely how scenarios have been useful and what type of communication has improved future scenario elaborations (series) and their communication. Enhancing the relevance and impact of the work requires a deeper consideration of justice concerns, which I could have included in the survey (Chapter 6) and, in more detail, have explored the various views of policymakers. Additionally, a future survey could elaborate more on the scenario knowledge obtained by participants and more detail on how scenarios are useful and not valid for policymaking, e.g., several cross-cutting questions complimenting each other.
- A key reason for the use of scenarios is anticipation. Often scenarios are used to visualize possible futures (Poli, 2010b). While anticipation processes have the ability and aim to open up future possibilities (Riahi et al., 2017), I could have focused more on potential closing-down dynamics (Muiderman, 2022b). This could have resulted in more specific recommendations of how the scenario process and communication of scenarios could become more transparent and include explicit illustrations of what choices are made and what is prioritized and marginalized (Jasanoff, 2004; Muiderman, 2022b). This would aim to make decision-makers and foresight practitioners aware of blind spots and how they actively participate in plausible closing-down dynamics.

Furthermore, it is not evident that I discovered all relevant critique papers or topics. Analyzing scenario criticism and development through the lenses of peer-reviewed critiques and, to a lesser degree, grey literature, and direct inputs from modelers, researchers, and policymakers also limited the work. Finally, the quantitative analysis of scenario performance included other variables than previous assessments. Including other variables, like convergence, could have added more clarity on the relevance of scenarios regarding climate justice or other elements that may be relevant for future choices.

8.3.2 Scenario reflections

It may be valuable to reassess and find new ways to balance comfort and urgency in scenario communication, e.g., whether the scenarios presented in the thesis unintentionally fostered a sense of comfort rather than motivating urgent and decisive action. It seems vital to reflect on how the scenarios can effectively communicate the urgency and magnitude of the climate crisis, encouraging countries to accelerate their mitigation efforts rather than assuming a false sense of security. The question is if scenarios could simply lead to too much expectation that the World will reach the mitigation targets set by the Paris Agreement. Paris-compliant scenarios aim to find out what is needed to meet the goal and thus 'disposed' to be optimistic. But the question is whether that part is realized by policymakers. The latter may be forced by scenarios typically including economic and technological constraints – but not social, ethical, or cultural ones.

Moreover, it may be relevant to broaden the range of mitigation pathway narratives to include discontinuity futures - broadening the number of issues covered in the content of the scenarios. As all models have limitations, and scenario series cannot explore all possible futures, it is recommended to regularly review storyline and variable assumptions and the reasons behind selecting specific scenarios over others in scenario series. Although discontinuity is not aligned with political preferences, it is possible for several reasons, such as discontinuity pathways related to climate change risks, biodiversity degradation, and alternative mitigation perspectives, such as degrowth, regrowth, or population regulation.

Furthermore, global South delegates have asked multiple times to consider a broader range of possible futures in the scenarios. The fact that this theme remains shows that no consensus has been reached between scenario developers and users on this topic. In general, an IPCC methodology and guide on climate change ethics might be relevant for guiding decision-making and science (considering also revised distinctions between rich and poor countries post-1992). More research may be needed. Considering the continued global South request, the IPCC may consider exploring justice issues in a dedicated IPCC-workshop for the Panel to make decisions regarding the following steps, e.g., requesting more research, a Special Report, or a Methodological/Guidelines Report. Notably, other principles than north-south economic aspects of justice could be considered, like gender, generations, historical responsibility, and consumer vs. producer emissions (emissions export).

Finally, there seems to have been a potential over-optimism in the scenario assumptions regarding the willingness and ability of both developing countries (DCs) and industrialized countries (ICs) to phase out fossil fuels. Considering those delays in phase-out efforts, it is necessary to critically evaluate whether the scenarios adequately account for the challenges and barriers DCs and ICs face in transitioning to low-carbon economies.

8.3.3 Eight recommendations for further scenario analysis to soften science-policy boundaries and increase credibility, legitimacy, and salience

I here present eleven recommendations on the future science policy interface regarding scenarios and improvements in the scenarios based on the synthesis in Chapter 7, but also reflecting on the main findings. The recommendations are categorized as recommendations for Science-Policy Interface adjustments (4) and Scenario developments (7).

8.3.3.1 Communication & Science-Policy Interface

No. 1. **Ongoing science-policy dialogue**: It is recommended that modelers and the IPCC engage in continuous science-policy dialogues with UNFCCC delegates and national decision-makers to improve scenario communication and development of salient scenario content. Science-policy dialogues may support identifying policy objectives and the information that could support policymaking in achieving those goals. Chapter 6 shows that the examined policymakers want other types of information than scientists, e.g., detail about mitigation actions, lower complexity, and higher transparency between variables and parameters. This also concerns capacity building and training, and enhanced perspectives reflecting the diversity of UNFCCC parties and global South regions (See recommendation 3).

No. 2. **Attach detailed policy roadmaps to scenarios**: Several examined policymakers requested more national detail and cost-efficiency analyses of scenario mitigation actions. To address this, the thesis recommends attaching decadal and century-long policy roadmaps to scenarios. Providing policy roadmaps may be sensitive but fulfills a policymaker's request for more national detail on mitigation actions. Chapter 6 indicated that the examined policymakers requested more explicit information that could be directly used to inform the development of sufficient adaptation and mitigation policies (e.g., sectoral reductions).

No. 3. **Provide funding for scenario development and use in the Global South**: It is challenging to address increased policy ambition (within the UNFCCC) without also addressing climate justice. I recommend promoting more equitable distribution of research efforts, particularly in underrepresented areas in the global South, e.g., the UNFCCC provides funding mechanisms to support or develop science and training in medium and least-developed countries, potentially creating a fourth pillar of climate financing under the Paris Agreement. To effectively anticipate climate change, all countries need access to scientific knowledge and resources to make informed policy decisions.

8.3.3.2 Scenario Development

No. 4. **Future scenario elaborations or extensions may explicitly account for institutional capacity**, particularly in global South regions, to achieve reliable and credible projections. Weak institutions comprise a plausible barrier to policy implementation. Thus, it is crucial to account for institutional capacity (and governmental willingness to mitigate) when analyzing the conditions for policy implementation, in particular, in global South regions since they are often very different from global North institutions (where model-based scenarios and their assumptions are primarily developed). It is further recommended that policymakers collaborate with scientific experts to develop quantitative governance scenarios, considering factors such as political stability, the rule of law, control of corruption, and accountability.

No. 5. **Conduct further research on consumption-based emissions in scenarios** to address the current trend of increasing CO_2 emissions in non-OECD countries and their relationships with high-consumption Annex-I and non-Annex-I countries. These scenarios may provide a more comprehensive insight into the dynamics of emission flows between countries and how to mitigate them. Chapter 4 identified that the models did not sufficiently project the fast-growing emissions in non-OECD regions. Most scenarios overestimated OECD CO_2 emissions growth but underestimated non-OECD CO_2 emissions.

No. 6. **Conduct analyses of differentiated regional energy infrastructures and sectoral emission reduction challenges**. This aims to enhance the credibility and salience of scenarios for decision-making. Contemporary models and global economic institutions tend to reproduce the idea that phasing out coal first is the optimal mitigation roadmap. However, focusing intensely on a specific issue may overlook other real-life complexities and implicitly convey a specific viewpoint on the challenge and related solutions, overlooking policy settings required for regional mitigation.

No. 7. **SSPs may further explore the relationships between realized policy actions and their mitigation effect**. Clear scientific communication of mitigation strategies and their implementation challenges is critical in solving complications presented in NDCs and informing cost-effective policy actions that reduce greenhouse gas emissions. This includes assessing the feasibility of existing policy strategies, like land-CDR (e.g., afforestation) and decarbonization targets, which have received critiques.

No. 8. **Broaden the imaginative capacity concerning narratives**. As all models have limitations, and scenario series cannot explore all possible futures, it is recommended to regularly review storylines and variable assumptions, and the reasons behind selecting specific scenarios over others. Although discontinuity is not aligned with political preferences, it is possible for several reasons, such as discontinuity pathways related to climate change risks, biodiversity degradation, and alternative mitigation perspectives, such as degrowth, regrowth, or population regulation.

List of publications by candidate

Peer-reviewed papers included as thesis chapters

Published peer-reviewed papers (Thesis chapters):

1) **Chapter 3: Pedersen, J.S.T**., van Vuuren, D; Gupta, J; Santos, F.D.; Edmonds, J; Swart, R. (2022). IPCC emission scenarios: How did critiques affect their quality and relevance 1990-2022? *Global Environmental Change, Elsevier* https://doi.org/10.1016/j.gloenvcha.2022.102538

2) **Chapter 4: Pedersen, J.S.T**., Santos, F.D., 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 Environmental Change (Elsevier)*, **66**, 102199. doi.org/10.1016/j.gloenvcha.2020.102199

    a. Article reproduced for policymakers and summarized by The European Commission's Science for Environmental policy (20th May 2021 Issue 561)
    b. Cited in IPCC Working group I: Science (2021a) and IPCC Working group III: Mitigation (IPCC, 2022b)

3) **Chapter 5: 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. *Communications Earth & Environment (Nature Journals),* 1(41), 1-7. doi.org/10.1038/s43247-020-00045-y

    a. Cited in IPCC Working group III: Mitigation (IPCC, 2022b)

Submitted and peer-reviewed but not yet published papers (thesis chapter)

4) **Chapter 6**: Pedersen, J.S.T.; Gomes, C.; O'Rourke, P.; Gupta, J.; van Vuuren, D.P.; Santos, F.D.; Swart, R.
Bridging Science-Policy and Closing the South-North Knowledge Divide: Surveying the Policy Relevance of Emission Scenarios.
Communication Earth & Environment, Nature Journals.
(Submitted on September 23rd 2023; resubmitted for 2nd review on November 5th, 2023)

    Open access "Dataset for the paper/chapter" (Survey and comparison of country categories):
    Pedersen, J.S.T., 2022. Survey of Emission Scenario Relevance in Policy UNFCCC Delegates Survey 2021 R v3. OSFHOME. https://doi.org/10.17605/OSF.IO/5QCTP

Parallel publications related to the thesis (not included as thesis chapters)

Peer-reviewed journal papers

1) Santos, F.D.; Ferreira, P.L.; **Pedersen**, J.S.T. (2022). The climate change challenge: a review of the barriers and solutions to deliver a Paris solution**.** Climate. MDPI. https://doi.org/10.3390/cli10050075
Includes a synthesis of asymmetries concerning Climate Justice

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Review of short-term policy scenarios

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1) **Pedersen**, Dias, Azevedo, Antunes, Adão, Castro, Lourenço, Kok*,* Santos, van Vuuren, Soares
The Portuguese forest scenarios: Strengthened policies are needed to reach the 2030 NDC and 2050 net-zero targets.
National SSP extensions (submitted to *Regional Environmental Change*, Springer)

2) Edmonds, Jae; Shinichiro Fujimori; Gokul Iye; Haewon McJeon; Patrick O'Rourke; **Jiesper Tristan;** Detlef van Vuuren, Sha Yu
Global Energy System Transitions
Paris Compliant Scenarios (submitted and accepted by *Review of Environmental Economics and Policy*, The University of Chicago Press Journals)

Book chapters

1) Santos, F.D.; Ferreira, P.L.; **Pedersen**, J.S.T. (2022) Climate Change and Sustainability in "The Blue Planet". Springer's Sustainable Development Goals Series
Includes a synthesis of asymmetries concerning Climate Justice

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1) Wp3 Emissions Scenarios, Narratives, and Socioeconomic Trajectories. 2020.
National Roadmap for Adaptation 2100: Portuguese Territorial Climate Change Vulnerability Assessment for XXI Century (RNA 2100)
Review of long-term scenarios informing the IPCC

Parallel publications not related to the thesis (developed during the thesis work)

1) **Pedersen, J.S.T.** & Manhice, H. (2020) The hidden dynamics of household waste separation: an anthropological analysis of user commitment, barriers, and the gaps between a waste system and its users. *Journal of Cleaner Production*, **242**, 116285. doi.org/10.1016/j.jclepro.2019.03.281

2) Macedo, P., Santos, F.D., Tristan **Pedersen, J**., Penha-Lopes, G., 2021. Climate action: is coronavirus what we have been waiting for? (and now what?). Local Environment. doi.org/10.1080/13549839.2021.1916902

Book chapters

1) Manhice H.; **Pedersen**, JST., Santos, F.S. et al. (2022) Holes in the Policy Net: An Analysis of Sustainable Food Production in Artisanal Fishing Communities and Policy Challenges to Ensure Long-Term Food Security in Sofala Bank, Mozambique in "Sustainable Agriculture and Food Security". World Sustainability Series, Springer-Nature. DOI: 10.1007/978-3-030-98617-9_21

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About the author

Jiesper Strandsbjerg Tristan Pedersen was born in Ringkøbing, close to the western coast of Denmark and the North Sea. He was educated electrician between 1991-1996, conducted a bachelor in anthropology at University of Aarhus 1999-2003 (including 1-year at the Political Science Institute at the same university, e.g., courses in statistical methods), and a master's in Anthropology at University of Copenhagen, Denmark (2003-2006). In addition, he has a master's in protreptic coaching (manager coaching based on ancient Greek methods by Aristotle) and is certified in process facilitation (e.g., initiation and group dynamics).

Jiesper Pedersen is a climate researcher (5 yrs), sustainability consultant (13 yrs), co-examiner in anthropology at four Danish universities, and participating in the public debate. As a member of the research unit CCIAMM and part of Portugal's RNA2100 adaptation roadmap 2020-2100 (Ministry of Environment & Climate Action), he develops national socioeconomic scenarios for Portugal, including LULUCF emission scenarios based on specific policy options. He is co-examinator fro the Danish Ministry of Higher Education (at four Danish universities). He consults companies and organizations on sustainable change, value change, ESGs, and avoiding greenwashing in sustainable marketing. He teaches in universities (since 2006), was a primary school teacher (2009-2011), and combat and navigation instructor in the Danish Army (2011-2012). Methods include surveys, usability testing, participant observation and fieldwork, interviews, coaching, workshops/focus groups, initiation processes, and dataset analysis.

Research: publications about emission scenarios, practice change, and (Paris) climate policy improvements in high-impact science journals (e.g., Elsevier and Nature journals). He is a reviewer in "Journal of Sustainable Production" (Elsevier), "Communications Earth and Environment" (Nature Journals), and on the Sixth Assessment Report (Working Group III) of the Intergovernmental Panel on Climate Change (IPCC). He participated in the UNFCCC Conferences of the Parties (COPs) COP-25 (Madrid) and COP-26 (Glasgow). He is invited to join COP-27 (Sharm El-Sheikh) as an informal part of the Portuguese delegation via the National Council of the Environment and Sustainable Development (CNADS). Participated as Danish and Portuguese delegate at the IPCC Expert Workshop on scenarios in Bangkok, April 2023.

Sustainable consultancy & projects: consulting development of an online climate-game platform for municipalities and voters – navigating adapting to a changing climate (informing about risks and solutions) and emissions reduction solutions connected to a range of political priorities (political image/popularity, market economy, organizational structure). Previously, he led practical research in gamification of Smart Home Energy saving, evaluated user waste separation in Rødovre municipality, and assessed a Veteran Para-sports project under the Danish Armed Forces. He led humanitarian development projects (improving the quality of health services in 42 Western Kenyan health facilities and building a health center).

Supplementary Information

SI 1: Scenario Developments and Classifications 1989-2019 (Chapter 4)

The four generations of emission scenarios within the IPCC

Historically, scenarios were used as early as the 1950s and 1960s for military and energy planning in the United States (Amer et al., 2013). There are few descriptions of the background of the models used in the first two series. For that I have used expert interviews with developers to document the considerations and information that is missing in the literature. This involves for instance to explore the reasoning behind changes in the scenario exercise from the first (SA90) to second (IS92) scenario generation.

Short synthesis of the four series

The perspectives on plausible futures have evolved over time. In 1990 IPCC presented emissions pathways with a high-emission future almost equal to emissions developments in the present time (Pedersen et al., 2021). The next series all introduced a higher emissions range (Leggett et al., 1992; Nakicenovic and Swart, 2000a; O'Neill et al., 2016). This was a direct result of intergovernmental processes enforced by the US, which excluded the Business-as-Usual term and introduced higher emissions ranges (IPCC, 1991). It resulted in two successive IPCC scenario generations, with no describing names attached to scenarios (e.g., pessimistic, or BaU as in the first generation) and two emission pathways higher than the high emission scenario in the first 1990-generation. However, from a scientifical point of view, scenarios should explore the entire plausible range of future emission levels (Pedersen, 2021). Therefore, scenarios are continuously adjusted to actual emissions (Peters et al., 2013; van Vuuren et al., 2010), and political in-action (Cope, 2009; Sandoval, 2018).

Emissions scenarios explore a range of plausible future socioeconomic developments, including high-impact cases and low-impact goals. As preparations for IPCC AR5, researchers developed four Representative Concentration Pathways for what might happen to greenhouse gasses and global warming by 2100 (IPCC, 2014c, 2007a; Moss et al., 2010; van Vuuren et al., 2011a). These were later coupled with the Shared Socioeconomic Pathways (SSPs) (O'Neill et al., 2017; Riahi et al., 2017), expressed as the SSP-RCP combinations (Gidden et al., 2019) informing the sixth IPCC assessment cycle (IPCC, 2021a).

A scenario storyline is a narrative description of a scenario (or family of scenarios), highlighting the main scenario characteristics, relationships between key driving forces, and the dynamics of their evolution (IPCC, 2018b). Storylines were developed for the SRES (3rd generation) and the SSPs (4th generation). The SA90 and IS92 (1st and 2nd generation) assumptions and quantifications were not underlying the extensive narrative descriptions of the later sets. The SRES, RCPs, and SSPs demographic and economic projections depict a wide uncertainty range consistent with the scenario literature (Nakicenovic and Swart, 2000a; Riahi et al., 2017).

"The SSP-RCP scenario framework facilitates the coupling of multiple socioeconomic reference pathways (SSP baselines) with radiative forcing (and temperature) projections by 2100. The latter represent climate model products via expressed as the representative concentration pathways

(RCPs). The scenario matrix architecture includes a third dimension: the Shared Policy Assumptions (SPAs). They capture key policy attributes, like mitigation and adaptation policy goals, instruments, and obstacles of measures" (Kriegler, 2014).

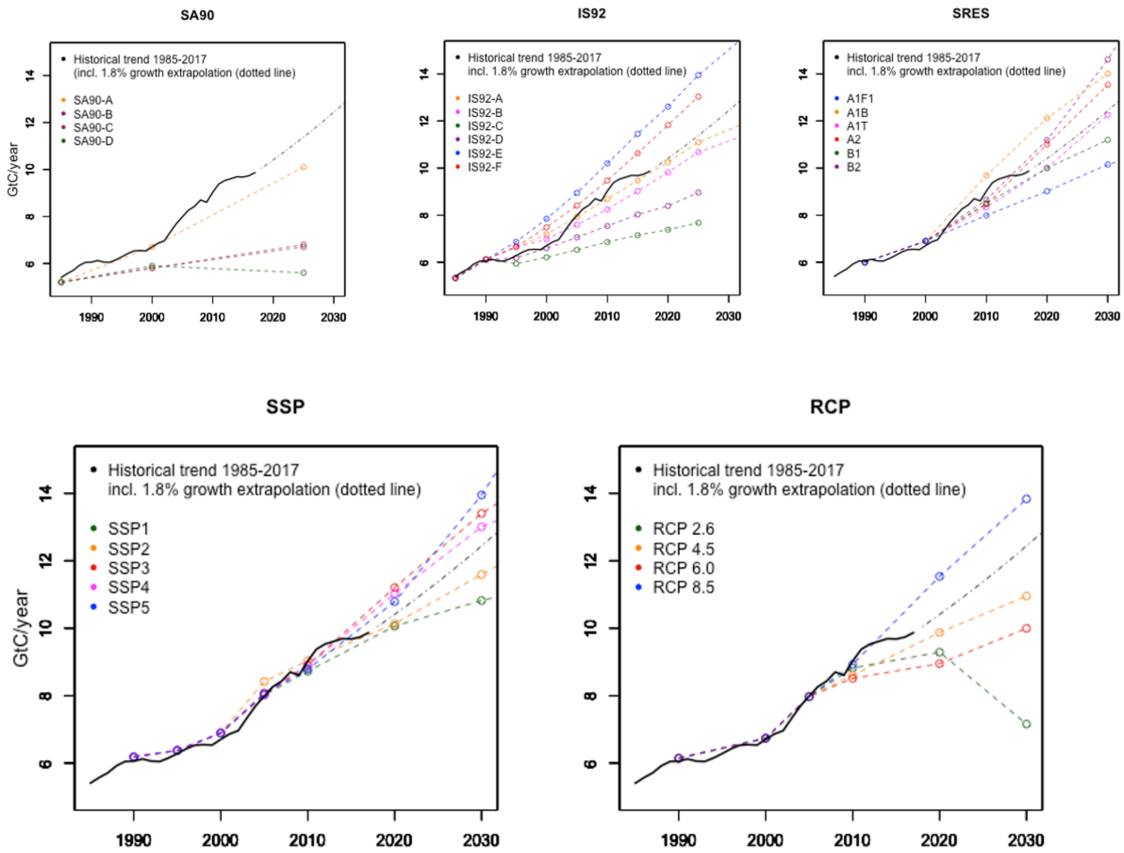


Figure SI- 1. Comparison of historical emissions trend 1990-2017 for CO_2 from fossil fuels and industry (black line) with emission projections in SA90 (top left), IS92 (top middle), SRES (top right), SSP-BL (bottom left), and RCPs (bottom right) 1985-2030. Black dotted line shows the extrapolation of 1.8% growth rates for historical emissions. Data source: IPCC (1990b), Pepper et al. (2005), Nakicenovic et al. (2000), Riahi et al. (Riahi et al., 2017), van Vuuren (2011a), GCP (2018).

Box SI- 1. Overview of emission scenario assumptions within the IPCC context

Scenario series developed between 1989-2019

1st Generation: SA90 scenarios. The series cover two baselines and two intervention scenarios examining the range of five GHG emissions based on average GDP growth assumptions and climate policy pathways (IPCC, 1990c), using a median population projection (IPCC, 1990b; Zachariah and Vu, 1987). Additionally, eight variants based on low/high-growth was prepared (IPCC, 1990d). They were developed by a group of five Dutch and American scientists under the Response Strategies Working Group (which later became WG3) (IPCC, 1990f). They applied a US model formerly used by the energy industry and modified to cover GHGs. The scenario series enabled analysis of a plausible range of global climate change scenarios developed by WG1 (IPCC, 1990d, 1990g). The SA90 scenarios were used in AR1.

2nd Generation: IS92 scenarios. The series was the first to provide estimates for the full suite of GHGs (IPCC, 1996). It adjusted the non-intervention scenarios of SA90, with two emissions scenarios similar to (IS92a/b) and two higher (IS92e/f) than SA90-A (Pepper et al., 1992) - of "medium-high" and "high" cumulative emissions pathways (IPCC, 2000a). The IPCC mandate explicitly excluded the development of new climate policy scenarios (Leggett et al., 1992). The six scenarios were based on one model, developed by authors from the same Dutch/American institutions. IS92 was included in the 1992 supplementary report (IPCC, 1992), and in scenario-based literature informing AR2(WG1-WG3), AR3(WG2), and AR4(WG2) (IPCC, 2007c, 2001b, 1995b). As a result of time lags in the impact assessment research cycle, mainly IS92-based impact assessments were mainly included in AR3(WG2)(IPCC, 2001c), and a combination of IS92 and SRES in AR4(WG2) (IPCC, 2007d).

3rd Generation: SRES scenarios introduced the concept of storylines/narratives. These socioeconomic scenarios interpreted alternative quantitative futures describing "economic versus environmental" (A-B) and "global versus regional" (1-2) development in four so-called scenario families/narratives. These were represented by four markers and two illustrative scenarios, with an additional 34 variations (Nakicenovic and Swart, 2000a). They were developed on the basis of the IS92 evaluation (Alcamo et al., 1995a; Nakicenovic and Swart, 2000a) and thus included global equality scenarios (i.e., A1 and B1 families). As specified in terms of reference by IPCC assumptions excluded population and mitigation policies (Nakicenovic and Swart, 2000a), and included the participation of multiple model teams across world regions(IPCC, 1996). The series was developed via six models using integrated assessments (IAM) and based on the Coupled Model Intercomparison Projection phase 3 (CMIP3) from Europe, Japan, and the USA, with contributions from authors and editors representing non-OECD countries (Nakicenovic and Swart, 2000b). SRES scenarios were used in scenario-based literature informing AR3 (IPCC, 2001d) and AR4 (IPCC, 2007a).

The 4th generation: The SSPs comprise more socioeconomic and societal input variables than the previous series. For example, educational attainment and urbanization are not represented quantitatively in the previous sets but comprise essential elements of the SSPs (Riahi et al., 2017). The RCPs comprise three out of four scenarios with possible CP assumptions: RCP2.6, RCP4.5, and RCP6.0. At the same time, RCP4.5 and RCP6.0, RCP8.5 represent possible reference cases to assess policies, describing low-end, median, and high-end baseline trends (in the absence of climate policy), respectively. It was stated that it was, at the high-end, close to the 90th percentile of emission scenarios published at that time (van Vuuren et al., 2011b). The SSP-RCP comprises five out of seven CP scenarios. These are SSP-1.9 and SSP-2.6, representing the 1.5 °C and 2 °C Paris policy goals, respectively, SSP4-3.4 and SSP2-4.5 (moderate mitigation), and SSP4-6.0 (weak mitigation) Gidden et al. 2019). Additionally, the UNFCCC requested IPCC to explore 1.5-pathways (IPCC, 2018a; Kriegler et al., 2017b), resulting in four scenarios exploring 1. 5 °C pathways (SP1.5) published in an IPCC special report (IPCC, 2018b).

Detailed scenario description and contemporary contexts

The IPCC scenarios were born in Washington, D.C. in January 1989. The IPCC response group under working group III was requested to develop these emission scenarios for use in analyzes and assessments of future climate (WG1), mitigation strategies (WG3), and impact assessments (WG2).

The scenario development involved research institutions localized in Annex-I countries. United States Environmental Protection Agency (USEPA) (Dennis Tirpak) and the Dutch Environment Ministry (Pier Vellinga) volunteered to take the lead in developing emission scenarios (IPCC, 1990b) and funded/assigned ICF (Bill Pepper, US) and RIVM (Jan Rotmans and Rob Swart, NL) to do the scenario work with their models.[A] The first generation scenarios were a result of two expert meetings held in April and December 1989, including also United Kingdom observers from Working Group I (IPCC, 1990b).

In May 1989, an expert group developed these three scenarios and a draft report and presented them to the RSWG. Later, at the general IPCC meeting in June 1989 in Nairobi, the group decided to add a fourth scenario that would lead to stabilization of greenhouse gas concentrations of CO_2 equivalent levels well below the CO_2 doubling level (IPCC, 1990a, 1989a). In addition, Working Group I requested some changes in the initial three scenarios (one baseline (later called SA90-A), one energy efficiency (SA90-B), and one mitigation scenario (SA90-C: control policies)). The request from the IPCC meeting in June 1989 led to an alternative fourth (mitigation) scenario (SA90-D: accelerated policies) similar to but with lower estimates of CO_2 emissions during the first decades from 1990 (IPCC, 1990b).

The first generation: SA90 (Developed 1989-1990)

The contemporary context 1989-1991

IPCC was newly established by country delegates primarily from Environmental Ministries. The contextual framing was that climate change is a real risk, let's explore where emissions can go and what can be done about them (IPCC, 1989a).

The AR1 was generally well-received, and a 2nd assessment was planned. As one component, a new scenario series were to be developed (IPCC, 1991). During 1988 and 1991, world leaders, such as Margret Thatcher and George Bush, publicly acknowledged and supported a need for action on climate, while also expressing concerns regarding a perceived trade-off between climatic/environmental and economic interests(Bolin, 2007a; IPCC, 1990f, 1989a). In contrast, developers experienced that, in particular, the United States delegation changed their arguments in IPCC sessions and asking different types of questions, such as questioning the reality of global warming (based on modeler interviews). Furthermore, several interviewees argue that the fossil fuel energy was surprised by the political attention the 1990 IPCC assessments received and started to reorganize and maybe drafted some of the US delegations arguments (based on modeler interviews).

Four scenarios (including intervention/mitigation)

The SA90 scenarios are often illustrated as four scenarios, which were originally presented in the IPCC First assessment report (AR1). These are based on average economic growth assumptions. Additionally, eight scenarios were modeled based on high and low growth. The 12 scenarios are shown in the IPCC AR1 Appendix report on emission scenarios (IPCC, 1990d). All based on the Atmospheric Stabilization Framework (ASF), an integrated set of computer models used in the SA90 and IS92 update (Pepper et al., 1992).

The scenarios were developed between 1989 and 1990 (Pepper et al., 1992), to support and interact with the three IPCC WGs (IPCC, 1989a). The four marker scenarios assumed a range of possible futures involving a no-change pathway (SA90-A) with growing future supply of fossil

fuels for a continuously expanding market, a scenario describing shifts in energy mix/efficiency (SA90-B), and two with climate policies (SA90-C/D)(IPCC, 1990b).
As such, the series consisted of two baselines (SA90-A-B) and two intervention scenarios (C-D), obtained by examining the range of carbon emissions via similar economic growth and different climate policy pathways (IPCC, 1990c), all using the same median population projection (Zachariah and Vu, 1987). They assumed a growing future supply of fossil fuels for a continuously expanding market and possible shifts in energy mix/efficiency, and policies.
They assumed a range of possible futures involving a no-change pathway with growing fossil fuels (SA90-A), shifts in energy mix/efficiency with slow emissions growth (SA90-B), and two scenarios with climate policies (SA90-C/D)(IPCC, 1990b). Sometimes Scenario-A was termed Business-as-Usual (BaU), suggesting a most likely continuation of historical/present trends (IPCC, 1990e, 1990b).

