°CICERO
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Climate Research

UN environment programme
finance initiative

Pathways to Paris

A practical guide to climate transition scenarios for financial professionals

Acknowledgements

The pilot project was led by a Working Group of thirty-nine banks convened by the UN Environment Programme Finance Initiative:

ABN-AMRO
ABSA
Access Bank
Bank of Ireland
Barclays
BMO
Bradesco
Caixa Bank
CIBC
CIMB
Citibanamex
Credit Suisse
Danske Bank
Deutsche Bank
DNB
EBRD
FirstRand
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Intesa Sanpaolo
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Scotia Bank
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Standard Bank
Standard Chartered
TD Bank
TSKB
UBS

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Executive Summary

In the face of growing climate risks, regulators and financial institutions are increasingly using climate scenario analysis to answer questions about institutional preparedness for the low-carbon transition and systemic financial stability. Following the 2008-2009 Global Financial Crisis, scenario analysis became a common tool for risk managers in the financial sector. However, climate transition scenarios (herein referred to as climate scenarios) and the models that produce them differ in meaningful ways from traditional macroeconomic scenarios. Institutions and supervisors need to fully understand the assumptions of these climate scenarios to ensure they can be effectively used for risk management and strategy setting.

Pathways to Paris, produced as part of United Nations Environment Programme Finance Initiative (UNEP FI) Phase II Task Force on Climate-related Financial Disclosures (TCFD) banking sector programme, explores climate transition scenarios and the generation of emission pathways and their mechanics, structure, and application. In this paper, UNEP FI partnered with the CICERO Center for International Climate Research, a global expert in understanding climate scenarios and models.

This report is a guide for financial sector users of climate scenarios. Readers will gain insights into the key assumptions and sectoral coverage of the Integrated Assessment Models (IAMs) used to produce climate scenarios. In addition to covering the benefits and limitations of using climate scenarios, the report features case studies from several of the banks in UNEP FI's TCFD programme who applied these scenarios to their own portfolios and detailed their experiences.

Major areas of discussion

Structure of IAMs

IAMs are computer models that were initially developed for climate and energy decision making processes. IAMs generate emission pathways which can be integrated into climate models to study potential changes to the climate system. These pathways show changes in production and use of energy and infrastructure over time, technological changes, natural resource use and impacts of climate policy. Only recently have IAMs been adopted for financial institutions as they can describe the interaction between economic activity, greenhouse gas (GHG) emissions, and climate change.

Nature of IAM outputs

For each pathway generated by an IAM for a given temperature, a set of assumptions are made, with most IAMs assuming optimising behaviour. Actual costs and performances of technologies can differ from the technological assumptions made in IAMs due to high uncertainties about future technological developments. Hence the future realised pathway is likely to differ from the optimal pathways depicted in IAMs. Another important assumption of IAMs is that global climate policies will be implemented in a cost-optimal manner, and consumers and firms will respond optimally. IAMs typically do not consider non-monetary preferences, social justice, energy security, affordability, and interactions with other policy goals, which might make cost-optimal pathways less desirable and less politically tenable than non-optimal pathways.

Benefits and limitations of IAMs

IAMs are useful tools for financial institutions to identify, assess and manage transition risks. However, as IAMs were not originally designed for use by the financial industry, there are associated limitations. IAMs generally show what combination and timing of mitigation measures will generate a certain amount of global emissions at the lowest cost. Therefore, most IAMs use cost analysis to compute the most theoretically optimal pathway to a climate target rather than the most feasible or desirable pathway. These models have global scope and long time horizons which are necessary for assessing long-term climate targets but the IAMs therefore necessarily depend on many simplifying assumptions and provide limited granular detail. Though broad coverage is achieved in evaluating a climate transition, important market and policy dynamics are often stylized. In many instances, IAMs provide adequate details for a relatively disaggregated view of mitigation pathways with the ability to assess trade-offs and constraints but may lack all the financial details and granularity needed for risk managers.

Bank case studies

Bank participants from UNEP FI's TCFD banking program produced case studies using UNEP FI's transition risk methodology to provide perspectives on selected climate scenarios for analysis. Key takeaways from the piloting banks included:

- The IAMs provide detailed coverage of energy sectors (oil & gas and utilities). However, questions were raised about the underlying economic assumptions of sector dynamics. Additional explanation of these assumptions would help institutions justify the outputs produced using climate scenarios.
- Recognition that further enhancement of the scenarios is needed to support the requirements of financial risk assessments, specifically greater detail on sectoral and regional factors.
- To fully integrate scenario outputs into decision-making, institutions must go further in translating climate variables into financially relevant factors. The UNEP FI transition risk methodology aids in this approach, but more work is needed to address gaps.
- Institutions are looking for additional clarity on how to evaluate specific borrowers under the different scenarios. This can be addressed both through increasing the granularity of the scenarios themselves (to provide more relevant variables for particular borrowers) and coming up with further guidance on what data is needed from the individual borrowers.

Recommendations for IAM modelers and users

The use of IAMs for climate scenario analysis is important to get an understanding of the transition risks different companies and financial institutions might face. However, there are limitations on what IAM scenarios can say about certain financial and macroeconomic factors. It is important to understand which outcomes of scenario analysis are robust and which are based on uncertain assumptions. In reality, the transition to a low-carbon future will most likely differ from any scenario as the pathway will be dependent on a variety of hard-to-predict factors. Therefore, the most effective applications of IAMs involve drawing broad conclusions about risks and sector behaviour.

This paper provides a series of recommendations for enhancing the development and application of IAMs by financial institutions:

- Improving sectoral granularity and sectoral coverage
- Improving regional and national granularity
- Including endogenous macroeconomic factors
- Incorporating non-linear and second order effects
- Integrating physical risk impacts
- Considering shorter time horizons
- Reconsidering financial market dynamics

Contents

1. Introduction

After the Task Force on Climate-related Financial Disclosures (TCFD) released its guidance on climate risk disclosures in 2017, the United Nations Environment Programme Finance Initiative (UNEP FI) convened a consortium of banks to pilot these new recommendations. This exercise included 16 international banks and became known as Phase I of UNEP FI's TCFD Banking Program. The consortium collaborated with Oliver Wyman, a global management consulting firm, to develop an approach for evaluating corporate lending portfolio exposure to transition risk under different climate scenarios (UNEP FI 2018). A similar effort was conducted to develop a physical risk assessment methodology in collaboration with Acclimatise, a climate-focused consultancy.

This paper was produced as part of United Nations Environment Programme Finance Initiative's (UNEP FI) Phase II Task Force on Climate-related Financial Disclosures (TCFD) banking sector programme. The programme originated in 2017 when the TCFD secretariat released its initial guidance on climate risk disclosures. In Phase I, UNEP FI convened a consortium of global banks to pilot these new recommendations and develop methodologies for assessing physical and transition risks.

Phase II expanded on Phase I by bringing together a diverse set of thirty-nine banks from across six continents to enhance their climate risk toolkits and improve their climate risk disclosures. Programme participants worked to develop a variety of tools, frameworks, and thought papers to drive the financial sector forward in identifying, assessing, managing, and disclosing climate risks. Climate scenario analysis was a central component of the programme as a way for participants to evaluate the nature and magnitude of portfolio climate risks.

1.1. A note on climate scenarios

The term "climate scenario" has different meanings depending on the context.

In providing technical guidance for climate scenario analysis, the TCFD secretariat defined climate scenarios as:

"A path of development leading to a particular outcome. Scenarios are not intended to represent a full description of the future, but rather to highlight central elements of a possible future and to draw attention to the key factors that will drive future developments"

TCFD 2017

In that spirit, this report considers climate transition scenarios, specific emissions pathways that provide insights about the dynamics of broad economic sectors. Integrated Assessment Models (IAMs) are used to generate these emission pathways, and these pathways can be used as inputs to more complex climate models to detail potential changes to the climate system. Depending on the application, the focus may be more on the emission pathways (transition risk) or the changes to the climate system (physical risk). This paper focuses on the generation of emission pathways, for a range of different temperature levels (or policy stringency).

1.2. Context

Climate scenario analysis has become a topic of critical importance throughout the financial sector. Regulators interested in assessing financial stability are considering how scenario analysis can provide insights into systemic risk readiness at the world's largest financial institutions. External stakeholders eager to see progress on climate goals are looking at scenario analysis to assess financial institutions' readiness and support for the low-carbon transition. Financial institutions themselves recognize both the external pressure to conduct climate scenario analyses and the operational and strategic value these analyses can provide in a changing world.

However, at present, climate scenario analysis in the financial sector remains in its infancy. Institutions are just beginning to learn how to conduct scenario analyses and use climate scenarios. Many of the models that produce energy transition scenarios, so-called integrated assessment models (IAMs), were designed to support climate and energy decision making and planning, rather than financial risk analysis. Only recently have IAMs been adopted for use by financial institutions. As a result, there are limitations on what IAM scenarios can tell us about certain financial and macroeconomic factors. These limitations are particularly relevant for certain economic sectors and geographies. The limitations do not necessarily reflect flaws in the IAMs or the scenarios they generate, but they show that financial users need different information compared to the original purpose of these models and scenarios. By appreciating the nature of IAMs, financial institutions can use them appropriately and unlock the insights they can provide for risk managers and other executives. At the same time, identifying scenario limitations for financial risk analyses can help scenario modelers continue to develop more nuanced and granular outputs that will continue to be useful across the financial sector.

1.3. Report overview

For this report, UNEP FI has partnered with the CICERO Centre for International Climate Research, a global leader in climate scenario research. CICERO experts provided a series of seminars on climate scenarios to participants in the TCFD banking program pilot. This report aims to synthesize lessons from these seminars into a guide for all financial sector stakeholders and scenario users seeking to better understand climate scenarios. Section 3 explains the mechanics of the integrated assessment models (IAMs) used to produce scenarios. Section 4 explores some of the material assumptions that differentiate the underlying models and scenario pathways from each other. These include macroeconomic assumptions, energy and technology assumptions, and policy assumptions. Finally, the paper covers several major economic sectors and discusses how these particular sectors are incorporated into the IAMs and at what level of granularity. Together these three sections should provide a clear and concise explanation of how scenarios work in the financial sector context.

The last part of section 5 provides case studies from banks that participated in the TCFD banking program. The case studies reflect the experience of these institutions in applying the UNEP FI and Oliver Wyman methodology developed through the TCFD banking program. That methodology takes climate scenarios as an input and connects them to financial risk drivers to produce financial loss estimates. While a deep dive into that methodology is outside the scope of this paper, a full description of its implementation can be found in the Extending Our Horizons Report (UNEP FI and Oliver Wyman, 2018). Rather than focusing on methodological issues (as was done in the Extending Our Horizons report), the case studies included here provide institutional perspectives on the severity, comprehensiveness, and assumptions of the scenarios for given sectors. UNEP FI hopes that the combination of case studies and insights into IAMs will show useful future directions for scenario analysis that will enhance the ability of financial institutions to conduct such analyses across all major markets.

2. Climate scenario analysis in the financial sector

2.1. Scenario analysis pre- and post-Global Financial Crisis

Scenario analysis has a long history in the financial sector. For decades, institutions have posed "what-if" questions and used those questions to assess performance under different future conditions. As such, sensitivity analyses and scenario modelling are well-known tools for risk managers in the financial sector.

Scenario analysis has also been used to evaluate financial stability across the industry. In 1999, the International Monetary Fund (IMF) and the World Bank, conducted stress tests using a variety of different scenarios as part of their Financial Sector Assessment Program (FSAP) (BIS 2018). National banking regulators and supervisors had also explored the use of scenarios following the Mexico peso crisis in 1994 and the 1997 Asian Financial Crisis. However, until 2008, the prudential regulatory assessment and analysis of the financial sector risk models was often piecemeal and rarely mandatory for supervisees.

Things changed abruptly after the Global Financial Crisis (GFC) in 2008. The GFC demonstrated how systematic risks could create a ruinous cascade of consequences throughout the economy. Preserving systemic stability in the financial sector, the GFC showed, requires that regulators determine whether institutions are sufficiently prepared for future shocks and that they better understand the networked nature of financial risks across different institutions. The time frame assessed in these tests was typically around 3-5 years. In theory, stress testing under a variety of economic scenarios would demonstrate to the regulators that individual institutions and the financial system as a whole are adequately capitalized. For institutions themselves, new regulatory pressure for enhanced risk modelling and capital buffers were coupled with an appreciation that old risk management techniques had proven inadequate. Regulatory stress tests by the US Federal Reserve (the Fed) and the European Banking Association (EBA) led the way in developing a comprehensive assessment regime based on scenario analysis.

Since the Global Financial Crisis financial institutions have built programs to conduct these annual (and biannual) firmwide assessments. These programs include teams of modelers, model validators, and dedicated stress testing personnel. As a result, institutions have gained significant experience in conducting holistic scenario analyses over the past decade. While there are meaningful differences in the scope and nature of the scenario analyses, elements of the modelling approaches developed following the GFC are being considered for assessing new threats such as climate change and COVID-19.

2.2. Climate scenario analysis

Now more than ever, financial actors have recognized the existential risks that climate change and associated systemic risk factors pose to modern society and the global economy. Physical impacts of a warming world can devalue assets and disrupt vital supply chains (physical risks). At the same time, the need to rapidly transition to a low-carbon economy will create major challenges for many businesses (transition risks). Climate scenarios represent a new tool for financial institutions and regulators alike in managing these climate risks and planning for an orderly transition.

Financial regulators have rightly recognised the potential for climate change to disrupt the financial sector. In short, climate risk is a financial risk. In 2015, under the leadership of Mark Carney and Michael Bloomberg, the G20's Financial Stability Board launched the Task Force on Climate-related Financial Disclosures (TCFD). The TCFD provides firms with a structured framework for disclosing their climate risks (see Figure 1). With over 1000 corporate adopters, the TCFD has become the de facto standard for climate risk disclosures and has driven the creation of a climate risk scenario analysis and modelling industry for corporate users.

Governance	Strategy	Risk Management	Metrics & Targets
Disclose the organisation's governance around climate-related risks and opportunities.	Disclose the actual and potential impacts of climate-related risks and opportunities on the organisation's businesses, strategy, and financial planning where such information is material.	Disclose how the organisation identifies, assesses, and manages climate-related risks.	Disclose the metrics and targets used to assess and manage relevant climate-related risks and opportunities where such information is material.
a) Describe the board's oversight of climate-related risks and opportunities.	a) Describe the climate-related risks and opportunities the organisation has identified over the short, medium, and long term.	a) Describe the organisation's processes for identifying and assessing climate-related risks.	a) Disclose the metrics used by the organisation to assess climate-related risks and opportunities in line with its strategy and risk management process.
b) Describe management's role in assessing and managing climate-related risks and opportunities.	b) Describe the impact of climate-related risks and opportunities on the organisation's businesses, strategy, and financial planning.	b) Describe the organisation's processes for managing climate-related risks.	b) Disclose Scope 1, Scope 2, and if appropriate Scope 3 greenhouse gas (GHG) emissions, and the related risks.
	c) Describe the resilience of the organisation's strategy, taking into consideration different climate-related scenarios, including a 2°C or lower scenario.	c) Describe how processes for identifying, assessing, and managing climate-related risks are integrated into the organisation's overall risk management.	c) Describe the targets used by the organisation to manage climate-related risks and opportunities and performance against targets.