The developers applied an integrated assessment model framework formerly used by the energy industry and modified to cover GHGs. The scenarios were developed using the Atmospheric Stabilization Framework (ASF), initially developed for energy projections by USEPA, and were corroborated by the Dutch IMAGE model (Bolin, 2007b; IPCC, 1990e, 1990b).
The emissions projections comprised five GHGs, based on four integrated four modules energy, industry, agriculture, and land-use (comprising six models). Additionally, the framework included an ocean model for heat and carbon uptake and an atmospheric composition module measuring the global radiation balance.
The four marker scenarios quantified similar population and average economic growth, and different developments in oil prices, energy demand and efficiency, agriculture, and deforestation/reforestation. The quantifications comprised in the four markers were the same rate of average economic and population growth (based on World Bank projections), oil prices, energy supply, demand, and efficiency, agricultural activities, and deforestation/reforestation (IPCC, 1990b). Eight scenario variants defined an uncertainty range and were based on higher and lower economic growth (IPCC, 1990b).

Already during the SA90 development, the use of the term BaU was questioned, because it would suggest an unwarranted certainty about future developments (Expert interviews). Although external scenario critique was almost absent at the time, internal concerns voiced at a WG3 subgroup meeting in 1989 suggested that the SA90-A assumptions of 2% annual emissions growth rates were too high compared to the historical trend of 1.8% (Bolin, 2007b).
Additionally, to anticipate external criticism (Bolin, 2007b), IPCC stressed that the scenarios were neither predictions nor descriptions of desirable futures (IPCC, 1989a). In 1991, US economist Cline(1991) criticized the scenario time limits, arguing a need to extend future projections beyond 2100 to improve policymaker decisions about long-term problems. During interviews, SA90 developers stated that they had the big numbers right but missed the dynamics of the development of great economies like Russia and China, e.g., they were not even close to estimating that the Chinese economy would grow this large that fast. Additionally, other scientists in the United States and Europe, such as IIASA, worked on different scenario approaches, but they, in general, agreed on the basic assumptions.

Box SI- 2. Description of the SA90 scenarios published in 1990

The SA90 scenarios: the developers provided no narratives other than lower, average, and higher economic growth and different levels of climate policy. The four average growth scenarios were chosen for assessments in AR1. Additional eight variants based on low (4) and high (4) growth were modeled (IPCC, 1990b, 1990c).

The four types of assumptions involve:

SA90-A: Baseline scenario. It was called the Business as Usual or the 2030 High Emissions Scenario. It assumes few or no steps taken to limit GHG emissions. It assumes that energy use and clearing of tropical forests continue and fossil fuels (in particular coal) remain the world's primary energy source

SA90-B: labeled the 2060 Low Emissions Scenario. It assumes that several environmental and economic concerns result in steps to reduce the growth of greenhouse gas emissions. It also assumes full compliance with the Montreal Protocol and that tropical deforestation is stopped and reversed. It quantifies slow emissions growth via energy efficiency and a doubling of cumulative CO2 around 2060.

SA90-C: Intervention or mitigation scenario labeled control policies.

SA90-D: Intervention scenario labeled Accelerated policies. Both SA90-c and SA90-D assume rapid utilization of renewable energy sources, strengthening the Montreal Protocol, and adopting agricultural policies to reduce emissions from agriculture, livestock, crops, and fertilizers (IPCC, 1990b).

The second generation: The IS92 update of SA90 (Developed 1991-1992)

The IS92 scenarios was considered an update of the SA90, requested by the 1991 IPCC session. The scenarios adjusted the non-intervention scenarios of SA90 (SA90-A), with two similar emissions scenarios (IS92a and IS92b) and two higher (IS92e/f) than SA90-A, and two lower (IS92c and IS92d (Pepper et al., 1992). The IPCC mandate explicitly excluded the development of new climate policy scenarios (Leggett et al., 1992).

The contemporary context 1991-1995

IPCC planned a 2nd assessment (AR2) was planned. As one component, the IPCC panel decided that new scenarios were to be developed (IPCC, 1991). The IS92-development marked a shift in the political context.

The UNFCCC was established in 1992, and intergovernmental tension had arisen, particularly between the US (a country not preferring a targets- and-timetables-approach to policy) and the EU (believing in a science-based targeted approach that had been agreed successfully in addressing earlier environmental challenges) and willing to start mitigation without full understanding of the problem) (Bolin, 2007a; Hecht and Tirpak, 1995; Oberthür and Ott, 1999b).

In the IPCC sessions, gradually several countries changed their intergovernmental representatives from environmental ministries to other (often more powerful) departments, like the US State Department. New delegations asked fundamental questions about climate change's reality and the desirability and costs of mitigation (Hecht and Tirpak, 1995) (Expert interview). As a consequence, several countries argued that emission reductions were premature, and that future emissions could be much lower (or higher) than the SA90 baseline. Responding to these changes, the composition of the scenario development team was expanded, also including economists (Jae

Edmonds). However, the economists' models could not capture non-CO_2 and land use emissions like the ASF and IMAGE models.
The regional composition of the SA90 scenario team was not questioned. Countries other than EU and US appeared much more interested in the WG1 work than in the emission scenarios. Arguably because these countries continued to send MetOffice delegates (The Meteorological Office) to IPCC events (expert interview). However, this changed when Jyoti Parikh entered the scene and made the groundbreaking point about inequality, although addressing it as IPCC strategies rather than scenarios (Parikh, 1992a).

The IS92 scenario exercise and development process

The IS92 series was an update of the SA90, developed using the same ASF model framework. This time it included the entire suite of GHGs (Alcamo et al., 1995a). IS92 had more regional detail and more diverse economic and population developments (IPCC, 1990b; Pepper et al., 1992).

As a result of intergovernmental decisions during the 6th IPCC session (IPCC, 1991) the developments were restricted by three intergovernmental mandates:

1) The term Business-as-Usual was excluded.
   However, two scenarios (IS92a/b) described pathways with continuing trends similar to the SA90-A high-emission scenario (Leggett et al., 1992; Pepper et al., 1992). In practice, IS92a became an often-preferred reference case in the scenario literature (Alcamo et al., 1995a; IPCC, 1995c, 1990a).
2) The range of the IS92 series was increased upwards and defined by distributions[9] of possible CO_2 scenarios (Edmonds et al., 1992; Pepper et al., 1992)
   As e result, the series included low, medium, and high emission pathways comprising a significantly higher range than the SA90. The latter described high population growth (IS92f) and fossil-driven rapid economic growth (IS92e) (Pepper et al., 1992).
3) Policy assumptions were excluded.
   As a result, the IS92 series have no mitigation scenarios.

The term Business-as-usual was not included in the IS92, but two scenarios illustrated no-change pathways similar to the SA90 high-emissions scenario(Leggett et al., 1992; Pepper et al., 1992). In the literature, there is no clear evidence explaining why policy assumptions were not included and the emissions range was raised in the IS92 series. These decisions were made in intergovernmental processes (Bolin, 2007a; IPCC, 1991) rather than scientifically developed.

During intergovernmental discussions, one delegation argued a need to develop a sensitivity range of scenarios as options and thus a need for multiple scenarios, which reflected different levels of emissions (Bolin, 2007a; IPCC, 1991). Experts and developers later stated that these arguments appeared to be drafted or derived from scenarios developed in the fossil energy industry.[A] As such, the range of the IS92 series was defined by probability distributions of possible CO2 scenarios (Edmonds et al., 1992; Pepper et al., 1992).
Some delegations also argued that, if no international climate policy would be agreed, there would be a technical-scientific need for a higher and wider range of no-policy emission scenarios (IPCC, 1991). One reason for this, which was also officially stated (IPCC, 1991), could be that, if no international climate policy would be made there would be a technical-scientific need for a higher emission range. Another explanation for such decision is that countries less interested in an international agreement sought to provide a larger operating space for increasing emissions

[9] No probabilities were assigned to the scenarios.

and implicitly legitimating continued exploitation of fossil resources (See also the section about UNFCCC).

Box SI- 3: Description of the six IS92 scenarios published in 1992

The IS92 scenarios adjusted the non-intervention scenarios of SA90 (SA90-A), with two similar emissions scenarios (IS92a and IS92b) and two higher (IS92e/f) than SA90-A, and two lower (IS92c and IS92d (Pepper et al., 1992). The IPCC mandate explicitly excluded the development of new climate policy scenarios (Leggett et al., 1992).

IS92a was not labeled BaU but followed similar assumptions and a medium-high emission pathway similar to SA90-A(Leggett et al., 1992) and the later SSP2 Middle-of-the-road scenario.

IS92b, a modification of IS92a but with slightly lower emissions. It that assumes that OECD Member countries stabilize or reduce CO2 might. However, this will have a small impact on greenhouse gas emissions and will not offset substantial growth in the rest of the world (Leggett et al., 1992).

IS92c is the lowest IS92-scenario. It has emission levels, and assumptions comparable to an intervention scenario argued to be the side effect of non-climate/environmental policies (Alcamo et al., 1995a; Pepper et al., 1992). It quantifies low economic, population, and energy growth, and energy transition, and assumes increased environmental awareness/policies. It is similar to SRES global sustainability. However, both SRES and SSP global sustainability quantify higher economic growth (see SRES and SSP).

IS92d: similar to regional sustainability (see SRES). Quantifies low economic growth and low population growth and moderate technology innovation in high-income regions leading a steady to medium-slow global emissions growth throughout the century

IS92e: The highest emissions scenario in the series. It assumes moderate population growth, high economic growth, high fossil fuel availability, and eventual hypothetical phase-out of nuclear power (Leggett et al., 1992). Similar to rapid economic growth based on high fossil energy consumption (see SRES).

IS92f: Quantifies high emissions throughout the century based on high population and energy growth, low economic growth, and slow technological change (Leggett et al., 1992). It is similar to SSP3 and A2, but different from SSP4, which assumes continued global inequality but energy transition in high-income regions.

Arguably, the increased range was solid from a scientific-technical point of view, while it also provided a larger political operating space for increasing national emissions and legitimating continued exploitation of fossil resources (Hecht and Tirpak, 1995; Oberthür and Ott, 1999b). It initially opened up for new possibilities, such as no international mitigation agreements. However, assessing the credibility of scenario narratives and plausible global developments in a century long, the exclusion of policy assumptions made no sense. In technical terms, the exclusion of assumptions implicitly meant that in the future it would not be possible to compare historical emissions with the projected emissions, in case of international agreement and implementation of mitigation policies.

The exclusion of climate policy assumptions was less solid scientifically, since it limited the range of input assumptions. Thus, the series excluded plausible futures in which climate policy would develop. This meant that it would not be possible to compare historical with projected emissions in the future in case of international agreement of mitigation policies. Despite this restricted mandate, a medium-low emission scenario assuming low population growth (IS92d) and a low emission scenario quantifying low economic and primary energy growth with changed energy-mix (IS92c) were included (Leggett et al., 1992; Pepper et al., 1992).

The third generation: SRES (developed 1996-1999)

The Special Report on Emissions Scenarios (SRES) was a report published by the Intergovernmental Panel on Climate Change (IPCC) in 2000 that provided a set of scenarios of greenhouse gas emissions based on different assumptions about future socio-economic and technological developments.

The four SRES scenarios

The IPCC panel commissioned a new report on emissions scenarios (IPCC, 1996)
Resulting in the Special Report on Emissions Scenarios(SRES). The SRES scenarios are as the IS92s known by unimaginative scenario names but different from the IS92s they represent scenarario narratives (A1, A2, B1, and B2). These narratives are characterized by two overall dimensions: globalization versus regionalization, and focus on economy versus environment. The A1 and A2 worlds' primary focus is maximizing income, with little consideration for environmental goals. In contrast, the B1 and B2 worlds prioritize local environmental objectives, such as reducing air pollution and preventing soil degradation. The A1 and B1 scenarios involve further globalization, while in A2 and B2, the regions remain more diverse and isolated. Globalization can stimulate rapid technological advancements, resulting in low fossil energy consumption, as seen in the A1 scenario. Multiple modeling groups have created detailed trajectories for GDP, population, and final energy demand to depict the stories behind these four scenarios (Nakicenovic and Swart, 2000a).

Since then, there have been several updates to the emission scenarios that consider new information, such as technological advances and changes in economic and social trends. One update was the post-SRES scenarios, presented in AR3 (IPCC, 2001a). The post-SRES emission scenarios do include assumptions about mitigation policies. One of the primary purposes of developing these scenarios was to assess the potential effectiveness of different mitigation policies in reducing greenhouse gas emissions and limiting the impacts of climate change (Bollen et al., 2014; IPCC, 2001a).

The contemporary context 1996-2000

At IPCC meetings, views on possible future climate change were divided, and resistance was observed “from the energy industry, the Senate, and Republican congressmen” in the United States (Bolin, 2007b). During the 1982-1994 period, US officials were worried about the cost of an energy transition and favored less government regulation than discussed??? in UNFCCC for a (Hecht and Tirpak, 1995). However, following AR2, President Clinton called for investments in research “to encourage efficiency and the use of cleaner energy sources” (The White House, 1997). As such, the character of the US presidency has had a significant impact on UNFCC negotiations (Hecht and Tirpak, 1995; Oberthür et al., 1999)[A], and also on the scenario development process.

In conclusion, the IS92 and SRES did not evaluate or explore the environmental and climatic consequences of "intervention" futures, but the TAR did via the post-SRES scenarios (IPCC, 2001a). Additionally, the TAR examined the feasibility and costs of mitigating GHGs from different regions and sectors, which was not incorporated in the SA90. However, during preparations for the fourth generation, experts evaluated earlier scenarios and identified a need to describe possible emissions reductions for different countries and regions (IPCC, 2005d). With the broadening of the author team, as regards regional background and discipline (IPCC, 2006b), and by conceiving more accessible narrative storylines (Nakicenovic and Swart, 2000a), more people got interested in the emission scenario series.[A]

The SRES was developed between 1996 and 1999 (IPCC, 1996; Nakicenovic and Swart, 2000a; van Vuuren and O'Neill, 2006), under the strictest terms of reference (IPCC, 2006b, 2005d, 1996, 1991, 1989). Thus, they moved closer into being a boundary object compared to IS92 (and SA90). For the first time, the terms of reference set by the IPCC via intergovernmental discussions did not only put boundaries on the technical aspects of the scenario development (as for IS92) but also the development process.
The socioeconomic scenarios interpret alternative quantitative futures with no-policy assumptions via four scenario families/narratives (marker scenarios) and additional two illustrative scenarios. Additionally, 34 variations grouped under the four narrative families are available in the SRES database (Nakicenovic and Swart, 2000a).

Scenario exercise: the development process
The SRES was developed between 1996 and 1999 (IPCC, 1996; Nakicenovic and Swart, 2000a; van Vuuren and O'Neill, 2006), under more detailed terms of reference (IPCC, 2006b, 2005d, 1996, 1991, 1989) than the IS92.
Thus, the scenarios moved closer into being a **science-policy boundary object** compared to IS92 (and SA90). Based on peer-reviewed criticism of North-South income assumptions and an IPCC review (Alcamo et al., 1995a). Via IPCC intergovernmental panel sessions, it was decided that

1) the new series should be supported by a wider range of integrated assessment models (IAMs) and disciplines, and allowing issues related to policy questions.
2) the SRES developments involved a broad team of experts from various world regions (rather than a small technical modelers team, as in the SA90 and IS92)
3) It was further discussed if IAMs could become a standard methodology to integrate science into policy (IPCC, 1996, 1995a).

For the first time, the terms of reference set by the IPCC via intergovernmental discussions did not only put boundaries on the technical aspects of the scenario development (as for IS92) but also the development process. Inspired by the global inequality presented by the Indian scientist Jyoti Parikh (1992a) and based on the IPCC scenario evaluation of the IS92 (Alcamo et al., 1995a), the session agreed on widening the author team. Thus, the SRES development involved a broad writing team of experts from various regions rather than a small technical modelers team, including developing and developed region researchers with local expertise and modeling teams (IPCC, 1996). Emissions drivers other than energy technologies, like economic drivers, got more attention than previously. According to interviews, this was additionally a result of economists got more involved (interviews).

According to previous mandates the socioeconomic storylines neither included population policies nor climate mitigation policies (Nakicenovic and Swart, 2000a). Only seven years after the SRES and fifteen after the IS92 publications, researchers started to criticize the non-intervention nature of the scenario sets, as political considerations and intergovernmental trade-offs (Girod et al., 2009) were limiting development of scientific knowledge (Girod et al., 2009; Schenk and Lensink, 2007).
Despite the mandate low emissions scenarios were included in both the IS92 and the SRES. IS92c assumed low economic and primary energy growth, as well as a major shift in the energy mix towards renewables. The SRES-B1-family, describing global sustainable development, quantified an emissions pathway with low emissions as a result of non-climate environmental policies. As such, reduced emissions of GHGs were considered as a possible side effect of environmental policies and technological advances (Alcamo et al., 1995b; Nakicenovic and Swart, 2000a). The latter is exemplified in the A1T low-emission scenario.
Despite excluding policy assumption, during IPCC sessions, it was agreed that modeling teams (beyond the SRES team) were requested to develop policy scenarios for assessments in AR3 (IPCC, 1996), which several modeling groups did (Morita and Robinson, 2001; Raskin et al., 2005). In 2003, the IPCC panel decided to use both SRES (Nakicenovic and Swart, 2000a) and post-SRES scenarios (Hanaoka et al., 2006; Nakicenovic et al., 2003) for AR4 based on similar socioeconomic assumptions (R. Pielke et al., 2008). IPCC assessments evaluated the environmental and climatic consequences of "intervention" futures published in the literature and the feasibility and costs of mitigating GHGs from regions and sectors, which were not incorporated in the SA90, IS92, and SRES (IPCC, 2001e). Preparations for the fourth scenario generation identified new needs to describe emissions reductions for different countries and regions (IPCC, 2007a, 2005d).

Developments and characteristics
Via quantifications from six modeling groups, the SRES highlights interdependency between demographic change, social and economic development, and direction of technological advances (Nakicenovic and Swart, 2000a). Specific economic drivers got more attention (Nakicenovic and Swart, 2000a), compared to SA90 and IS92, which focused on energy technologies and just involved low-high economic growth variants (IPCC, 1990b; Nakicenovic and Swart, 2000a; Pepper et al., 1992). As such the economic assumptions have advanced over time from the SA90 to the SRES. For example, in the IS92 low and high economic growth resulted in low and high emissions output, respectively. In the SRES, high economic growth in A1T (technology transition) and B1, results in low emissions output.

For the first time the scenarios were based on narratives or storylines rather than the simpler assumptions expressed in the SA90 and IS92. The socioeconomic scenarios interpreted alternative quantitative futures with no-policy assumptions.

Box SI- 4. SRES emission scenarios: four marker and two illustrative scenarios

The four narrative families are labeled along two orthogonal axes: (1-2) Global vs. Regional and (A-B) Economic vs. Environmental.

This resulted in four marker scenarios and additionally 2 illustrative scenarios from the A1 rapid economic growth scenario family (Additionally, 34 variations based on the four narratives were published):

A1-family: rapid or high economic growth and global convergence (between global South and North) (Nakicenovic and Swart, 2000a). Scenario A1 was represented by A1B

- **A1FI**: Fossil fuel intensive (marker)
- **A1B**: Balanced energy (fossil fuel and renewables/biomass/nuclear)
- **A1T**: Technology transition towards renewables/biomass/nuclear.
  A1T could be categorized as both a rapid economic growth narrative, since GDP growth is high. But also, as a global-sustainability/low-emissions scenario since cumulative emissions are low.

A2: Somehow exemplifies a continuation of historical developments and referred to as a dynamics-as-usual scenario (Riahi and Roehrl, 2000) with continued economic growth based on fossil fuels, population growth and inequality between global North and South (Nakicenovic and Swart, 2000a).

B1: Global sustainability and low emissions via environmental policies. Global convergence.

B2: Regional sustainability based on increasing environmental policies in high-income countries. Assumes moderate technology innovation in high-income regions and quantifies global medium-slow emissions growth throughout the century.

The series comprises a high uncertainty range of future GHG emissions, similar to the IS92. It ranges from low levels (B1, A1T) to very high levels (A2, A1FI) in 2100 (Nakicenovic and Swart, 2000a). The SRES highlights the interdependency between demographic change, social, and economic development, as well as the direction of technological advances, as the major driving forces of future emissions (Nakicenovic and Swart, 2000a). Each of the four scenario families is built on a set of (qualitative) assumptions and GDP projections that form a coherent storyline. The SRES authors attempted to combine them based on their interdependency (Grübler and Nakicenovic, 2001).

The fourth generation: SSP-RCP-SSA framework (Developed 2006-2019)

RCP/SSP scenarios were designed as a new framework utilized to design scenarios that combine socioeconomic and technological development. They are inspired by the SRES (van Vuuren and Carter, 2014), aiming to be used for multiple research communities, exploring the future interactions between human societies and the natural environments during from present till 2100 (Fujimori et al., 2017). They were initially described in Moss et al. (2010a).
The framework is a scenario matrix architecture. It combines three types of scenarios and modeling. The **Shared Socioeconomic Pathways** (SSPs) describe and quantify five different future worlds with different societal developments (O'Neill et al., 2017; Riahi et al., 2017). The SSP worlds are coupled with the **Representative Concentration Pathways** (RCPs), which express future climate radiative forcing (RF) outcomes by 2100 (van Vuuren et al., 2011a). Additionally, the SSPs are coupled to the **Shared Policy Assumptions** (SPA) that describe adaptation and mitigation policy and international cooperation as either fragmented or various (Fujimori et al., 2017; Kriegler et al., 2014; van Vuuren et al., 2014b).

The SSP-RCP structure standardizes all socioeconomic assumptions (e.g., population, gross domestic product, and poverty, among others) across modeled representations of each scenario. It additionally allows for more nuanced investigation of the variety of pathways by which climate outcomes can be reached (Gidden et al., 2019c).

Reflections

The RCPs were “predefined” as starting points for the integrated modelers. The SSPs which were developed outside IPCC can be considered to some extent as a combination of backcasting and forecasting (however, projections without likelihoods attached) within the range constrained by the RCPs, and could be given names (like sustainability and inequality) different from the earlier sets (letters and numbers). As to backcasting, the interviewees of the thesis stressed that it was difficult in an IPCC context for a long time because the agreement would have to be reached as to the (un-)desirable endpoints, a highly politically charged issue.

The Representative Concentration Pathways
As preparations for the Fifth Assessment Report (AR5) from the Intergovernmental Panel on Climate Change (IPCC) researchers developed four Representative Concentration Pathways for what might happen into greenhouse gasses and global warming by 2100 (IPCC, 2014c, 2007a; Moss et al., 2010; van Vuuren et al., 2011a). The lowest describe a world where global warming will most likely be kept below 2 °C by 2100 relative to 1850-1900 average (IPCC, 2014c), represented by RCP2.6 (van Vuuren et al., 2011a). Nations later pledged to reach this goal under the Paris Agreement in 2015 (UNFCCC/COP, 2015b).

The RCPs originally comprised four abstract emissions pathways, developed to explore a wide range of possible climate futures, the RCP4.5, RCP6, and RCP8.5 could all represent baselines (i.e., medium-low, medium, and high emission futures), while RCP2.6 is a mitigation scenario, i.e., implying climate policy (van Vuuren et al., 2011a). They represent different radiative forcing levels by 2100. The emission trajectories are partly inspired by the SRES. The RCPs were finished in time to be used in the IPCC Fifth Assessment Reports (IPCC, 2014c). The RCPs are the product of a collaboration between integrated assessment modelers, climate modelers, terrestrial ecosystem modelers and emission inventory experts. The collaboration resulted in a comprehensive dataset of external forcings for use by climate models (GHG concentrations, land use change maps etc.) with high spatial and sectoral resolutions for the period extending to 2100.

The shared Socioeconomic Pathways (SSPs)
The SSPs were developed over a series of meetings and workshops from 2010 and published in 2017 (Riahi et al., 2017). They describe alternative socio-economic developments that may influence future GHG emissions. The series comprises five narratives partly inspired by the SRES. They were designed to span a range of futures in terms of the socioeconomic challenges they imply for mitigating and adapting to climate change (Rao et al., 2017).
The SSP baselines (SSP-BLs) describe five different ways in which the world might evolve in the absence of climate. The SSPs describe different narratives, including model quantifications, which span potential futures of green defined by the SSP1 (van Vuuren et al., 2017b) or fossil-fueled growth, SSP5 (Kriegler et al., 2017a), high inequality between or within countries described as “growing nationalism or regional rivalry” in the SSP3 (Fujimori et al., 2017) and as “highly unequal investments in human capital“, with diversity in economic growth, adaptation and mitigation efforts between high-income and low-income regions in SSP4 (Calvin et al., 2017), and the SSP2 “middle-of-the-road” scenario (Fricko et al., 2017). Six integrated assessment models were used to quantify these five SSPs (Fujimori et al., 2017). The main emissions drivers across the SSPs are growth in population over the 21st century and increase in global GDP. The SSPs are quantified in terms of energy, land-use change, and emission pathways for both no-climate-policy reference scenarios (SSP baselines) and mitigation scenarios (several of the SSP-RCP combinations) some of which follow similar radiative forcing pathways as the representative concentration pathways (RCPs) assessed in AR5 WGI, while some explore additional levels of mitigation.

For each SSP, a number of different RF targets can be met depending on policies implemented, either locally or globally, over the course of the century (Riahi et al., 2017), and how different levels of climate change mitigation could be achieved when the mitigation targets of RCPs are combined with the SSPs.

The Shared Policy Assumptions
The SSP-RCP scenario framework facilitates the coupling of multiple socioeconomic reference pathways (SSP baselines) with radiative forcing (and temperature) projections by 2100. The latter represent climate model products via expressed as the representative concentration pathways (RCPs). The scenario matrix architecture includes a third dimension: the Shared Policy Assumptions (SPAs). They capture key policy attributes, like mitigation and adaptation policy goals, instruments, and obstacles of measures (Kriegler, 2014).

Assumptions about climate policy play a key role in the SSP-RCP framework, linking socioeconomic futures with radiative forcing and climate outcomes (Kriegler et al., 2014; O'Neill et al., 2020). Five out of seven scenarios express policy (Gidden et al., 2019a). The shared climate policy assumptions (SPA) introduce an important additional dimension to the SSP-RCP-SPA scenario matrix, describing key policy characteristics, like targets, instruments, and complications of mitigation (and adaptation) actions (Kriegler et al., 2014).
The various SSP models may interpretate SPA differently. One model defines policy assumptions from SPA0 to SPA5. The ideal situation (SPA0) is described as a World with total mitigation control where all mitigation begins immediately from 2015 with regions and sectors work cooperatively to reduce emissions. The remaining policy assumptions are worse describing limited participation of either sectors or regions. SPA1 considers 2020's emissions constraints consistent with Cancun pledges, however including a relatively high carbon price. SPA2-5 expressed gradually lower carbon prices and mitigation controls and more and more fragmented participation. The exogenous emissions pathways are adjusted to meet the RCP forcing target (Fujimori et al., 2017).
The long-term scenarios informing IPCC assessments are based on long-term assumptions. Thus, they differ from the short-term policy scenarios emerging from around 2010 (UNEP, 2010). These origins from various institutions and assess the plausible effect of current national policies and Paris pledges (CAT, 2021b; UNEP, 2021b) and the scenarios of the International Energy Agency (IEA) that via energy technology and policy perspectives explore the efforts needed to reduce carbon dioxide emissions by 2050 (IEA, 2021b). The CAT and UNEP short-term scenarios provide more detail on national policies and strategies.

The SSP-RCP combinations
Because the SSPs are more complex (including socioeconomic narratives) the development process was longer than the RCPs. The SSP-RCP combinations were first published in 2016 (O'Neill et al., 2016) and used in the most recent round of climate modeling, the Coupled Model Intercomparison Project version 6 (CMIP6) - climate model experiments which use a variety of emissions scenarios as input, which are related to socioeconomic scenarios, notably SSPs for the last phases (CMIP5 and 6). Since about 2019/2020 the emissions quantifications in SSP CMIP6 (nine selected SSP-RCP combinations) have started to inform scientific research and literature (e.g., Carvalho et al., 2020) informing the 6th IPCC Assessment Cycle planned published in 2021/2022 (IPCC, 2018c).

As mentioned above, the RCPs originally comprised four abstract emissions pathways.

The forcings pathways not covered by the original RCPs (CMIP5)(van Vuuren et al., 2011a) are reaching 7.0, 3.4, and below 2.6(1.9) Wm^{-2} in 2100. 1.9 Wm^{-2} was chosen to informing understanding of the 1.5 ∘C goal in the Paris Agreement(O'Neill et al., 2016), while SSP4-3.4 explore the space between warming below 2 °C (SSP1-2.6) and around 3 °C (SSP2-4.5) by 2100. The baselines comprise a worst case (SSP5-8.5) and medium-high (SSP3-7.0 (similar to SSP3-BL)) no-policy scenario. The overshoot-scenario SSP5-3.4OS follow SSP5-8.5 till 2040 and thereafter declines depending highly on negative-emissions, while the experimental SSP3-lowNTCF explore forcing around 6.3 Wm^{-2} assuming near-term climate forcing (Gidden et al., 2019c).

SSP-RCP combinations were used in IPCC reports such as the Special Report on Global Warming of 1.5°C to assess different scenarios and AR6. They are also attended to ensure consistency in analyses across the scientific community, e.g., represented by the three IPCC WGs. For instance, a core sub-set of five scenarios based on SSP-RCP combinations was prescribed by a modeling intercomparison project (MIP) called ScenariosMIP to the climate modeling community for consistent assessment of climate simulations. Those five scenarios were evaluated in the AR6 WG I report (IPCC, 2021). The further development of the SSP-RCP framework is crucial to support the consistent use of climate and societal assumptions in future analysis (IPCC, 2023b).

SI 2: Scenario Critiques (Chapter 3)

Supplementary information for Chapter 3: IPCC emission scenarios: How did critiques affect their quality and relevance 1990–2022?