Figure 1: TCFD framework

In 2017, the TCFD secretariat released a technical supplement to their climate disclosure framework that focused on climate scenario analysis. In that technical supplement, the TCFD described scenario analysis as an "important and useful tool…both for understanding strategic implications of climate-related risks and opportunities and for informing stakeholders about how the organization is positioning itself in light of these risks and opportunities" (TCFD 2017). The technical supplement provides guidance on how institutions can undertake climate scenario analysis including suggestions on key analytical choices (e.g. parameters, assumptions) and publicly available climate scenarios to consider. Importantly, the timeframe for assessing climate risks is often significantly longer than in traditional scenario analyses. Figure 2 shows the TCFD's recommended structure for applying scenario analysis to climate risks and opportunities.

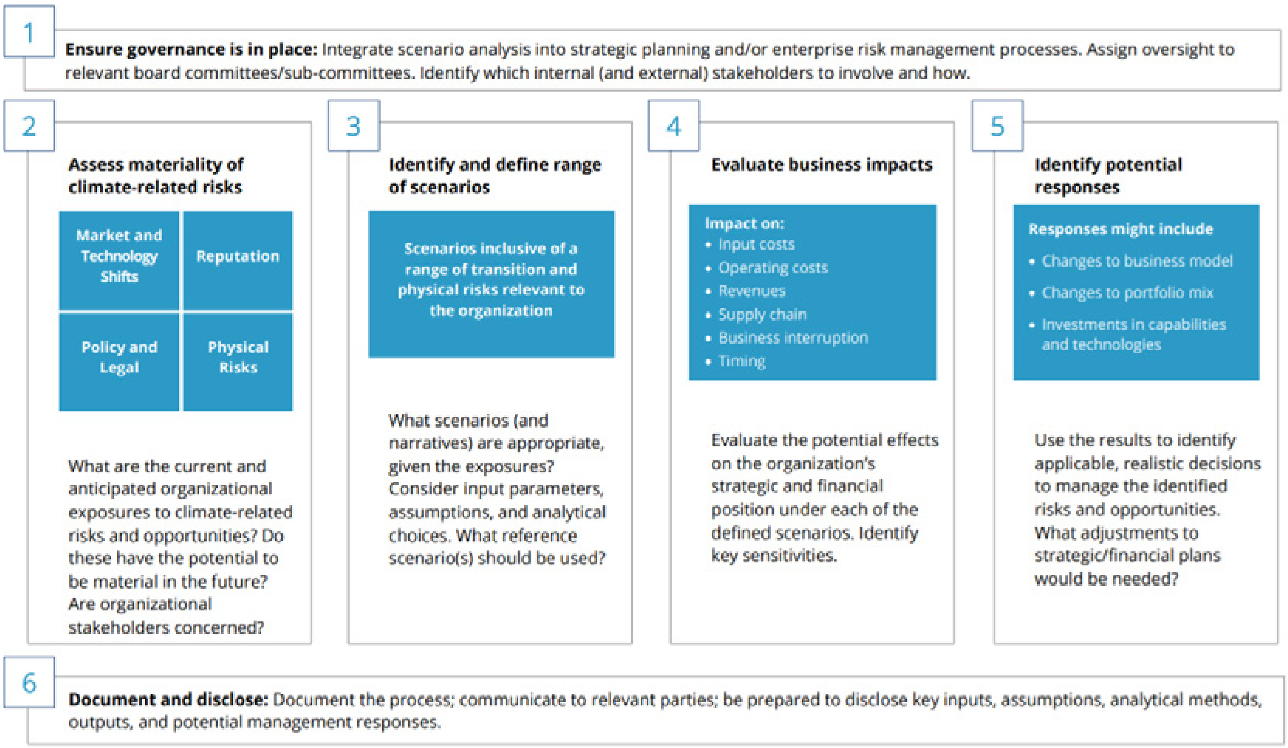


Figure 2: A Process for Applying Scenario Analysis to Climate-Related Risks and Opportunities

Building on the TCFD's framework, in June 2020, a worldwide group of central banks and supervisors came together to form the Network for Greening the Financial System (NGFS). The NGFS developed climate scenario guidance for regulators as well as "reference" scenarios. These reference scenarios were produced in conjunction with leading integrated assessment modelers1 and will greatly enhance the comparability of climate scenario analysis across the financial sector (NGFS 2020). NGFS climate scenarios examine a variety of different climate futures from an orderly transition to a low-carbon economy, to a disorderly or disruptive transition, to a 'hothouse' world, where insufficient action is taken to halt global warming (Steffen et al 2018). Within each of these classifications are specific storylines that have implications for how decarbonization will proceed, such as different temperature targets or different deployment of carbon dioxide removal technologies. Figures 3and 4 show the different scenario classification and storylines considered by the NGFS.

1 Potsdam Institute for Climate Impact Research (PIK), International Institute for Applied Systems Analysis (IIASA), and the Pacific Northwest National Laboratories and University of Maryland (PNNL-UMD)

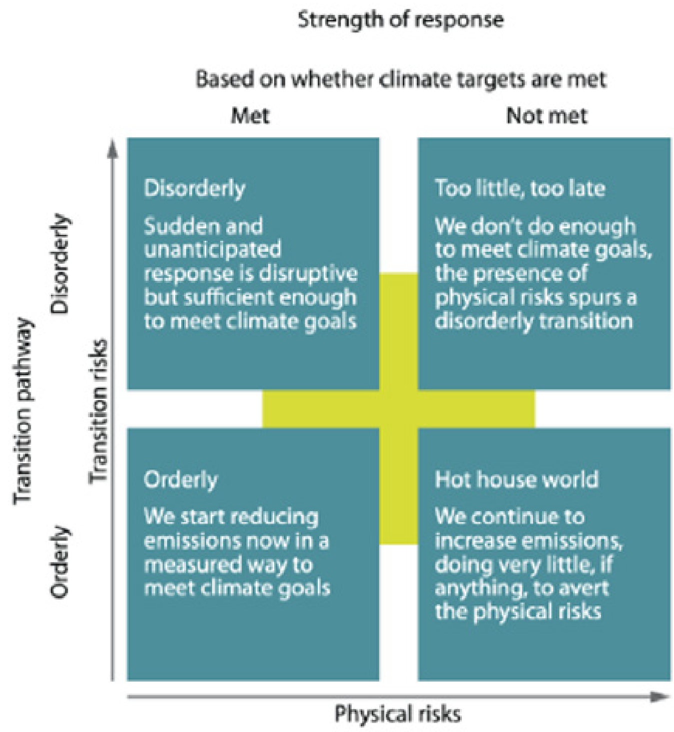


Figure 3: NGFS scenario classifications

Scenario	Classification	Storyline
Current policies	Hot house world	Current climate policies are followed for all regions, similar to IEA's current policies scenario, implies rise of approx. 4°C by 2100
Nationally determined contributions (NDCs)	Hot house world	Nations follow unconditional nationally determined contributions based on the Paris Agreement, implies rise of approx. 3°C by 2100
Immediate 2°C	Orderly transition	Collective action is taken now to reduce emissions towards a 2°C target, very similar in structure to the old 2°C scenarios
Immediate 1.5°C	Orderly transition	Collective action is taken now to reduce emissions towards a 1.5°C target, very similar in structure to the old 1.5°C scenarios
Immediate 2°C (low CDR)	Orderly transition	Aggressive collective action begins now on 2°C pathway, limited use of negative emissions
Delayed 2°C	Disorderly transition	Aggressive collective action only begins after 2030 to align with a 2°C target
Delayed 2°C (low CDR)	Disorderly transition	Aggressive collective action only begins after 2030 to align with a 2°C target, limited use of negative emissions
Immediate 1.5°C (low CDR)	Disorderly transition	Aggressive collective action begins now on 1.5°C pathway, limited use of negative emissions

Figure 4: NGFS scenario storylines

These reference scenarios are likely to be used both by financial institutions conducting analysis for their TCFD reports, as well as by regulators designing climate stress tests. The wide application of these reference scenarios reflects the growing importance of climate scenario analysis for evaluating climate risks in the financial sector. Given the increasing prominence of climate scenarios, it has become critical that firms understand the design, nature, and assumptions that underpin them. This paper aspires to offer practitioners a detailed view of climate scenarios and the types of analyses they are best suited to support and where gaps remain.

3. Climate scenarios

3.1. Introduction to integrated assessment models (IAMs)

Integrated assessment models (IAMs) are computer models used to describe interactions between economic activity, greenhouse gas (GHG) emissions, and climate change. The word "integrated" indicates the combination of knowledge from two or more domains, such as economics, engineering, and climate science, into a single framework. Although IAMs vary in model structure and detail, the core of most IAMs is based on either macroeconomic theory or energy systems engineering. Most of the IAMs used to analyse climate policy tend to focus on the energy system, with simpler representations of the climate system, land system, and other emitting systems (e.g., air pollution). A growing number of IAMs, however, include detailed representations of some of these non-energy systems.

There are two main types of IAMs:

Cost-benefit IAMs: Cost-benefit IAMs balance the costs and benefits of mitigation to identify an optimal level of global warming and associated emission pathways. Examples of cost-benefit IAMs include the well-known DICE (Nordhaus, 1992) and RICE (Nordhaus & Yang, 1996) models. This type of IAM represents mitigation and climate damages in a highly stylized manner. Cost-benefit IAMs have been used, among other things, to compute the social cost of carbon.2 Much of the criticism that has been directed towards IAMs has been aimed specifically at cost-benefit IAMs (Pindyck, 2013; Stern, 2016).

Complex IAMs: Complex IAMs calculate detailed energy and economic system transformation pathways consistent with different levels of global warming. These IAMs are considerably more complex and larger in size than cost-benefit IAMs. They can be based on hundreds, if not thousands, of equations (for comparison, DICE consists of only 16 equations). Instead of computing the theoretically optimal level of global warming, these IAMs usually compute the least-cost way of meeting a given climate target, such as the Paris Agreement target of limiting global warming to "well below 2°C". Complex IAMs generally do not consider climate damages and are usually used for cost-effectiveness analysis instead of cost-benefit analysis, leaving the climate target up to policy makers to decide. These IAMs are sometimes also referred to as large-scale or process-based IAMs to distinguish them from cost-benefit IAMs. Other terms include energy-economy models, energy-economy-environment (E3) models, and climate policy models.

Because cost-benefit IAMs lack much of the technological and sectoral detail necessary for assessing climate risks in the financial sector, this report focuses on complex IAMs. Complex IAMs are the most useful for financial institutions and regulators, but since they were not designed for this purpose, we outline the opportunities and challenges with using these models. Many of the most widely circulated quantitative global mitigation scenarios are generated using complex IAMs. Key publications include the IPCC assessment reports (IPCC, 2001, 2007, 2014), the IPCC special report on Global Warming of 1.5°C (IPCC, 2018), and the International Energy Agency's (IEAs) World Energy Outlook (WEO) (IEA, 2019). The reference scenarios provided by NGFS are based on complex IAMs.

UNEP FI Phase I & II used complex IAMs namely REMIND and MESSAGE for their scenarios.

The pathways generated by complex IAMs show how economic and technological variables, such as energy investment and technology deployment, change over time. Pathways may depict changes in the production and use of energy and infrastructure, the pace and direction of technological change, natural resource use (energy resources, land, forests), and air pollution, in addition to the responses of these variables to climate policy (usually a carbon tax). Even mitigation

2 The most prominent government agency using the social cost of carbon has been the United States' Environmental Protection Agency. See US EPA (2017) 'The social cost of carbon:' https://19january2017snapshot.epa.gov/climatechange/social-cost-carbon_.html

pathways that are not directly dependent on IAMs are often (unknowingly) based on outputs from complex IAMs, such as carbon budgets (e.g., how much carbon can be emitted to stay within a certain temperature level) and emissions levels in specific years (e.g., 50% reduction in emissions by 2030). The term IAM will be used in this report to refer to complex IAMs, unless otherwise indicated.

What sorts of questions do IAMs answer?

While IAM outputs provide considerable detail, the questions they typically provide answers to are quite limited. The most authoritative assessment of IAMs and IAM scenarios, the IPCC Fifth Assessment Report assessment of transformation pathways (Chapter 6), outlines three broad questions:

1. What are the near-term and future choices that define transformation pathways?
2. What are the key decision making outcomes of different transformation pathways?
3. How will actions taken today influence the options that might be available in the future?

The IPCC Special Report on Global Warming of 1.5°C (SR15) has a similar list of questions:

1. What role do CO_2 and non-CO_2 emissions play in aggressive mitigation scenarios?
2. To what extent do 1.5°C pathways involve overshooting and returning below 1.5°C during the 21st century (using carbon dioxide removal technologies)?
3. What are the implications for transitions in energy, land use and sustainable development?
4. How do policy frameworks affect the ability to limit warming to 1.5°C?

It is noteworthy that both these major assessment reports focus on broad overarching questions. This is the strength of complex IAMs; framing the entire mitigation discussion, such as the trade-off between short-term action and delay. IAMs are less capable of giving robust answers to more concrete and granular questions (Nikas et al., 2021), such as the level of oil demand in 2030. The limitations of IAMs to answering some of these more concrete and granular questions are the focus of the following sections.

Understanding IAMs

It is clear by the questions used to frame these major IPCC assessment reports that IAMs focus on the overall climate mitigation picture and not granular or sector specific details. IPCC Assessment Reports include several sector-specific chapters, often not based on IAMs, that consider more specific questions relating to the emissions trajectories for energy, agriculture, industry, transport, and other sectors.

Another key factor which limits the types of questions that IAMs can answer is the many degrees of freedom in emission pathways. IAMs find that there are multiple pathways that reach the same temperature target, and similar pathways can be distinguished from each other in meaningful ways (IPCC AR5 Ch6). There is no single, unique pathway to meet a specific climate target. For example, different combinations of coal, oil, and gas can be consistent with the same emission, and non-fossil sources could use more or less wind, solar, nuclear, hydropower, biomass, all depending on the behaviour and assumptions in a particular model. Instead, IPCC assessment reports focus on the key characteristics of transition pathways, rather than focussing on specific pathways. Consequently, often broad conclusions are drawn from IAMs, rather than specific concrete outcomes. For example, the amount of oil used in a 1.5°C pathway varies across different IAMs, but all IAMs show that less oil is used in a 1.5°C scenario than in 2°C or baseline scenarios.

A further critical point is that IAMs generally do not consider the feasibility of achieving generated emissions pathways. Feasibility in an IAM often does not go "beyond cases where physical laws might be violated [and therefore] these integrated models cannot determine feasibility in an absolute sense" (IPCC AR5 Ch6). IAMs focus "on geophysical dimensions and technological and economic enabling factors", and generally defer discussions of feasibility to the social sciences (IPCC SR15). As a result, considerations of political viability are not incorporated into the IAM mitigation strategies. In essence, IAM studies tend not to rule things out unless they are impossible, and rarely weigh in on whether certain outcomes are more or less likely.

While IAMs provide many insights into long-term transformation pathways, and may contain an impressive amount of detail, they can only address certain types of questions, such as the ones listed above. To answer more specific question, IAMs may need to be considered together with other types of analysis, modelling, and context (Gambhir, 2019).