Download Word document (491KB), Supplementary data 1

Download spreadsheet (182KB), Supplementary data 2 (list of reviewed emission scenario critiques (peer-reviewed and grey literature)

Key Critiques and Responses

Not all arguments raised in the peer-reviewed literature were addressed formally by the IPCC or IPCC authors. Several scenario critiques, like income convergence, were discussed in IPCC sessions (IPCC, 2006b, 1996) and expert meetings (IPCC, 2005c), while others, like economic metrics and probabilities, were analyzed in IPCC ARs (IPCC, 2014b, 2007b)). Because of the nature of IPCC, delegates at an IPCC session agreed that experts, rather than IPCC, should publish responses in peer-reviewed journals (IPCC, 2003).

Table SI- 0-1 summarizes some main arguments and broader debates from the scenario assessments. Arguments that were followed up and discussed by other peer-reviewed are categorized as debates.

Table SI- 0-1. Overview of key debates and responses grouped by topic.

Topic	Scenario	Critique	Scenario series targeted	Response
Assumptions				
Income convergence	1992-1996	South-North injustice	IS292 (Parikh, 1992a)	Convergence pathways (Alcamo et al., 1995a; IPCC, 1996) included in SRES and SSPs
	2003-2006	Economic metrics (IPCC skepticism)	SRES (Castles and Henderson, 2003b)	PPP accepted; GDP metric did not affect emissions projections (Nakicenovic et al., 2003)
Negative emissions (NETs)	2014-2020	Feasibility of low-end scenarios	RCP1.9, 2.6, SR1.5, (Anderson, 2015; Fuss et al., 2014)	In case of slow policy actions, NETs are necessary to reach the Paris Goals (van Vuuren et al., 2017a)
Energy assumptions	2008	Too optimistic energy advances Aim: feasibility of low-end scenarios without policy actions	SRES (R. Pielke et al., 2008; Richels et al., 2008; Romm, 2008; Smil, 2008)	Good evaluation practice requires distinction between long-term and short-term trends (van Vuuren et al., 2010)
	1997-1998; 2008-2017	Depletion vs. demand Aim: feasibility of high-end scenarios	SRES-A1FI/RCP8.5 (Brecha, 2008; Rogner, 1997; Wang et al., 2017)	No response. Found unrealistic by developers (conference) (O'Neill et al., 2019)
Range of Emission Scenarios				
Emission ranges	2007-2013	Emission ranges: Are high-end scenarios too low?	SRES/RCP(R. Pielke et al., 2008; Raupach et al., 2007)	Good practice requires a distinction between long-term and short-term trends (van Vuuren et al., 2010)
	2019-	RCP8.5 is too high (unlikely)	RCP8.5, SSP-RCP	Low-possibility high-impact scenarios are still relevant (J. S. T. Pedersen et al., 2020)

Missing scenarios	2007-2009	Intervention scenarios excluded politically, but are scientifically justified	IS92, SRES (Girod et al., 2009; Schenk and Lensink, 2007)	Policy assumptions included in SSP-RCP framework
	2007-2012	Conflict-impact		Extensions on violent conflict (O'Neill et al., 2020)
	2000-	Sustainability: Degrowth, biodiversity, SDGs, oceans, etc. non-continuity	SRES, SSPs(Otero et al., 2020; Raskin, 2005)	Update narratives to inform analyses on key international goals beyond Paris Agreement (O'Neill et al., 2020)
	2006-	Solar radiation modification (SRM)	SRES, RCP, SR1.5 (Reynolds, 2021; Wigley, 2006)	SRM is untested with ethical implications (IPCC, 2018a)
Methodological Issues				
Process	1998-2007	IPCC monopoly of knowledge Too-much in-crowd Multiple topics analyzes (IPCC skeptic)	IS92, SRES, AR1,2,3(Castles and Henderson, 2003b; Gray, 1998)	No direct response
Method	2007-2011	Scenarios assessed as forecasts (IPCC skeptic)	SRES, AR4(Green and Armstrong, 2007; Idso et al., 2013)	2007-nature-web blog (Trenberth, 2007)
	2008-	Improve internal consistency	SRES (Schweizer and Kriegler, 2012)	CBI method applied to SSPs (Schweizer and O'Neill, 2014)
Transparency	2009-	IAMs are cloudy		SR1.5 database (IPCC, 2017b),
Resolution	2000-2004	Insufficient resolution for impact assessment (scenario database)	SRES (Arnell et al., 2004; Parry, 2002)	Improved databases (Dellink et al., 2017; Gaffin et al., 2004)
	2007-	Connecting scenarios across scales via stakeholder involvement	SRES, SSPs(Biggs et al., 2007; Kok et al., 2007)	Regional extensions are valuable (O'Neill et al., 2020)
Policy relevance & implications				
Policy relevance	1991	Extend projections beyond 2100	SA90(Cline, 1991)	No response; Implemented in RCP/SSP
Probability	2000-2002, 2007	Policy relevance Probability	IS92, SRES (Allen et al., 2000; Webster et al., 2002a)	Probabilities from natural sciences should not be imposed on the social sciences (Grübler and Nakicenovic, 2001). Comparative analyses (in AR4 (IPCC, 2007b); Frequency distributions in AR5 (IPCC, 2014b)
	2020	Best-guess Aim: Improve decision-making	RCP8.5/SSP(Allen et al., 2000; Webster et al., 2002a)	

See the full list of assessed critiques in the Supplementary Material of Pedersen et al. (2022) (Download spreadsheet (182KB)).

Grey literature sources comprise reports (Webster et al., 2008), books (Bolin, 2007a), public media (Economist, 2003b) websites (Le Quéré et al., 2010). We recognize that the inventories of literate sources are not complete. We additionally consulted the primary scenario literature (e.g., Leggett et al., 1992) and IPCC materials, e.g., IPCC session reports (https://www.ipcc.ch/documentation/ipcc-wg/), executive meeting reports (https://www.ipcc.ch/documentation/executive-committee/), background papers (IPCC, 2018d)) to explore scenario developments, development in scenario exercises and attached considerations. These were included as context to analyze the contexts and outreach of scenario critiques over time.

Table SI- 0-2 summarizes the political context during scenario developments, the series' stated objective, and some key questions they generated scientifically and politically (i.e., critique paper examples). The table does not comprise a complete selection of critiques.

Table SI- 0-2. Context of the four generations of emission scenario generations, their objectives, and the questions they generated.

Scenario series	**Political Context**	**Scenario Objectives**	**Breeding of new science questions**		
			Substance (Assumption or range)	Method	Policy
SA90 (1989-1990)	IPCC establishment (1989): Mainly Environmental Ministry Delegates. Discourse: Climate change is a real risk. Let's explore policy options (IPCC, 1990a; Rotmans, 1990)	SA90 explores future emissions and plausible mitigation. Informing the three IPCC WGs (IPCC, 1990a).	IPCC session: Include multiple pathways, increase high-end emissions range (IPCC, 1991) Scientific questions: Extend projections beyond 2100	Exclude best guess/ business-as-usual scenario	Exclude Policy-assumptions
IS92 (1991-1992)	UNFCC establishment (1992): More Financial Ministry Delegates. A counter-discourse questions the reality of climate change, the desirability and costs of mitigation.	SA90-update; explores non-policy scenarios; increased emissions range (Leggett et al., 1992).	IS92a projects continued global inequality (Parikh, 1992a) It is relevant to consider UNFCCC policy formulations (Alcamo et al., 1995a)	Need for more diverse author team/worldviews and several IAMs (Alcamo et al., 1995a)	
SRES (1996-1999)	More economists and low-income country experts involved in scenario developments. Historical context: Some countries still don't accept the reality of climate change and needs for mitigation/adaptation.	Respond to IS92's weaknesses identified in IPCC 1995 scenario evaluation (Alcamo et al., 1995a) Based on narratives No policy assumptions; Kyoto emissions targets not included	Increased understanding of driving forces (Webster et al., 2002a) New economic metrics (PPP) to compare actual welfare across regions (Castles and Henderson, 2003b) Climate impacts make A2 impossible (Conference)	IPCC in-crowd critique (Castles and Henderson, 2003b) Resolution too low (Arnell et al., 2004) Multi-scale scenarios/Involve local stakeholders (Kok et al., 2007) IAMs are black boxes (Jancovici, 2007)/ Little socioeconomic info (conference)	Likelihood may improve policy relevance (Allen et al., 2000)

		(Nakicenovic and Swart, 2000a).	Emissions too low (Castles and Henderson, 2003a) or too high (Raupach et al., 2007) Too optimistic energy assumptions (R. Pielke et al., 2008) Energy assumptions, A1FI too high? (Höök, 2011) Missing conflict scenarios (Nordås and Gleditsch, 2007) Continuity biased/ missing transformation scenarios (Raskin et al., 2002)	Too long development-time (conference) Intergovernmental: IPCC should facilitate not develop knowledge; include non-governmental institutions (IPCC, 2005a)	
RCP (2005-2011)	Copenhagen Accord: climate change is a global challenge and "strong political" will to act to stay below 2 °C (UNFCCC/COP, 2009).	Facilitated (not developed) by IPCC. Radiative forcing levels by 2100 (and 2300). Few socioeconomic assumptions; including policy (van Vuuren et al., 2011a)	Mitigation assumption not feasible/NETs RCP2.6 too low? (Fuss et al., 2014) RCP8.5 too low (Christensen et al., 2018; Peters et al., 2013)		(NETs distract real policy actions) RCP8.5 is unlikely & overused in the literature (Hausfather and Peters, 2020)
SSP-RCP (2005-2019)	Paris Agreement: national pledges and adjusted target (<1.5 °C) (UNFCCC/COP, 2015a).	SSP-RCP: Five socioeconomic narratives (Riahi et al., 2017) combined with radiative forcing levels (Gidden et al., 2019a) exploring challenges for mitigating and adapting by 2100	Missing local-sustainability scenario (Conference: O'Neill et al., 2019) Missing degrowth scenarios (Raskin and Swart, 2020) More diverse SD scenarios Slow renewable projections (Pedersen et al., 2021)	Involve/support non-state mitigation stakeholders (Weber et al., 2018b)	Too complex for national analyzes (Barata et al., 2018; O'Neill et al., 2019)
SP1.5 (2017-2018)	UNFCCC request for <1.5°C pathways (Kriegler et al., 2017b)	Explore 1.5 °C goals	Missing Solar Radiation Management (Reynolds, 2021)		Public media Governments with high fossil fuels dependency: "mitigation actions not accepted" (Slezak, 2018)

Note: Critiques addressed at conferences and not found in the literature are marked (conference).

The use of scenarios in IPCC Assessment Reports & Working Groups

Table SI- 0-3 illustrates when the various emission scenarios (SA90, IS92, SRES, RCP) were included in the successive IPCC assessment reports and the Working Groups (WGs). SA90 was included in analyses for all three working groups in the first assessment report (1990). The use of IS92 in the scenario-based literature that was included in WG1 and WG3 ended with AR2 (1995), while it was used in WG2 in three successive assessment reports: AR2, TAR (1995), and AR4 (2001). SRES-based analyses did (almost) not make it into impact assessment until AR4.

Table SI- 0-3. The inclusion of scenarios or scenario-based literature using the various emission scenarios in the various IPCC assessment reports.
Data sources: IPCC Assessments Reports (https://www.ipcc.ch/reports/)

IPCC Assessment Report Year	Working Group	SA90	IS92	SRES	RCPs/SSPs
1990 1st Assessment Report	WG3	1			
	WG1	1			
	WG2	1			
1992-assessments	WG3		1		
	WG1		1		
	WG2		1		
1995 2nd Assessment Report	WG3		1		
	WG1		1		
	WG2		1		
2001 3rd Assessment Report	WG3			1	
	WG1			1	
	WG2		1	1	
2007 4th Assessment Report	WG3			1	
	WG1			1	
	WG2		1	1	
2014 5th Assessment Report	WG3				1
2013	WG1				1
2014	WG2			1	1
2021 6th Assessment Report	WG3				1
	WG1				1
	WG2				1

SI 3: Databases: scenario and emissions data (Chapters 4 and 5)

Supplementary information for Chapters 4 and 5.

This chapter's SI materials are available at https://www.nature.com/articles/s43247-020-00045-y#Sec7 (Chapter 5)

The scenario data was obtained from the following sources

- SA90 (IPCC, 1990a, 1990d): https://www.ipcc.ch/site/assets/uploads/2018/03/ipcc_far_wg_III_chapter_02.pdf; data for model variants were obtained from "Appendix. Report of the Expert Group on Emissions Scenarios (RSWG Steering Committee, Task A)"
- IS92 (Leggett et al., 1992; Pepper et al., 1992): https://sedac.ciesin.columbia.edu/ddc/is92/
- SRES (Nakicenovic and Swart, 2000a): http://sres.ciesin.org/final_data.html
- RCP (van Vuuren et al., 2011a): https://tntcat.iiasa.ac.at/RcpDb/dsd?Action=htmlpage&page=about
- SSP (Riahi et al., 2017): https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=10

The historical emissions data was obtained from the following sources:

- Global Carbon Project. (2019). Supplemental data of Global Carbon Budget 2019(GCP, 2019): https://www.icos-cp.eu/global-carbon-budget-2019
- Global: 2019 Global Budget v1.0 (metadata). Carbon dioxide (CO_2) emissions from fossil-fuel combustion, cement production, and gas flaring.
- Regional: 2019 National Emissions v1.0 (metadata). Production-based CO_2 emissions (Sheet: "Fossil fuels and cement production emissions by country (territorial, GCB)"); Consumption-based CO_2 emissions (Sheet: "Consumption emissions (GCB)").

The historical emissions driver data was obtained from the following databases:

- Primary energy
  - BP primary energy consumption 1965-2018 https://www.bp.com/content/dam/bp/en/corporate/pdf/energy-economics/statistical-review/bp-stats-review-2018-full-report.pdf
  - IEA primary energy supply 1990-2017: https://www.iea.org/statistics
  - IEA primary energy supply 1971-2016: http://wds.iea.org/WDS/
- GDP
  - World bank (MER, constant 2010 US$): https://data.worldbank.org/indicator/NY.GDP.MKTP.PP.KD
  - World Bank (PPP, constant 2011 international $): https://data.worldbank.org/indicator/NY.GDP.MKTP.KD
- Population
  - World Bank data: https://data.worldbank.org/indicator/SP.POP.TOTL
  - United Nations Statistic Division: http://data.un.org/Default.aspx

The historical policy scenario data was obtained from the following databases:

- United Nations Environmental Programme (UNEP) Emission gap reports: https://www.unenvironment.org/resources/emissions-gap-report-2019

- Climate Action Tracker (2020): https://climateactiontracker.org/countries/eu/current-policy-projections/

Websites accessed between March 2018 and October 2021.

SI 4: Scenario categorization for cross comparisons (Chapters 4 and 5)

Supplementary information for Chapters 4 and 5

Part of this chapter's SI is available at at https://www.nature.com/articles/s43247-020-00045-y#Sec7 (Chapter 5). SI materials for Chapter 4 is not open access available online.

Categorizing scenarios by cumulative emissions (quantifications)

The individual scenarios can be grouped into four categories based on "cumulative emissions 1990-2100" categories as defined by the IPCC (IPCC, 2000a): low (0-1099 GtC) (green), medium-low (1100-1429 GtC) (Aquamarine), medium-high (1430-1799 GtC) (orange), and high emissions (>1800 GtC) (blue) (J. T. S. Pedersen et al., 2020).

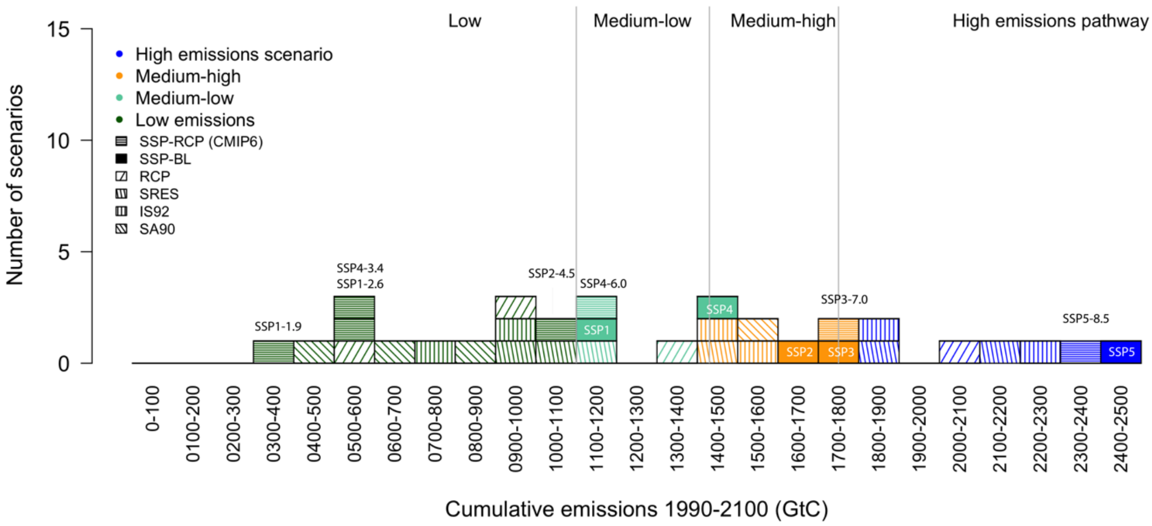


Figure SI- 2. Total global cumulative CO_2 emissions (GtC) from 1990 to 2100 by scenario. Total CO_2 from Land-use, industry, and fossil fuels. The Scenarios are illustrated via a histogram of their distribution by scenario groups high-emissions, medium-high, medium-low, and low-emissions scenarios defined by the vertical lines. Panel A: SA90, IS92, SRES marker/illustrative, and SSP-Baseline scenarios by scenario families – 19 baselines & 2 mitigation scenarios. Panel B: histogram of the distribution of SSP baseline and mitigation scenarios by SSP scenario groups – 5 baseline & 21 mitigation scenarios. Regarding the SSPs, Panel A shows the ranges of cumulative emissions for the SSP baseline scenarios and Panel B the ranges of the SSPs when they are linked with the RCP forcing levels (1.9, 2.6, 3.4, 4.5, and 6.0) according to Phase 5 of the Climate Model Intercomparison Project (CMIP5). Data sources: IPCC AR1(IPCC, 1990a) for SA90 and scenario databases for IS92, SRES, RCP, and SSP. High to low emissions categories are defined by IPCC (IPCC, 2000a).

The short-term growth rates of the scenarios do not necessarily reflect the long-term emission trajectory (e.g., several scenarios have a peak-and-decline-shaped trajectory, such as SA90-B, IS92c, SRES-A1B/T/B1, RCP4.5, SSP1, and SSP4). Table SI- 0-4 presents the emission scenarios informing IPCC assessment reports 1990-2021 grouped by cumulative total CO_2 emissions. We focus on "marker scenarios" (e.g., SSP baseline (SSP-BL) and SRES marker/illustrative scenarios).

Table SI- 0-4. The emission scenario generations grouped by cumulative emissions pathways. Scenario series informing assessments for IPCC Assessment Reports 1990-2022. Cumulative emissions 1990-2100 categories as defined by the IPCC (IPCC, 2000a): low (0-1099 GtC), medium-low (1100-1429 GtC), medium-high (1430-1799 GtC), and high emissions (1800- GtC). The categorization of cumulative emissions is based on values introduced in IPCC (2000a). The emissions estimates are extracted from the scenario databases: IPCC (1990a), Pepper et al. (1992), Nakicenovic & Swart (2000a), Riahi et al. (2017), van Vuuren (2011a), Gidden et al. (2019c).

Emission Pathway Cumulative CO_2 1990-2100	**SCENARIO SERIES/GENERATIONS**					
	SA90	**IS92**	**SRES**	**RCP**	**SSP**	**SSP-RCP**
Low emission pathways 0-1099 Gt C	SA90-D: "Acc. Policies" SA90-C "Control policies" SA90-B "Energy efficiency"	IS92c IS92d	B1: Global SD* A1T: Energy transition	RCP2.6 RCP4.5		SSP1-1.9 (1.5C target)** SSP1-2.6 (2C target) SSP2-4.5 (moderate mitigation) SSP4-3.4 SSP5-3.4-OS*** (mitigation beyond 2040)
Medium-low emission pathways 1100-1449 Gt C			B2: local solutions	RCP6.0	SSP1: Global Sustainability SSP4: A divided road	SSP4-6.0 (weak mitigation)
Medium-high emission pathways 1450-1799 Gt C	SA90-A: High emissions **(BaU)**	IS92a IS92b	A1B: Balanced energy		SSP2: Middle of the road SSP3: Regional rivalry	SSP3-7.0 (baseline) SSP3-LowNTCF***
High emission pathways >1800 Gt C		IS92e IS92f	A1FI: Fossil intensive A2: Self-reliance	RCP8.5	SSP5: Fossil-fuel **growth**	SSP5-8.5 (baseline)

* Sustainable Development (SD)
**SSP1-1.9 provides the lowest estimate of future forcing matching the most ambitious goals of the Paris Agreement (pursuing efforts to limit the global average temperature increase to 1.5C above pre-industrial levels). SSP1-2.6 represents efforts to limit the global average temperature increase to 2C above pre-industrial levels (1850-1900).
*** Experimental scenarios: SSP5-3.4-OS (OS: Overshoot Scenario = emissions are above Paris temperature targets) and SSP3-LowNTCF (NTCF: near-term climate forcing)

IS92a and IS92b represented updates of SA90-A (Leggett et al., 1992). IS92a was not labeled BaU but followed similar assumptions and a medium-high emission pathway similar to the later SSP2 “Middle-of-the-road”. The “regional-sustainability” family assumes moderate technology innovation in high-income regions and quantifies global slow emissions growth throughout the century. The “rapid-growth” and “global-sustainability” families generally represent the highest and lowest cumulative emissions pathways, respectively (IPCC, 1990a; Nakicenovic and Swart, 2000a; Pepper et al., 1992; Riahi et al., 2017).
IS92f quantifies high emissions throughout the century based on high population, low economic growth, and slow technological change, similar to SSP3 and A2 (but different from SSP4, assuming continued inequality and energy transition in high-income regions). Although the SSP series do

not have a "regional-sustainability" scenario, SSP4 quantifies a medium-low emissions pathway with a trajectory similar to "global-sustainability" scenarios (peak-and-decline).

Categorizing by narrative families (storylines and assumptions)

We see that insights into future developments have changed over time when comparing the assumptions and storylines across scenario series. This section analyses the representation of scenarios in families with narratives as a way to organize the scenarios across the four series in a broad range of different types of future developments. Afterward, we compare historical developments, emissions, and drivers and finally analyze historical developments with scenarios.

The representation of scenarios in families according to their narratives is a way to organize/categorize the scenarios across the generations. Storylines were developed for the SRES and additionally for the SSPs. The SA90 and IS92 assumptions and quantifications can effectively be related to specific, more extensive narrative descriptions of the later sets. Despite the two earliest generations having more simplified assumptions, we categorize all emission scenarios in five scenario families based on storylines to compare scenarios across all four generations.

Five Main "Scenario families"

Nakicenovic & Swart (2000a) introduced the concept of scenario families and analyzed it further in van Vuuren et al. (2012). Storylines were developed for the SRES and additionally for the SSPs. The first two series, SA90 and IS92, had assumptions for key variables (IPCC, 1990a; Leggett et al., 1992) rather than storylines. However, the SA90 and IS92 quantifications can effectively be related to specific, more extensive narrative descriptions of the later sets. The SA90 and IS92 assumptions and quantifications can effectively be related to specific, more extensive narrative descriptions of the latest sets. Despite the two earliest series having more simplified assumptions, it is possible to categorize emissions scenarios in five scenario families based on storylines to compare scenarios across all four series (Table SI- 0-5).

Table SI- 0-5. Scenarios categorized by narrative families.
Main five storyline families underlying the SA90, IS92, SRES, and SSP-baseline scenario series. Scenarios are additionally classified according to their cumulative total CO_2 emissions trajectory 1990-2100 (low, medium-low, medium-high, high) based on IPCC (2000a). Scenarios with an emissions trajectory different from the general scenarios in their family (grey text) are located twice, and in the family that customarily has similar trajectories (grey text in brackets). The categorization of scenario families is based on van Vuuren et al. (2012), and the categorization of cumulative emissions is based on values introduced in IPCC (2000a). Cumulative emissions pathways are indicated for each scenario (in brackets). From Pedersen et al. (2021).

Scenario Narrative Families	**Scenario generations**			
	SA90	**IS92**	**SRES**	**SSP**
"Global sustainability" (low to medium-low cumulative emissions)*	SA90-C: Control policies (low)* SA90-D: Accelerated policies (low)	IS92c (low)	B1: global solutions (low)	SSP1: SD (medium-low)
"Regional sustainability" (low to medium-low)	SA90-B: OECD energy efficiency (low)	IS92d (low)	B2: local solutions (medium-low)	
"Middle of the road" (medium-high)	SA90-A: High emissions (medium-high)	IS92a IS92b: OECD efficiency (medium-high)		SSP2: Middle of the road (medium-high)
"Regional competition" (medium-high to high)		IS92f (high)	A2: Self-reliance (medium-high)	SSP3: Regional rivalry (medium-high)
				SSP4: A divided road; Regional SD (medium-low)
"Rapid growth" (high to low)		IS92-E (high)	A1FI: Fossil intensive (high) A1B: Balanced energy (medium-high) A1T: Energy transition (low)	SSP5: Fossil-fuel **growth** (high)

*Emissions pathways Cumulative total CO_2 emissions 1990-2100. Total includes land-use change and fossil fuel & industry carbon emissions.

The general storylines of the scenario families do not necessarily reflect the long-term emission trajectory. The global sustainability scenarios have a peak-and-decline-shaped trajectory, where emissions peak during the century and decline towards 2100. Four other scenarios have a peak-and-decline pathway (two SRES rapid-growth, the SA90 regional sustainability, and an SSP regional competition (SSP4)). To make the differences between individual scenario quantifications transparent, I added the cumulative emissions category in brackets to the Table above.
Some scenarios have emissions pathways (cumulative emissions 1990-2100) different from most scenarios in the various families (narratives). SRES-A1B is categorized in the "rapid-growth" family according to its narrative. However, its medium-high emission pathway is similar to the "middle of the road" scenarios. The SSP series doesn't have a "regional sustainability" scenario. However, SSP4-BL quantifies a medium-low emissions pathway and a trajectory with the same shape as global sustainability scenarios and SRES-AT1. It is challenging to allocate A1T in both low and high rows because GDP growth is high, but low with emissions growth. The idea of the modeling teams was explicit to show that low emissions could be low because of either technological

development (SRES-A1T) or structural change (SRES-B1). Thus, they suggested economic growth and increased consumption (A1T) as an alternative pathway to reducing emissions as achieved by technology advances, stimulated by environment-friendly innovation policies rather than climate policies. This reflects two dominant and opposing views on how emissions can or should be lowered up to today.

Therefore, the allocation of some scenarios (i.e., A1B, A1T, SSP4) according to emissions quantifications goes across the scenario narrative family category (dependent on the selected decisive scenario element). For example, A1T could be categorized in the "rapid-growth" family because GDP growth is high. Also, in the "global-sustainability/low-emissions" category since cumulative emissions are low.

None of the series describe degrowth or zero-growth scenarios. However, also such a scenario would be plausible, e.g., as a result of externalities of the current economic system, such as material scarcity, increasing climate impacts, ecosystem breakdown, or finance system instability (Costanza, 2014; Meadows et al., 1972; Ngo et al., 2019) as well as a political choice to address such risks (Ward et al., 2016). However, in an IPCC context, this was considered to have a small likelihood and low political acceptability at the time (based on interviews. See Pedersen et al. (2021)).

The assumptions underlying the storylines

Developing the SA90 scenarios in the late 1980s, modelers made assumptions on what would be possible future socioeconomic developments and associated GHG emissions (Bolin, 2007a; IPCC, 1990a). The developers provided no narratives other than lower, average, and higher growth and different levels of climate policy. This involved one baseline, called both "High Emissions" and "Business-as-Usual (BaU)" (assuming few or no steps taken to limit GHG emissions); one "low emissions", and two 'intervention' scenarios (including mitigation policies). No intervention scenarios were included in IS92 and SRES. The lowest IS92-scenario, IS92c, had emission levels and assumptions comparable to an intervention scenario that was argued to be the side effect of non-climate/environmental policies (Alcamo et al. 1995) and global sustainability SRES-B1. Elaboration of the scenarios at the regional level was less well developed (IPCC, 1990a). Thus global (in-)equality considerations or convergence assumptions were less explicit. Inequality later became one of the governing principles of the SRES and SSP assumptions (Nakicenovic and Swart, 2000b; O'Neill et al., 2014).

Box SI- 5. Description of the five scenario narrative families

Global sustainability scenarios: The scenarios quantify a peak and decline in emissions from about 6 GtC/year in 1990 to a range of 3-7 GtC/year by 2100. They assume a shift in values from economic growth to sustainable development (e.g., climate or environmental policy assumptions). No intervention scenarios (climate policy assumptions) were included in IS92 and SRES. After the SA90s, policy assumptions were excluded via the IPCC mandate for IS92 (IPCC, 1991; Leggett et al., 1992) and SRES (IPCC, 1996; Nakicenovic and Swart, 2000a). Thus, both IS92 and SRES evolved in the absence of climate policy assumptions (Leggett et al., 1992; Nakicenovic and Swart, 2000a). However, low emissions scenarios were included based on other assumptions, such as side effects of non-climate/environmental policies (Alcamo et al. 1995) and technological development (Nakicenovic and Swart, 2000a). Emissions by 2100 range from 3 to 7 GtC/year (Annual growth rates: -0.4 to 0.3%).

Regional sustainability: Scenarios in this family assume moderate technology innovation in high-income regions and quantify global slow emissions growth throughout the century. In these scenarios, emissions will increase to between 10 and 14 GtC/year by 2100 (Annual growth rates: 0.6-0.7%).

Middle-of-the-road: These scenarios follow similar assumptions and medium-high emission pathways. The original Business-as-Usual (BaU) scenario in the SA90 was criticized at IPCC sessions, and thus this label was officially excluded in the successive scenario terminologies (IPCC, 1991). However, this type of scenario was represented in the IS92 via two scenarios (Leggett et al., 1992) and in the SSPs, labeled 'Middle-of-the-road'. The SRES series does not have such a scenario narrative. The scenarios in this family increase from about 6 GtC/year in 1990 to about 20 GtC/year in 2100 (Annual growth rates: 0.8-1.3%).

Regional competition: Generally, these scenarios assume low environmental regulation, high population, weak economic growth, and slow technological change. Three scenarios (SSP3, A2, and IS92f) fit this description best. They project an increase in the range of 22-28 GtC/year by 2100 (Annual growth rates: 1.2-1.7%). One SSP scenario assumes continued global inequality with energy transitions in high-income regions and thus quantifies a peak-and-decline emissions pathway with 12 GtC/year by 2100 (Annual growth rates: 0.7%).

Rapid growth: These scenarios assume rapid economic growth. In most rapid growth scenarios, growth is provided via a fossil-fuel intensive energy sector and quantifies emissions in the range of 30-35 GtC/year by 2100 (Annual growth rates: 1.5-1.8%). As mentioned earlier, two of the SRES rapid-growth quantify high economic growth but medium-high and low cumulative emissions because of various degrees of the energy transition. They quantify annual growth rates in the range of -0.3 to 0.7%.

The storyline focus of the scenario sets has changed over time: from energy mix and efficiency (SA90) to population, income, and fossil fuel resources (IS92), to "regional vs. global" and "economic vs. environmental" (SRES) (Girod et al., 2009). Most recently, there has been a shift to energy system demand and supply characteristics as a function of a set of demographic and economic drivers broader than previous scenarios, providing a more solid basis for complementary mitigation and adaptation analyses with the SSP/RCP (Riahi et al., 2017).
RCP/SSP scenarios were designed as a new framework utilized to design scenarios that combine socioeconomic and technological development. Aimed to be used in multiple research communities, exploring interactions between human societies and the natural environment (Fujimori et al., 2017).
At one end of the emissions range, a family of optimistic scenarios explores worlds in which governments join forces, e.g., through adopting environmental or other sustainable development policies, or by other means, global advances in low-carbon technologies are enforced. At the same time, poverty and inequality are reduced (Global sustainability). Because of their terms of reference, IS92 and SRES explicitly exclude specific climate or greenhouse gas emissions reduction policies. At the other end of the emissions range, scenarios include rapid global economic growth based on fossil fuels and reduced inequality (rapid growth) or examine countries that upgrade their use of cheap fossil fuels, pursuing national economic growth (regional competition).

Some remarks on individual scenarios (alternative choices of categorizations)

According to emissions quantifications, the allocation of some scenarios (i.e., A1B, A1T, SSP4) is more subjective (dependent on the selected decisive scenario element) than most. For example, A1T could be categorized in the "rapid-growth" family because GDP growth is high but also in the "global-sustainability/low-emissions" category if one would focus on the low emissions growth. The idea of the modeling teams was explicit to show that emissions could be low because of either technological development (A1T) or structural change (B1). This reflects two dominant and still important opposing views on how emissions can or should be lowered in the IS92, SRES, and SSP series.

It was argued that IS92b was an intervention scenario because it included policy assumptions related to the Montreal Protocol (Girod et al., 2009). The Montreal Protocol was an international treaty designed to protect the ozone layer (UN, 1989) and not to be considered a climate treaty like the Kyoto Protocol (UNFCCC/COP, 1997) and Paris Agreement (UNFCCC, 2015b). The Montreal Protocol reduced CFC gasses (Chlorofluorocarbons) and does not include climate gasses. However, it had a negative side effect since CFC was substituted with HFCs (Hydrofluorocarbons), which has a strong global warming potential (IPCC, 2014b).

Later the Kigali Amendment, ratified by 72 countries by 2019, aims to reduce the MP substitute gasses HFC, HCFC, and CFC gas emissions. Scientists estimate that the Kigali agreement can reduce temperature change by 0.4 °C by 2100 (McGrath, 2016; Riahi et al., 2017; UNEP, 2016).

The lowest scenarios (IS92c) and global sustainability SRES-B1 had emission levels and assumptions comparable to an intervention scenario argued to be the side effect of non-climate/environmental policies (Alcamo et al., 1995a). The storyline focus of the series has changed from energy mix and efficiency (SA90) to population, income, and fossil fuel resources – with assumptions regarding cost reductions over time, resources, and technological change (IS92), to "regional vs. global" and "economic vs. environmental" (SRES series) (Girod et al., 2009; Pepper et al., 1992) to energy structures and its coupling with more advanced demographic and economic drivers, as well as future implications for mitigation and adaptation (Riahi et al., 2017). Elaboration of the scenarios at the regional level was less well developed (IPCC, 1990a), and thus, global (in-)equality considerations were less explicit. This later became one of the governing principles of the SRES and SSP assumptions (Nakicenovic and Swart, 2000b; O'Neill et al., 2014).

IS92a and IS92b represented updates of SA90-A (Leggett et al., 1992). IS92a was not labeled BaU but followed similar assumptions and a medium-high emission pathway similar to the later SSP2' Middle-of-the-road'.

IS92f quantifies high emissions throughout the century based on high population, low economic growth, and slow technological change, similar to SSP3 and A2 (but different from SSP4, assuming continued inequality and energy transition in high-income regions). Although the SSP series do not have a "regional-sustainability" scenario, SSP4 quantifies a medium-low emissions pathway with a trajectory similar to "global-sustainability" scenarios (peak-and-decline).

The “regional-sustainability” family assumes moderate technology innovation in high-income regions and quantifies global slow emissions growth throughout the century. The “rapid-growth” and “global-sustainability” families generally represent the highest and lowest cumulative emissions pathways, respectively (IPCC, 1990a; Nakicenovic and Swart, 2000a; Pepper et al., 1992; Riahi et al., 2017). lar to “global-sustainability” scenarios (peak-and-decline).

The “regional-sustainability” family assumes moderate technology innovation in high-income regions and quantifies global slow emissions growth throughout the century. The “rapid-growth” and “global-sustainability” families generally represent the highest and lowest cumulative emissions pathways, respectively (IPCC, 1990a; Nakicenovic and Swart, 2000a; Pepper et al., 1992; Riahi et al., 2017).

SI 5: Emission Driver Equations (Chapters 4 and 5)

Supplementary information for Chapters 4 and 5

Part of this chapter's SI is available at at https://www.nature.com/articles/s43247-020-00045-y#Sec7 (Chapter 5). SI materials for Chapter 4 is not open access available online.

Certain complications or barriers are crucial to consider before scenario comparisons:

1. Different models' use causes differences in estimates/projections across scenarios (such as varying starting values). Additionally, indicator components (i.e., GDP) differed between IS92/SRES and SSP databases. *Therefore, growth rates were used for comparisons rather than absolute numbers*.
2. The SSP database does not include historical estimates for primary energy. Thus, the International Energy Agency (IEA) estimates were used to calculate growth rates (see section 0)
3. Different non-OECD/OECD-categories in the IS92/SRES and the SSP databases require recalculation of the historical estimates for according to the IS92/SRES, SSP definitions (see section 0)
4. Energy conversion methods are less emphasized in the
    a. SSP nuclear projections are arguably based on the physical content method (PCM), while IEA data are based on and "converted" via the Partial Substitution Method (PSM). However, IEA nuclear methodology is more complicated (read further in section 0)
    b. IS92 and SRES methodologies are unclear. According to IEA-methodology, the partial substitution method was used for hydro and solar before 2005.
    c. IS92 Biomass estimates were surprisingly low (0EJ) for 1990 (Pepper et al., 1992), compared to contemporary IEA estimates (38EJ) (IEA, 1994) – *no action applied on this matter*.

Growth rates, filtering, sub-periods, and correlations

In the scenario databases, absolute values differ between the different scenario databases and between scenarios in the same series. Several reasons can explain the inter scenario differences, such as the use of multiple models, a variation of indicator components, and the use of backcasting methods (e.g., O'Neill et al., 2017). The SRES and SSP scenarios were developed via multiple models, which may imply the use of different historical datasets by the modeling teams and various indicator components (such as that biomass was not included in "SRES-B2 MESSAGE"). Additionally, GDP currencies differ between IS92/SRES/SSP series and historical records (e.g., US$2005, US$1990) as well as that the indicator component changed in the SSP series (i.e., purchasing power parity) compared to the IS92 and SRES series (i.e., market exchange rates). Thus, the absolute estimates between datasets differ, and growth rates were used for comparisons.

Both historical and projected annual average growth rates were calculated as "Compound annual growth rates".

Equation 1
The Formula for CAGR is:

$$Compound\ annual\ growth\ rate\ (i) = \left(\frac{\mathrm{CO2_{t1}}}{\mathrm{CO2_{t2}}}\right)^{\frac{1}{n}} - 1$$

- i = Compound annual growth rate
- $CO2_{t1}$ = CO_2 estimate beginning of the period
- $CO2_{t2}$ = CO_2 estimate end of the period
- n = number of years for the period

Example: CAGR for CO_2 for IS92a (period: 1990-2020)

$$= \left(\frac{\mathrm{CO2_{2020}}}{\mathrm{CO2_{1990}}}\right)^{\frac{1}{2020-1985}} - 1$$

$$= \left(\frac{10.2}{6.1}\right)^{\frac{1}{2020-1990}} - 1$$

= 1.74%

$$Compound\ average\ annual\ growth\ rate\ (\mathrm{i}) = \left(\frac{\mathrm{Vyear2}}{\mathrm{Vyear1}}\right)^{\wedge(1/\mathrm{n})} - 1$$

i = period of analysis
Vyear 1 = Value beginning of the period
Vyear 2 = Value end of the period
n = number of years for the period = year2-year1

Example: Growth grate for GDP for SSP1 period: 1990-2020):

$$Average\ annual\ growth\ rate\ (1990-2020) = \left(\frac{101.8\ US\$}{35.3\ US\$}\right)^{1/(2020-1990)} - 1$$

= 3.6%

Filtering/moving averages

We calculated weighted moving averages based on eight-year estimates using equal weight filtering to analyze and assess long-term trends for emissions and emission drivers. This method reduces the noise from interannual growth rates by "smoothing" the time series to highlight the underlying trend (Hyndman, 2009).

A key concept in traditional time series analysis is the decomposition of a given time series Y_t into a trend m_t, a seasonal component s_t, and the remainder ε_t.
We used a linear filter for obtaining the trend with p_1, p_2 positive integers:

Equation 2

$$\hat{m}_t = \sum_{i=-p_1}^{p_2} a_i y_{t+i}$$

Example of symmetric filter with equal weights $a_i = {}^{1}{}_{2p+1}$

$$\hat{}mt = \frac{Yt - p + \cdots Yt + \cdots Yt + p}{2p + 1}$$

$$= \sum_{i=-p}^{p} \frac{1}{2p+1} y_{t+i}$$

The filtering was carried out in R with this filter command, as follows:

```
#Read data (growth rates) and plot interannual growth rates 1996-2017
png(file="Fig2_CO2.png") #File name and type
EM_GR1<-ts(scan("Em_GR_1966-2017.txt"),start=1966) #Load data
plot(EM_GR1,ylab="", xlab="",  xlim=c(1966,2020), ylim = c(-4,7), axes = FALSE) #plot interannual growth rates 1996-2017
axis(1,cex.axis=1.2) #develop frame
axis(2,cex.axis=1.2)
box(col = 'black')
abline(h=0.0, col='dark red') #plot 0% line

#Prepare and plot filtering
mtext("Annual growth rates (%)", side=2, line=2.2, cex=1.3) # y-axis title
p <- 8 #set value: mean of eight observations
weights<-rep(1/(2*p+1), times=2*p+1) #Calculate weights
trend <- filter(EM_GR1, sides=2,filter=weights) #develop trendline
lines(trend, col="blue", lwd=2) #plot trendline (8-year average)
png(file="Fig2_CO2.png") #print/save file
```

Sub-periods of low and high growth

For the period 1960 to 2017, we identified eleven sub-periods of low/high CO_2 emissions growth rates (Figure SI- 3) as sub-periods of high growth rates (>1%) and sub-periods of lower growth (1% or lower). Four years were treated as outliers: 1961 (0.2%), 2001 (0.8%), and 2009 (-1.4%) were included in high growth sub-periods although below 1%; 1993 (1.1%) was above 1% but included in a low-growth sub-period. An alternative, more structural view to analyze the emission period is analyzing the sub-periods: 1960-1979 (High growth), 1980-1983 (Low growth), 1984-1991 (high growth), 1992-1998 (medium-slow growth with average growth ayes near 1%), 1999-2011 (High growth), 2013-now (medium-slow growth).

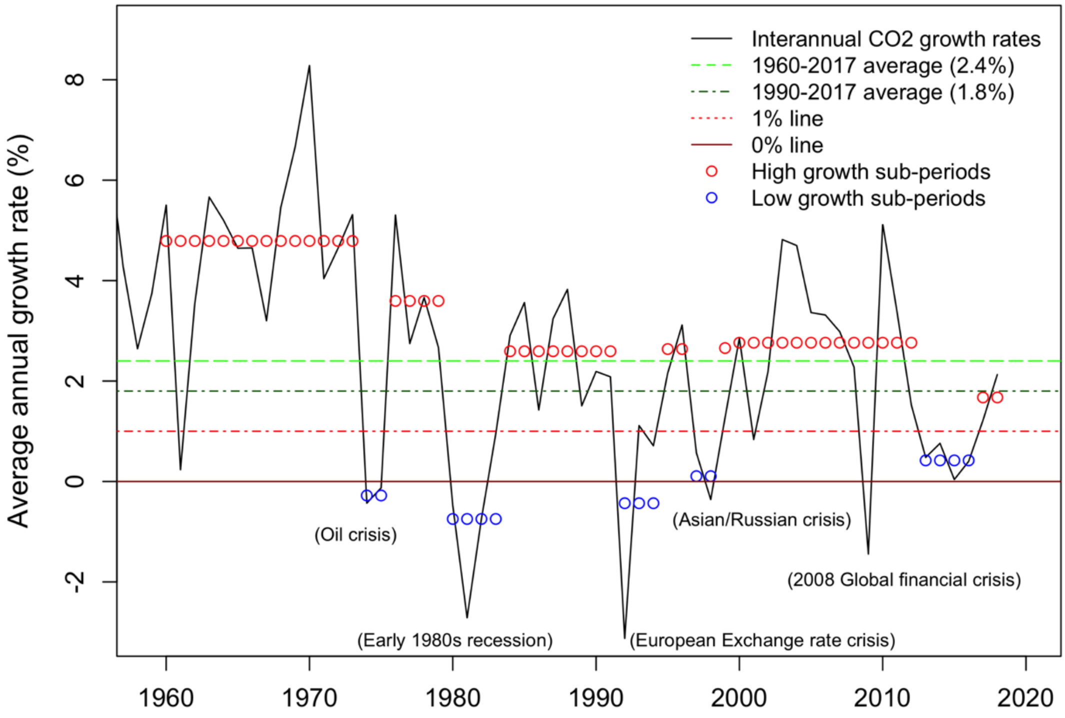


Figure SI- 3. Development of inter-annual growth rates for "CO_2 from fossil fuels and industry" (black) with "low-growth sub-periods", i.e., averages of years with 1% or lower growth rates (blue dots) and "high-growth sub-periods", i.e., averages of years above 1% (red). "Annual average growth rate 1960-2017" (green) & "annual average growth rate 1990-2017" (dark green), "1% line" (red), and "0% line" (dark red). Data source: (GCP, 2019)

Historical estimates for SSP CO_2 and primary energy

The SSP emissions growth rate projections were based on historical data presented in the SSP database CMIP6 Emissions CO_2 (Riahi et al., 2017), for each of the five regions (Asia, MAF, LAM, REF, and OECD). The aggregated sum was lower than World CMIP6 Emissions CO_2" (which cover all CO_2 emissions), but very close to "CO_2 from fossil fuel and industry" as measured in the RCP database and the Global Carbon project database (GCP, 2018; van Vuuren et al., 2011a). SSP's primary energy projections and growth trends. IEA energy data was applied by various SSP modeling teams (Bauer et al., 2017). Thus, IEA estimates were also used in our analyses to calculate SSP growth rates between 1990-2020. The 1990-estimate was extracted from the IEA Database (2019).

Table SI- 0-6. Data sources for primary energy projections

Historical estimate	IEA (1990-2017)	IEA 2019
SSP Projections	IEA (1990)* + SSP database (2005-2020)	Riahi et al. (2017), IEA (2020)
SRES projections	SRES database	Nakicenovic & Swart (2000a)
IS92 projections	IS92 database	Pepper et al. (1992)

*Country estimates for OECD-members was downloaded, and IEA estimates for the SSP definitions of non-OECD/OECD categories were recalculated

Specific non-OECD/OECD definitions for individual databases

Historical estimates for non-OECD and OECD categories were calculated according to IS92 and SSP database definitions. The historical datasets and scenario datasets use various OECD and non-OECD categories. Thus, for our analysis, we calculated historical emissions based on the scenario database definitions.

- SSP database definitions: Used for SSP-BL (CMIP5)
- IS92 database definitions: Used for IS92, and SRES

Overall Non-OECD acronyms:

- **OECD**: Includes the OECD member countries primarily from Europe, Northern America, and Asia
- **REF**: Countries from the Reforming Economies of Eastern Europe and the Former Soviet Union.
- **MAF**: This region includes the countries of the Middle East and Africa.
- **LAM**: This region includes the countries of Latin America and the Caribbean.
- **ASIA**: The region includes most Asian countries except for the Middle East, Japan, and some former Soviet Union states (see specific countries).

SSP definitions: Used for SSP (CMIP5) and SSP-RCP (CMIP6)

- **OECD**: **OECD 90** and **EU member states and candidates** (Albania, Australia, Austria, Belgium, Bosnia and Herzegovina, Bulgaria, Canada, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Guam, Hungary, Iceland, Ireland, Italy, Japan, Latvia, Lithuania, Luxembourg, Malta, Montenegro, Netherlands, New Zealand, Norway, Poland, Portugal, Puerto Rico, Romania, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, The former Yugoslav Republic of Macedonia, Turkey, United Kingdom, United States of America)
- *Missing country (OECD):* United States Virgin Islands

- **REF**: **Reforming Economies of Eastern Europe and the Former Soviet Union** (Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Republic of Moldova, Russian Federation, Tajikistan, Turkmenistan, Ukraine, Uzbekistan)
- **ASIA**: most **Asian** countries *except for the Middle East, Japan, and Former Soviet Union states* (Afghanistan, Bangladesh, Bhutan, Brunei Darussalam, Cambodia, China (incl. Hong Kong and Macao, excl. Taiwan), Democratic People's Republic of Korea, Fiji, French Polynesia, India, Indonesia, Lao People's Democratic Republic, Malaysia, Maldives, Micronesia (Fed. States of), Mongolia, Myanmar, Nepal, New Caledonia, Pakistan, Papua New Guinea, Philippines, Republic of Korea, Samoa, Singapore, Solomon Islands, Sri Lanka, Taiwan, Thailand, Timor-Leste, Vanuatu, Viet Nam)
- **MAF**: **the Middle East and Africa** (Algeria, Angola, Bahrain, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Congo, Côte d'Ivoire, the Democratic Republic of the Congo, Djibouti, Egypt, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Iran (Islamic Republic of), Iraq, Israel, Jordan, Kenya, Kuwait, Lebanon, Lesotho, Liberia, Libyan Arab Jamahiriya, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mayotte, Morocco, Mozambique,

Namibia, Niger, Nigeria, Occupied Palestinian Territory, Oman, Qatar, Rwanda, Réunion, Saudi Arabia, Senegal, Sierra Leone, Somalia, South Africa, South Sudan, Sudan, Swaziland, Syrian Arab Republic, Togo, Tunisia, Uganda, United Arab Emirates, United Republic of Tanzania, Western Sahara, Yemen, Zambia, Zimbabwe)

- **LAM**: **Latin America and the Caribbean**: (Argentina, Aruba, Bahamas, Barbados, Belize, Plurinational State of Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, El Salvador, French Guiana, Grenada, Guadeloupe, Guatemala, Guyana, Haiti, Honduras, Jamaica, Martinique, Mexico, Nicaragua, Panama, Paraguay, Peru, Suriname, Trinidad and Tobago, United States Virgin Islands, Uruguay, the Bolivarian Republic of Venezuela)
- Missing countries (non-OECD): French Guinea, Martinique.

IS92 definitions: Used for SA90, IS92, and SRES

OECD90:

- **United States**: United States of America, Guam, Puerto Rico, U.S. Virgin Islands, Wake Island.
- **OECD EUROPE/CANADA**: Andorra, Austria, Belgium, British Virgin Islands, Canada, Denmark, Faeroe Islands, Falklands, Finland, France, Fed. Rep. of Germany, Gibraltar, Greece, Greenland, Guernsey, Iceland, Ireland, Isle of Man, Italy, Jersey, Liechtenstein, Luxembourg, Malta, Monaco, Netherlands, Norway, Portugal, Reunion (Fr), Saint Helena (Br), St. Pierre and Miquelon, San Marino, Spain, Sweden, Switzerland, Turkey, Turks and Caicos (Br), United Kingdom, Vatican City
- **OECD PACIFIC**: Australia, Cook Islands, Fiji, French Polynesia, Japan, New Caledonia, New Zealand, Niue, Tonga, Tuvalu, Ty Island, Wallis and Futuna, and Western Samoa (Pepper et al., 1992).

Non-OECD (IS92):

- **Asia**: China (Mainland), Kampuchea (Cambodia), Korea, North, Laos, Mongolia, Vietnam, Afghanistan, American Samoa, Bangladesh, Bhutan, Brunei Darussalam, Burma, China (Taiwan), Hong Kong, India, Indonesia, Kiribati, Korea, South Macau, Malaysia, Maldives, Nauru, Nepal, Pakistan, Papua New Guinea, Philippines, Singapore, Solomon Islands, Sri Lanka, Thailand, Timor (East Timor), Vanuatu
- **MAF**: Bahrain, Cyprus, Gaza Strip, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syria, United Arab Emirates, West Bank, Yemen (Aden), Yemen (Sanaa), Nigeria, Rwanda, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, Somalia, South Africa, Sudan, Swaziland, Tanzania, Togo, Tunisia, Uganda, Western Sahara, Zaire, Zambia, Zimbabwe, Algeria, Angola and Cabinda, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros and Mayotte, Congo, Djibouti, Egypt, Equatorial Guinea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Ivory Coast, Kenya, Lesotho, Liberia, Libya, Madagascar, Malawi, Mali, Mauritania, Mauritius, Morocco, Mozambique, Namibia, Niger
- **LAM**: Anguilla, Antigua and Barbuda, Argentina, Aruba, Bahamas, Barbados, Belize, Bermuda, Bolivia, Brazil, Cayman Islands, Chile, Colombia, Costa Rica, Cuba, Dominica, Dominican Republic, Ecuador, El Salvador, French Guiana, Grenada, Guadeloupe, Guatemala, Guyana, Haiti, Honduras, Jamaica, Martinique, Mexico, Montserrat, Netherlands Antilles, Nicaragua, Panama, Paraguay, Peru, Saint Christopher and Nevis--> Saint Kitts, Saint Lucia, St. Vincent and the Grenadines, Suriname, Trinidad and Tobago, Uruguay, Venezuela

- **REF**: Albania, Bulgaria, Czechoslovakia, German Dem. Rep., Hungary, Poland, Romania, USSR, Yugoslavia

SRES definitions

- The OECD90 region groups together all countries belonging to the Organization for Economic Cooperation and Development (OECD) as of 1990, the base year of the participating models, and corresponds to Annex II countries under UNFCCC (1992).
- The REF region stands for countries undergoing economic reform and groups the East European countries and the Newly Independent States of the former Soviet Union. It includes Annex I countries outside Annex II as defined in UNFCCC (1992).
- The ASIA region stands for all developing (non-Annex I) countries in Asia.
- The ALM region stands for the rest of the world and includes all developing (non-Annex I) countries in Africa, Latin America, and the Middle East (Nakicenovic and Swart, 2000a).

SA90 definitions were not found.

SI 6. Changing Statistical Methods for primary energy: cross scenario comparisons (Chapter 4)

Supplementary information for Chapter 4

This chapter's SI is not open access available online.

Chapter summary & main results

Due to the IEA methodology changes and adjustments of the historical IEA estimates post-2005, historical primary energy estimates for some non-fossil energy sources have changed over time in successive IEA primary energy updates. Therefore, the energy quantifications in the scenarios developed before 2005 (SA90, IS92, SRES) may rely on another terminology than the SSPs.[iv]

Comparisons of energy variables between scenario series as well as and between scenarios and historical estimates are challenging. One reason for this is that the IEA methodologies have changed over time (OECD/IEA, 2005). Thus, conversion methods of various energy sources (such as nuclear, solar, wind) differ between historical data and scenario databases. Therefore, SSP nuclear projections were converted via the partial substitution method, and IS92 and SRES non-biomass renewable projections were converted via the physical content method. This was done to match contemporary IEA methodology and make a significant comparison between scenario series and historical data. Another reason is that IEA estimates have improved or changed over time. Thus, the most recent energy estimates for the early 1990s were remarkably lower for in particular non-OECD primary energy and, thus, global energy and various energy sources in earlier IEA estimates (IEA, 1994). Thus, energy values in the IS92 and SRES from 1990 and onwards are lower than contemporary IEA estimates (International Energy Agency, 2020).

Two fundamental challenges are detected related to our comparative analyses:

1. IEA estimates have changed or improved in successive PES updates
2. Different energy conversions exist between scenario databases and between scenario databases and the most recent historical estimates from IEA.
3. SSP nuclear primary energy was about three times lower than historical estimates
4. SRES models seem to have used input data based on different conversions for nuclear and other renewables.
5. All IS92 and three SRES scenarios had biomass 1990-estimates equal to 0EJ, similar to the historical database (IEA, 1991). Three SRES scenarios had estimates of about 46EJ
6. IS92 hydro was three times higher than historical estimates, while solar was similar

As such, the IS92 and SRES energy scenarios were likely based on energy inputs different from current historical IEA databases, as well as the SSP estimates. However, it is uncertain which conversion methods were used for the scenario databases' data sources. In the following four sub-sections, we show how we assessed, which methodologies were likely used in IEA methodology before and after 2005, and which methods were likely to have been underlying the IS92 (0), SRES (0), and SSP (0) primary energy estimates. And which conversion was made to prepare the comparative analyses.

Conclusions

SSP *nuclear* primary energy was converted (via the partial substitution method, multiplied by 1/0.33) according to present IEA methodology (OECD/IEA, 2005) to provide sufficient comparisons between historical and scenario databases. Afterward, we recalculated *total and non-fossil* estimates to allow for meaningful comparisons between energy projections and historical trends. Because of the uncertainty of the actual considerations made by the developers of IS92 and SRES - 20 to 30 years ago - we used the original data.

No conversions are made for SRES and IS92 scenarios.

SRES *"other renewables"* primary energy for A1FI and B1 scenarios could be converted to physical content (multiplied by 0.36). The *"other renewables"* is a single standing category for non-biomass renewables in the SRES database.
SRES *"nuclear"* primary energy for A1B, A1T, A2, B1, and B2 scenarios could be converted to partial content (multiplied by 1/0.33) to be comparable to historical IEA databases. However, this would change the balance between scenarios, making A1B to a more energy intensive scenario by 2100 of total primary energy, compared to A1FI.

IS92 *"hydro"* primary energy could be converted to physical content (multiplied by 0.36) to be comparable to historical IEA databases. However, IS92 *"solar"* is lower than historical estimates. Solar and hydro cover the non-biomass renewables for IS92.

Historical background regarding IEA methodology change

In 2005, IEA changed the method for calculating energy from renewable sources in their "primary energy supply" (OECD/IEA, 2005). Since assumptions in all four series are based on IEA statistics, the statistical energy data and forecasts underlying assumptions in the SA90, IS92, and SRES (all developed before 2005) may differ from the IEA energy estimates used in the current SSP development process. This complicates the comparative assessment of the scenario variables and consistency with historical trends. BP's "primary energy consumption" estimates of nuclear, hydro, biofuels, and renewable sources are based on the "partial substitution method". Therefore, the primary energy estimates are derived from the equivalent amount of fossil fuel required to generate the same electricity volume in a thermal power station, assuming a conversion efficiency of 38% (BP, 2018b, 2018c). This gives the electricity production from renewable sources an energy value equal to the hypothetical amount of the fuel required to generate an equal amount of electricity in a thermal power station using fossil fuels. Before 2005, IEA also used the partial substitution method, based on the assumption that hydro, wind, solar electricity had displaced thermal generation. Adopting the "physical content method", IEA does not convert for electricity from several energy categories. IEA does not convert (and increase) the energy value of the electricity 'generated' from "Hydro" and "Wind, solar, etc." in their primary energy supply statistics (International Energy Agency, 2020; OECD/IEA, 2005). This means that nuclear and coal power both are counted threefold relative to the power generated from renewables, considering that about three units of coal or nuclear energy are needed to make one unit of electrical power (Sauar, 2017). Hydro, wind, and solar became "energy products" measured statistically as the electricity generated in the plant although, the method excludes energy losses such as kinetic energy in wind turbines (Millard and Quadrelli, 2017).

For nuclear energy, the IEA imputes the primary heat production value for nuclear plants from the gross electricity generation using a thermal efficiency of 33% (OECD/IEA, 2005, p. 138). This means that if a scenario dataset has the electricity (secondary energy) equal to the primary energy, then the primary energy in the scenario database may be converted (i.e., multiplied by 0.33) to be comparable to the historical data. We assume a thermal efficiency of 33% to make the conversion. However, this depends on the estimates' size and differences between historical estimates and the scenario databases' estimates.