Stylized representations of complex real-world processes

To find pathways consistent with a given degree of global warming by the end of this century (e.g., "well below 2°C"), IAMs need to consider how greenhouse gas emissions will evolve in the long-term. Carbon dioxide, the main driver of climate change, is a cumulative pollutant with slow decay times, meaning that emissions must drop to zero for the global average temperature to stop rising. Other greenhouse gases can have faster decay times (e.g. methane with around 10 years) and others slower (e.g., sulphur hexafluoride with 3,000 years). Further, the climate system has slow timescales (tens to hundreds of years) due to the slow processes involving the deep ocean. These long-term properties of greenhouse gases and the climate system is a key challenge for climate policy and associated modelling. A rapid decline in carbon dioxide emissions is needed in the short-term to get a clear difference in global warming decades ahead (Figure 5).

In addition to the long timescales of the climate system, energy infrastructure and decommissioning processes can also last for 50 years or more after construction. Some energy infrastructure in place today will still be emitting well after emissions need to reach net zero to align with existing climate targets. For these reasons, IAMs have to be global in scope and have a long time horizon. This time horizon usually extends up to 2100 but must cover the time period at least up to when net-zero carbon dioxide emissions are reached, with 2050 being the most cited target year to keep global warming below 1.5C.

This long time horizon of IAMs can be problematic for some users, who make decisions with time horizons of months or years, with a decade often being considered long-term in many financial contexts. Despite this, IAMs need to operate over long-term horizons as insufficient action in the short term means greater action in the long term. The decisions made in 2020-2030 affect global warming in 2020-2030, but also in 2050 and 2100 and should be considered and explained in decision-making and target setting processes. One of the key advantages of using IAMs is their ability to capture this long-term dynamic. This, however, also partners with a key disadvantage: that IAMs are not designed to capture processes that operate on smaller than 5 to 10 year time scales.

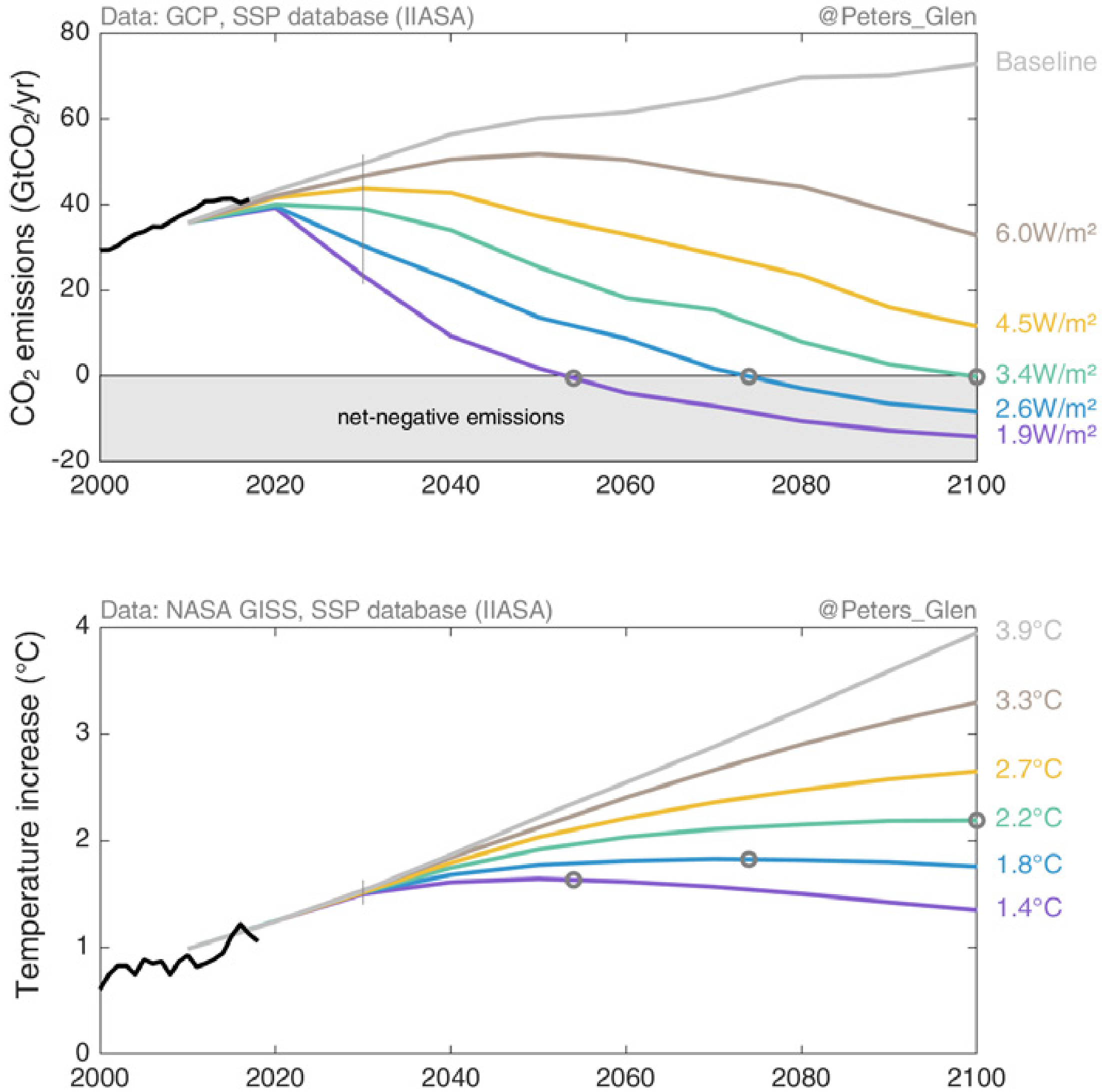


Figure 5: Carbon dioxide emissions and temperature increases under a variety of radiative forcings (colours)

Carbon dioxide is a cumulative pollutant and there is considerable inertia in the climate system. Even with radical short-term reductions in emissions by 2030, the temperature will keep rising until emissions reach net-zero (circles). Rapid emissions reductions in the short-term, however, avoid much larger temperature increases decades into the future (relative to pathways with less reductions in emissions). Thus, even if users are most interested in short-term information, IAMs still need to indicate outcomes over long-term time horizons for users to be able to understand what short-term actions are needed. This is particularly important given that energy infrastructure may have a lifetime of 50 years or more. The colour coding in the above two graphs match, i.e. a 2.6 (W/m2) scenario in the top graph implies approximately 1.8°C warming by 2100 in the bottom graph.

In all models there is a trade-off between the level of detail and the scope of analysis. Importantly, the global scope and century-long time horizon of IAMs limit the amount of detail that can be included for practical and computational reasons. Thus, although complex IAMs have significant detail, they can only provide stylized representations of the systems responsible for global emissions and the dynamics of emissions reductions. Essentially, all IAMs:

> **"are simplified, stylized representations of highly-complex, real-world processes, and the scenarios they produce are based on uncertain projections about key events and drivers over often century-long timescales. Simplifications and differences in assumptions are the reason why outputs generated from different models, or versions of the same model, can differ, and projections from all models can differ considerably from the reality that unfolds."**
>
> IPCC, 2014a, p.10

Care should therefore be taken when using IAM outputs as inputs to other analyses. IAM scenarios are neither forecasts nor predictions, but "plausible description[s] of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces (e.g., rate of technological change (TC), prices) and relationships" (IPCC, 2014a, p. 1270). In particular, it is important to realize that: (i) some outputs are more certain than others, and that (ii) most IAMs compute only the theoretically optimal way of meeting a given climate target, not the most likely way, nor necessarily the most desirable or effective way. Given the uncertain and, at times, value-laden assumptions (Schneider, 1997) required to compute transformation pathways, IAMs should be used to provide "insights, not numbers" (Peace & Weyant, 2008). For example, while there is considerable uncertainty regarding the exact market shares of renewable energy technologies in 2050, the fact that the share of renewable energy technologies must increase significantly and the share of unabated fossil technologies must decrease rapidly to limit global warming to "well below 2°C" is beyond dispute. These are the kinds of insights that can be drawn from IAMs. Often, they are more qualitative than quantitative.

To assess transition risk, it is important for analysts to have access to robust IAM insights that are not overly sensitive to uncertain or arbitrary assumptions or the choice of IAM. An example of a robust result that holds across IAMs is that "investments in unabated coal [are] halted by 2030 in most available 1.5°C-consistent projections" (SR15 Table 2.5), even if there is a particular IAM that may have a different outcome. While modelled coal investments may be dependent on the world staying below 1.5°C, the immediate implementation of stringent global climate policies, and a variety of technological assumptions, it remains clear that coal investments and use must go down dramatically in the short-term. On the other hand, "the literature is less conclusive for investments in unabated gas and oil" (SR15 Table 2.5). In this case, the analyst needs to weigh up the model outputs with the modelling assumptions and other (non-model) factors. In general, insights – as opposed to just numbers – are obtained by knowing not only what the outputs are, but how the outputs depend on the assumptions, and what the assumptions are.

For this reason, the outputs of IAMs need to be coupled with some degree of expert judgement. Even when IAMs agree on results, there may be good reasons to question the likelihood that these will materialize. For example, many IAMs find a relatively high level of coal power electricity generation with carbon capture and storage (CCS). In practice, there may be several market failures that prevent this from happening: a coal market in secular decline, policies reducing coal supply, cost and difficulty of making CCS commercially viable, transport and storage logistics, cheaper alternatives for electricity generation, social resistance, ineffective government institutions and regulatory frameworks, and so on. A broader assessment of factors not included in IAMs may lead to different conclusions than those indicated by an IAM. This does not necessarily mean that the IAM is wrong, but often that the IAM was answering a different question, using a different set of assumptions. Recall that IAMs usually compute least-cost pathways from a techno-economic perspective, not most likely pathways, nor even necessarily feasible pathways, if non-technical and non-economic factors are considered. Similar to how economic analyses have long shown that for instance household energy efficiency improvements represent economically rational ways of reducing environmental pressures (Gerarden et al., 2017), IAMs show what combination of mitigation measures over time will generate a given amount of global emissions reductions at the lowest cost. But just as history has shown that households often don't make economically rational decisions regarding energy efficient improvements, and that there are many reasons for why this is be the case, the future is also likely to show that the world will not follow the cost-optimal way of reducing greenhouse gas emissions. Many other factors beyond cost matter to the mitigation pathway that will ultimately be taken.

3.2. Where do IAMs come from?

IAMs integrate knowledge from multiple domains. Still, the core of most IAMs stems from macroeconomic theory and/or energy systems engineering. Knowing where IAMs come from, and what components they include, can help users exercise the informed judgment required for understanding and using IAM outputs as inputs to other analyses.

IAMs primarily have three historical roots (Sanstad & Greening, 1998), which have led to different modelling approaches:

1. **Neoclassical growth theory (Ramsey growth model).** IAMs based on neoclassical optimal growth theory include the REMIND, WITCH, MERGE, BET, MESSAGE-MACRO, and MARKAL-MACRO models. These models optimize welfare or consumption in a general equilibrium framework and are often referred to as optimal growth IAMs. In these IAMs, the global economy is represented as a single production sector, in which output is determined by capital, labour, and energy. Even though there is only one economic sector, the world economy in these IAMs is still separated into different regions, the number of which depends on the IAM. These IAMs represent the energy sector with varying degrees of detail.
2. **Neoclassical general equilibrium theory (Arrow-Debreu).** IAMs based on neoclassical general equilibrium theory, so-called computable general equilibrium (CGE) IAMs, include IMACLIM, Phoenix, SGM, ENV-Linkages, G-CUBED, GEM-E3 and MIT EPPA. CGE IAMs represent multiple markets for energy and non-energy goods and services. In these markets, consumers are assumed to maximise utility and firms are assumed to maximise profits, which ensures that supply meets demand (i.e. all markets clear). Because CGE IAMs separate the economy into multiple sectors, CGE IAMs tend to be more complex than optimal growth IAMs. The effects that a carbon tax will have on an economy's output and emissions, for example, is a typical question that CGE IAMs are used to analyse.
3. **Large-scale energy systems models.** Energy systems modelling arose as a field through the 1970s oil crises, which increased demand for tools for strategic energy planning. IAMs based on energy systems modelling provide highly detailed descriptions of the energy system, including energy supply processes, conversion technologies, and end-use, while treating the rest of the economy either exogenously or via relatively simple feedbacks. Examples of energy systems IAMs include MESSAGE (when this is not linked to the macroeconomic model MACRO), TIAM, DNE21+, MARKAL/TIMES, POLES, PRIMES, World Energy Model (WEM), and GCAM. Energy systems models are often classified as either optimisation models or simulation models.
   a. **Energy systems optimization models (ESOMs).** ESOMs identify the pathway that minimizes total energy systems cost (i.e. they find the least-cost or "optimal" pathway) given constraints, including constraints on emissions, but also other constraints, such as on the maximum rate of technology deployment, or the minimum future cost of new technologies (floor costs). Widely used ESOMs include MESSAGE (without MACRO), TIMES/MARKAL, and TIAM.
   b. **Energy systems simulation models.** Energy systems simulation models often seek to capture technological and economic behaviour and dynamics as realistically as possible (Nikas et al., 2019) and tend not to assume perfect foresight. Examples of energy systems simulation models include GCAM, POLES, and WEM.

Knowing the underlying modelling approach is important for understanding the questions that IAMs are designed to answer, and related, how to interpret and use IAM outputs. Different approaches have different strengths and weaknesses, and different blind spots.

Although not all IAMs fall into the three broad categories described above, most IAMs do. It is worth noting, however, that many IAMs today combine macroeconomic and energy systems elements to form so-called "hybrid" IAMs. MESSAGE, for example, was combined with MACRO in 2000 to form what is now the standard MESSAGE version. MARKAL has also been combined with MACRO to form MARKAL-MACRO. WITCH and REMIND, although at their core still optimal growth IAMs, also contain enough technological detail to call themselves "hybrid" IAMs. IEA's WEM is another example of a hybrid IAM.

Examples of IAMs that do not fit into the above categories include E3ME and the Oxford Global Macroeconomic and Energy Model, both of which are macroeconomic IAMs, and IMAGE, which is a particularly detailed simulation model focused on representing the processes related to the use of energy, land, and water. In addition to the above historical roots, it is also common to classify IAMs by distinguishing IAMs that assume perfect foresight from IAMs that do not (i.e. IAMs that assume myopic behaviour), and distinguishing IAMs that assume general economic equilibrium from IAMs that look only at certain markets, assuming equilibrium only in those markets (i.e. partial equilibrium models). This classification, which was used in the IPCC Fifth Assessment Report, puts non-equilibrium models in a separate category. Table 1 uses this classification to group many well-known and widely used IAMs.

	Equilibrium		Non-equilibrium
	General equilibirum (full economy)	**Partial equilibirum (partial economy)**	
Perfect foresight (optimisation)	REMIND, WITCH, BET, MERGE, MESSAGE-MACRO, MARKAL-MACRO	MESSAGE, TIMER/MARKAL, TIAM, DNE21+	E3ME, Oxford Global Macroeconomic and Energy Model
Myopic (simulation)	IMACLIM, GEM-E3, ENV-Linkages, Phoenix, SGM, G-CUBED, MIT EPPA	IEA WEM, IMAGE, GCAM, POLES	

Table 1 : Common modelling approaches with example IAMs.

Table 1 shows how most optimal growth IAMs and ESOMs, including REMIND, MESSAGE, WITCH, MERGE, and MARKAL/TIMES, assume perfect foresight. IAMs that feature myopic behaviour, which is seen to increase the realism of transformation pathways, include IMAGE, GCAM, IMACLIM, Phoenix, ENV-Linkages, and GEM-E3. Myopic IAMs are sometimes also referred to as "simulation" IAMs to distinguish them from ("pure") optimization IAMs. Simulation IAMs tend to put more emphasis on the representation of real-world processes and mechanisms. The IEA's WEM, for example, is often classified as a simulation model due to its aim to replicate how energy markets function rather than to identify pathways that minimize total discounted energy systems costs. But even pathways generated by myopic IAMs, tend to depict cost-effective pathways given this myopia.

3.3. Advantages and limitations of IAMs

This section focuses on advantages and limitations of IAMs, which are summarized in Table 2.

Global scope and long time horizon

Carbon dioxide is a cumulative global pollutant, and many other GHGs have long atmospheric lifetimes. Changes to the climate system also operate on long timescales because of slow ocean circulation. Additionally, socioeconomic systems and built infrastructure have lifetimes of decades, and even centuries in the case of urban infrastructure. Together, these factors mean that the analysis of transformation pathways consistent with a given level of global warming must be global in scope and combine short-term political, financial and technological factors with a long time horizon aligned with climate systems change. Most IAMs run scenarios 30-80 years into the future (2050-2100). By capturing all key sources of GHG emissions globally, IAMs can be used to explore transformation pathways consistent with long-term climate targets, such as the Paris Agreement target of limiting global warming to "well below 2°C". The long time horizon is necessary for understanding and planning for the required short-term transformations in the energy system. The ability to provide a long-term decision-making framework is one of the key strengths of IAMs.

The global scope and long-time horizon, however, also limit the ability of IAMs to provide deep and context-dependent insights regarding specific countries, sectors, and processes. IAMs often model the implementation of policies that are harmonized across sectors and regions, with an implicit assumption that any distributional and equity issues can be dealt with through emissions trading or economic transfers via a carbon tax or other instruments. In reality, climate policies consist of a mix of regulations, subsidies, indirect support, and international transfers are rare, and thus the use of efficient carbon prices in IAMs may stimulate different sectors and technologies compared to what is the case with real policies acting in the real world. The rapid deployment of solar and wind faster than most models foresaw, is one common example. Global models generally need to harmonise assumptions to make the problem tractable, and even if global models represent key regions and sectors, they still may miss contextual insights for specific sectors, processes, or countries. For example, pathways depicted by IAMs for India might fail to account for barriers and costs to an energy transition that are specific to India, and thus give a simplified picture compared to what national models might provide. Similarly, future oil consumption in IAM pathways might not integrate the detailed dynamics of electrical vehicle diffusion and battery supply chains, and thus provide a simplistic picture compared to what models focused on those aspects alone would provide. Electricity sector models need high temporal and spatial resolution to model changes in battery deployment and power grid modernisation, but these generally only have simplified parameterisations in long-term models. Thus, while IAMs are broad in scope and cover most aspects of the climate transition problem, they achieve this by removing, or at least significantly limiting, country and sector-level detail.

Single integrated framework

IAMs enable analysis of whole-system transformations consistent with long-term climate targets and associated trade-offs. At the same time, every IAM component as well as the interactions between them are based on many assumptions, including assumptions about technological progress, underlying socio-economic developments, future energy demand, and the geographic and temporal patterns of future policies (IPCC, 2018). This leads to two challenges.

First, most of these assumptions represent simplifications of the real world, many of which are characterized by deep uncertainty. The integration of different systems such as energy, economics, and land use, into a single integrated framework means that the underlying uncertainties are multiplied. The long time horizon further increases this uncertainty. Overall, this contributes to a high degree of uncertainty associated with many IAM outputs. The simulation time steps in the models are typically 5 to 10 years. The output is not suited for day-to-day decisions of financial engagement but can provide insights to different future potential effects.

Secondly, the many assumptions in complex IAMs mean that it can be difficult to know what assumptions have determined the IAM outputs in any given case. Because the size of most complex IAMs prohibits comprehensive uncertainty analyses, it can be difficult to know what IAM outputs are robust to the underlying uncertainties. As an example, it is not clear what causes the large variation in CCS deployment across IAMs (Koelbl et al., 2014). Determining the causes of these large variations may require intensive model specific sensitivity analyses, which is often not prioritised given the preference for model intercomparisons (Nikas et al., 2021).

The use of optimization in this context can also sometimes complicate the interpretation of results. Among other things, it can be difficult to know whether a mitigation option such as CCS is used in an IAM to reach a given climate target because it is necessary (meaning the given target would be unachievable without CCS) or because it is the cheapest option among many alternatives (such as more extensive use of nuclear power or more rapid deployment of renewable technologies). While all IAMs use large amounts of CCS in pathways consistent with stringent climate targets, there are also model studies that have reached stringent targets when avoiding the use of CCS by imposing low energy demand on the system (Grubler et al., 2018). It is possible that CCS could be avoided through other mechanisms, but there is little information on how no or low CCS may effect overall coal, oil, gas, and non-fossil energy use. CCS has been used as an example here, but the same issues arise for all technologies in IAMs. To date, most of the literature has focused on generating pathways consistent with given targets, with less literature examining the drivers behind results.

'What-if' analysis

The most effective way of using IAMs to obtain "insights, not numbers" is by using IAMs to analyse 'what-if' questions. One of the key advantages of IAMs is their comprehensive and detailed accounting of energy, emissions, and technologies, and associated techno-economic variables, in a consistent framework. This makes IAMs useful for analysing trade-offs between different mitigation options, and this has been a focus in previous IPCC assessment reports. A well-known 1.5°C scenario assessed in the IPCC Special Report on Global Warming of 1.5°C (SR15) had low energy demand and did not use any CCS (Grubler et al., 2018). This scenario is really a 'what-if' scenario: if we reduce energy demand as fast as possible, is it possible to stay below 1.5°C without CCS? The answer, according to the study, is yes, but this does not imply the authors are advocating not to use CCS. Rather, they are arguing that CCS is not necessary if demand reductions are sufficiently fast.

Other examples of 'what-if' questions that IAMs can be used to analyse include:

i. What if carbon dioxide removal (CDR) is not feasible at a large scale?
ii. What if the cost of solar PV falls faster than expected?
iii. What if electric vehicles are deployed faster than assumed?
iv. What if climate policy implementation is highly fragmented within and across regions?
v. What if economic growth stagnates?
vi. What if autonomous energy efficiency improvement is slower than assumed?

Some IAMs can also consider other trade-offs, such as between different transformation pathways and biodiversity loss, air pollution, and even economic equity.

'What-if' analysis, which in many ways represents the essence of scenario analysis, is key to exploring risks and opportunities. 'What-if' analysis can be used to identify outputs that are sensitive to assumptions and reveal associated risks. By investigating how assumptions affect results in a systematic manner, 'what-if' analysis can also be used to explore the full possibility space associated with given climate targets and associated opportunities.

At the same time, because most IAMs compute theoretically optimal pathways, the answers to 'what-if' questions usually only tell us how the theoretically optimal pathway changes. For example, 'what-if' analysis might tell us how the optimal pathway changes if CCS is not available or if solar PV costs fall faster than expected. If one wanted to know how the most likely pathway changes under different 'what-if' assumptions, one would have to use an IAM that predicts the most likely pathway. If one wanted to know how pathways might change if we don't assume optimal behaviour and planning, one would have to change structural model assumptions.

For climate scenarios to be useful for financial risk assessments, it is important that 'what-if' questions relevant to financial users are captured. A key challenge associated with the use of existing scenarios is that this might not be the case. Performing relevant 'what-if' analysis therefore likely requires close collaboration between scenario users and producers (modellers).

High level of detail

Complex IAMs provide detailed and highly disaggregated pictures of mitigation, and the level of detail appears to be continuously increasing as a response to ever expanding policy questions. The high level of detail is both a strength and a weakness of complex IAMs.

On the one hand, many policymakers, stakeholders, and other users of IAM scenarios are interested in impacts of climate targets on specific sectors, specific technologies, specific natural resources, or future economic growth. Many complex IAMs provide relatively detailed outputs related to many such aspects (with variations in the granularity and scope across IAMs).

On the other hand, due to the many uncertain assumptions, the increasing level of detail of IAM pathways is viewed as misleading by many researchers. Critical researchers argue that this level of detail is unwarranted. For example, some have argued that the cost of emissions mitigation is unknowable and that IAMs should therefore stop trying to estimate it (Rosen & Guenther, 2015).

Cost-effectiveness (given climate targets)

Most IAMs are set up to compute the pathways that will reach given climate targets in a cost-optimal manner. There are both pros and cons associated with this feature.

One the one hand, this makes IAMs useful for cost-effectiveness analysis. Building on this cost-effectiveness paradigm, IAMs can calculate the costs of changing assumptions or different trade-offs. Even though CCS, renewable energy, and nuclear power represent similar mitigation options from an emissions perspective, the costs and timelines can vary considerably across the different technologies. These shortcomings can be overcome by excluding certain technology options (such as CCS) when running IAMs and estimating the overall change in costs. This approach provides a proxy value for the economic value of those options.

On the other hand, although IAMs can quickly identify cost-effective pathways towards given climate targets, and this might be useful, those pathways may be unrealistic. The rapid reduction in CO_2 emissions required by 2030 (highlighted in IPCC SR15) are based on assuming globally harmonised carbon pricing in all regions and sectors, starting in 2020 (and sometimes earlier). Such policy pathways are highly unlikely in the real-world. IAMs are not well-equipped to balance the political, social, and technical elements that constrain how real-world pathways evolve and whether the target will be met. Questions of feasibility are rarely addressed in IAMs, and often delegated to other scientific disciplines (cf. IPCC AR5, SR15). Thus, if the user intends to use IAM outputs to assess how the world could evolve, it is important that the user considers how real-world pathways are likely to deviate from the theoretical pathways, in terms of both policies and technology and social dynamics.

IAMs generally do not have a tradition of forecasting, in the sense of analysing where the world may be headed with given policy, technology, and social assumptions and constraints. Scenarios, or forecasts, showing the likely path of emissions, and how policy, society, and technology may change these pathways is often requested by users, but represents a large gap in the literature (Berg et al., 2018).

Quantification

Since scenarios are quantified (leading to hard numbers), scenarios enable comparisons of different assumptions and impacts, and a better understanding of the scale of the challenge and what factors matter the most. For example, by computing the actual capacity of solar, wind, and CCS that could reduce emissions in line with the Paris Agreement, the feasibility of different options, such as how much CCS can be built, at what rate and at what scale, can be examined more closely. As such, hard quantified numbers can serve as a useful test for scenarios.

At the same time, much knowledge and expertise, including business intuition, for instance regarding renewable energy markets, is subjective and difficult to quantify. Many key aspects of climate mitigation, including changing consumer preferences, investment decisions, expectations, and behavioural change, and even constraints on technology deployment are hard to quantify and therefore mostly left out of IAMs. As an example, users often react to the scale of CCS in many scenarios, but it is hard to put limits on the scale of CCS (outside of physical constraints like storage capacity) and therefore most IAMs leave technology deployment unconstrained. Exceptions to this do exist, as some models still find it necessary to apply constraints on rates of deployment to keep solutions realistic. Similarly, behavioural changes leading to demand reductions are hard to model, and scenarios with low demand often achieve this by forcing options within the model (Grubler et al., 2018). In essence, models require all information to be quantified to be usable. This in turn limits the sort of information they can consider.

Pros and cons of IAMs	
Advantages	**Limitations**
Global scope	
Necessary for identifying pathways consistent with long-term climate targets	Highly stylized representation. Missing factors and dynamics that can be important. Limited region- and sector-specific information.
Long time horizon	
Necessary for identifying short-, medium-, and long-term changes consistent with long-term climate targets	Uncertainty increases the further into the future we look. Limited region- and sector-specific information.
Single integrated framework	
Enables analysis of whole-system transformation consistent with long-term climate targets and key techno-economic feedbacks.	The hundreds or thousands of assumptions required lead to cascading uncertainty and non-transparent and difficult-to-interpret results.
'What-if' analysis	
Understanding the range of possibilities and how results depend on assumptions.	Not all 'what-if' questions that are relevant to financial users have been explored. Existing answers are limited largely to how theoretically optimal pathways will change and technical topics of interest to IAM researchers.
High level of detail	
Ability to provide a more disaggregated and granular view of mitigation. Ability to assess trade-offs and constraints.	IAMs still lack the detail needed by most decision makers. A high level of detail can also lead users to get a false sense of certainty.
Cost-effectiveness (given climate targets)	
The fact that (most) IAMs compute optimal pathways consistent with given climate targets make them suited for cost-effectiveness analysis. They can also be used to estimate the economic value of different options.	The feasibility and desirability of pathways generated by IAMs must be assessed ex post. In practice, climate action is likely to differ from the smooth trajectories depicted in IAMs, potentially leading to both slower and faster changes in investments and technology.
Quantification	
Enables understanding of the scale of the challenge and identification of the most important factors.	Much knowledge and expertise, including business and market intuition, is subjective and tacit and difficult to quantify.

Table 2: A summary of the key advantages and limitations of IAMs

4. Key assumptions

IAM scenarios are neither forecasts nor predictions and IAMs should be used for "insights, not numbers". Understanding the key assumptions is a prerequisite for obtaining robust and reliable insights based on IAMs for use as inputs to other analyses. One way of ensuring that scenarios are not used incorrectly is to use IAMs as tools for learning about the complex dynamics and interactions that may affect the pathway that will ultimately be taken, rather than to predict what will happen.

Models are only as good as the assumptions that go into them, and, when it comes to climate mitigation and rates of technological change, most assumptions are highly uncertain. This means that IAM outputs, such as the optimal amount of solar PV installed by 2050 or the cost of mitigation over time, are uncertain. This uncertainty does not preclude researchers from using IAMs to learn about how assumptions affect results. Asking 'what-if' questions, such as the ones outlined in the previous section, is an important avenue for learning. To ask good what-if questions, however, it is necessary to know what the key assumptions in IAMs are.

4.1. What do IAM scenarios show?

Many socioeconomic and technological pathways are consistent with the same emissions pathway, and many emissions pathways are consistent with the same climate target. However, for a given set of assumptions, each IAM generates only one pathway for a given climate target. Even though there are many different IAMs, the majority of IAMs either explicitly or implicitly assume optimising behaviour. Although it is useful to know what the least-cost pathways to achieving different climate targets are, it is important to understand that theoretically optimal pathways are likely to deviate from the pathways that will be taken in the real world. There are multiple reasons for this.

First, due to inherent uncertainties regarding future developments and technological change, the cheapest way of reducing emissions in the future is likely to differ from least-cost pathways predicted by IAMs today. The future cost and performance of technologies are highly uncertain and will likely differ from what is assumed in IAMs. IAMs have, for example, failed to predict the rapid cost declines seen for wind and solar technologies in the last decade. IAMs are even less likely to accurately predict the optimal energy system 30 years from now. This means that the pathway that, in reality, will minimize costs will deviate from the optimal pathways depicted by IAMs today.

Second, even if IAMs were to accurately predict optimal pathways, the real-world rarely evolves in an optimal manner. Most IAM pathways assume that global climate policy (typically represented as a globally uniform carbon price) can be effectively implemented, and that consumers and firms respond optimally (often with perfect foresight) to these. IAMs do not consider political feasibility and only represent other real-world constraints to a certain extent. Technologies are assumed to work efficiently and at the specified costs (e.g., there are no cost overruns on nuclear and CCS options are available at scale). For these reasons, theoretically optimal pathways are likely to remain theoretical, that is, they are unlikely to be achieved in practice.