Regarding IEA hydro, because of the lower efficiency of thermal power generation (typically 36%), a far more considerable amount of energy in the form of fuels is required to compensate for the electricity lost from hydro plants. This imbalance was overcome by substituting hydro production with an energy value nearly three times (1/0.36) its physical energy content (OECD/IEA, 2005, p. 137). It is argued that IEA measures the electricity produced for nuclear energy biomass-based power plants, and after that multiply it with 1/03 for biomass and 1/0.33 for nuclear energy (Sauar, 2017). The IEA manual is less specific about the methods applied for *wind* and *solar* sources before and after 2005. It is uncertain why there is a 3% difference between IEA primary energy and electricity (International Energy Agency, 2020).
In IEA (1994): the hydro primary energy supply and electricity output are similar (8 EJ). Hydro is not used for other energy uses than electricity (e.g., heat). Thus, arguably the physical content method was used for hydro in IEA 1994 dataset.

Geothermal primary energy is heat, but the end-use form can be either heat or electricity. For electricity, a thermal conversion process is used by IEA, assuming a 10% efficiency (OECD/IEA, 2005). According to IEA methodology, geothermal energy is converted by using a factor 1/0.1, while nothing is stated regarding wind and solar (OECD/IEA, 2005).
Assessing IEA data (1994), the electricity output for solar (0.1 EJ) was about 10% of the *solar* primary energy (1.3 EJ), and thus a conversion method was arguably used. It is expected that solar was used for other things than electricity (e.g., heat). Therefore, it is likely that the partial substitution method was used in IEA (1994) "Geo/Others" primary energy estimates. Assessing the most recent dataset (International Energy Agency, 2020), the electricity for Geothermal, Solar PV, Wind, and solar was 10% of the primary energy category "wind, solar, etc.". This also included geothermal, tide, and other sources[10] in 1990. This share of primary energy constantly grew during the last three decades to 55% in 2017. The explanation of the increased efficiency may be that *geothermal* (which is converted) grew on average, 1% annually during the period, while *solar PV*, *wind*, and *tide* all grew about 1.5% (International Energy Agency, 2020).
If the geothermal secondary energy components of heat and electricity exist in the scenario series' databases, it may be useful to consider a need for conversions on geothermal primary energy. For instance, in case the primary energy is the same as the secondary energy (electricity). Conversion is equivalent to the IEA estimates – from the electricity (secondary energy) into a heat estimate (primary energy), using a 10% efficiency assumption. The estimated heat then add to the reported heat in secondary energy, resulting in a total new primary (heat) energy supply.
For nuclear energy, the IEA imputes the primary heat production value for nuclear plants from the gross electricity generation using a thermal efficiency of 33% (OECD/IEA, 2005, p. 138). Before 2005, a similar conversion was used for some non-biomass renewable sources. Because of the lower efficiency of thermal power generation (typically 36%), a far more substantial amount of energy in the form of fuels is required to compensate for the electricity lost from hydro plants. This imbalance was overcome by substituting hydro production with an energy value nearly three times (1/0.36) its physical energy content (OECD/IEA, 2005, p. 137). Furthermore, it is argued that IEA measures the electricity produced for nuclear energy biomass-based power plants, and after that, multiply it with 3.0 for biomass and 3.03 for nuclear energy (Sauar, 2017). It is less transparent to explore the conversion factor for wind and solar in the IEA manual, but it may have been the same as hydro.

[10]. *Geothermal*, *wind* and *solar* are considered the three major sources in this category.

The IEA manual is describing some, but not all, energy conversions (such as solar). However, the sources involved in possible changed estimates are biomass, nuclear, and non-biomass renewables. See a summary of the IEA literature reviews and data analyses in Table SI- 0-7.

Table SI- 0-7. IEA statistical methodology and conversion factors before and after 2005. It is based primarily on the IEA statistical methodology (OECD/IEA, 2005) and comparisons of most recent IEA primary energy estimates (International Energy Agency, 2020).

Variable	Our Analysis	Result	Statistical method	Data source
Nuclear	IEA Primary energy (PES) vs. IEA electricity	The electricity is 33% of the primary energy	Data suggests that partial substitution was used	IEA (2020)
	2005-methodology	Source 1 (Outside Eurostat): Multiplied by 1/0.33 (1)	Partial substitution for some parts	OECD/IEA (2005, p. 138)
		Source 2 (Eurostat statistics): Nothing added	Heat from steam generation	
	Pre-2005 method	Multiplied by 1/0.33	Data suggests that partial substitution was used	IEA (1994)
Biomass	PES vs. electricity for biomass	"Biofuels & waste" electricity accounts for a small fraction of PES (between 1% (1990) and 4% (2015))	No conclusion regarding methods and conversion can be reached	IEA (2020)
	2005-methodology	Methods suggest net calorific value of biomass in PES (2)	Physical content	OECD/IEA (2005)
	Pre-2005 method	No data nor description exists for analysis	-	IEA (1994); OECD/IEA (2005)
Hydro	PES vs. electricity	Hydroelectricity (secondary energy) is 3% higher than hydro primary energy	Physical content is assumed	IEA (2020)
	2005-methodology	Nothing added	Physical content	OECD/IEA (2005)
	Pre-2005 method	Multiplied by 1/0.36	Partial substitution	OECD/IEA (2005, p. 137)
Non-biomass renewables	PES vs. IEA electricity (geothermal, solar, wind, tide, and other)	Electricity vary from 14% (1990) to 51% (2015) of primary energy	No conclusion regarding methods	IEA (2020)
	2005-methodology	For non-thermal electricity generation, the PES is equal to secondary energy	Physical content for electricity (i.e., all non-heat)	OECD/IEA (2005)
		For geothermal energy, a 1/0.10 multiplication is used	Partial substitution for geothermal	OECD/IEA (2005, p. 138)
		Nothing regarding solar thermal electricity		
	Pre-2005 method	Electricity is 10% of the primary energy We found no description in the IEA 2005-manual	The partial substitution method is assumed by other sources (2017)	IEA (1994) Sauar (2017)

(1) Outside the Eurostat dataset, nuclear heat production (primary energy) is estimated using a conversion (1/0.33) from electricity (secondary energy). The main objective is to account for nuclear heat, which is the primary energy. IEA uses two nuclear data (OECD/IEA, 2005): 1) outside the Eurostat statistics (i.e., non-EU countries, which don't account for heat). Here (primary energy), heat is estimated from the electricity generation, assuming a 33% efficiency (partial substitution method). 2)

Eurostat statistics (i.e., EU countries and non-EU countries but IEA members with similar information). The second source is based on the steam generation, which accounts for the heat (primary energy).
(2) The IEA biomass used in electricity generation is probably accounted for in primary energy using its net calorific value. IEA definition "*The calorific value of natural gas varies according to its composition, that is, the amounts it contains the constituent gases. The gas composition depends on the oil or gas field from which it is extracted and its treatment. Some of the gas constituents may be "inert" with no calorific value (for example, carbon dioxide or nitrogen)"* (OECD/IEA, 2005).

A difference between IEA primary energy production and primary energy supply

A critical difference exists between IEA Primary energy production and primary energy supply (PES). The IEA PEP statistics show very different estimates for the share of fossil and non-fossil sources on regional levels. In the database for primary energy production, extraction of fossil fuels is included in the statistics for the country it is extracted – not the country where it is burned/used. Countries like Saudi Arabia and Norway have a considerably higher PEP than PES because of the countries' extraction and export of oil (IEA, 2018; OECD/IEA, 2018).

Comparing IEA databases (before and after 2005) with scenario databases

When we compare contemporary historical IEA records with the emission scenario series, there is reason to believe that IS92 hydro was based on the partial substitution method. This provides a reason to convert them to physical content (multiplied by 0.36) to make them comparable to historical records. However, solar is almost half compared to historical records. IS92 nuclear primary energy estimates for 1990 are about 75% lower than historical records - and thus, similar conversion methods are likely used in all three databases.
Renewable energy in some SRES scenarios (A1FI and B1) seems to have been using input data based on PSM. One could multiply by 0.36 to make projected estimates comparable to contemporary historical data. Additionally, was A1FI the only SRES nuclear scenario with 1990-estimates comparable with historical estimates – here partial substitution seems to have been used for input data.
In contrast, the remaining five marker/illustrative scenarios seem to have nuclear data estimates for 1990 closer to historical data converted to the physical content method (three times lower). For comparative reasons only, the remaining five scenarios could be converted from by multiplying with 1/0.36. This made some smaller changes in the total primary energy growth and non-fossil primary energy growth for the assessed period, but even smaller for the century-long growth rates. However, the energy-mix (e.g., the share of non-fossil energy) dropped significantly for those scenarios. This, however, has no impact on fossil growth, unless it affects assumptions. See differences in total and non-fossil primary energy growth in Table SI- 0-8 below.

Table SI- 0-8. Fossil & non-fossil primary energy growth rates SA90-SSPs for original and converted scenario estimates.

Only SSP conversions were used in the analyses in the paper. The following conversions were made: IS92 (original solar and hydro were multiplied by 0.36), SRES (other renewables was multiplied by 0.36), SSP (nuclear was multiplied by 1/0.33)

Scenario	**Total Primary energy growth 1990-2020**		**Non-fossil Primary energy growth 1990-2020**	
	Original	Converted	Original	Converted
IS92-A	2,60	2,54	3,51	3,84
IS92-B	2,60	2,54	3,51	3,84
IS92-C	1,66	1,57	3,85	4,47
IS92-D	2,38	2,30	4,92	5,70

IS92-E	3,29	3,24	3,50	3,52
IS92-F	2,89	2,85	2,81	2,80
SRES A1FI	3,35	2,37	2,56	3,10
SRES A1B	2,86	2,30	1,84	2,61
SRES A1T	2,75	2,10	2,75	2,76
SRES A2	2,92	2,18	3,74	3,18
SRES B1	2,13	2,01	1,93	3,81
SRES B2	1,98	1,64	1,72	1,88

Scenario	**Total Primary energy growth 2005-2020**		**Non-fossil Primary energy growth 2005-2020**	
	Original	Converted	Original	Converted
SSP1	2,59	2,58	1,06	0,80
SSP2	2,54	2,57	2,26	2,47
SSP3	2,88	2,94	1,54	1,60
SSP4	3,44	3,48	2,14	2,67
SSP5	3,42	3,49	1,89	1,36

The scenario literature is not specific about the use of statistical methods for energy. Therefore, we compared historical and scenario databases to optimize consistency between scenario databases and IEA estimates to provide a meaningful and reliable comparison between historical and projected energy trends. Based on these analyses, one may assume that IS92 hydro was based on the partial substitution method. Also, five SRES (A1B, A1T, A2, B1, and B2) and all SSP-BL nuclear primary energy were based on the physical content method.
Making such conversions would result in lower IS92 *non-biomass renewables* estimates (multiplied by 0.36), and higher SRES/SSP *nuclear* estimates (multiplied by 1/0.33) compared to the original database values. These conversions do not affect the SSP nuclear growth rates, calculated, and used for comparative analyses. But it changed the *total* and *non-fossil* primary energy growth rates (and estimates.

In the case of special interest comparisons of energy databases for the IS92, SRES, and SSP-BL is explored and explained in the subsections below (sub-sections 0 - 0).
We compared and assessed the differences and similarities between energy data in the scenario series and IEA databases. It was done to better to understand the statistical methods behind the scenario databases. These are not described in terms of statistical methods behind the energy estimates. Second, allow meaningful comparisons between energy projections, emission projections, and historical trends.

IS92 statistical assessments

It is unclear which methodology was used for energy projections in the IS92 and SRES series. Also, IEA estimates have changed or improved in successive IEA Primary energy supply updates. Therefore, we used the earliest accessible IEA dataset (IEA, 1994). It has estimates for 1991, which was used to compare with the 1990-estimates in the scenario databases.

Summary of comparisons

The IS92 estimates both nuclear (17.2 EJ), Solar (0.7 EJ), and Hydro (23.7 EJ) primary energy estimates are similar to IS92 electricity output. Thus, it appears that the physical content method was used for all three sources. However, comparing IS92 data with IEA estimates, IS92 *hydro* primary energy (23 EJ) was significantly higher than the IEA (1994) 1991-estimate (8 EJ) and IEA (2019) 1990-estimate (7.7 EJ).

Conclusion: to make hydro comparable to IEA estimates, we found it possible to convert using the physical content method. In case of conversion, we will recommend adjusting both *hydro* and *solar* in the IS92 database according to contemporary IEA methodology (pre-2005) (OECD/IEA,

2005) because the changes in methods are real - even though it leads to larger differences between IS92 and IEA (2019) estimates.
However, because none of the IS92 authors contacted, remember which considerations were made during the development, we did not make any changes for our analyzes.

For comparable reasons only we adjusted various estimates. When adjusting the IS92 non-biomass renewable estimates (i.e., *solar* and *hydro*) - assumed based on partial substitution method - to be in alignment with the IEA methodology (physical content method), the IS92 global energy-mix (non-fossil share of total energy) in 2020 change from a range encompassing 14-31% (original database) to 9-26% (converted hydro and solar). The historical estimate in 2017 was 19%.
It is comparing to contemporary historical estimates (IEA, 1994), when applying the above-described conversions, the IS92 estimate for global total primary energy changes from 343EJ (original) to 328EJ (converted) and thus similar to the historical IEA 1991-estimate (328EJ). For, *non-fossil* primary energy 1990-estimates change from 46EJ to 26EJ (IS92a), while the historical IEA 1991-estimate was 32EJ. In the most recent historical IEA database from 2019, the non-fossil is larger (69EJ). This is primarily caused by the fact that biomass changed from 0EJ in the 1991 database to 38EJ in the 2019 database.
When IS92 solar and hydro are converted, the 1990 share of non-fossil energy in IS92 drops from 12% to 8%. The historical estimate is ~10% (IEA, 1994).

Comparisons of IEA vs. IS92

See analyses and comparisons of IS92 and IEA datasets in Table SI- 0-9.

Table SI- 0-9. Statistical Primary Energy Analysis for IS92: Partial substitution or Physical content method? Analyzing the plausible energy conversion method.

Variable / analysis	**IS92 : IEA (1994)***	**Our Conclusion**	**For Our analysis**	
IS92 PE nuclear vs. IS92 electricity		Electricity and primary energy are similar (1:1)		
IS92 PE nuclear vs. IEA (1994) PES nuclear	17.2 : 23 EJ	IEA is different IS92a-f estimates, however not very different. Probably the same methods.	Likely, the partial substitution method is used in the IS92a-f model (similar to IEA method)	No conversions made
IS92 PE biomass vs. IS92 electricity biomass		No electricity data		
IS92 PE biomass vs IEA (1994) PES biomass	0 : 39 EJ	We found no reason why the IS92 estimate is zero while contemporary historical estimates are about 40 EJ	The difference between IEA total PES (367EJ) and IS92 total PE (343) is 24EJ Almost the same as the missing biomass	No conversions made
IS92 PE solar vs. IS92 electricity solar		Electricity and primary energy are similar (1:1)		No conversions made
IS92 PE solar vs. IEA (1994) PES solar	0.7 : 1.3 EJ	Estimates are almost similar		
IS92 PE hydro vs. IS92 hydro electricity		Electricity and primary energy are similar (1:1)	Scenarios could be multiplied by 0.36	No conversions made
IS92 PE hydro vs IEA (1994) PES hydro	23.7 : 8 EJ	Almost 3 to 1 difference	Could be converted from partial substitution to physical content method (multiplied by 0.36)	

* Comparisons between IEA 1991-estimates and IS92 1990-estimates. 1990-estimates were not specified in IEA (1994), which was the earliest available version of IEA primary energy statistics we were able to locate.

The IEA 1991-estimate for global *Total* primary energy demand was 343 EJ, and the non-fossil share was ~10% (IEA, 1994), while the most recent IEA 1990 estimates are 367EJ and 19%, respectively (International Energy Agency, 2020). The IS92 1990-estimates (343EJ and 12%) (Pepper et al., 1992) are closest to the earliest IEA estimates (IEA, 1994).

In the IS92 dataset, the values for *nuclear*, *solar*, and *hydro primary energy use* and *electricity generation* are similar. Thus, it is likely that no conversion factor was used for energy values in the IS92 dataset.

The *hydro* primary energy in IS92 is three times bigger than in IEA, suggesting that a 0,33-correction factor must be used to compare it with historical data. Although nuclear primary energy in IEA (both 1994 and 2019 datasets) is around 25% higher than the IS92 initial 1990-value, they are similar in order of magnitude.

We consider that the *solar* primary energy category in IS92 corresponds to the IEA (1994) “Geo/Others” and the IEA (2020) category “Wind, solar, etc.” primary energy. The IEA category “Geo/Others” (1.3 EJ in 1991) (IEA, 1994) is relatively close to the 1990-estimate of the IS92 category "solar" (0.7 EJ). IEA estimate is close to the IS92. Therefore, maybe the same statistical method was used in both datasets.
Also, the IEA estimates have improved over time (the 1991 estimate in the most recent IEA update is 1.6 EJ). For some reason, the IS92 authors implemented a historical estimate smaller than estimated in the IEA record. Compared to historical records also IS92 biomass 1990-estimates are low (0 EJ) compared to IEA (about 38 EJ) (IEA, 1994; International Energy Agency, 2020) as well as to the 1990-estimates in the SRES database. We have not found any explanation for these differences.

SRES statistical assessments

Nuclear: IEA nuclear primary energy estimate for the 1990 database (International Energy Agency, 2020) is three times larger than that of the SRES 1990-estimates for five out of six models. A1FI 1990-estimate (24EJ) (Nakicenovic and Swart, 2000a) was quite similar to IEA historical data (23EJ) (IEA, 1994).

Conclusion: It could imply a reason to convert SRES nuclear estimates for A1B, A1T, A2, B1, and B2 (multiplied by 1/0.33) and afterward recalculate SRES *Total* primary energy and *non-fossil* primary energy.

Effect: When adjusting those SRES nuclear scenarios (assumed based on physical content method) to be in alignment with the IEA methodology (partial substitution method), the SRES global energy-mix (non-fossil share of total energy) in 2020 change from a range encompassing 8-21% to 13-29%. The historical IEA estimate in 2017 is 19%.

Other renewables: We found an inconsistency in SRES “Other renewables”. Here A1FI (24 EJ) and B1 (61 EJ) scenarios have very high *other renewable* 1990-estimates compared to the other four SRES models (8-10 EJ). The IEA estimate is 8 EJ (IEA, 1994).

The effect of the above described nuclear and other renewables would result in lower estimates for A1FI total primary energy by 2100 compared to A1B.

It's difficult to explain why biomass is estimated to be zero in 1990 in the IS92 model and zero or close to zero in three of six SRES models (A1FI/A2 (0EJ) B1 (3EJ)). And why SRES A1B, A1T, and A2 has an estimation of almost 50EJ in 1990 (Nakicenovic and Swart, 2000a).

See a summary of analyses in Table SI- 0-10.

Table SI- 0-10. Statistical Primary Energy Analysis for SRES: Partial substitution or Physical content method? Analyzing the plausible energy conversion method.

Variable / analysis	SRES : IEA (1994)	Assessment	Conclusion	
SRES PE nuclear vs. SRES electricity		No electricity data is presented in the SRES database.		
SRES PE nuclear vs IEA (1994) PES nuclear	7 : 23 EJ	IEA is three times larger for B1 & A1F1.	The physical content method is most likely used in SRES (IEA uses partial substitution) Four scenarios (A1B, A1T, A2, B2) could be Multiplied x1/0.33	No conversion made
SRES PE biomass vs IEA (1994) PES biomass	0-3 : 39 EJ	A1FI/A2 (0EJ), B1(3EJ), A1T/B2 (46EJ), A1B (50EJ) in 1990	Three models are quite similar to IEA, while three are almost zero (like the IS92 model)	No conversion made
SRES PE ”other renewables” vs. IEA (1994) PES renewables (hydro + “Geo and others”)	8.3 : 8-10 EJ A1B/A1T/A2/B2 8.3 : 24-61 EJ A1FI/B1	A1FI (24 EJ) has high, and B1 (61EJ) has very high values. A1B, A1T, A2 & B2 (8 to 10 EJ) are relatively similar to IEA (1994)	Can we justify converting renewable energy in some scenarios? A1FI & B1?	No conversions are made

There seem to exist some inconsistencies between SRES scenarios/models

- The A1T scenario is the most problematic
- The scenarios logic will become imbalanced if conversions are made
    - The energy mix (share of non-fossil sources of total energy) would change compared to the original data
    - Total primary energy will change for all scenarios, but in particular, it will become low for the fossil fuel-intensive A1FI scenario (and lower than A1B)

SSP statistical assessments

Summary

Nuclear: The SSP nuclear projections are about three times lower than IEA estimates. Thus, it is likely that the SSP methodology implies the "physical content method".

Conclusion: SSP nuclear primary energy projections were converted for all years in all scenarios. Thus, total primary energy (and non-fossil primary energy) was recalculated (absolute numbers and growth rates).

Effect: When adjusting the SSP nuclear scenarios (assumed based on physical content method) to be in alignment with the IEA methodology (partial substitution method), the SSP global energy-mix (non-fossil share of total energy) in 2020 change from a range encompassing 13-18% to 16-22%. The historical estimate in 2017 is 19%.

Solar, Wind, and Geothermal: In the various SSP scenarios, different assumptions are underlying geothermal conversions from primary energy to electricity and heat.
Conclusion: no adjustments made
Comparisons and assessments

Table SI- 0-11 summarizes the energy conversion methods analyzes for the SSP database.

Table SI- 0-11. Statistical Primary Energy Analysis for SSP: Partial substitution or Physical content method. Analyzing the plausible energy conversion method.
Note: non-biomass renewables appear irregular. We may have to look individually at solar, hydro, and geothermal.

Variable / analysis PE = primary energy	SSP : IEA(2019)	Our Conclusion	For Our analysis	Added
SSP PE nuclear vs. SSP electricity		Electricity is similar to primary energy use.		
SSP PE nuclear vs. IEA PES (2020) nuclear	10EJ : 22EJ (Based on SSP2)	IEA is about three times larger than SSP estimates	Likely, the physical content method was used in SSP SSP Nuclear is changed to the partial substitution method (used by IEA)	Multiplied by x(1/0.33)
SSP PE biomass vs. SSP electricity biomass	-	Comparison is not possible		No conversion
SSP PE biomass vs IEA (2020) PES biomass	48 vs. 38 (SSP2)	IEA estimate includes waste. Not stated if SSP models include waste	Biomass is more or less the same and not enough to make a conversion	
SSP PE "Geothermal", "solar", and "wind" vs SSP electricity		Some irregularities with Geothermal between models – and data is not sufficient	Geothermal may need some conversion, but difficult to define how for the various scenarios	No conversion
SSP PE "solar, wind, geothermal" vs. IEA (2020) PES "solar, wind, etc."	1972: 1.5 (SSP2)	Not very different		No conversion
SSP PE hydro vs. IEA hydro (2020)	10.6 : 7.7 EJ (SSP2)	Different but not enough to make a conversion		

In SSP scenario datasets, the primary nuclear energy is three times smaller than the IEA datasets. This suggests a 33% efficiency correction factor (OECD/IEA, 2005) is required to make nuclear scenarios comparable to IEA nuclear estimates (International Energy Agency, 2020). This is done to increase the reliability of comparisons. *Nuclear growth rates will remain the same, while total and non-fossil energy estimates and growth rates will change.*
However, making a 100% accurate conversion is more complicated than that. The IEA thermal energy is reported using both measured steam energy (mainly EU countries) and estimates for non-EU, including an assumption of 33% of thermal conversion to electricity (OECD/IEA, 2005). For the SSP2/3 baseline scenarios, nuclear primary energy is close to the electricity estimates (secondary energy). In the remaining SSPs, nuclear primary energy is equal to the secondary energy. In SSP3, the data suggests that direct heat usage starts to appear (4.8% in 2020) and SSP 2 (1,5% in 2020). We apply the correction based on the differences between estimates in the SSP database (Riahi et al., 2017) and IEA (International Energy Agency, 2020).

Regarding non-biomass renewables, Geothermal, wind, and solar, are considered the three major sources in this category. The IEA energy category "wind, solar, etc." including also geothermal, tide, and other sources is about three times higher than SSP2 (1/0.36) in 2005. According to IEA methodology, geothermal energy is converted by using a factor 1/0.1, while nothing is stated regarding wind and solar (OECD/IEA, 2005).

SSP2 and SSP3 have the necessary information regarding the heat and electricity components of geothermal energy use. We can detect, which part of the primary energy goes to each of the two energy types (heat and electricity). This information is necessary to make a conversion in the electricity generation, using the IEA estimated efficiency of 10% (OECD/IEA, 2005). SSP1/4/5 baselines (Riahi et al., 2017) do not have sufficient information to make such conversion (e.g., heat and electricity estimates). Thus, no conversions are considered for geothermal. However, applying a conversion could increase the reliability of comparisons with historical data conversion. In case all scenarios had the necessary data, a correction could be considered.[v]

SI 7: Emissions Driver Analyzes and Trends (Chapter 4)

Supplementary information for Chapter 4 (not available open access online)

Emissions and emissions drivers

CO_2 emissions from fossil fuels and industry grew about 1750% between 1900 and 2017, with an average annual growth rate of 2.5% (Fig. 1 left). Emissions growth rates (Fig. 1 right) decreased from 1960 to 1990, followed by increasing growth rates.

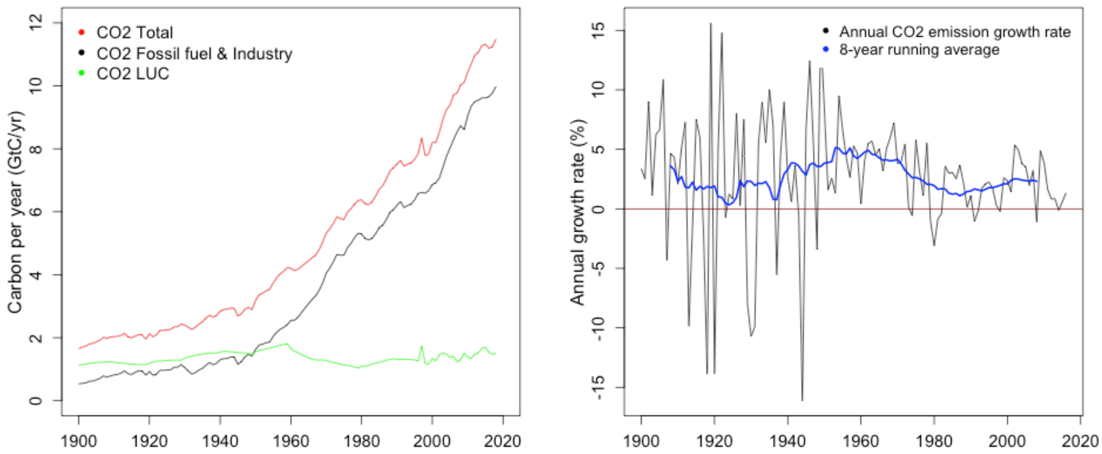


Figure SI- 4. Development in global CO_2 emissions 1900-2018 & interannual growth rates 1900-2017

Left: Development in global CO_2 emissions 1900-2018; "Total" (red line), "Fossil fuels and industry" (black), and "Land-Use Change" (green). Right: Interannual emissions growth rates 1900-2017 (black) with eight-year running averages (blue), and "0% line" (dark red). Data source: GCP (2019).

The strong decrease in variability in the annual growth rate from the end of the second world war to the present may be explained by geostrategic reasons (such as economic crisis and wars in the first half of the century). Another explanation may be a statistic reason: the absolute variations may stay similar, but as the basic emissions grow, the relative differences become smaller.

A comparison of sub-periods of higher and lower growth is illustrated in Table SI- 0-12.

Table SI- 0-12. Comparison of global average annual growth rates (%) in several sub-periods ranging from the end year 1960 to end the year 2017.
CO_2 (fossil fuels and industry) and key emissions drivers (population, GDP MER, and primary energy). Growth rates for sub-periods of higher (above 1% per year) and lower emissions growth (1% or below). Growth rates are based on the CAGR method (see methodology 0). Four outliers were detected: 1961 (0.4%) and 2009 (-1.1%), which were included in high growth subperiods, although below 1%; as well as 1991 (1.1%), which was above 1% but had as a single standing outlier in a slow-growth subperiod.

Period	CO2 fossil fuel & industry	Population	GDP (MER)	GDP (PPP)	Primary energy (IEA)	Primary energy (BP)	Carbon intensity CO2/PES (IEA)	Carbon intensity CO2/GDP (MER)	Income GDP(MER)/POP
1961-1973 (End 1960 to end 1973)	4,72	1,98	5,39					-0,64	3,34
1974-1975	-0,28	1,91	1,30		0,67	0,50	-0,95	-1,56	-0,60
1976-1979	3,59	1,76	4,30		3,99	3,94	-0,38	-0,68	2,50
1980-1983	-0,76	1,77	1,66		0,02	-0,02	-0,78	-2,38	-0,11
1984-1991	2,59	1,74	3,49		2,52	2,57	0,07	-0,87	1,71
1992-1994	-0,45	1,55	2,10	2,18	0,62	0,92	-1,06	-2,50	0,54
1995-1996	2,64	1,48	3,21	3,56	2,55	2,49	0,08	-0,55	1,70
1997-1998	0,10	1,41	3,13	3,23	0,77	0,86	-0,66	-2,93	1,70
1999-2012	2,64	1,25	2,96	3,76	2,34	2,45	0,30	-0,31	1,69
2013-2016	0,42	1,18	2,73	3,43	0,90	1,30	-0,48	-2,25	1,54
2017	1,22	1,14	3,16	3,77	1,52	1,91	-0,30	-1,88	1,99
Long-term									
2006-2017 (End 2006 to end 2017)	1,66	1,20	2,71	3,58	1,64	1,81	0,02	-1,03	1,50
1991-2017 (End 1990)	1,70	1,31	2,81	3,39	1,74	1,91	-0,04	-1,08	1,48
1972-2017 (End 1971)	1,85	1,51	3,06		2,04	2,15	-0,19	-1,18	1,52

Correlations: CO_2 vs. non-fossil, fossil, and carbon intensities

All examined emissions drivers have been continuously growing throughout the examined (and IPCC) period. The historical estimates for the IPCC period (1990-2017) suggest a total growth in population (42%), GDP (MER:111%, PPP: 146%), primary energy supply (60%), and CO_2 emissions from fossil fuels and industry (63%). During the period, the average annual growth rates for primary energy and CO_2 for the period were similar. The average annual growth rates of 1971-2017 were higher for all variables than the 1990-2017 period (IEA, 2018; International Energy Agency, 2020; WB, 2021, 2019; World Bank, 2019).

Correlations between emissions and the emission drivers show a positive linear relationship between emissions and all three variables (, top). However, when we compare growth rates (Figure SI- 5, bottom) rather than absolute values, differences in correlations materialize. Here, correlations show a good fit between primary energy and CO_2: a weaker relationship is found between GDP MER and emissions, a stronger connection is found between GDP/POP and emissions, while no significant link is found between the growth rates of population and emissions. In the short-term, GDP arguably varies much more on an annual basis.

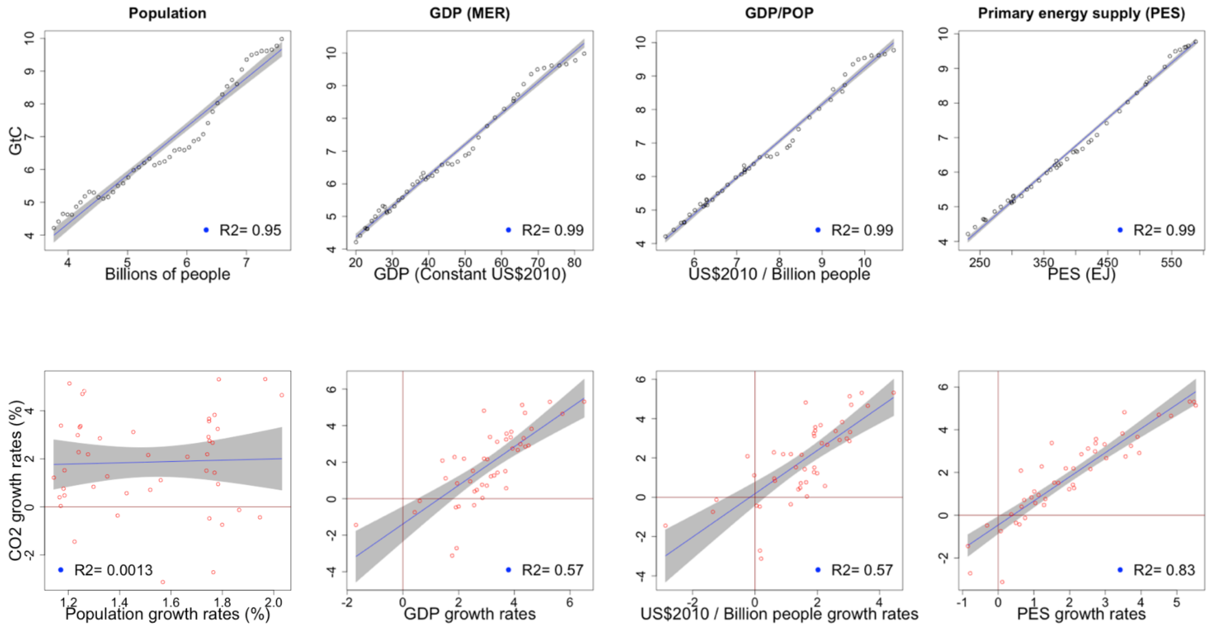


Figure SI- 5. CO_2, Population, GDP MER, GDP/POP, and Primary energy supply correlations

Correlations between CO_2 (fossil fuels and industry) and Population, GDP MER, GDP/POP, and Primary energy supply (PES) 1971-2017 (top); and the corresponding growth rates (bottom). Legend: 0% growth rate line (red), trend line (blue), and 0.95-confidence interval (grey area). Data source: GCP (2019), WB (2021, 2019), IEA (2018).

Total primary energy and CO_2 emissions from fossil fuel and industry will show a less good fit if the primary energy mix changes (Figure SI- 5). Population size correlates very well with emissions, while population growth (since it hardly varies) does not. Population growth rates alone do not explain much regarding short-term emissions development. However, regional population growth, emissions per capita, and income arguably are related to the development of consumption and energy use. Therefore, developments in the economy, technology, and population are considered useful explanatory variables for energy developments. Additionally, demographic variables (e.g., regional lifestyle trends, education, population growth, and urbanization) play significant roles.

Figure SI- 6 shows correlations for fossil and non-fossil primary energy and the indexes of emissions intensity per energy and per GDP. Regarding growth rates, only fossil primary energy correlates well with emissions.

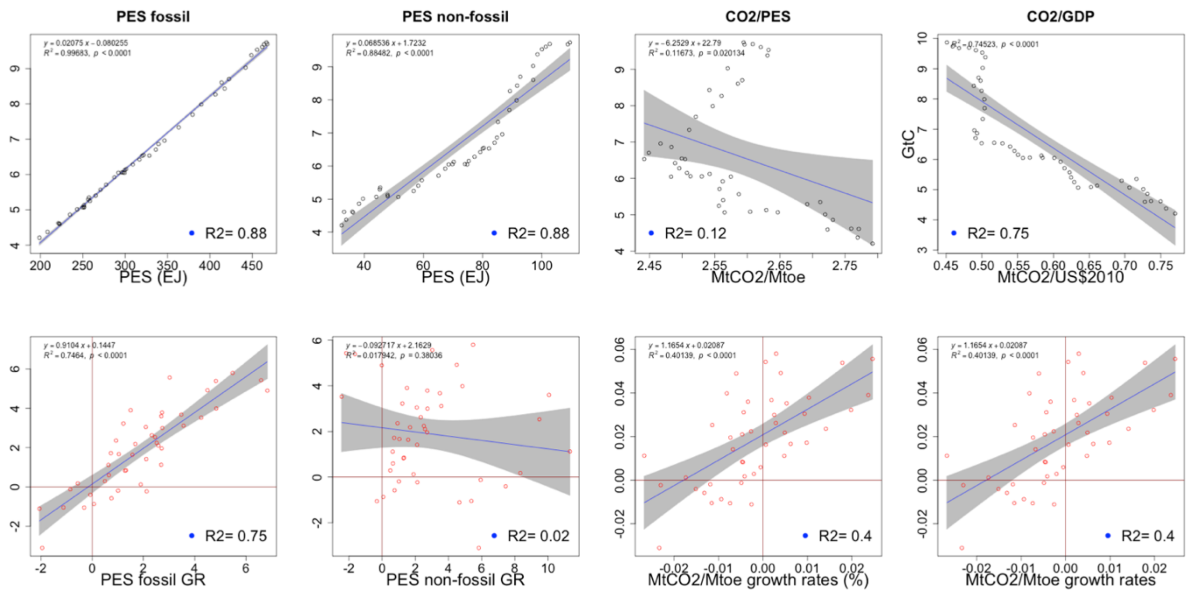


Figure SI- 6. Correlations including fossil and non-fossil primary energy

Correlations between CO_2 (fossil fuels and industry) and “fossil primary energy supply (PES)”, “non-fossil primary energy supply (PES)”, CO_2/GDP MER“, and CO_2/PES”, and “primary energy” 1971-2017 (top); and the corresponding growth rates (bottom).
Legend: 0% growth rate line (red), trendline (blue), and 0.95-confidence interval (grey area). Data source: GCP (2019), WB (2021, 2019), IEA (2018; 2020).

Primary energy supply and the share of energy sources in non-OECD and OECD

During the 1990-2017 period, the share of global non-fossil energy sources was relatively stable between 18-20% (Figure SI- 7). From 1990 to 2017, global primary energy from both fossil and non-fossil sources grew on average by 1.7%, while renewables grew by 3.8%.

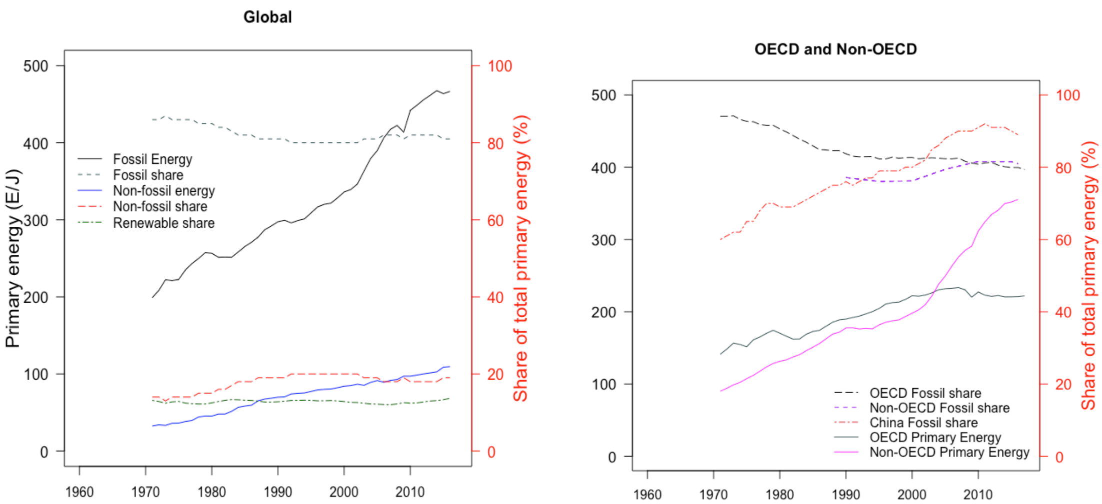


Figure SI- 7. Global, non-OECD, and OECD primary energy 1971-2016

Development in primary energy for the world fossil and non-fossil sources (left), and primary energy supply in OECD and Non-OECD (right) 1971-2016.
Data source: IEA (2018; 2020).

Altogether, China, India, and OECD account for 70% of global fossil fuels and industry CO_2 emissions. Since 2000, small increases in non-fossil sources and efficiencies have caused slow emissions and energy growth in the OECD. Emissions and energy growth in the non-OECD region are dominated by increasing demand for energy from higher rates of economic growth in India and China (International Energy Agency, 2020) and fossil energy investments by G20 countries in low-income regions (Doukas et al., 2017). Developments in fossils/non-fossils primary energy during the most recent low-growth period (2013-2016) emphasize that the most recent emissions slowdown was, in particular, driven by short-term developments in OECD-Asia and China (BP, 2018a; IEA, 2018).

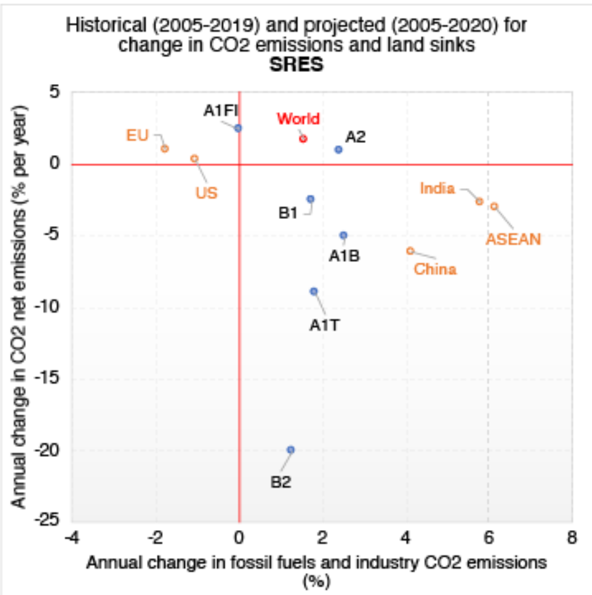
Global primary energy supply grew about 60% from about 230 to 560 EJ/year between 1971 and 2016. The share of non-fossil primary energy sources (nuclear, biomass, and renewables) remained almost unchanged and between 18 to 20%.
During 1990-2016, global bioenergy (waste, biomass, and biofuel) has remained stable at about a 10% share of total primary energy, nuclear declined from 6% to 5%, while hydro (2% to 2.5%). Non-biomass renewables (e.g., geothermal, solar, wind, tide) increased (0.4% to 1.6%).
As illustrated in the main body of this article (Fig.4), primary energy in non-OECD primary energy has increased rapidly since about 2002, while it has been stationary in the OECD countries since 2010. Therefore, non-OECD countries also had the highest average emissions growth rate between 1990-2017. The OECD increase was primarily driven by a change in OECD-Asia with decreases of fossil sources (-3%) and increases in non-fossil (22%). In China, a short-term energy transition materialized in the same period with a decline in fossil (-1%) and an increase in non-fossil (24%). Some smaller changes are identified for OECD-America (-1 fossil /-1% non-fossil), OECD-Europe (-2/+3%), OECD-Asia (-3/+22%), and China (-1/+24%) (IEA, 2018). It is plausible that the energy and emissions stalling in OECD are also caused by changes in global production and trade patterns, redistributing emission sources from the forty or so developed countries to the 150 developing economies and emerging economies such as China (GCP, 2019; Peters et al., 2011).

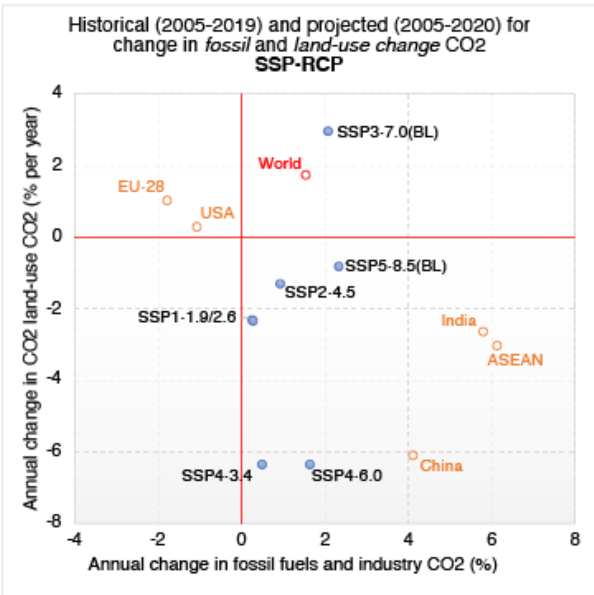
For China, carbon intensity per unit of primary energy supply (CIPES) increased remarkably 1971-1997 (2.2-3.2 $MtCO_2$/mtoe), decreased 1998-2001 (to 2.8 $MtCO_2$/mtoe), followed by increase 2002-2011 (3.4 $MtCO_2$/mtoe), and declined 2012-2016 (3.3 $MtCO_2$/mtoe) (GCP, 2018; IEA, 2018). The recent global emissions slowdown 2013-2016 was characterized by a 2% increase in global primary energy (1% increase in fossil and a 7% increase in non-fossil energy). During this period, non-fossil energy shares changed slightly: from 18 to 19% globally, in the OECD region from 19 to 20%, and non-OECD from 18% to 19%, including China (9 to 10%). The OECD increase was primarily driven by a change in OECD-Asia with decreases of fossil sources (-3%) and increases in non-fossil (22%). A short-term energy transition materialized in China in the same period, with a 1% decline in fossil and a 24% increase in non-fossil (International Energy Agency, 2020).

Past and present projections

Several scenario critiques advocate continuously exploring new possibilities within a scenario series' chosen scenarios to remain science- and policy-relevant, e.g., that some scenario variables like impact-costs (Taconet et al., 2020) or economic growth externalities (Otero et al., 2020) are not yet sufficiently considered in existing SSP-RCPs. On the contrary, models have been critiqued for being too imaginative or over-optimistic, like GDP ranges (Castles and Henderson, 2003a), decarbonization rates (R. Pielke et al., 2008), and NETs (Fuss et al., 2014). Chapter 4 rebutted the GDP critique, while actual global decarbonization of the economy has been faster than the SRES projections (Figure SI- 8, right bottom panel), showing that overoptimistic or very imaginative may not be impossible.

The SSP1-1.9, SSP1-2.6 (global sustainability), SSP2-4.5 (middle of the road) project faster emissions growths than their older equivalents in the previous IPCC scenario generation, the SRES, published in 2000 (Nakicenovic and Swart, 2000). Historical fossil fuel emissions 2005-2019 grew faster than high-emission scenario SRES-A2 (similar to regional rivalry SSP3-7.0) and just below the highest impact scenario SRES-A1FI (fossil-fuel driven growth, similar to SSP5-8.5). Thus, between 2005-2019, the World has developed in a more pessimistic way than projected (expected) by scenario developers two decades ago, and worse than projected in the dynamics as usual or middle of the road scenarios (SSP2, SRES-A2). See SRES projections in Figure SI- 8 (right bottom panel).





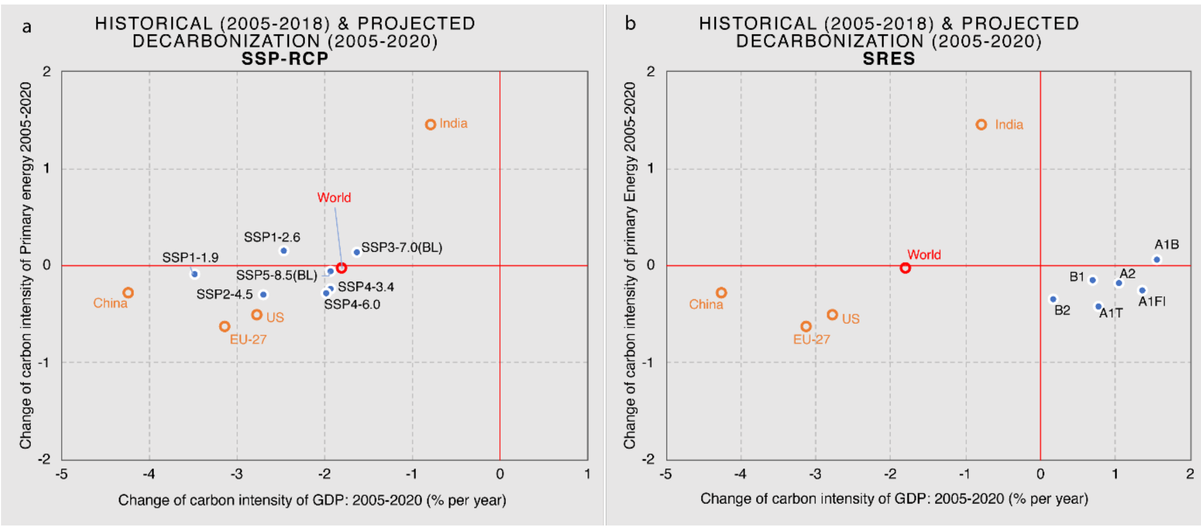


Figure SI- 8. Change in emissions historically and for the global SRES and SSP scenarios (top) and change in decarbonization rates historically and for the global the SRES and SSP scenarios (bottom).

Each scenario series is updated according to historical trends. Thus, it is possible to assess historical change in the light of past projections and assumptions about plausible future developments. Here we see that SRES were less optimistic about technology advances than the SSPs. SSPs assumptions and quantifications are more optimistic since historical developments have been faster than expected/projected. On the other hand, were SRES's emissions projections more positive than actual developments. Historical fossil fuel emissions grew faster than high-emission scenario SRES-A2 (in family with regional rivalry SSP3-7.0) and just below the highest impact scenario SRES-A1FI (in family with SSP5-8.5).

SI 8: Expert interviews: Scenario evolution and critiques (Chapter 3)

SI data for Chapter 3 is available at: IPCC emission scenarios: How did critiques affect their quality and relevance 1990–2022?

Interviewees, interview guides, and survey

Scenario critiques and developments

I conducted ten expert interviews with academic scholars between 2017-2020 from primarily Europe and the United States, presently or formerly involved in the IPCC or directly in the construction of the emissions scenarios, namely:

Table SI- 0-13. Interviewed researchers and scenario developers

No.	Name	Nationality	Scenario development	IPCC author (IPCC session delegate)	UNFCCC delegate	Interview location
	Scenario developers					
1	Dennis Tirpak	United States	SA90	AR1, AR4 (1989)	1992-1995	Skype
2	Pier Vellinga	Netherlands	SA90	*COC: AR1, AR2; *LA: AR3	1989-1992	Skype
3	James Edmonds	United States	SA90, IS92, SRES, SSP/RCP, SR1.5	AR1 to AR6		Denver University (United States); Lisbon (Portugal)
4	Rob Swart (supervisor)	Netherlands	SA90, IS92, SRES	AR1 to AR4		Skype; Lisbon (Portugal)
5	William Pepper	United States	IS92, SRES			Washington D.C. (United States)
6	Ged Davis	United Kingdom	SRES			Skype
7	Detlef van Vuuren (became supervisor later)	Netherlands	RCP, SSP, SR1.5	AR4, AR5		The Hague (Netherlands)
8	Kasper Kok	Netherlands	SSP			Skype
	IPCC authors					
9	Kirsten Halsnæs	Denmark		AR4 & AR5		Copenhagen (Denmark)
10	Filipe Duarte Santos	Portugal		Reviewer: AR5	2000-present	Lisbon (Portugal)
11	Maria Figueroa	Venezuela		AR5 & AR6		Copenhagen (Denmark)
12	Jim Skea	United Kingdom		*LA: 2AR, 3AR; *VC: AR5, SP1.5, AR6		Skype

* Notes: LA: Lead Author, COC: Co-chair, VC: Vice-chair

The interviews served to recall memories and experiences of scenario developers regarding scenario exercises (which is less documented for the SA90), the argumentation and considerations involved in the various developments, and the context (e.g., UNFCCC and IPCC sessions).

Interview persons were selected via their involvement in scenario development and was contacted by either Rob Swart or Jiesper Pedersen. Jiesper conducted the interviews, while Rob was present in one of them. The interviews included several coauthors of this paper. Rob Swart was part of coordinating the paper and content, and during this process we made an in-depth interview. Jae Edmonds and Detlef van Vuuren were interviewed during the development of the paper and were included later in the process, contributing to aspects overlooked, learnings, and discussion aspects. These three authors together cover all scenarios developed to support IPCC assessments 1989-2019(IPCC, 2018a, 1990a; Nakicenovic and Swart, 2000a; Pepper et al., 1992; Riahi et al., 2017; van Vuuren et al., 2011a).

The question guide explored the following topics:

Intro
In you work with scenarios ..
What do you enjoy the most about your work?

What do you intend to achieve from your work? (do you have a mission)

Role and participation in IPCC (or climate governance)
To begin with, I would like to hear something about your involvement and role in IPCC. Which processes (assessments or scenario developments) have you participated in?

	AR1	AR2	AR3	AR4	AR5	AR6
In which Assessment Reports have you participated?						
	SA90	IS92	SRES	RCP	SSP	
In which global scenario development processes?						

Other reports: ___________________

Emission scenario developments
2. Scenario development processes?
  2.1. What do you remember most clearly from the processes? (any particular episode?)
  2.2. What guided the scenario process? (assumptions, aims, focus points?
  2.3. Did you avoid anything in the process? (e.g., assumptions or data?)
  2.4. Did someone group, person, country affect the development process?
  2.5. Did any review comments affect the outcome significantly? What was it about? What was it motivated by/from?

1. 2.6. How will you evaluate the development process (from beginning to end)? Scenario: _______________

Mainly ... bad ☐ ☐ ☐ ☐ ☐ Good
Mainly ... difficult ☐ ☐ ☐ ☐ ☐ Easy

The process was characterized by scientific consensus?
Not at all ☐ ☐ ☐ ☐ ☐ Yes, totally

The process was characterized by disputes/disagreements?
Not at all ☐ ☐ ☐ ☐ ☐ Yes, totally

2.7 Did you experience any special interests from actors in the scenario development work that was motivated by other interests than scientific (for instance personal opinions, viewpoints from national or regional identity)?
2.8. Which things do you remember most clearly? Did it affect the work or result?

3. What do you think about the critique of the scenarios?
SA90
IS92
SRES:
RCP
SSP
What do you think is the most likely scenario?

Emission scenario assessment
4. How will you evaluate the climate scenarios?
4.1. What are their strengths? Weaknesses?
4.2. Have they been applied functionally in science?
4.3. Have they been applied/useful in governance?
4.4. How could the scenarios be improved?
4.5. Which scenario is the most likely?
4.6. What is the main emission driver?

5. How do you feel about Climate Change?

5.1. Are you concerned about the future?
How much are you concerned on a scale from 0-10?
Never 0☐ 1☐ 2☐ 3☐ 4☐ 5☐ x 6☐ 7☐ 8☐ 9☐ 10☐ I think about it almost every day

SI 9: Interviewee, Survey, and interview question guide (Chapter 6)

Semi-structured Interview guide for Policymakers

Table SI- 0-14. Interviewed policymakers and delegates

No.	Name	Nationality	Role	IPCC author (IPCC session delegate)	UNFCCC delegate	Interview location
	Policymakers and researchers					
13	Tom van Ierland	Belgium	Policy enabler /Researcher (EC/DG Climate Action), Former UNFCCC negotiator		2008-2018 Represent EU	Telephone (Brussels)
14	Allen Fawcett	United States	Policymaker/researcher			Interview (Microsoft, Washington DC)
15	Klaus Radunsky	Austria	Delegate Policymaker	IPCC delegate (Austria)	UNFCCC delegate (EU)	Email/Survey
16	Pedro Barata	Portugal	Policy enabler UNFCCC delegate, former negotiator		1999-2020	Survey/Interview (Lisbon, Zoom)
17	Halaze Manhice	Mozambique	Policy advisor National policymaker, associate professor & researcher			Interview (Maputo, Zoom)
	Global South scenario critics and IPCC reviewers					
18	Antonina Ivanova	Bulgaria/Mexico	Researcher Informing policy role	2002- AR4, AR5, AR6 (WC/WG3 2008-2015)		Skype (Skype, La Paz, Mexico)
19	Jyoti Parikh	India	Researcher, guiding policy	IPCC reviewer		Interview (Skype)

The policymaker interviews followed the following semi-structured question guide:

1. Social variables
   S1. What is your nationality
   S2. Your role/occupation (can also be your previous role)
      a. Researcher
      b. UNFCCC Delegate
      c. Politician
      d. Policymaker
      e. Other [which?]

S3. Which country do you represent in intergovernmental processes (e.g., IPCC, UNFCCC)?
    a. IPCC representation: [years/reports],
       Participation in IPCC sessions or other IPCC intergovernmental forums [yes/no, years]
    b. UNFCCC representation: [which years]

2. Main (research) questions
   1. It seems like you know the tool of "**emissions scenarios**" quite well? Is that correct?
      Not at all(1), not really(2), in-between(3), yes(4), yes totally(5)

   2. Do you find the emissions scenario to be policy relevant?
      Not at all(1), not really(2), in-between(3), yes(4), yes totally(5)

   3. Which scenarios do you consider **most** policy-relevant

   4. Other regions/ countries? Do they use scenarios to model for policymaking?
      UNEP, CAT, Others

   5. In which way are emissions scenarios relevant (or not relevant)

      a. Do they support raising awareness of causes / emissions drivers?

      b. Do they provide topics to discuss in negotiations? Do they support specific arguments for or against mitigation in negotiations? Or

         1. Do they support the development of roadmaps/actionable policy options for climate mitigation? Adaptation?

      c. Do they provide topics to implement in international treaties?

      d. Do they provide topics/causes to implement in international national policies?

      e. Do they effectively explore plausible future socioeconomic developments?

   6. Are you satisfied with the emissions scenarios informing the IPCC assessments?
      Not at all(1), not really(2), in-between(3), yes(4), yes totally(5)

   7. What are their weaknesses/strengths?

   8. How can scenarios be improved to support policymaking

   9. How can scenarios be improved to support UNFCCC intergovernmental processes

10. In your perspective, you see the benefits of involving policymakers and stakeholders in scenario development? (yes - no)
    a. There is a risk that it will affect the scenario developments significantly

Not at all(1), not really(2), in-between(3), yes(4), yes totally(5)

    b. There is a risk that it will affect the emission range

Not at all(1), not really(2), in-between(3), yes(4), yes totally(5)

11. Who else should I interview?

Invited Survey Participants

Identification and recruitment of informants

Informants were found via supervisor and co-author network in the IPCC research, national policymaking, and UNFCCC delegate environments. This had characteristics of snowballing sampling. Additionally, national policymakers and delegates in low-income countries were supplemented by the Community of Portuguese Speaking Countries (CPLP) via the NGO "Forúm Energi e Clima" where I have worked as program manager during the final stages of the thesis. To ensure a robust and solid sample and a clear population, the additional invited CPLP participants were not included in the final analysis and results.

Participants were contacted via email and asked to participate and also distribute to relevant colleagues. There exists a list of participants from the latest COP-25 (UNFCCC) without contact information and a list of national focal points with email (between 1-5 delegates per party). There is no easily available data of the delegates' demographic information besides the country they represented. Thus, it was challenging to locate the personal email addresses of delegates, I ended up contacting focal points, and additionally trying to create a linear snowball effect - all focal points distributing to one or more colleagues without asking them to distribute it further to a third or four chain of survey participants. In this case I have I could keep track of the participants, making somewhat sure that participants were recruited from the right population (UNFCCC delegates or national policymakers).

Countries included in the first round (groupings made via experts and literature (WB, 2021)):

- Lower- & middle-income countries:
    - Uganda, Tanzania, Kenya, Mozambique, Madagascar, Guinea-Bissau, Equatorial Guinea, Panama, Uruguay, Honduras, Costa Rica, Cuba, Mexico, Venezuela, Bolivia, Peru, Papua New Guinea.
    - Medium-income: Angola, India, China, Mexico, Brazil.
- Vulnerable Island states:
    - Cape Verde, Sao Tome and Principe, Kiribati, Maldives, Vanuatu.
- High-income:
    - Neutral: Germany, Chile, Denmark, France, Italy, Japan, Czech.
    - Higher-income climate progressors: Netherlands, Spain, Portugal, Sweden
    - Higher-income historically halting UNFCCC negotiations: Australia, USA, Canada, Poland, Hungary.

In data collection round 2, all UNFCCC National Focal points (278 out of 299) between June 11 and 13th, 2021. Twenty-one email addresses were rejected.

Survey questionnaire

(Survey briefing & intro text)
Thank you for participating in our survey!
As an expert in climate change and policymaking, your knowledge is essential to understand the role of scientific knowledge in policymaking in various countries.