Mitigation in the real world will be achieved using a combination of different policies (subsidies, targeted support to renewables, regulation, standards, taxes, etc.) at different points in time and in different regions and sectors, rather than the uniform application of a global carbon price that (in theory) leads to mitigation when and where it is cheapest. The effects of varied policy instruments will be different from the effects of a global carbon price, especially on technology choices and investment decisions, and therefore on energy system transformation pathways. As an example, a moderate carbon price may not be sufficient to justify the commercial deployment of solar and wind at the rates currently observed driven mainly by renewable energy portfolios or subsidies. In addition to this, many aspects of firm and consumer choice are not captured by IAMs. This means that IAMs might provide poor descriptions of real-world responses to policies, whether these are carbon prices, subsidies, or standards. A consumer may, for example, not buy an electric vehicle if the cost of petrol is increased through a carbon tax but may if subsidies make the purchase price of an electric vehicle lower or incentives are introduced to change tolls and parking fees. Thus, even if a uniform global carbon price was implemented, the result of doing so would most likely differ from what is depicted by IAMs. In short, most IAM pathways represent "first-best" pathways with no other market failures and frictionless implementation of climate policy. In the real, "second-best", world, the presence of market failures and imperfect policy implementation will generate pathways that look different from theoretically optimal pathways.

Third, all IAMs struggle to capture key elements of transformative change, including disruption, innovation, and nonlinear change in human behaviour (Rockström et al., 2017). It has been shown that modelers tend to underestimate the importance of unmodeled surprises and that forecasters systematically underestimate factors leading the real-world to fall outside the entire range of forecasts. Simplifying assumptions that are made partly for tractability reasons (e.g. assumptions of equilibrium and decreasing returns to scale) can contribute to this. For example, even though technological learning (reductions in technology costs with increased deployment) is widely observed and known to play a key role in technology innovation and diffusion, many IAMs don't represent such dynamics. In the real transition, we should expect the unexpected, not only when it comes to the deployment and cost of new technologies, but also behavioural changes, such as the abrupt global shift to working from home through the COVID-19 pandemic. Such surprises can lead certain changes to happen much faster than what IAMs indicate, and other changes to happen much more slowly.

Fourth, even if IAMs were able to accurately predict the optimal pathway, and even if one could remove all other market failures and ensure frictionless implementation of climate policy so as to achieve this pathway in the real world, the theoretically optimal pathway may not be the most desirable pathway. Total discounted cost (or consumption) is only one of many considerations for policy makers, stakeholders, and citizens. Energy security, affordability, social justice, and interactions with other policy goals may be equally, or in some cases even more, important. As might non-monetary preferences, related to for instance nuclear energy, wind power, and transportation choices. Different technology options, such as CCS, renewable energy, and nuclear may also have different risks that are not reflected in optimal pathways (cost-overruns, technological failure, etc). This means that, even though cost is an important factor, the most desirable pathway might differ from the most cost-effective pathway.

Overall, for the reasons outlined, and based on the fact that many IAMs are not independent (IAMs may be based on similar frameworks and simplifying assumptions, and use similar input data), it is not unlikely that the pathway taken in the next couple of decades will fall outside the entire range of pathways depicted by IAMs, particularly at the more disaggregated level of the energy system (e.g., coal or solar use in 2050). For this reason, care should be taken when using IAM outputs as inputs to other analyses. In short, IAMs are not forecasts and they should be interpreted accordingly. Most IAMs compute the optimal way of meeting a given climate target (i.e. they are run in "backcasting" mode). This means that they work backwards from a given target, rather than forwards from where we are by continuing current trends. This is simply not what (most) IAMs were designed to do.

This, however, does not negate the fact that IAMs contain lots of information based on a consideration of many key factors and interactions, all of which can be used as a starting point for assessing the implications of different climate targets. The fact that the real world will not evolve in an optimal manner also does not mean that climate targets are not achievable; some things might change more rapidly, and others more slowly. This is important to consider when using IAMs for stress testing in the financial sector.

4.2. What socioeconomic and policy assumptions do IAMs make?

Exogenous socioeconomic drivers

Two of the most important drivers of emissions are population and GDP growth. Population is an exogenous driver in all IAMs, and GDP is an exogenous driver in most IAMs. A handful of IAMs, however, treat GDP endogenously (e.g. AIM-CGE, BET, and GEM-E3). Several other drivers related to economic and technological progress, such as energy efficiency improvements, productivity, and technical progress, are often also exogenous in IAMs.

The IAM community has also gone through a process of harmonizing some exogenous drivers to aid comparability. The most common set of harmonized socioeconomic data is the Shared Socioeconomic Pathways (SSPs) (van Vuuren et al., 2017). The SSPs consist of five qualitative narratives that describe alternative developments of the world, which have been quantified to give pathways for population, GDP, and other socioeconomic variables. The five developments of the world correspond to varied challenges to mitigation and adaptation:

- SSP1 Sustainability – Taking the Green Road (Low challenges to mitigation and adaptation).
- SSP2 Middle of the Road (Medium challenges to mitigation and adaptation)
- SSP3 Regional Rivalry – A Rocky Road (High challenges to mitigation and adaptation)
- SSP4 Inequality – A Road Divided (Low challenges to mitigation, high challenges to adaptation)
- SSP5 Fossil-fuelled Development – Taking the Highway (High challenges to mitigation, low challenges to adaptation)

These SSP narratives are first quantified into population (Figure 6) and GDP (Figure 7). Climate mitigation does not affect population numbers, so all SSPs have the same population regardless of mitigation policies. Mitigation does affect GDP, and the difference between GDP in the baseline scenarios and the mitigation pathway is one way to estimate mitigation costs. Based on these inputs, IAMs are then used to find optimal pathways that meet different levels of radiative forcing in 2100 (as a proxy for climate impact). These radiative forcing levels, such as 1.9 Watts per meter squared (W/m^2), 2.6 W/m^2, 3.4 W/m^2, 4.5 W/m^2, 6.0 W/m^2, 7.0 W/m^2, and 8.5 W/m^2 link to different warming levels, with 1.5°C scenarios consistent with a forcing level of 1.9 W/m^2 and "well below 2°C" consistent with 2.6 W/m^2. Previously, in the IPCC Fifth Assessment Report, these forcing levels were known as Representative Concentration Pathways (RCPs). The new generation of scenarios link the socioeconomic assumptions with the forcing level, as an example, SSP1–19 is a scenario using SSP1 as input and achieving a forcing of 1.9 W/m^2 in 2100 or approximately 1.5°C.

Any modelling group is free to use the SSPs, but there is one well-known multi-model inter-comparison based on the SSPs that involves six IAMs (GCAM, AIM/CGE, IMAGE, MESSAGE, REMIND, WITCH) (Riahi et al., 2017). A selection of these quantified SSPs, called marker SSPs in this document, are used in complex climate models to estimate the detailed climate impacts resulting from each SSP (O'Neill et al., 2016).

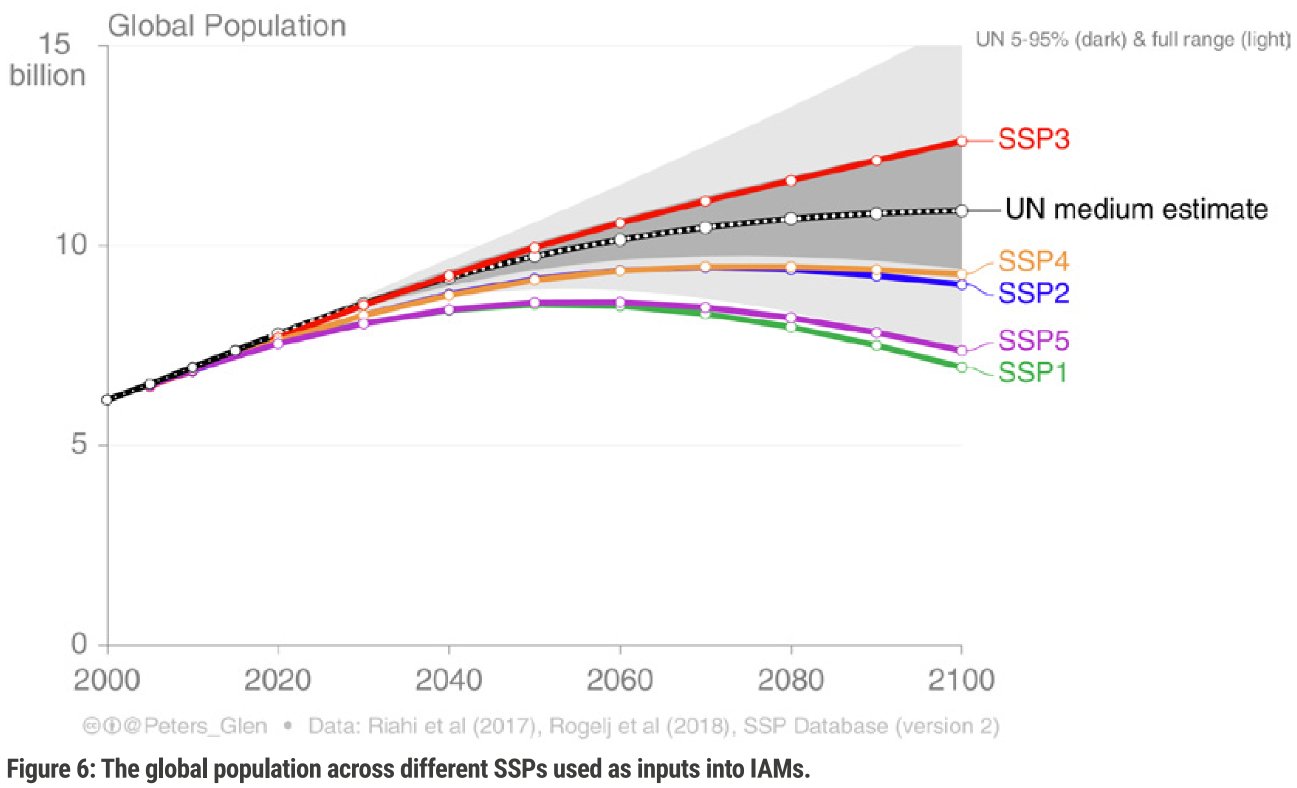


Figure 6: The global population across different SSPs used as inputs into IAMs.

The black line shows historical population (before 2020) and the UN medium scenario after 2020 with the full UN range shown in light grey and the 5–95% range in the dark grey.

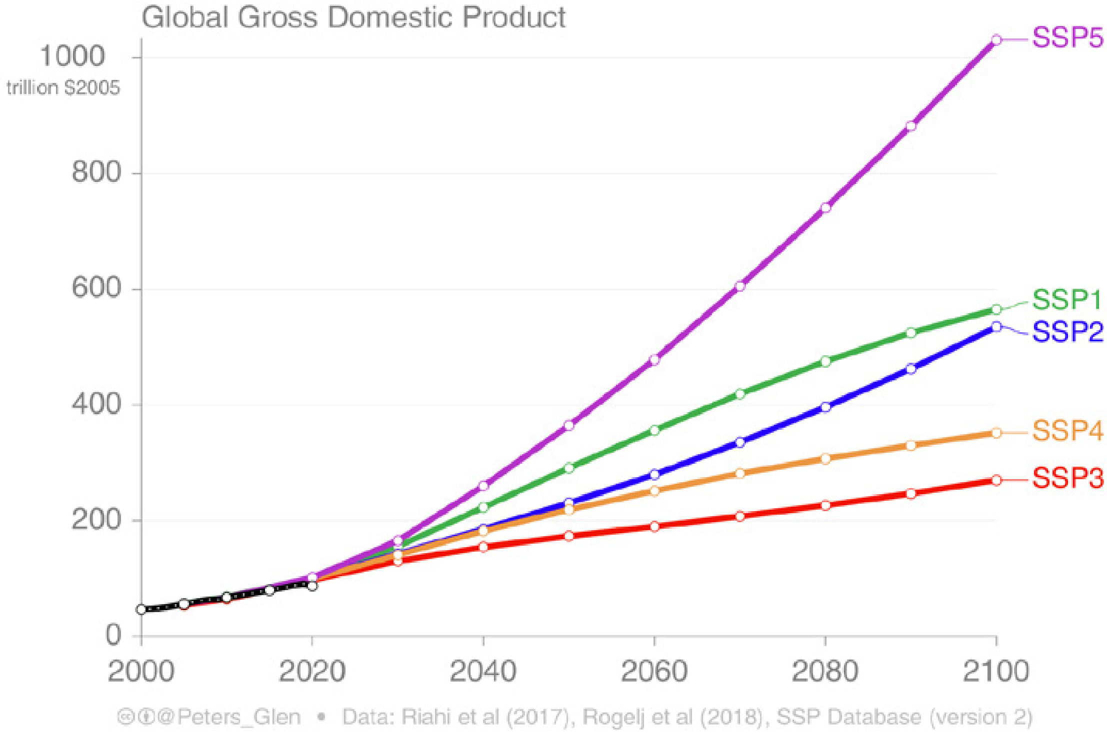


Figure 7: Global GDP across different SSPs

The black line shows historical estimates up to (and including) 2020.

Given population, GDP, and other relevant socioeconomic variables from the SSPs, IAMs are used to estimate emissions in a baseline case (no climate policy) and in various mitigation cases reaching different levels of global warming in 2100 (Figure 8). The warming levels are defined by the level of radiative forcing in 2100. Thus, SSPs are labelled depending on the narrative and forcing level: SSP2–4.5 is a scenario based on the SSP2 narrative reaching a forcing level of 4.5W/m^2 in 2100. SSP5-Baseline is the no climate policy pathway assuming SSP5 narrative, reaching a forcing level of 8.5W/m^2 in 2100 (sometimes referred to as SSP5–8.5 or its predecessor RCP8.5[3]). Each SSP and forcing level combination can be modelled by different IAMs, leading to a large range of outcomes.

An important takeaway from all this is that the assumptions associated with different SSPs have significant impacts on the difficulty of meeting climate targets and the pathways that can and cannot be produced in IAMs. If SSP5 or SSP3 (both implying high challenges to mitigation) are used, for example, it is much harder to reach stringent climate targets and mitigation costs go up. Figure 8 shows different baselines (in grey) and stabilization targets (forcing levels) computed by IAMs that use different SSPs. While all modelling groups are free to use any of the SSPs and use these to explore impacts of socioeconomic assumptions on mitigation and resulting transformation pathways, many modelling groups just apply one SSP (typically SSP2 – middle of the road). This is something to be aware of when using IAM scenario outputs.

3 RCP8.5 should not be considered business-as-usual but represents the absence of additional climate policy and the pursuance of SSP 5 (Fossil fueled development).