Your answers are voluntary, but your opinions are important.

Your responses will remain anonymous and will only be reported in aggregate. Depending on your answers' length, the survey should take between 10 and 18 minutes to complete.

Thank you in advance for your cooperation and insights.
Questions or challenges with the survey? Email: japedersen@fc.ul.pt.

(1/4) Initial questions about you and your role:

A. Your nationality, residence country, and age

Your nationality ____

Your country (the country you represent) ____

Your age ____

B. Regarding your work with climate change, which of the following matches your role (or previous role) the best?

(1) ❑ Researcher

(2) ❑ Policymaker

(3) ❑ Politician

(4) ❑ Stakeholder

(5) ❑ Other (please specify) _____

C. Which of the following best describes your role regarding policymaking?

(2) ❑ Informing role (neutrally informing)

(1) ❑ Following role (e.g., policy wishes are guiding your work/research)

(3) ❑ Advisory role (e.g., guiding policy options)

(4) ❑ Leading role (e.g., forming policies)

(7) ❑ Coordinating policy

(6) ❑ No role

(5) ❑ Other (please specify) _____

F. In your opinion, how important is it to act now and anticipate the future to avoid future events of ...

	Not important	Low importance	Neutral	High importance	Very high importance
Terror	(1) ❑	(2) ❑	(3) ❑	(4) ❑	(5) ❑
Pandemics	(1) ❑	(2) ❑	(3) ❑	(4) ❑	(5) ❑
Climate change-related impacts	(1) ❑	(2) ❑	(3) ❑	(4) ❑	(5) ❑
Biodiversity loss	(1) ❑	(2) ❑	(3) ❑	(4) ❑	(5) ❑

D. Have you participated in IPCC/UNFCCC intergovernmental sessions or other policy activities? (if not, then you can continue to the next question)

	If yes, Please add the years/periods of participation (e.g., "2012, 2015-2019")
In IPCC	_____
UNFCCC	_____
National policymaking	_____
Regional policymaking (e.g., UNASUR, EU, Pacific Affairs)	_____

E. Are you or have you been a UNFCCC negotiator?

(1) ❑ Yes, I am currently a UNFCCC negotiator

(2) ❑ Yes, I am a former UNFCCC negotiator

(5) ❑ I have been a negotiator in another intergovernmental forum (please specify) _____

(3) ❑ No, I have not been

(2/4) Scientific knowledge, policymaking, and emissions scenarios

	Highly delaying policy actions (3)	Moderately delaying (2)	Slightly delaying (1)	Neutral (0)	Slightly driving (1)	Moderately driving (2)	Highly driving policy actions (3)
a. Scientific knowledge about climatic changes in the future	(1) ❑	(2) ❑	(3) ❑	(4) ❑	(5) ❑	(6) ❑	(7) ❑
b. Recorded national climate-related impacts/catastrophes	(1) ❑	(2) ❑	(3) ❑	(4) ❑	(5) ❑	(6) ❑	(7) ❑
d. Economic assessments of the cost of national mitigation actions vs. no-action	(1) ❑	(2) ❑	(3) ❑	(4) ❑	(5) ❑	(6) ❑	(7) ❑

	Highly delaying policy actions (3)	Moderately delaying (2)	Slightly delaying (1)	Neutral (0)	Slightly driving (1)	Moderately driving (2)	Highly driving policy actions (3)
c. Economic assessments of future climate-related impacts	(1) ❑	(2) ❑	(3) ❑	(4) ❑	(5) ❑	(6) ❑	(7) ❑
e. Voter's interests (e.g., national public opinion)	(1) ❑	(2) ❑	(3) ❑	(4) ❑	(5) ❑	(6) ❑	(7) ❑
f. Public media debate	(1) ❑	(2) ❑	(3) ❑	(4) ❑	(5) ❑	(6) ❑	(7) ❑
g. Advocacy/interests of NGO's	(1) ❑	(2) ❑	(3) ❑	(4) ❑	(5) ❑	(6) ❑	(7) ❑
h. Advocacy/interests of fossil energy industries	(1) ❑	(2) ❑	(3) ❑	(4) ❑	(5) ❑	(6) ❑	(7) ❑

1. In your opinion, which of the below factors is either "Delaying" (left) or "Driving" (right) climate mitigation policy actions (emissions reductions) in your country?

(1) What is the most important driver? (Has anything changed over time?)

____

____

2. In a national context, which of the following types of "Scientific knowledge" are useful to design "mitigation (emission reduction) policies" in your country?
Assessments of ...

	Not at all	Not really (to a low degree)	In-between (maybe)	Yes, to some degree	Yes, to a high degree
.. possible future temperature rises and climatic changes (e.g., climate scenarios)	(0) ❑	(1) ❑	(2) ❑	(3) ❑	(4) ❑
.. possible future climate change-related impacts (e.g., impact scenarios)	(0) ❑	(1) ❑	(2) ❑	(3) ❑	(4) ❑
.. possible future socioeconomic developments and emissions trends (e.g., emission scenarios)	(0) ❑	(1) ❑	(2) ❑	(3) ❑	(4) ❑
.. recommended policy actions and their time estimates (e.g., roadmaps)	(0) ❑	(1) ❑	(2) ❑	(3) ❑	(4) ❑
.. economic costs of future climate-related impacts	(0) ❑	(1) ❑	(2) ❑	(3) ❑	(4) ❑
.. economic costs of mitigation actions vs. no-action	(0) ❑	(1) ❑	(2) ❑	(3) ❑	(4) ❑

(2) How can scientific knowledge be improved to better support NATIONAL policymaking?

____

3. Emission scenarios (some people know them, and others don't): Honestly, how well do you know the scientific tool of emission scenarios?
Description: Emissions scenarios describe future pathways and projections of future global socioeconomic developments and associated greenhouse gas emissions in, for instance, 2030, 2040, 2050, and 2100.

(1) ❑ No, I don't know them at all

(2) ❑ Not really (I may have heard about them)

(3) ❑ In-between (I have heard about/seen them but not sure what they express)

(4) ❑ Yes, I know them (I have seen them and know a little about the variables included)

(5) ❑ Yes, I know them very well (I know several variables and what the scenarios express)

(6) ❑ I participated in the developments of some scenario series

4. In a national context, have the "emission scenarios" used in IPCC assessment reports been policy-relevant? (e.g., supported designing national mitigation policies in your country?)

	Not at all	Not really (to a low degree)	In-between (maybe)	Yes, to some degree	Yes, to a high degree	I don't know
SA90 (informing the 1st IPCC Assessment Reports (1990))	(1) ❑	(2) ❑	(3) ❑	(4) ❑	(5) ❑	(6) ❑
IS92 (informing the "IPCC 1992-supplementary report" & "2nd IPCC Assessment Reports (1995)")	(1) ❑	(2) ❑	(3) ❑	(4) ❑	(5) ❑	(6) ❑
SRES (informing the 3rd & 4th IPCC Assessment Reports (2001 & 2007))	(1) ❑	(2) ❑	(3) ❑	(4) ❑	(5) ❑	(6) ❑
RCPs (informing the 5th IPCC Assessment Reports (2013/2014))	(1) ❑	(2) ❑	(3) ❑	(4) ❑	(5) ❑	(6) ❑
SP1.5 pathways (IPCC special report 2018)	(1) ❑	(2) ❑	(3) ❑	(4) ❑	(5) ❑	(6) ❑
SSP-RCP combinations (informing the 6th IPCC Assessment Reports (planned 2021))	(1) ❑	(2) ❑	(3) ❑	(4) ❑	(5) ❑	(6) ❑

(4) How do they support (or don't support) national policymaking?

____

5. Have scenario series (outside the IPCC context) been policy-relevant, e.g., been useful for national policymaking?

	Not at all	Not really (to a low degree)	In-between (maybe)	Yes, to some degree	Yes, to a high degree	I don't know
UNEP Emission gap reports 2013-2019 (policy assessments/assessing National Determined Contributions (NDCs) & Paris targets)	(1) ❑	(2) ❑	(3) ❑	(4) ❑	(5) ❑	(6) ❑
Climate Action Tracker (policy assessments of NDCs & Paris targets)	(1) ❑	(2) ❑	(3) ❑	(4) ❑	(5) ❑	(6) ❑
IEA (International Energy Agency) scenarios	(1) ❑	(2) ❑	(3) ❑	(4) ❑	(5) ❑	(6) ❑

6. Emissions scenarios would become more policy-relevant (e.g., support national policymaking) ...

	No, incorrect	No, it is partly incorrect	In-between (maybe)	Yes, it is partly correct	Yes, it is correct
1. If the emission scenarios, their variables, and storylines were communicated more simplistic? (e.g., making it easier to understand which different futures they express)	(1) ❑	(2) ❑	(3) ❑	(4) ❑	(5) ❑

	No, incorrect	No, it is partly incorrect	In-between (maybe)	Yes, it is partly correct	Yes, it is correct
2. If the emission scenarios were less complex to implement in policy analyzes (i.e., my country needs expertise/knowledge to understand & use scenarios)	(1) ❑	(2) ❑	(3) ❑	(4) ❑	(5) ❑
3. If the emission scenario output data were less demanding to process (i.e., my country needs computer capacity to use scenarios)	(1) ❑	(2) ❑	(3) ❑	(4) ❑	(5) ❑
4. If scientists identify best guess scenarios? (e.g., the most likely futures)	(1) ❑	(2) ❑	(3) ❑	(4) ❑	(5) ❑
5. If policymakers were included in the emission scenario development process? (e.g., participated in scenario planning meetings)	(1) ❑	(2) ❑	(3) ❑	(4) ❑	(5) ❑
6. If policymakers were included in the emission scenario development process? (e.g., participated in scenario planning meetings)	(1) ❑	(2) ❑	(3) ❑	(4) ❑	(5) ❑

(6) How can emission scenarios be improved to be more policy-relevant? (e.g., to be applicable in national policies)

____

(3/4) Evaluating the relevance of scientific knowledge in the ”UNFCCC” context
(UNFCCC: United Nations Framework Convention on Climate Change)

7. In the context of UNFCCC, which of the below factors are either "Delaying" (left) or "Driving" (right) UNFCCC negotiations towards international climate treaties?

	Highly delaying policy actions (3)	Moderately delaying (2)	Slightly delaying (1)	Neutral (0)	Slightly driving (1)	Moderately driving (2)	
Scientific knowledge about climatic changes	(1) ❑	(2) ❑	(3) ❑	(4) ❑	(5) ❑	(6) ❑	(7) ❑
Recorded historical climate-related events/catastrophes	(1) ❑	(2) ❑	(3) ❑	(4) ❑	(5) ❑	(6) ❑	(7) ❑
Economic assessments of the cost of mitigation (emission reduction) actions vs. no-action	(1) ❑	(2) ❑	(3) ❑	(4) ❑	(5) ❑	(6) ❑	(7) ❑
Economic assessments of future climate-related impacts	(1) ❑	(2) ❑	(3) ❑	(4) ❑	(5) ❑	(6) ❑	(7) ❑
Public opinion (voter's interests)	(1) ❑	(2) ❑	(3) ❑	(4) ❑	(5) ❑	(6) ❑	(7) ❑
Public media debate	(1) ❑	(2) ❑	(3) ❑	(4) ❑	(5) ❑	(6) ❑	(7) ❑
The interests/advocacy of NGO's	(1) ❑	(2) ❑	(3) ❑	(4) ❑	(5) ❑	(6) ❑	(7) ❑
The interests/advocacy of fossil energy industries	(1) ❑	(2) ❑	(3) ❑	(4) ❑	(5) ❑	(6) ❑	(7) ❑

(7) What is the most important driver? (Has anything changed over time?)

____

8. In the context of UNFCCC, which of the following types of "Scientific knowledge" are applicable (supportive) to design international climate treaties?
Assessments of ...

	Not at all	Not really (to a low degree)	In-between (maybe)	Yes, to some degree	Yes, to a high degree
.. possible future temperature rises and climatic changes (e.g., climate scenarios)	(0) ❑	(1) ❑	(2) ❑	(3) ❑	(4) ❑
.. possible future climate change-related impacts (e.g., impact scenarios)	(0) ❑	(1) ❑	(2) ❑	(3) ❑	(4) ❑
.. possible socioeconomic developments and the related emissions trends (e.g., emission scenarios)	(0) ❑	(1) ❑	(2) ❑	(3) ❑	(4) ❑
.. recommended policy actions and their time estimates	(0) ❑	(1) ❑	(2) ❑	(3) ❑	(4) ❑
.. economic costs of future climate-related impacts	(0) ❑	(1) ❑	(2) ❑	(3) ❑	(4) ❑
.. economic costs of mitigation (emission reduction) actions vs. no-action	(0) ❑	(1) ❑	(2) ❑	(3) ❑	(4) ❑

(8) How can scientific knowledge be improved to better support UNFCCC processes? (Is anything needed?)

____

9. Have some of the below emission scenarios been relevant for UNFCCC negotiations?

	Not at all	Not really (to a low degree)	In-between (maybe)	Yes, to some degree	Yes, to a high degree	I don't know
SA90 (informing the 1st IPCC Assessment Reports (1990))	(1) ❑	(2) ❑	(3) ❑	(4) ❑	(5) ❑	(6) ❑
IS92 (informing the "IPCC 1992-supplementary report" & "2nd IPCC Assessment Reports (1995)")	(1) ❑	(2) ❑	(3) ❑	(4) ❑	(5) ❑	(6) ❑
SRES (informing the 3rd & 4th IPCC Assessment Reports (2001 & 2007))	(1) ❑	(2) ❑	(3) ❑	(4) ❑	(5) ❑	(6) ❑
RCPs (informing the 5th IPCC Assessment Reports (2013/2014))	(1) ❑	(2) ❑	(3) ❑	(4) ❑	(5) ❑	(6) ❑
SP1.5 pathways (IPCC Special Report 2018)	(1) ❑	(2) ❑	(3) ❑	(4) ❑	(5) ❑	(6) ❑
SSP-RCP combinations (informing the 6th IPCC Assessment Reports (planned 2021))	(1) ❑	(2) ❑	(3) ❑	(4) ❑	(5) ❑	(6) ❑
UNEP Emission gap reports 2013-2019 (policy assessments of NDCs)	(1) ❑	(2) ❑	(3) ❑	(4) ❑	(5) ❑	(6) ❑
Climate Action Tracker (policy assessments of NDCs)	(1) ❑	(2) ❑	(3) ❑	(4) ❑	(5) ❑	(6) ❑
International Energy Agency scenarios	(1) ❑	(2) ❑	(3) ❑	(4) ❑	(5) ❑	(6) ❑

(9) How do emission scenarios support UNFCCC processes? (Or why don't they support)

____

10. The scenarios reaching the 2 °C target (RCP2.6) and 1.5 °C target (SSP1-1.9 & the SP1.5 pathways) include mitigation assumptions of "Negative Emissions Technologies (NETs)".
In your perspective, do these assumptions distract policy actions (e.g., delay real current mitigation actions)?
NETs cover various technologies such as BECCS (bioenergy with carbon capture and storage) CDR

(and carbon dioxide removal) to remove CO2 from the air. These technologies are not yet realized, developed, or made it possible to implement on the large scale as required to reach the 1.5 or 2-degree targets.

(1) ❑ Yes, It has distracted negotiations and postponed current actions

(2) ❑

(3) ❑

(5) ❑ Neutral (It has not distracted or delayed the negotiations)

(4) ❑

(6) ❑

(7) ❑ No, It has inspired and strengthened current actions

(8) ❑ I haven't heard about NETs

(10)

(1) ❑ I never heard about NETs

(2) ❑ I heard about NETs

(3) ❑ I know the concept of NETs

(10) You are welcome to explain which advantages or complications NETs have for future policies:

____

(4/4) Climate mitigation policy

11. Do you agree or not agree?

	No, it is incorrect	No, it is partly incorrect	In-between (maybe)	Yes, it is partly correct	Yes, it is correct
1. The mitigation policies formulated by my country (the country I represent) are possible to implement in practice?	(1) ❑	(2) ❑	(3) ❑	(4) ❑	(5) ❑
2. The country's institutions have the capacity to implement them?	(1) ❑	(2) ❑	(3) ❑	(4) ❑	(5) ❑
3. The country has the technology to implement the stated law/policy effectively?	(1) ❑	(2) ❑	(3) ❑	(4) ❑	(5) ❑
4. The NDC of my country will be implemented	(1) ❑	(2) ❑	(3) ❑	(4) ❑	(5) ❑

12. Politicians in your country would be more motivated to implements mitigation policies if ...

	No, it is incorrect	No, it is partly incorrect	In-between (maybe)	Yes, it is partly correct	Yes, it is correct
.. they are informed about the cost of mitigation actions vs. no-action?	(1) ❑	(2) ❑	(3) ❑	(4) ❑	(5) ❑

	No, it is incorrect	No, it is partly incorrect	In-between (maybe)	Yes, it is partly correct	Yes, it is correct
.. they are informed about national climate change impacts & costs in the near-term future (e.g., 2030/2040)?	(1) ❑	(2) ❑	(3) ❑	(4) ❑	(5) ❑
.. they are informed about climate change impacts & costs in the long-term future (e.g., 2070/2080)?	(1) ❑	(2) ❑	(3) ❑	(4) ❑	(5) ❑
.. the voters request mitigation action?	(1) ❑	(2) ❑	(3) ❑	(4) ❑	(5) ❑

(11 & 12) You are welcome to explain the above answers (and to add final reflections)

____

Thank you very much for your participation!
(Feel free to distribute the survey link to relevant contacts)

Please add your email if you want preliminary results:

_____

Survey coding

The following questions (their answers) were transformed into nominal (classification) or ordinal (ordering) variables. Coding values are shown in the tables below.

Table SI- 0-15. Coding of Likert scale survey questions

Question A

Categories for Analyses	Multiple choice answers: Nominal variable (classification)	Ordinal variable (ordering)
High-income & low-income countries	EU, US, China, Brazil	(2)
	Remaining	(1)
Non-OECD & OECD regions	Non-OECD	(1)
	OECD	(2)
Climate halter & climate progressor	Progressor (small island states, Spain, Portugal, Netherlands, Sweden)	(3)
	Middle (Germany, Denmark, France)	(2)
	Halter (US, China, Poland, Hungary, Brazil)	(1)

Question B

Categories for Analyses	Multiple choice answers: Nominal variable (classification)	Ordinal variable (ordering)
Researcher vs. no-researcher	Researcher	(1)
	Policymaker	(2)
	Other + guiding, forming or leading policy (**Question C** – see below)	(2)
	Stakeholder	(3)
	Other + following policy = stakeholder	(3)
Researcher vs policymaker	Researcher	(1)
	Policymaker	(2)
	Stakeholder	(0)
	Other	Depending on qualitative answer:

		(0) if no policy tasks (2) If the respondent indicates having policy tasks (e.g., policy advisor, negotiator)

Question C: Which of the following best describes your role regarding policymaking?

Multiple choice answers: Nominal variable (classification)	Ordinal variable (ordering)
1 No role / 1 role	(1)
2 Informing role (neutrally informing) / Informing role (3ly informing)	(2)
3 Following role (e.g., policy wishes are guiding your work/research)	(3)
4 Advisory role (e.g., guiding policy options)	(4)
5 Leading role (e.g., forming policies)	(5)
6 Coordinating policy	(5)

Question F

Multiple choice answers: Nominal variable (classification)	Ordinal variable (ordering)
5 Very high importance	(1)
4 High importance	(2)
3 Neutral	(3)
2 Low importance	(4)
1 Not important	(5)

Question 1 & 7

Highly delaying policy actions (3)
Moderately delaying (2)
Slightly delaying (1)
Neutral (0)
Slightly driving (1)
Moderately driving (2)
Highly driving policy actions (3)

Question 2, 4, 5, 8, 9

Yes, to a high degree (5)
Yes, to some degree (4)
In-between (maybe) (3)
Not really (To a low degree) / Not really (2)
Not at all (1)
I don't know (0)

Question 3

Multiple choice answers: Nominal variable (classification)	Ordinal variable (ordering)
I participated in the developments of some scenario series	(6)
Yes, I know them very well (I know several variables and what the scenarios express)	(5)
Yes, I know them (I have seen them and know a little about the variables included)	(4)
3 (I have heard about/seen them but not sure what they express)	(3)
Not really (I may have heard about them)	(2)
No, I don't know them at all	(1)

Question 6, 11, 12

Yes, it is correct (5)
Yes, it is partly correct (4)
In-between (maybe) / In-between (3)
No, partly incorrect (2)
No, it is incorrect (1)

Question 10

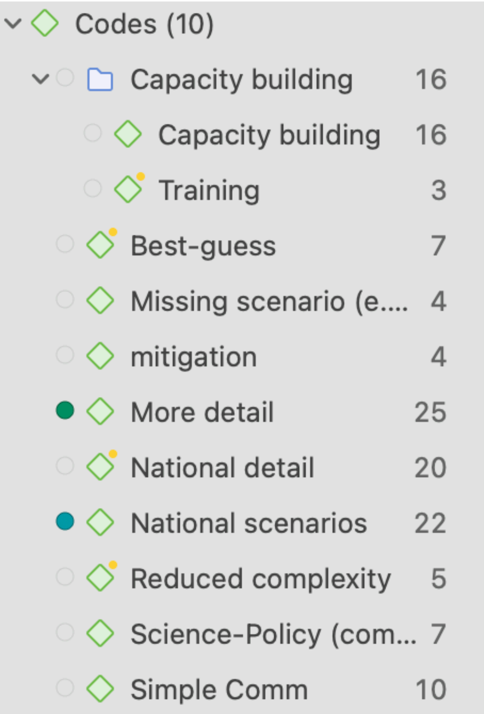
Multiple choice answers: Nominal variable (classification)	Ordinal variable (ordering)
1 Yes,	(1)
2	(2)
3 (3)	(3)
4 Neutral (It has not distracted or delayed the negotiations)	(4)
5	(5)

6	(6)
7 No, It has inspired and strengthened current actions	(7)
4 I haven't heard about NETs	(4)

Coding of open-ended questions

The answers to the open-ended questions (attached to Q1, Q2, Q4, Q6, Q7, Q8, Q9, Q10, and Q11/12) were exported to the Atlas.it software via a Word document. Here they were coded according to various topics. The final topics and how many participants addressed them are expressed in Figure SI- 9 (Figure SI- 9each topic was counted once per participant). For example, a request for "Simpler communication" (Simple Comm) was addressed by ten participants, while 22 participants requested a need for "national scenarios".

Figure SI- 9. Coding and quantification of topics addressed in the open-ended questions. Software: Atlas.it



P-values: variable correlation and sample t-tests

Simple linear regression results conducted for this analysis can be found in Table SI- 0-16. The results indicate that high scenario familiarity is associated with higher perceived relevance of emissions scenarios to a statistically significant level for national policymaking (to the 5% level, p-value = 0.0389) and the UNFCCC context (to the 10% level, p-value = 0.095). When evaluating the HDC sample participants, no statistically significant relationships are found. However, the LDC & MDC sample participants exhibit a statistically significant relationship between high scenario familiarity and the relevance of emissions scenarios for the UNFCCC context to the 10% level (p-value = 0.0708).

Table SI- 0-16. Simple Linear Regression Results

Sample Group	Y variable	X variable	Coefficient of X variable	P-value
All sample participants	Emissions Scenario relevance – National Policy Context	High Scenario familiarity Indicator	0.7330	0.0389
HDC sample participants	Emissions Scenario relevance – National Policy Context	High Scenario familiarity Indicator	0.3750	0.39
LDC & MDC sample participants	Emissions Scenario relevance – National Policy Context	High Scenario familiarity Indicator	0.7500	0.149
All sample participants	Emissions Scenario relevance – UNFCCC Policy Context	High Scenario familiarity Indicator	0.5437	0.095
HDC sample participants	Emissions Scenario relevance – UNFCCC Policy Context	High Scenario familiarity Indicator	0.1875	0.732
LDC & MDC sample participants	Emissions Scenario relevance – UNFCCC Policy Context	High Scenario familiarity Indicator	0.7857	0.0708

A two-sample t-test aims to compare the means of two independent groups or samples to determine if there is a statistically significant difference between them. The null hypothesis (H0) states no difference between the means, while the alternative hypothesis (H1) states a difference.
In a two-tailed (two-sided) t-test, the alternative hypothesis does not specify the direction of the difference. It simply states that there is a difference between the means. This type of test is appropriate to detect any difference between the groups, whether an increase or a decrease. The p-value obtained from a two-sided t-test represents the probability of observing a difference as extreme or more extreme than the one obtained if there were no differences between the means. In a one-tailed t-test, the alternative hypothesis is specific about the direction of the difference between the means. Here the t-tests show no significant change between the population and sample group at a 1% level (P-value: 0.0114) and UNFCCC country Annex distribution and the sample Annex distribution at a 5% level (0.383). The sample and population groups appear different considering income distribution/development level.

Table SI- 0-17. Two-Sample t-test results

Sample Group; n=57	Reference group	X variable	P-value (1-tailed)	P-value (2-tailed)
All sample participants	Population (invited UNFCCC Focal Points); N=299	Annex-I, non-Annex-I distribution	0,0114	0,02288
All sample participants	Population (invited UNFCCC Focal Points); N=299	LDC, MDC, HDC distribution	0,4681	0,9363
All sample participants	Distribution of UNFCCC Parties; 196 states	Annex-I, non-Annex-I distribution	0,0324	0,0648
All sample participants	Distribution of UNFCCC Parties; 196 states	LDC, MDC, HDC distribution	0,3828	0,7655

SI 10: Method description and reflections (Chapters 3 & 6)

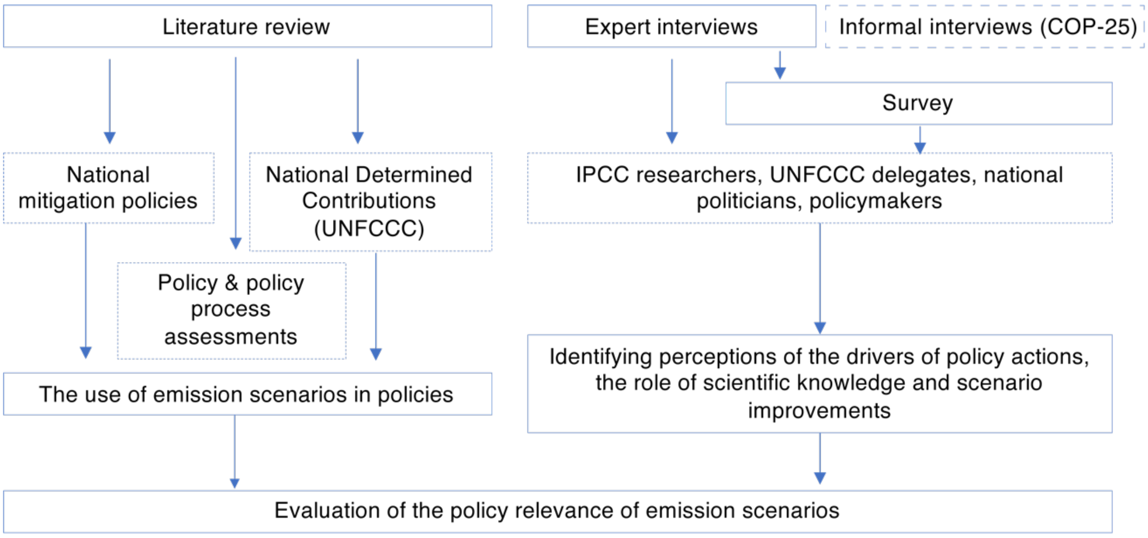


Figure SI- 10. Framework for evaluating the policy relevance and actionability of emission scenario series via interviews and survey (RQ 3).

Archival approach: Literature review

Literature review assessing UNFCCC background papers of the various COPs leading to the NDCs and their evaluations via www.UNFCCC.ch. This also includes literature analyzing the development of the climate regime, the Paris and Kyoto Treaties, and the processes leading to the treaties (e.g., Dimitrov, 2016; e.g., Oberthür and Ott, 1999c). Additionally, I reviewed climate mitigation policies and GDP, energy, and emissions forecasts from the major global emitters US, EU, India, and China.

A limited number of literature sources deal with the dynamics during intergovernmental processes. The intergovernmental processes and negotiations are, to some degree, documented (UNFCCC, 2008). However, they often reveal formal and approved information about the outcome of processes and very little about the actual dynamics during the meetings. To a lesser degree, the processes of national policymaking are documented and described in the literature. Thus, I conducted interviews, participant observation, and survey methods to open the hidden knowledge base of policy experts and UNFCCC delegates (and stakeholders, becoming increasingly crucial for mitigation (Nature)).

Qualitative approach

Expert Interviews

Supplementary to the literature and historical analysis, I conducted six semi-structured interviews with policymakers and researchers with the scenario and IPCC experience from the EU, Mexico, India, and the US. The interviews aimed to explore the knowledge base of policymaker experiences and researchers’ views on emission scenarios in a political and policymaker context.

All policymaker interviews were conducted online via Zoom or Skype between March and May 2020 (during the Covid-19 lockdown). The interview structure was based on an interview guide developed via insights from literature critiques and policy papers.

The interviews aimed to explore the experiences and opinions of experts engaged in policy, focusing on perceptions and work practices related to the use of scientific knowledge and the potential use of emissions scenarios in policymaking and UNFCCC negotiations. Therefore, I interviewed Policymakers (2), UNFCCC delegates (3), and IPCC authors and scenario developers with intergovernmental experience (2) to explore similarities and differences between the science and policy communities. One delegate replied to the questions via email. I additionally interviewed a Minister at COP-25 in Madrid in December 2019. These also served to develop the survey questionnaire.