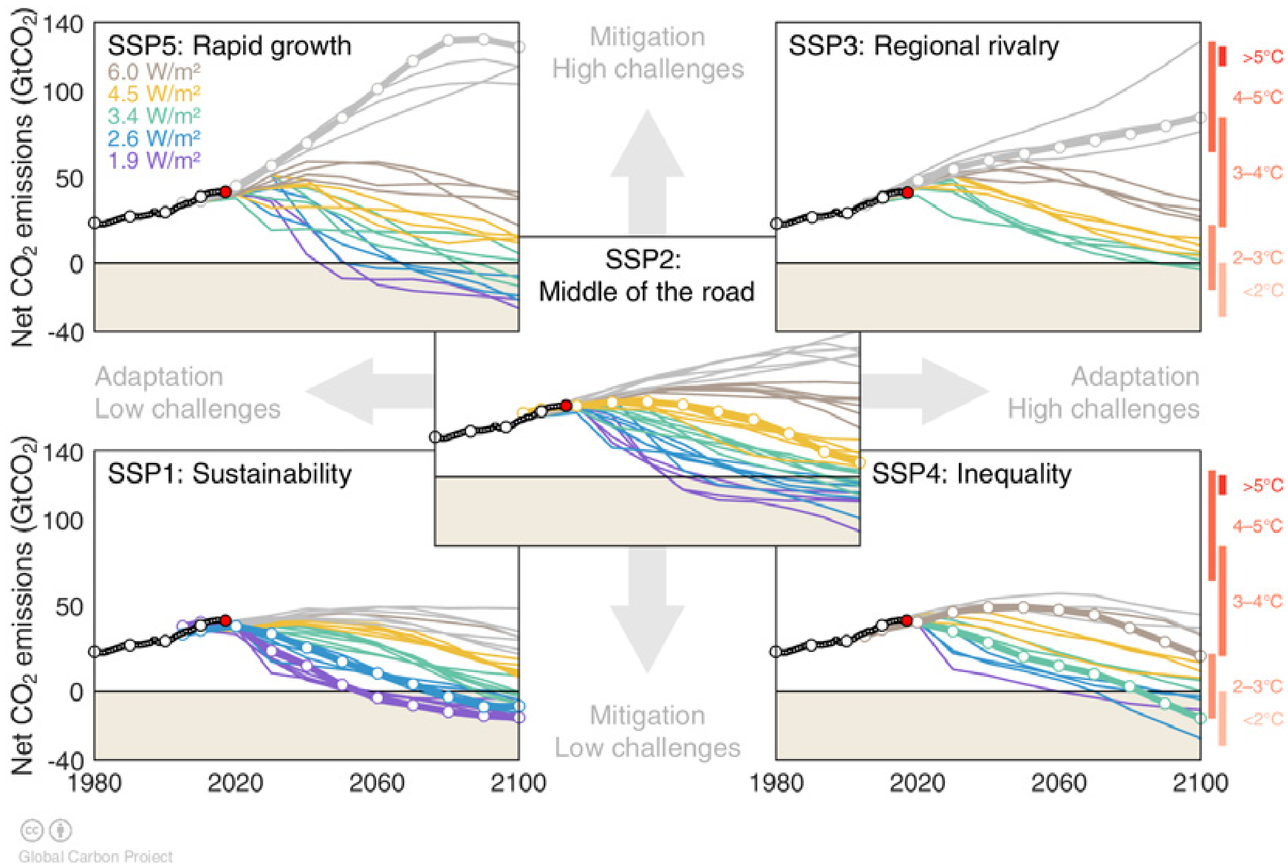


Figure 8: The CO_2 emissions for SSPs (panels) for a variety of forcing levels (colours)

The multiple coloured lines in each panel representing the results from one of the six IAMs. Not all IAMs ran all combinations of SSPs and forcing levels, and some IAMs could not produce certain combinations of SSP and forcing level.

Policy representation

Climate policy in IAMs is most often represented via a globally uniform carbon price. Carbon pricing and emission caps are essentially interchangeable, with models using one or the other depending on how the model operates. In IAMs with an economic core, equilibrium is achieved by finding the prices that equate supply and demand for goods in all markets. The carbon price in these IAMs reflects the constraints on emissions imposed by the climate target (the emission cap). Thus, the climate policy (i.e. the carbon price), is often an output rather than an input to IAMs – it reflects the effort needed to meet the given target. Other IAMs may run multiple carbon prices until they find the price that meets the given emission gap.

Carbon prices in IAMs should not be conflated with suggested levels of carbon pricing in real policy contexts, which involve multiple goals and often include a portfolio of policy instruments adapted to specific contexts. In general, the carbon price generated by an IAM reflects how difficult it is to reduce emissions in that IAM, in essence, it is a mathematical construct with a real world interpretation. This depends on model assumptions and parameter values, for instance regarding technology learning (which may make mitigation "easier") or discount rates. Different IAMs will generate different carbon prices for the same climate target, and the differences can by significant (Figure 11) . A carbon price in a model that gets higher and higher is an indication that the forcing level is becoming infeasible in that model, and the level at which this happens will vary significantly by IAM.

Some IAMs may combine carbon prices with other policy instruments. For example, the IEA WEM often uses carbon prices for electricity and industry, but emissions standards for the transport sector. Thus, the IEA WEM will have a lower carbon price, since transport often has higher marginal mitigation costs. Thus, comparing the carbon prices used in the IEA WEM with other IAMs may be misleading, just as it is when comparing carbon prices across different IAMs.

Although many IAMs can represent other policies such as fuel taxes, subsidies, standards, capacity targets, R&D, and feed-in-tariffs, many IAMs still rely on carbon prices as the only policy lever. As mentioned above, this poses an issue for the accuracy of the pathways depicted because climate policy in the real world is, and will most likely continue to be, based on a mixture of different kinds of policies, rather than a globally uniform carbon price. The diversity of policy instruments that can be used to reduce emissions has an impact on how emissions reductions take place across markets. Targeted renewables subsidies, for example, may lead to a faster deployment of renewables, but no scaling up of CCS. Similarly, tightening fuel standards can be expected to have a larger and more immediate impact on transport emissions than a uniform carbon price would have.

There is often very little regional variation in carbon prices in most IAMs (Figure 9). This is partly by design and partly by necessity. In most scenarios, it is assumed that global climate policy is implemented straight away, but IAMs do allow for regional differentiation in carbon price.

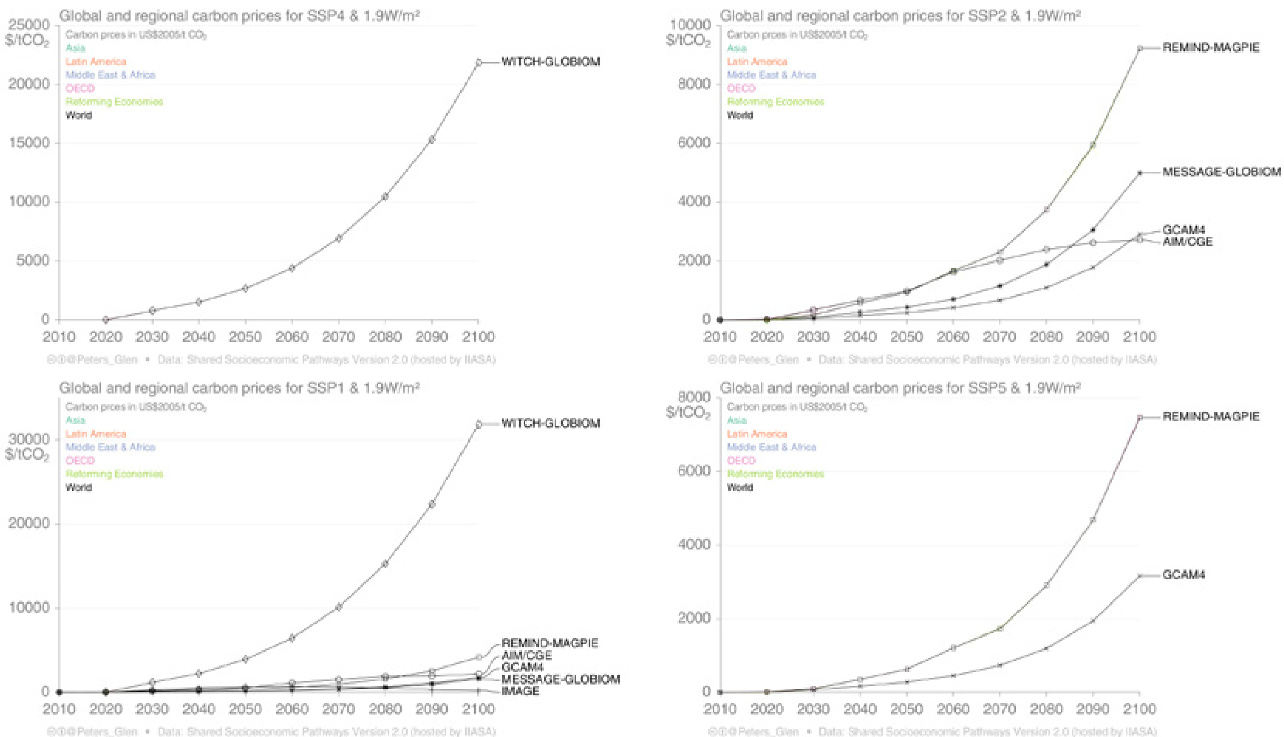


Figure 9: The carbon price across six different IAMs for forcing levels of 1.9W/m2 (1.5°C) and different SSPs (panels).

The multiple coloured lines in each panel representing the results from one of the six IAMs. Not all IAMs ran all combinations of SSPs and forcing levels, and some IAMs could not produce certain combinations of SSP and forcing level.

Discounting

When IAMs assume perfect foresight to identify the theoretically optimal pathway of meeting a given target, future costs are discounted to compute the net present value. This means that costs and benefits that accrue in the future are reduced relative to costs and benefits that accrue today.

Cost-benefit IAMs have been heavily criticized for using high discount rates, which means that future climate damages are reduced relative to the cost of mitigating those damages today. High discount rates in these IAMs mean that higher levels of global warming are optimal from a welfare perspective.

In complex IAMs, the discount rate does not affect the overall level of mitigation, because this is determined by the given climate target, but it has an impact on the timing and choice of mitigation measures and costs. A lower discount rate will bring mitigation forward in time, which translates into less need for carbon dioxide removal later (Emmerling et al., 2019)such as climate change, has been widely acknowledged. However, the choice of the discount rate is hardly discussed when translating policy targets –such as 1.5 and 2°C– into emission reduction strategies with the possibility of overshoot. Integrated assessment models (IAMs. Similarly, a higher discount rate pushes mitigation further into the future and therefore places a higher burden on future generations. The discount rate therefore represents a value-laden assumption. Despite the importance of the discount rate for transformation pathways generated by complex IAMs, the discount rate assumption in complex IAMs have not faced the same scrutiny as it has in cost-benefit IAMs.

Overall, the impacts of the choice of discount rate on transformation pathways is underexplored in complex IAMs. Many IAMs assume a social discount rate of about 5% per year, but the rate varies between around 2–8% (Forster et al., 2018).

Modelling the cost of climate mitigation

IAMs are frequently used to estimate the cost of reaching different climate targets. Most IAMs estimate the cost of mitigation to be a few percentage points of GDP (often around 1–2% and usually less than 3%). The use of optimization in optimal growth IAMs, CGE IAMs, and ESOMs, however, can mean that any constraints on emissions (and thus any amount of climate policy) imply economic costs. This happens if the baseline - the no climate policy reference scenario - is assumed to be optimal, an assumption which is often made in IAMs. In practice, some climate policies can be constructed in a way that increases GDP, such as via changing the tax system to reduce employment taxes and increase carbon taxes, or via the stimulatory effect of investments in clean energy, transport infrastructure, the built environment, and in human capital development. Some researchers have also argued that the cost of mitigation is too uncertain to warrant meaningful estimates.

The cost of mitigation should only really be considered as a model-specific consistent measure of effort and not what will be realized in practice. This is because most IAMS indicate climate mitigation costs relative to a baseline scenario without climate policy, which is a hypothetical pathway that does not exist. The marginal cost compared to current policies will be smaller. The costs represent the myriad of assumptions in each IAM and changing technology costs or background socioeconomics will further impact on the actual costs. Significantly, complex IAMs also do not include the cost of climate damages and this raises two key issues:

i. the assumed baseline may not be realizable due to climate impacts; and
ii. the costs of mitigation could be lower than the cost of damages.

The cost of mitigation can be a useful metric for sensitivity analyses in complex IAMs. By changing input assumptions, such as on technology, it is possible to see how those assumptions change cost and thereby estimate the value of that option to the system. For example, removing CCS as a technological option will increase the mitigation costs, which can be compared to the mitigation cost of removing nuclear power as a technological option. However, some policies and behavioural measures are hard to implement and cost in a model, and therefore, the mitigation cost is not always a useful metric. For example, the low energy demand scenario that avoids the need for CCS does not have associated cost information as the costs of the demand reductions are unknown (Grubler et al., 2020).

4.3. What technology assumptions do IAMs make?

It has long been known that transformation pathways generated by IAMs are very sensitive to technology assumptions (Keepin & Wynne, 1984). This means that small changes in technology cost assumptions can have significant effects on modelled technology pathways.

Moreover, the prediction of technology costs is a critical area of underperformance of IAMs. IAMs have underpredicted the cost reductions observed for solar (Creutzig et al., 2017) and wind (Shiraki & Sugiyama, 2020). This means that solar energy has emerged only as a minor mitigation option in most IAM pathways. The vast majority of IAM pathways in AR5 (which was published in 2014), for example, estimated values of solar deployment in 2015 that turned out to be less than half of the actual value of solar deployment in 2014. At the same time, IAMs have overestimated competing low-carbon technologies such as CCS and nuclear. For CCS and nuclear, real-world costs have been higher than anticipated (Rubin et al., 2015).

The systematic underestimation of solar in IAMs is due in part to IAMs not considering policy support, non-monetary consumer and industry preferences, and technological learning. The scenario literature is usually based on reference scenarios without climate policy. In practice, climate policies do exist, and many of these policies accelerate the deployment of clean technologies. Solar power, for example, has had decades of support for research and development, and recently has had support for deployment.

There are very few scenarios which attempt to model policies in place and how they may change in the near term, and thus, comparisons between IAMs and reality are difficult (as reality includes policies). Though, this is changing (e.g. Roelfsema et al., 2020)the global stocktake will assess the combined effort of countries. Here, based on a public policy database and a multi-model scenario analysis, we show that implementation of current policies leaves a median emission gap of 22.4 to 28.2 $GtCO_2eq$ by 2030 with the optimal pathways to implement the well below 2 °C and 1.5 °C Paris goals. If Nationally Determined Contributions would be fully implemented, this gap would be reduced by a third. Interestingly, the countries evaluated were found to not achieve their pledged contributions with implemented policies (implementation gap. The IEA WEO, for example, does attempt to model policies in place, but only considers the policies that have been implemented or stated (not if ambition is changed over time). The IEA would argue that the reason that it systematically underestimates solar deployment is that it does not try to predict the continuous renewal of supporting policies for renewable energy. A key advantage of modelling policies in place is that it is possible to model the effect of strengthening or weakening those policies.

Technological learning, which is known to be important in technology transitions, has also proven difficult to incorporate in IAMs in practice. This is at least in part explained by the computational complexity technological learning introduces, especially in optimization models. Although some IAMs, including GEM-E3, REMIND, WITCH, IMAGE, and MERGE-ETL, have incorporated learning for some technologies, technological change is still treated exogenously in many IAMs. This means that, in many IAMs, policies have no effect on modelled innovation and future technology costs, even though this is not supported by real world experience.