Informal interviews and participant observation at COP-25 (2019)

Since a limited number of literature sources deal with the dynamics of UNFCCC negotiations, I participated in COP-25 via an invitation from the Portuguese delegation (I was not an official member of the delegation (UNFCCC, 2019b). The participant observation in COP-25 was a perfect method to observe and analyze negotiations (e.g., the arguments and positions of various countries and topics at stake) and conduct informal interviews. It aimed to approach and catch a wide variety of delegates. Delegates were encountered randomly at meetings and evaluating the process after sessions, at cafeterias for lunch or coffee, at side events at country pavilions, and in the metro to and from the venue.
The approach was open and informal, inspired by grounded theory (Charmaz, 2017; Martin and Turner, 1986), seeking to make delegates openly reveal (Bundgaard et al., 2018) how they perceived the negotiations and progress, their countries aim, hopes, and disappointments, as well as the use of scientific knowledge (and scenarios). In informal interviews, I ensured that the conversations were natural, e.g., no straightforward question guide (Spradley, 1979), making them take various directions and address various unintended topics. As such, the participant observation gave another type of on-location insights, less accessible via the formalized interview (Hastrup et al., 2003).

My participation was moderate (Spradley, 1980). I had the status of "Party delegate" and thus access to official negotiations, but not closed meeting sessions (e.g., for the EU or informal negotiations between parties). I had no right to speak or express my opinion at meetings formally. Nevertheless, I observed debates, discussions on the key topic, paragraph 6 (carbon market), climate financing, various sum-up sessions, and side events of several Small Island events, African, Asian, and Latin American countries. I also talked to delegates and ministers from higher-, middle-, and lower-income regions.
The status as a delegate rather than an observer was essential for my field position. It made a difference for the interviews since I had the same status as my informants and the same types of access, rather than a (lower) status and less access to meetings, e.g., as an observer status. I believe this made talks easier, e.g., informants may be less suspicious about hidden agendas from Observer participants (Positioning was stated and highlighted in colors on the official name tags).

Interview coding

The notes were taken via and after interviews (shared with informants) and were coded using Nvivo (time-consuming) and Word (tables and maps). It involved several corresponding steps. I began the initial *open coding* process immediately after I had conducted my first interviews. In this process, common themes and topics were identified, such as "researcher despair towards politicians and missing mitigation actions", "vested interests", including the role of the fossil fuel industry, and "IPCC intergovernmental challenges related to mandates". For the second round of interviews, other questions were asked related to the role of emission scenarios in policymaking. I identified topics like "limited world views", "North-South assumptions", and "politicians having low mitigation interest". I then explored alternative takes on the data (Charmaz, 2017). I produced several maps before (literature review) and parallelled them with my coding process. Taking as a point of departure, the maps containing the participants' situational experiences of emission scenarios and critiques and development (interview round 1) and policy relevance and actionability (round 2) supported an initial, messy overview of my data (Atkinson and Coffey, 2003).

Table SI- 0-18. Example of initial mapping (combining modeler/researcher & policymaking interviews)

MITIGATION	ASSUMPTIONS	VESTED INTERESTS	POLICY ASSUMPTIONS	SCENARIO USE IN POLICY
Lower-income countries need to reduce drastically	NETs divide delegates	Fossil industry	Fixed policy is not a reasonable assumption	IPCC defines Net-zero by 2050 target
Politicians not interested	Stakeholders do not believe in NETs	Voters difficult to let go of existing comfort	Lots of different uses for baselines	CAT & UNEP informed national policy scenarios in North
Voters' interest is important		North-South	Low-income need to grow	IEA not used
Short-term focus	Population (+GDP) has become essential in Africa and India	Economic development	Low-income need tech support	
Researcher frustration			Missing: Institutional capacity (in lower income)	
Accountability of historical emissions				

I returned to the mapping technique several times during data processing to support the disclosure of new themes and process interviews in a "fresh way". It intended to provoke a deeper analytical exploration of my data (Clarke, 2005: 83), and I designed survey questions to explore literature and interview viewpoints in the broader population. I drew relational maps when the interviews were completed (Figure SI- 11). It linked different elements, including scenario assumptions, actors (politicians, policymakers, voters/public opinion), policy halters-drivers, climate financing/international cooperation, etc., discursive and symbolic components, constituting participants' accounts of policy processes. Here, I made comparisons across interviews within and between interview rounds and synthesized a growing body of data (Charmaz, 2017).

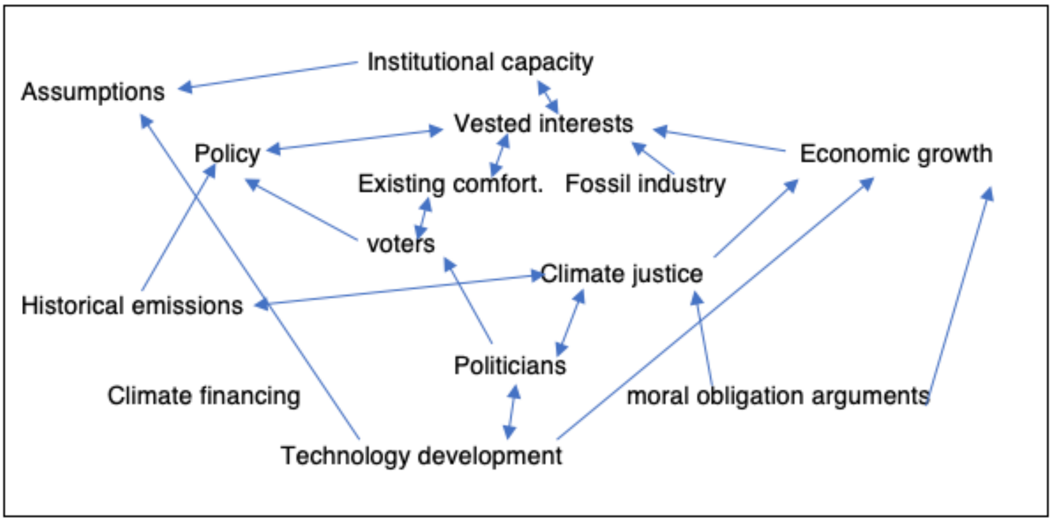


Figure SI- 11. Relational mapping – initial stage (policymaker interviews, March-May 2020)

Quantitative approach: Survey

A survey in English and Portuguese was distributed via email to the first 131 participants - 113 UNFCCC focal points (including 7 UNFCCC delegates and non-focal points), 15 researchers and policymakers partly recommended by supervisors (6), and 17 researchers, policymakers, and UNFCCC delegates representing the nine CPLP countries and recommended by the NGO Energy and Climate Forum working with these countries. It included two reminders. Second, I sent a similar email to all UNFCCC National Focal Points (299) representing 196 Parties. Participants could respond via a link in the email to an online survey generated in SurveyXact.

The survey aimed to investigate researchers', policymakers', and stakeholders' perceptions of climate policymaking and the use of science (and scenarios). The survey contained close-ended (multiple choice) and open-ended questions. The first to provide quantifiable data for cross-comparisons. The second was designed to produce a meaningful answer and create rich, qualitative data using the subject's own knowledge, experiences, and feelings.

To make the survey clear and concise, I used five-point (56 questions) and seven-point (3) Likert scale items (36 questions) and multiple-category replies for social variables (8). Social variables included age, policy, intergovernmental experience, overall role (researcher, stakeholder, politician, policymaker, other), role in policymaking (following, informing, advisory, coordinating, leading, no role), and knowledge about emission scenarios.

The survey is replicable. The questions were tested by researchers (3) and delegates (2) to ensure that non-ambiguous, simple, and neutral questions were written in easy-to-understand language to ensure answer reliability. It was done to increase reliability, that informants perceive and answer the same questions.

Residents were first asked to evaluate which factors drive vs. halt national climate policies and UNFCCC negotiations (e.g., the weighted importance of science compared to other factors, such as voters, public opinion, and advocacy). The key topics concerned: the actionability of various types of scientific knowledge (in national policymaking and UNFCCC negotiations), suggested scenario improvements, and complications. Finally, they were asked about policy implementation in their country. The data was processed in Excel, SPSS, and R.

Survey Coding

I transformed the survey answers for statistical analyses. I added labels to the values of social variables (e.g., country, role in policymaking, researcher/policymaker), obtaining a **factor** or **classification** (*nominal variable*). For the multiple-choice Likert scale questions containing experiences and/or opinions (e.g., the use of scenarios), I added labels to the values of the variables' answers to obtain an ordered factor (*ordinal variable*) ranging from 1 to 5 (Agresti and Finlay, 1997).

Analyzing Likert Scale data

The question responses were designed as Likert scale responses (mainly five-point, but also one seven-point (NETs)). It is a broadly used method for scaling responses in survey studies. Participants are invited to indicate their level of agreement, from "strongly agree" to "strongly disagree". Although commonly used (Carifio and Perla, 2008), statisticians have debated how to analyze the outcome – e.g., using parametric or nonparametric tests (Joshi et al., 2015). An advantage of a nonparametric test is that they don't require that the data follow a normal distribution. However, statistical hypothesis tests are more often analyzed via parametric tests.

Survey method reflections

To explore the perspective of policymakers, a survey is an excellent research method where you may get information from a comprehensive share of the global population of policymakers via their responses to questions. Typically, a policymaker has limited time and a packed annual calendar, which became apparent during interviews, setting them up, and talking at COP-25 in Madrid. Thus, a survey is a comprehensive method to reach broad and explore if views presented during interviews are represented more broadly in the population. An example is that scenario policy assumptions do not sufficiently cover institutional capacity and complications in the South. Two researchers from low/medium countries stated that the statements covered a large share of the interview sample but not necessarily a viewpoint represented in the broader population. A survey can further examine to which degree such opinion is shared by other South researchers (and policymakers). However, presented broadly or not, the history of scenario critiques shows that sometimes a few researchers have discovered a shortfall which, via their critique becomes broadly acknowledged.

The survey practices standardized procedures, meaning that each survey participant is asked the same questions in the same format. The questions in a survey are usually about opinions, beliefs, and attitudes, e.g., the use and relevance of scientific knowledge within UNFCCC and, in national policymaking, ideas for improvement of that knowledge. These are supplemented by demographics, like age, country, level of responsibility (i.e., UNFCCC negotiator or country representative), years of IPCC or UNFCCC experience, and role in policymaking (informing, following, etc.).

Data collection reflections

The data collection methodology is not a *convenience sampling* since there are required criteria for being part of the sample (being engaged in policymaking as a researcher, national policymaker, or UNFCCC delegate). However, the inclusion of survey participants is simplified, i.e., less easy to track the identity of the participants recruited by focal points. However, judging by the number of participants, it appears most participants received an email directly from me (and did not distribute or had the luck to recruit colleagues).

The advantages of Snowball Sampling are that the method may quickly track and find participants recommended via reliable sources. Thus, it was time and economically efficient. Additionally, climate policy is a potentially sensitive topic, e.g., alliances with different parties and obligations to the country and government that the delegates and policymakers (and researchers) represent. Thus, some potential participants may not want to come forward and participate in research studies (e.g., an interview) because they don't want their identity to be exposed. An example is that some interviewees, who came forward, specifically said they didn't want to be quoted if they, e.g., stated that their party/country's politicians were not interested in making mitigation policies. In this case, they could be identified without publicly exposing their opinion. For the survey, Snowball sampling supports such wishes or needs. Via recruitment, the method may also create, as participants are asked to participate by people they trust since the population consists of people with a tight schedule. The response rate increased when I sent a personal email, writing that they were recommended by one of their colleagues or supervisors.

Some disadvantages of Snowball Sampling are **sampling bias** or **margin of error** in case the focal points refer to those they know and have similar traits. This creates a possibility that the sample may be biased. However, the sample may also be biased toward highly engaged policymakers (Pedersen and Manhice, 2020) in climate policies. On the other hand, less engaged participants or delegates in favor of less policy regulation may have less interest in participating since they participate in the COPs for other reasons (e.g., to halt the policy process).
The margin of error is defined by the degree of error in results received from random sampling surveying. A higher margin of error may cause reduced validity of the results since the sample does not represent the desired population. I can check this via a Sample T-test or compare the number of respondents from each country in the survey with the number of country delegates represented at COP-25 and calculate shares for each country. However, it will be more reliable to compare e.g. the share of invited participants from e.g. developed (Annex1) versus developing (non-annex1) countries and participants from progressive versus less progressive countries. This shows if some categories of countries are more likely to participate than others in the categories I examine and compare. If the bias is high, it needs to be considered in translating the results. Or more weight needs to be put on the qualitative interviews (Pedersen and Manhice, 2020).
Some reasons for low participation could be resistance towards climate policy or the UNFCCC. Potential resistance from developing countries was partly examined via interviews. Here researchers and delegates expressed that the policy tools were less valuable for their countries because of, e.g., lower capacity. However, this did not affect the motivation to participate in mitigation efforts. Another reason could be a lack of interest in cooperation from delegates favoring low policy regulation or representing the fossil energy industry or governments supporting fossil energy investments, e.g., the US government under Donald Jr. Trump or the Australian government during COP-25. For example, several informants repeated during interviews that it was easier to negotiate with US delegates under a Democratic government than a Conservative-led government.

UNFCCC delegates are often difficult to include because of a heavy workload and a booked calendar. Thus, the covid pandemic and the postponement of COP-26 became an advantage for recruiting survey participants for this study.

Ethical considerations

Well-founded results

Psychological and sociological research has at least two types of ethical responsibilities. First, a commitment to publish only well-founded and sincere research results. Second, it is essential to reflect on the risk of adverse social effects of the studies. Therefore, the research concerns the prevailing ethics, morality, and political climate (Aarts et al., 2015; Leal Filho et al., 2018; Meltzoff, 1998). I openly present my results (https://osf.io/5qctp/), calculations, assumptions, and analyses.

Epistemological reflections

During my data collection and processing, I was stroked by feelings of disappointment in the lack of action (and responsibility) in policymaking. Opposed to the amount of evidence (Oreskes, 2004b), it appeared short-termed and unwise. In addition, I became resentful of the fossil fuel industry's (malice) re-messaging campaign, the researchers/writers involved (The Luntz Research Companies, 2003), the continued exploitation of fossils in lower-income regions, and the lack of social responsibility in those countries (Rawoot, 2020). These are examples of emotions I had to deal with to conduct objective-founded and not opinion-based analyses. However, no one can be considered objective. Since all scientists have a standing point, which colors their analyses and results, it is important to clarify and express this for the readers (Haraway, 1988).
During participant observations, interviews, and literature, I also discovered how dependent politicians are on their voters and their opinions (on climate change) (Oreskes and Conway, 2010). Politicians are accountable for their voters and local developments rather than global commitments, making global agreements challenging. Fossil companies are part of the same economic discourse, and their directors are evaluated primarily on economic performance. The DNA of a company is to survive and focus on self-interests primarily.

The complexity of values and interests involved in the field and the barriers these represent in reaching global cooperation are interesting from a scientific and analytic point of view. This made me focus on exploring this complexity rather than putting judgments on various actors to conduct objective research and analyses of climate governance and the role of science.

Interviews and survey participants

Research must strictly follow ethical principles when working with respondents and clients (Sales and Folkman, 2000). The most important ethical considerations are confidentiality, anonymity, privacy, consent, hidden intentions, mental and psychological stress, discomfort during the study, and involuntary participation.

Ethical considerations are crucial in producing knowledge through the interaction of an interviewer and an interviewee subject. Here, close attention to the personal interaction involved in interviews is essential (Kvale, 2011). The ethical issues go beyond the interview situation, such as social science research needs to obtain the subjects' informed consent to participate and for the researcher to use the information. It is crucial to secure the subjects' confidentiality (e.g., consider the consequences of participating in the research project and understand and be attentive to how the researcher perceives their role in the study (EC, 2018; Kvale, 2011).

Interviewees approve all quotes in the following results and discussions, and survey quotes are disguised (e.g., not mentioning country or other aspects that may reveal their identity). Interview notes and quotes used in the thesis were sent to each participant for their consent and ensured I had the correct interpretation of what they said. All quotes are anonymous to respect the subjects' confidentiality and ensure that no issue would arise due to their professional roles, e.g., for delegates concerning their national governments or employers.
In qualitative research, it is a unique challenge to maintain respondent confidentiality while presenting rich, detailed accounts of social life (Kaiser, 2010). As such, I credit interviewees' participation but mask their answers while survey participants remain anonymous. Informants are categorized as attached to specific regions or categories of countries (e.g., high-income countries) rather than individual countries. As such, the origin of "off-the-record statements" and statements that could have consequences for informants are disguised adequately.

Reliability and validity

Additionally, regarding the reliability and validity of data and results, briefing and debriefing of informants are essential. To create trust between the research/researcher and informant to honestly state their perspectives and experiences (Pedersen and Manhice, 2020). Carefully considering the audience for one's research and re-envisioning the informed consent process, qualitative researchers can avoid confidentiality dilemmas that might otherwise lead them not to report rich, detailed data (Kaiser, 2010). Furthermore, climate governance and justice topics represent sensitive information and dilemmas, making trust between researcher and informant crucial. I focused on whether any statements would be quoted anonymously during the briefing. If mentioned in publications, I would share and validate (e.g., ask for permission) with the interviewee before any publication of those results (interview briefing). For the survey, the following was stated in the survey email invitation: *"You will remain anonymous, and responses will be communicated in aggregate. Data will be handled and stored according to EU law."* (Survey invitation). I consider principles implemented to ensure confidentiality and anonymity towards respondents and techniques that avoid deceiving respondents. Regarding debriefing, I focused on the possibility that the informant might regret statements after the interview - in such case, they were welcome to contact me to delete those data/statements or the entire interview from the research.

In addition, in the email and Survey intro (briefing), I reminded them about informant anonymity and confidentiality and that I would contact them in case of quoting them. I used debriefing only for interviews. I briefed the survey participants to contact me if any questions or regrets arose (however, I could have mentioned this at the end of the survey as a way of debriefing).

Finally, I presented the examined population (researchers, UNFCCC delegates, and national policymakers) and survey focus in the survey invitation email. I found it reliable to present these beforehand and ensure that respondents respond most naturally (IAAU, 2020). To further enhance this, I stated the importance of honest responses and reminded myself about anonymousness.

SI 11: Landmarks on the global climate regime

It is argued that effective international action to protect the planet is enforced when scientific knowledge improvements catch the attention of convention delegates and global decision-makers (IISD, 2022). The evolvement of evidence-based policymaking provided opportunities for intersections between science and policy (Burton et al., 2019).

The Stockholm Conference and Declaration of 1972 was the starting point of the environmental science-policy interface. It comprised an institutionalized multilateral environmental diplomacy and action process supported by scientific bodies (UN, 1973). The adoption of the UNFCCC or "the Convention" (UNFCCC, 1992) was closely interwoven with the development of scientific institutions, such as the IPCC, to assess the climate challenge and produce usable knowledge for political decision-makers (Bodansky, 1993; Demeritt, 2010).

The science-policy interface is an integral part of UN organs (Lichem, n.d.; UN, 2021), exemplified by the Montreal Protocol (MP) to protect the ozone layer (IISD, 2022; Kohler, 2020; UN, 1989), tracking of UN Sustainable Development Goals (SDGs) (Fritz et al., 2019), and Paris Agreement (UNEP, 2022). Since 1992, the United Nations Framework Convention on Climate Change (UNFCCC) and its annual Conferences of the Parties (COPs; since 1995) widely represent a global framework for climate governance (Gupta, 2014). They are informed by scientific bodies, with the IPCC as the most prominent (UNFCCC, 2019a).

On March 21st, 1994, the UNFCCC entered into force. In total, 198 countries have signed the Convention, and they are called Parties to the Convention. Since 1995, 27 intergovernmental Conferences of the Parties (COPs) have facilitated two follow-up agreements (UNFCCC/COP, 2015a, 1997). The UNFCCC aims to prevent dangerous human interference with the climate system by stabilizing GHG concentrations at a safe level in the atmosphere (UNFCCC, 1992). It builds upon the Montreal Protocol, borrowing language from that protocol, e.g., bounding member states to act in the interests of human safety even in cases of scientific uncertainty (UN, 1989; UNFCCC, 1992). The IPCC provides the scientific evidence, definitions, and timelines of dangerous climate change (UNFCCC, 2022b, 2022c).

Climate treaties

The UNFCCC COPs have facilitated two follow-up agreements, the Kyoto Protocol (KP) and Paris Agreement (PA). The KP was adopted on 11 December 1997. It entered into force in 2005, ratified by 192 Parties (UNFCCC, 2022c; UNFCCC/COP, 1997). The KP has top-down negotiated targets. It aimed at operationalizing the Climate Convention by committing Annex-I parties (industrialized countries and economies in transition) to stabilize or reduce GHG emissions in accordance with negotiated country-specific targets (by 2013 compared to 1990 levels). Because of the breakdown in Copenhagen COP15 to negotiate a new treaty, the Doha Amendment represented a second commitment period of the KP with renewed targets (by 2020 compared to 1990 levels) (UNFCCC, 2012; UNFCCC/COP, 2012).

The Paris Agreement (PA) presents a bottom-up approach where all parties decide on mitigation targets via their nationally determined contributions (NDCs) (UNFCCC/COP, 2015a). It does not include intergovernmental targets for countries but sets a stringent long-term objective for international climate policy (UNFCCC/COP, 2015a). Countries are encouraged to state what targets they will adopt in their Nationally Determined Contributions (UNFCCC/COP, 2015a).

Since 1992, parties have communicated different positions, exemplifying the complications of intergovernmental political consensus. During the 1990s and 2000s, Europe firmly believed in following science and the target approach, while the US showed reluctance (Hecht and Tirpak, 1995; Oberthür and Ott, 1999a). In addition, China has often taken a stance against industrialized Annex-I parties (e.g., the global North) on behalf of the least-developed countries (LDCs). In essence, multiple national interests transcend the UN intergovernmental processes toward climate treaties, e.g., developed Annex-I countries trying to keep their position and developing non-Annex-I countries striving to develop to Annex-I standards (Dimitrov, 2016; Gupta, 2014).

Table SI- 0-19. Landmarks of the International Climate Change Regime.
Data sources: IPCC assessment reports (1990, 1996), UNFCCC COP decisions, and Bodansky (2001)

Conference	Year	Organizer	Conclusions and principal recommendations
The 1979 World Climate Conference	1979	WMO	Referred to as the First World Climate Conference. 350 specialists from 53 countries and 24 international organizations
Villach Conference	1985	WMO/UNEP	Significant climate change is highly probable States should initiate consideration of developing a global climate convention
Toronto Conference	1988	WMO/Canada /UNEP	Global CO_2 emissions should be cut by 20% by 2005 States should develop a comprehensive framework convention on the “law of the atmosphere.”
UN General Assembly	1988	UN	Climate change is a "common concern of mankind.”
1st Session of the IPCC intergovernmental panel	1988	WMO/UNEP	Establishment of the IPCC and definition of the IPCC organization into three working groups (WGs)
Hague Summit	1989	Netherlands	Signatories will promote new institutional authority to combat global warming, involving nonunanimous decision-making
Noordwijk Conference	1989	Netherlands	Noordwijk Declaration on Climate Change: Industrialized countries should stabilize GHGs as soon as possible. Many countries support the stabilization of emissions by 2000
IPCC 1st Assessment Report (AR1)	1990	IPCC	Climate, impacts, and response assessment are made based on policy scenarios and a business-as-usual (BaU) emissions scenario called the most “pessimistic” and projecting continuation of continued trends Global mean temperature likely to increase by about 0.3 °C per decade under the BaU emissions scenario.
Second World Climate Conference UN General Assembly	1990	WMO & UNEP UN	Countries need to stabilize GHG emissions. Developed states should establish emissions targets/national programs or strategies Establishment of INC
UNCED Conference	1992	UNCED	UNFCCC opened for signature
IPCC AR2	1995	IPCC	Updated scenarios with two emission scenarios higher than the former BaU scenarios underly the IPCC climate, impact and response assessments. “CO2 remains the most important contributor to anthropogenic forcing of climate change”
COP1 (the 1st Conference of the Parties (COP)	1995	UNFCCC	The parties adopt the “Berlin Mandate” authorizing negotiations to strengthen FCCC commitments and to negotiate strengthened Annex-1 party commitments. The parties establish: - Subsidiary Body for Scientific and Technological Advice (SBSTA) - Subsidiary Body for Implementation (SBI)
COP2	1996	UNFCCC	The “Geneva Ministerial Declaration” calls to accelerate negotiations on a legally binding protocol. Parties acknowledge the IPCC 2nd assessment report
COP3	1997	UNFCCC	**The Kyoto Protocol**: legally binding mitigation targets for developed Annex-I parties of six GHGs (The Kyoto gasses). Most parties set targets of 6-8% reduction of Kyoto GHGs by

			2012 of 1990 levels, while a few Annex-I are allowed to stabilize or grow GHGs.
COP4	1998	UNFCCC	The Buenos Aires Plan of Action provides a deadline to finalize the Kyoto market-based mechanisms
IPCC AR3	2001		More than 66% likeliness that observed global average temperature increase is caused by human activities. Poor people and developing countries are most vulnerable to climate impacts.
COP8	2002	UNFCCC	Via the "Delhi Ministerial Declaration" the parties repeated the principle of common but differentiated responsibilities (CBDR), emphasizing that development and poverty eradication are the priorities for developing countries and technology transfer from developed to developing countries.
IPCC AR4	2007		More than 90% likelihood that global temperature increases are caused by anthropogenic GHG atmospheric concentrations
COP15	2009	UNFCCC	The Copenhagen Amendment: The first time all parties agree on the reality of Anthropogenic Climate Change The strong political will to combat climate change but no new treaty replacing Kyoto. The 2 °C target is recognized by the majority of parties (1.5 °C is considered). Unbinding Copenhagen pledges (2020-targets: non-Annex-I & Annex-I) Parties agree on implementing forest projects under the CDM and guidelines for reporting on GHG emissions and removals from agriculture, forest and land-use change ("LULUCF" emissions).
COP16	2010	UNFCCC	Formal agreement on the 2 °C target
COP18	2012	UNFCCC	**The Doha Amendment** (Kyoto 2nd period 2013-2020; cut GHGs by 15-24% by 2020; not all Annex-I have 2020 targets)
IPCC AR5	2013/14		More than 95% likelihood that global temperature increases are caused by anthropogenic GHGs.
COP19 & 20	2013 & 2014	UNFCCC	All Parties to communicate their intended nationally determined contributions (INDCs) to the UNFCCC secretariat before COP 21
21st COP	2015	UNFCCC	**The Paris Agreement**: The increase in global temperature should be below 2 degrees and preferable below 1.5 degrees Celsius New policy area accepted (INDCs/NDCs)
IPCC SR15	2018		1.5 C pathways. Parties need to reduce 45% GHG between 2010-2030, reaching 'net zero' by 2050 to stay on a 1.5 pathway and 25% for a 2 C pathway.
25th COP	2019	UNFCCC	The planned renewal of NDCs is postponed.
26th COP	2021	UNFCCC	The Precedency advocates for a 1.5 pathway. Fossil fuels are mentioned for the first time in a UNFCCC decision paper. At the last minute, India refuses to phase-out unabated coal A third financing pillar (Loss & Damages) is a cardinal point for the LDC countries supported e.g., by China. The EU hesitated while the US halted an agreement.
IPCC AR6	2021/22		"Average annual GHG emissions during 2010–2019 were higher than in any previous decade, but the rate of growth between 2010 and 2019 was lower than that between 2000 and 2009"
27th COP	2022	UNFCCC	Agreement about Annex-I financing "Loss & Damages" in the most vulnerable countries already experiencing climate-related impacts

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End notes (I, ii, iii, iv, v)

[i] Educational attainment and urbanization comprise essential elements of the SSPs. However, they are not represented quantitatively in the previous sets.

[ii] The scenario developers, authors, and modelers of the scenario sets have analyzed a broad spectrum of scenarios. A limited, representative number was eventually selected and published as so-called "marker scenarios"ii from these. Our analyses did not include the SSP mitigation scenarios - which were developed focusing on the forcing levels covered by the RCPs. The reasons for this are that scenarios with new climate policies are still being developed and since the IS92 and SRES do not include assumptions about climate policies beyond those already adopted at the time of scenario development. The RCPs are included in the emissions comparisons only for informative reasons. A complete assessment of the RCPs is less relevant in this paper's context, as they are not directly connected to particular sets of emissions drivers. However, it is pertinent to include the RCPs in the emissions comparison since there is no one-to-one match between the SSPs and RCPs in the SSP-RCP structure.

[iii] The levels of regional aggregation differ between the sets; thus, the distinction between OECD/Non-OECD was chosen. The OECD definition differs between historical databases (OECD 2012: 36 countries), IS92 (OECD90: 24 countries & 32 units), SSP (OECD 1990 and EU member states and candidates: 44 countries/units). Thus, for our analysis, we made the necessary adjustments – recalculating historical estimates for both the SSP OECD/non-OECD (OECD90+EU) and IS92 OECD/non-OECD (OECD90) - to compare the trends significantly (see supplementary material).

[iv] It is uncertain which methodologies (Physical content and Partial substitution, and the exact conversions) were used by the various modeling teams in the different scenario series. This complicates cross-scenario comparisons as well as comparisons with the historical estimates.

[v] The SSP 2/3/5 baseline scenarios present information of heat and electricity (secondary energy). When we sum heat and electricity estimates, the result matches the total amount of primary energy. Since the secondary energy in these scenarios is similar to the primary energy, we can assume that a conversion factor has to be used to make it comparable to historical data. The historical data shows a very different relationship between primary geothermal energy and electricity production (secondary energy), being ten times higher than the second. Thus we need to apply a partial substitution method to geothermal electricity secondary energy in SSPs. To do this, we need to multiply electricity by 1/0.1 - considering the 10% efficiency – and then add this amount to the total primary energy. At the same time, we also removed the original secondary energy from the primary energy. It is possible to correct the secondary electric energy data if all information is available. However, we choose not to make this conversion as each SSP scenario/models present various types of data - and information is needed for some scenarios (except for SSP3). SSP1 has information about geothermal energy. SSP2 has small differences (lower than 0,005 EJ/yr) between the total geothermal primary and the total secondary energy. In SSP4, there is no secondary heat data, and all primary energy is equal to the secondary electricity, although, in the real world, geothermal heat is produced and used currently. For SSP5, data is presented, but in the first six periods (from 2005 to 2050), secondary heat production is also equal to zero, which is also not realistic.