4.4. Carbon dioxide removal and overshoot

When the 2°C warming limit was first considered at a high-level in the late 2000s, IAMs had trouble finding pathways to keep warming below 2°C. Since models started including carbon dioxide removal (CDR) as a technology option, most notably by including bioenergy with carbon capture and storage (BECCS), IAMs have been able to find multiple pathways to 2°C, and even pathways consistent with 1.5°C of warming. Today, most mitigation pathways include CDR, most notably through large-scale afforestation or BECCS. A small number of models include Direct Air Capture with Carbon Storage (DACCS). It is also possible to include Enhanced Weathering and more elaborate land-base model updates such as different types of forest management or soil carbon uptake. CDR has become so prolific in IAMs, that it is even a key technology in non-aggressive mitigation pathways consistent with higher warming levels (e.g. 3°C in 2100).

The prevalence of CDR in scenarios was also aided by a subtle redefinition of climate targets. Initially climate targets were treated as a threshold that could not be crossed over the entire modelling period, while now, climate targets are often formulated as a 2100 target only. This means that the temperature (or radiative forcing) can exceed the target before 2100, it only matters that it meets the target by 2100. This peak and decline in temperature (known as overshoot) is due to a combination of introducing CDR, a 2100 climate target, and a cost-optimizing framework with discounted costs over time. Nearly all mitigation pathways reach net-zero emissions and then go into a period with negative net emissions. The temperature peaks around the time of net-zero carbon dioxide emissions, and the scale of negative net emissions largely dictates the size of the temperature overshoot.

The climate system only responds to the net emissions, but these net emissions can be a balance between positive and negative emissions (Figure 10). It is likely not possible to fully reduce carbon dioxide emissions to zero, either because it is not possible or it is too costly, and therefore there may still be some residual carbon dioxide emissions. These residual emissions need to be offset by carbon dioxide removal. Further, non-CO_2 emissions are unlikely to reach zero, and these need to be at least partially offset by carbon dioxide removal to offset the temperature response. On top of the need for carbon dioxide removal to offset continued emissions, additional carbon dioxide removal is used to make emissions net negative, and thereby cause the temperature to decline. Nearly all scenarios have these characteristics, but the size of the residual emissions, non-CO_2 emissions, and carbon dioxide removal varies by IAM.

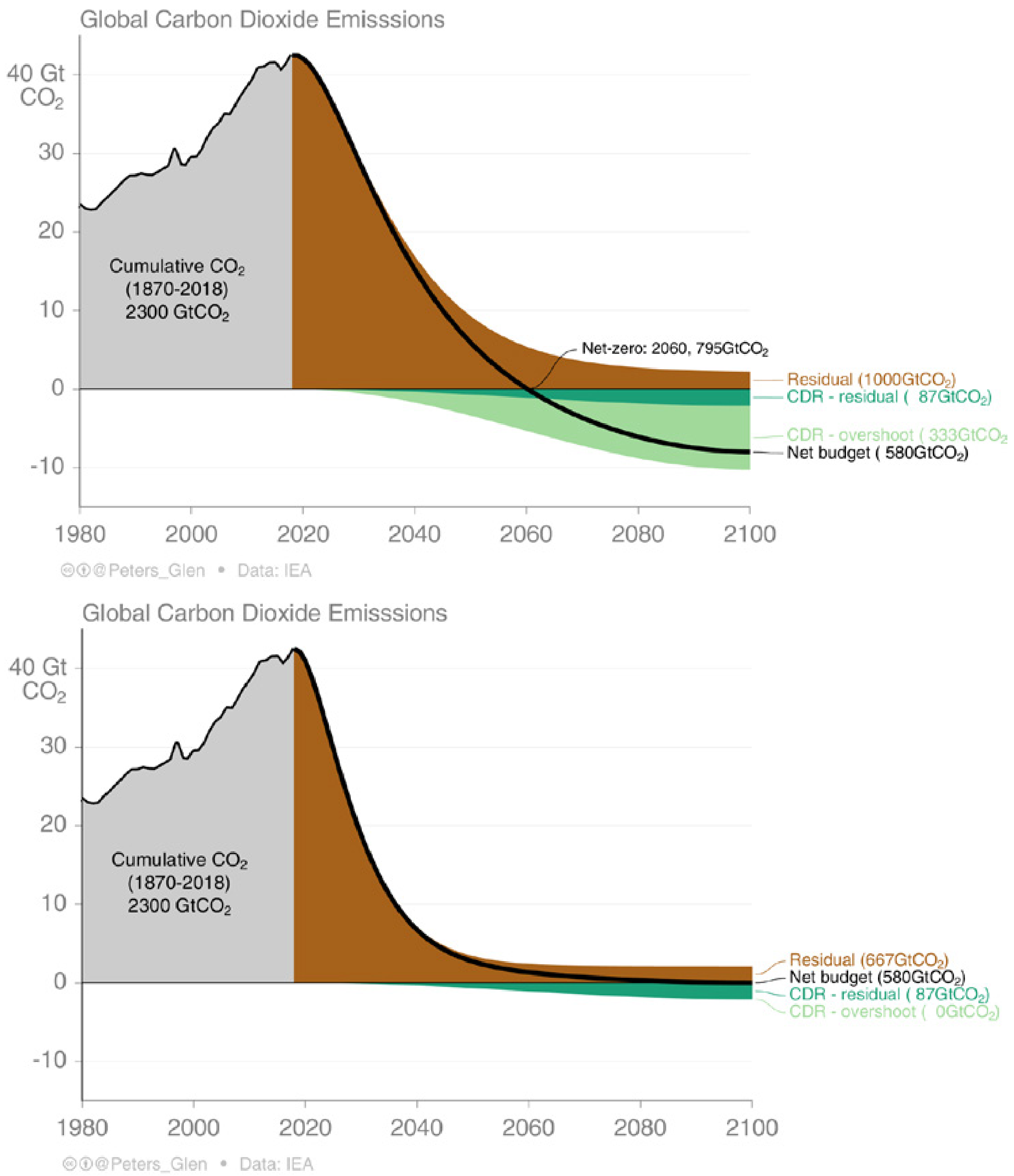


Figure 10: Two stylized IAM pathways to 1.5°C with the same cumulative emissions in 2100, but very different amounts of CDR

In the upper figure, the temperature will peak around 2050 and then decline to around 1.3°C in 2100 and keep declining afterwards. In the lower figure, the temperature will peak at around 1.5°C in 2100 and then stay at that level. The exact temperature in both cases will also depend on the abatement pathway for non-CO_2 GHG emissions.

The need for net-zero emissions follows from climate science, which finds that temperatures stop rising when CO_2 emissions become zero. The need for net-negative emissions is driven by the need to offset non-CO_2 emissions (e.g. methane from agriculture, melting permafrost and abandoned oil and gas wells) and CO_2 emissions in hard-to-mitigate sectors (e.g., industry and long-distance transport) But introducing negative net emissions in excess of these 'residual' emissions into an IAM is largely a design choice. Net negative CO_2 emissions in the latter part of the century imply slower emission reductions in the next decade or two. Figure 10 shows the differing temperature response to alternative emission pathways, both resulting in similar temperature levels in 2100. The upper panel still requires rapid short-term reductions, but less than in the lower panel where temperature overshoot is avoided. Nearly all the IAM literature is focussed on scenarios with an overshoot (hence negative net emissions), and there are virtually no 1.5°C, and very few 2°C, scenarios in the literature that do not exhibit some form of temperature overshoot. This may be because all IAMs find it is cheaper to reach climate targets by allowing for temperature overshoot followed by systematic application of CDR, or it might be because constraints in the models mean that it is not possible to reduce emissions quickly enough to reach the targets without carbon dioxide removal. While some level of CDR may be necessary to reach aggressive mitigation targets, the scale of CDR is affected by modelling choices. Key aspects affecting overshoot include the way the climate target is defined and implemented, the discount rate (lower rate implies less CDR), relative technology costs, and assumed constraints on technology deployment. There is very little literature with no or low levels of CDR, indicating that either climate targets are extremely difficult to reach or that modelling choices favour these sorts of technologies. Studies have shown that lower levels of CDR can be obtained with lower discount rates (Emmerling et al., 2019) or using additional constraints (Rogelj et al., 2019). A lower level of CDR generally means other technological or behavioural options are required. One implementation of the MESSAGE IAM can keep below 1.5°C without CCS but uses large-scale afforestation and extremely aggressive demand side reductions (Grubler et al., 2018). A study with the IMAGE IAM found that a combination of lifestyle changes such as reduced meat consumption and large scale reductions in long-haul travel, could greatly reduce or even eliminate the need for BECCS (Van Vuuren et al., 2018).

The prevalence of CDR in IAMs may also reflect a climate focus. If additional constraints are placed on biodiversity, water withdrawals, or even food prices, the levels of CDR obtained are likely to be lower, but mitigation costs higher. Perhaps more of a concern is that IAMs use large-scale CDR even at low mitigation levels. For higher warming levels in 2100 (Figure 11), BECCS are deployed at scale in all IAMs. The deployment of BECCS in 1.5°C and 2°C scenarios is even higher. The high use of BECCS in higher warming scenarios reinforces the likely importance of model structure and experimental design (e.g. backcasting) in modelled pathways.

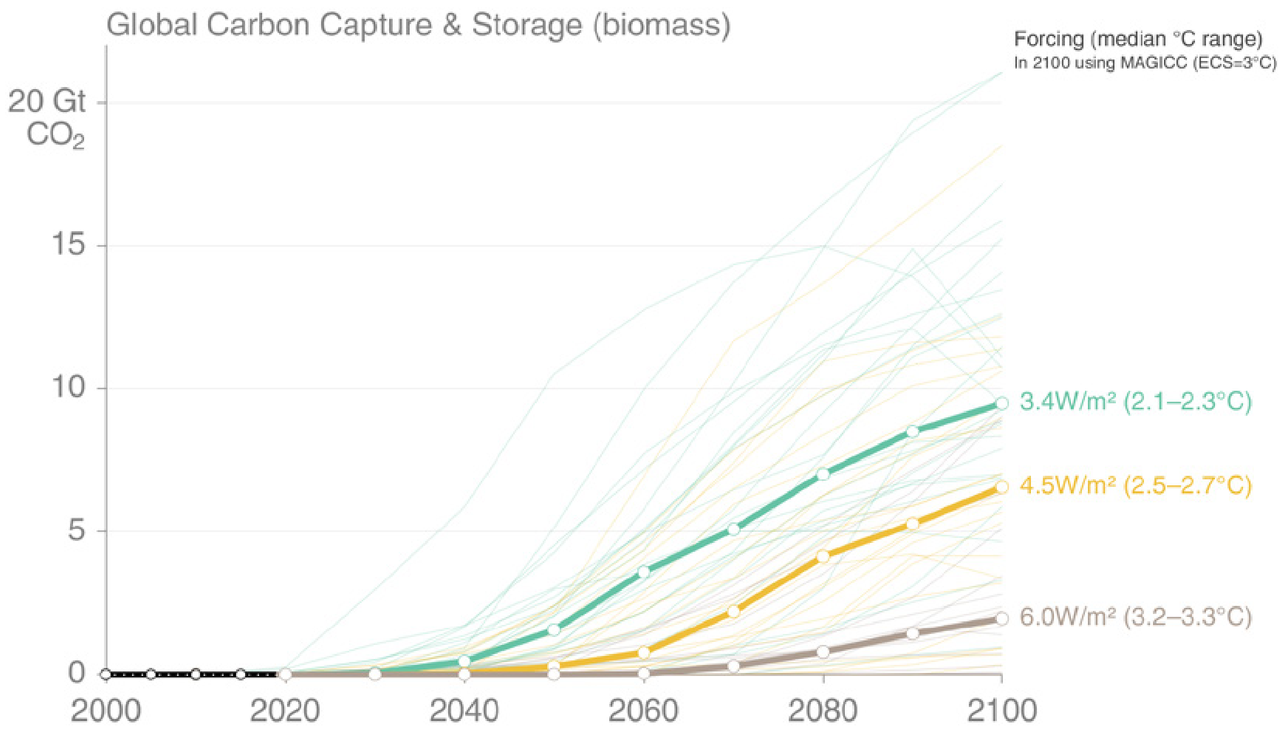


Figure 11: Bioenergy with carbon capture and storage (BECCS) in scenarios with higher warming levels, showing the high usage of BECCS.

4.5. Many pathways to 1.5°C

All IAM pathways that limit global warming to 1.5°C and 2°C show drastic near-term emission reductions, reaching net-zero CO_2 emissions around 2050 and 2070, before emissions become negative. Coal investments are dramatically reduced in the near-term and in general, unabated fossil fuels are reduced and non-fossil energy is expanded. Most IAMs use large amounts of CCS to achieve these two targets partly for structural and scenario-design reasons.Holding other scenario parameters constant, 1.5°C scenarios typically use more CCS than 2°C scenarios. The greater use of CCS in these more aggressive mitigation scenarios not only reflects the very limited carbon budget remaining, but also an estimation that future CCS will be the most cost-effective mode of emissions reductions. This latter rationale may be controversial as it depends on assumptions of discount rates, technological development, and the cost of future emissions. If CCS is not used at a large scale, emissions reductions in the near future have to be larger and faster, meaning fewer fossil fuels and more non-fossil energy. At the same time, IAMs differ considerably in what technologies they prefer (for example, whether they prefer wind or solar), and in terms of carbon prices required to achieve targets.

For these reasons, it is good practice to use multiple scenarios from different IAMs when considering the implications of different climate targets. When using multiple scenarios, at least two aspects are worth keeping in mind.

First, the range of pathways generated by existing IAMs is likely narrower than what is possible. Many assumptions are shared between IAMs, parameters and values may be based on similar sources, and most IAMs compute only the theoretically optimal pathway. These theoretically optimal pathways likely differ from the most likely and the most desirable pathways.

Second, agreement in results among IAMs does not necessarily imply certainty. Agreement can also be a result of shared assumptions or design choices (such as whether overshoot is allowed), which can sometimes be arbitrary or undesirable. For instance, even though all IAMs use large amounts of CCS to achieve the 1.5°C and the 2°C targets, the scale of CCS depicted in most IAM pathways may turn out to be either technically, economically, or politically infeasible, or simply undesirable when considering issues beyond climate change.

For these reasons, when using IAM scenarios to assess the implications of climate targets for the financial sector, it is recommended to:

i. Use different scenarios and IAMs to get an idea of the scale of change required and the range of pathways consistent with a given target.

ii. For variables of interest on which IAMs agree, consider what this agreement is based on. For example:

- **a. The rapid reductions in carbon dioxide emissions and coal investments seen in all IAM pathways consistent with the Paris Agreement target follows from climate science. There is high confidence that carbon dioxide emissions need to reach net zero to stop further temperature increases.**
- **b. The large deployment of any single technology in IAM pathways consistent with the Paris target should be queried. The scale depicted might not be feasible or desirable, and history has shown a diversity of solutions are used depending on regional contexts.**

iii. Beware of factors that are poorly represented in IAMs that may have a significant impact on variables of interest. Examples include behavioural change, technological learning, non-monetary preferences, political feasibility, and unexpected events such as the covid-19 pandemic.

5. Sectoral insights from climate scenarios

5.1. Regional, sectoral, and technological coverage in IAMs

The granularity, level of detail, and comprehensiveness of pathways generated by IAMs vary significantly.

Regional coverage

All IAMs capture global emissions but the regional disaggregation can vary significantly from one IAM to another. While MERGE-ETL, for example, divides the world into 10 regions, the Shell World Energy Model divides the world into 100 regions. Thus, some IAMs may include a considerable amount of country-specific detail, while other IAMs provide only an aggregated view of regions. When common scenario databases are used, such as the publishing scenarios assessed by the IPCC, results are usually only available for five world regions even if individual models may provide more detail.

Economic sectors

The number, and meaning, of economic sectors covered by IAMs varies and is generally related to the historical roots and associated underlying model approach.

A trademark of CGE models (such as IMACLIM, Phoenix, SGM, ENV-Linkages, G-CUBED, GEM-E3 and MIT EPPA) is their representation of many different and interacting economic sectors, such as agriculture, industry, energy, transport, and services. Different CGE IAMs, however, vary in their disaggregation of economic sectors (ranging from between 10-50).

Optimal growth IAMs (such as MERGE, MESSAGE-MACRO, REMIND, WITCH, and BET) represent the global economy as a single economic sector via a production function that uses capital, labour, and energy as its inputs. Thus, different economic sectors are not separated out in optimal growth IAMs. Emissions and energy in optimal growth IAMs, however, are still separated into the energy system, transport system, and buildings, but based around technologies and not economic activity.

Technologies

The fact that optimal growth IAMs represent the global economy as a single economic sector does not preclude optimal growth IAMs from representing a whole range of technologies and energy service sectors separately. Likewise, CGE models can have a detailed representation of economic sectors, but only a stylized representation of technologies and energy service sectors. The number of technologies represented depends on the IAM.

Almost all IAMs provide extensive coverage of different options for decarbonizing electricity generation including solar, wind, bioenergy, nuclear, and CCS. Electrification of energy demand in transport, buildings, and industry, and energy efficiency improvements are also covered by many IAMs. Options to decarbonize transport, industry, and agriculture will vary across IAMS. Although CDR technologies have come to play a key role in IAMs, most IAMs only model two types of CDR: afforestation and bioenergy with CCS.

The focus on the energy system means that the granularity of technologies and mitigation options in the energy system is much higher than in other systems. Even so, the level of technological detail in IAMs is generally less than in sector-specific models. Over time, IAMs are becoming more detailed in the non-energy sectors, such as agriculture, industry, and buildings. Ambitious mitigation pathways are increasingly dependent on the land-sector to aid mitigation (e.g. bioenergy and afforestation), and consequently many IAMs are starting to better model land use, though most IAMs still only represent land use in a stylized manner (e.g., constraints on bioenergy use without using a land use model). While the increased granularity of IAMs comes with many advantages, it also makes IAMs more complex and more difficult to decipher.

Energy supply and demand

The main focus of most IAMs is energy production. In the electricity sector, this includes electricity generating technologies such as coal, wind, and nuclear. However, not many IAMs include detailed representations of primary energy supply, such as detailed modelling of coal, oil, and gas extraction. Similar issues can arise for bioenergy use and production depending on the IAM. IAMs focus on the amount and location that coal, oil, gas, and bioenergy are used, but less focused on where the coal, oil, gas, bioenergy are extracted or produced. IAMs do not provide much detail on the location of extraction or production, and this means that the model robustness in estimating energy prices is much less than for carbon prices.

Most IAMs are detailed on the provision of energy for different energy services (such as heating, power, and transport), but are less detailed on how that energy demand may change in response to behaviour or policy. The options for decarbonizing electricity and for inter-fuel substitution (e.g. green hydrogen or biofuels for fossil fuels), for example, are much more extensive than demand side measures such as reduced energy service and material demand, structural changes in the transport sector, urban change, and lifestyle change such as dietary changes away from meat consumption, reductions in long distance travel, and limits on food waste.

5.2. Future energy mix in IAMs

All IAMs show decreased fossil energy and increased non-fossil energy in mitigation scenarios, but the specifics depend on the IAM (Figure 12). Different IAMs tend to prefer different technologies. One IAM might show high shares of solar, while another shows high shares of wind, and yet another will focus on nuclear energy. These differences may not be cost related but relate to other constraints or structural assumptions in an IAM.

Figure 12: Primary energy use in 1.5C emission scenarios with "no or low overshoot" that were the focus of the IPCC SR15 shown in blue lines (bold is the median)

The IEA Sustainable Development Scenario (SDS), consistent with about 1.7-1.8C of warming, is also shown, together with the two IEA baseline scenarios for current and stated policies. The figures show coal, oil, gas, and non-biomass renewables (biomass is not shown).

Technologies are chosen in IAMs primarily based on least-cost to the energy system for a given climate target, not necessarily the lowest cost of individual technologies. Additionally, IAMs impose several constraints, such as on the rate of technology deployment, to avoid technologies deploying too fast. The optimal technology mix varies between IAMs due to differences in technology cost and performance, technology constraints, whether learning is represented, what mitigation measures are included, the level of intermittency permitted in the electricity sector, model structure, and so on. Intermittency rules apply to variable renewable energy that is non-dispatchable due to its fluctuating nature, such as wind and solar power, as opposed to more controllable renewable energy sources including fossil fuels, hydroelectricity, biomass, or geothermal. Structural assumptions in models, such as whether they are based on perfect foresight or are myopic also affect technology deployment.

Across these variations, all IAMs provide consistent frameworks for analysing energy supply and demand. If one energy source is lower, then another has to be higher (or demand lower) to compensate. For example, if coal with CCS is lower, then another energy source has to grow faster to provide the required energy within the emission constraint. Some model pathways and trade-offs may not be intuitive. It is easy to assume that less CCS would mean less coal, but less CCS could equally mean less bioenergy with CCS to generate carbon dioxide removal that offsets continued oil use (so less CCS could mean less oil).

Figure 13 shows the energy mix in 2050 across six IAMs and the five SSPs for the baseline (no climate policy) and a forcing level of 2.6W/m^2 or <2°C in 2100. The energy mix varies strongly across SSPs and IAMs, in addition to when there is mitigation. In the baseline, SSP1 has lower energy use and lower coal use, compared to SSP5, and this reflects the SSP narratives. But, also, within a given SSP, each IAM gives a different energy use and energy mix result. For example, AIM uses less gas but more oil than some other models. GCAM generally has more coal and higher energy use. Similar characteristics occur in mitigation. The level of CCS varies across IAMs, GCAM has more coal with CCS while REMIND has more bioenergy with CCS. For non-fossil sources, GCAM has higher nuclear, WITCH has higher wind, and REMIND higher solar.

Despite vastly different energy uses and energy mixes across the scenarios, they all meet the same climate target. This highlights that there is no unique way to meet a given climate target, but there are certain important characteristics in meeting targets such as reductions in unabated fossil fuel use and increases in non-fossil energy sources. Why a model uses a lot of CCS or prefers wind, solar, or nuclear may be difficult to determine, and may not relate to costs, but instead relate to questions of model structure and implementation.

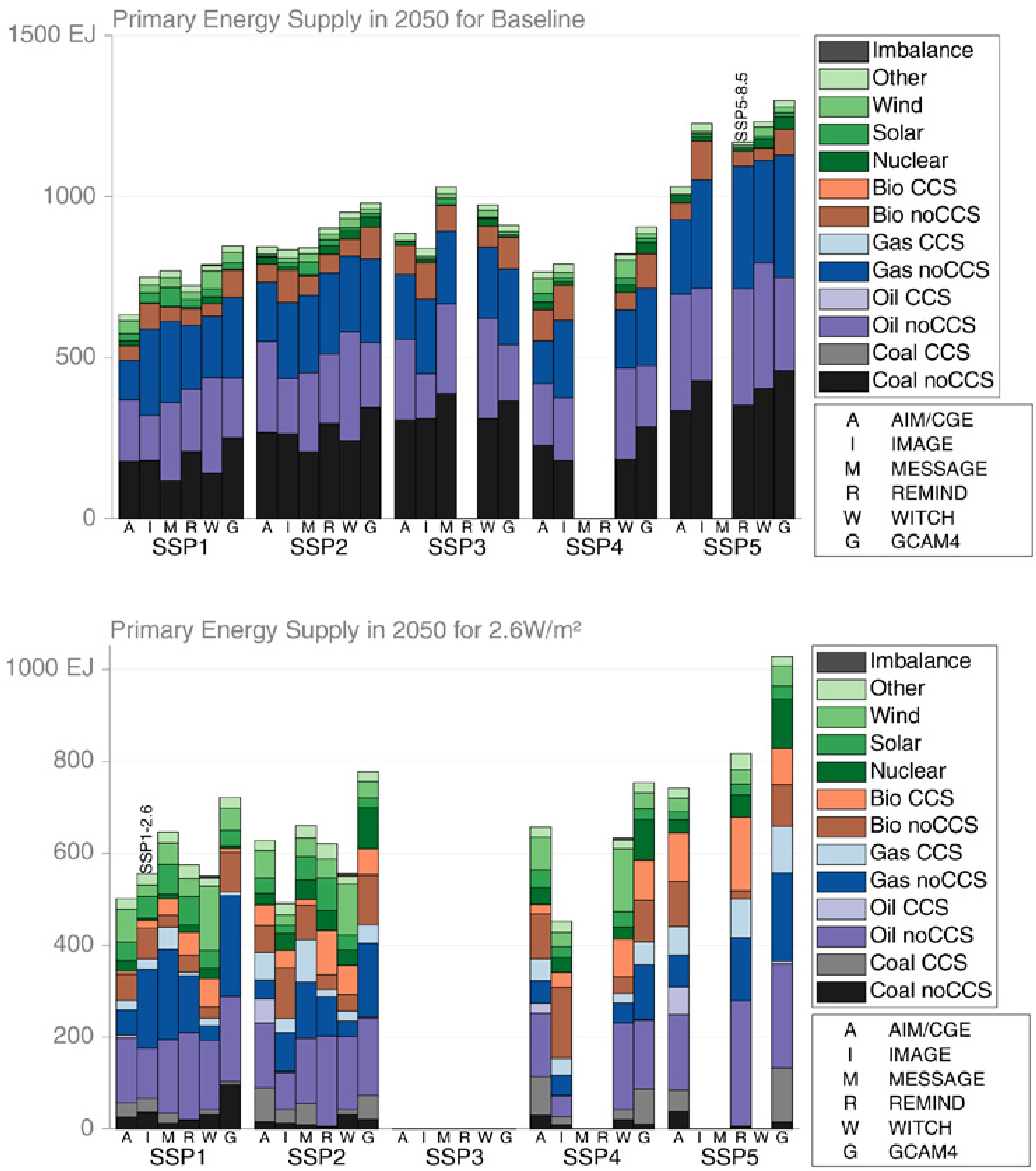


Figure 13: The energy mix in 2050 across SSPs and six IAMs for baselines (top) and a radiative forcing level of 2.6W/m2 in 2100 or <2°C (bottom)

The imbalance, if shown, represents small differences between the reported energy mix and the reported energy use.

5.3. Understanding sector specific impacts

What sectors are covered by IAMs?

The main focus of most IAMs has been and still is the global energy system. Although IAMs are starting to capture agriculture, forestry, and other land use (AFOLU) sectors, most IAMs only do so in a stylized manner. Reduced deforestation, afforestation, and bioenergy are among the most common measures in the land-use sector, with less comprehensive coverage of mitigation options in food and agricultural production. Similarly, the coverage of non-CO_2 greenhouse gases, such as methane, which is important for agriculture, varies across IAMs. Likewise, coverage varies for air pollutants, some of which also have indirect effects on climate.

Table 3 gives an overview over the sectoral coverage in IAMs.

Sector	Coverage (of mitigation options)
Electricity sector	Extensive coverage in all IAMs.
Transport	Significant coverage in most IAMs.
Industry	Some coverage but varies by model.
Agriculture, forestry, and other land use (AFOLU)	Highly varied but improving coverage (some models couple to dedicated land-use models).
Metals and mining	Minimal
Real estate	Minimal, except for energy use in buildings.

Table 3: Sectoral coverage in IAMs

Although certain sectors are generally better covered than others, there is significant variation between IAMs in terms of what is and isn't covered, and how well it is covered.

What do climate targets imply for future fossil fuel demand?

The fact that unabated fossil energy must give way to non-fossil energy must increase is a robust finding across all scenarios that are compliant with the Paris Agreement targets. All IAMs agree on this, even though IAMs vary in terms of whether they prefer solar or wind, or nuclear, and exactly how much CCS they deploy. IAMs also show variation in how fast coal, oil, and gas decline, particularly oil and even more so gas. When looking at specific sector impacts, such as the fossil fuel industry, it is important to understand how real-world trajectories might deviate from IAM trajectories. This section looks at what IAM scenarios tell us about future fossil fuel demand. Although the section is focused on fossil fuel demand, a similar logic can be applied to other sectors as well.

To help illustrate how fossil fuel demand is impacted in an IAM, we follow a simple narrative:

Climate policy in IAMs is generally represented as a price on carbon. The price on carbon that is used in most IAMs is the price that (in theory) minimises the cost of reaching a given climate target. The introduction of the carbon price means that carbon emitting technologies and processes become more expensive. Since most IAMs compute pathways that either minimise costs or are otherwise strongly driven by costs, a carbon price in an IAM will shift energy use away from carbon intensive technologies towards less carbon intensive technologies. The higher the carbon price, the stronger this effect will be. Thus, carbon dioxide emissions will grow more slowly or decrease when the carbon price goes up.

Carbon prices in IAMs should not, however, be confused with real world carbon prices. Carbon prices in IAMs are better understood as model specific proxies for climate policy. These proxies are far from perfect. Importantly, real-world climate policies such as subsidies, regulation, feed-in-tariffs, standards, and so on will have a different impact on technology choices compared to a carbon price. Policies targeted at renewables (such as renewables subsidies), for example, generally have a much stronger effect on renewables deployment than what an economy-wide carbon price that generated the same overall emissions reductions would have. Because renewable technologies are competing with fossil fuel technologies (both in power generation and for transport), the choice of policy instruments in the real world may also have a significant effect on the future demand for coal, oil, and gas.

IAM pathways that do not consider the impacts of real-world energy and climate policies may therefore underestimate the growth in some low-carbon technologies (wind, solar, EVs) and overestimate the growth in others (nuclear, CCS, CDR), all of which may have a significant impact on the future demand for fossil fuels. If large-scale CCS is seen as an option in the future, the research literature shows that all IAMs will find it more cost-effective to deploy CCS to compensate for emissions than it is to reduce emissions faster to avoid the need for CCS. If large-scale CCS deployment, however, is not seen as feasible or desirable, for instance for land-use, public safety, or water resource reasons, IAMs will have to reduce emissions faster earlier on. In this case, the deployment of low-carbon technologies would need to increase and the demand for fossil fuels would need to decrease further.

Thus, even though all IAMs agree that fossil fuel demand decreases rapidly, and non-fossil energy increases significantly in pathways compliant with the Paris Agreement target of limiting warming to "well below 2°C", current optimal pathways may still underestimate the rate at which this would need to happen. These and other factors that will affect the timing of fossil fuel decline relative to what IAMs depict are therefore important to consider in assessments of transition risk. Few IAMs have detailed data on coal, oil, or gas markets, meaning that they may not be reliable sources of energy prices. Many IAMs can, and do, still estimate energy prices (in addition to crop prices and some other commodities). Figure 14 shows the oil price used in six IAMs as part of a model intercomparison projection (Luderer et al., 2018). Each IAM estimates very different oil prices, they follow very different trajectories over time, and they show different behaviour in mitigation scenarios (relative to the baseline). In general, these IAMs see increasing oil prices in reference scenarios, and lower oil prices in mitigation scenarios, though the exact details vary widely across IAMs. It should be noted that these models are not specifically designed to estimate fossil fuel prices.

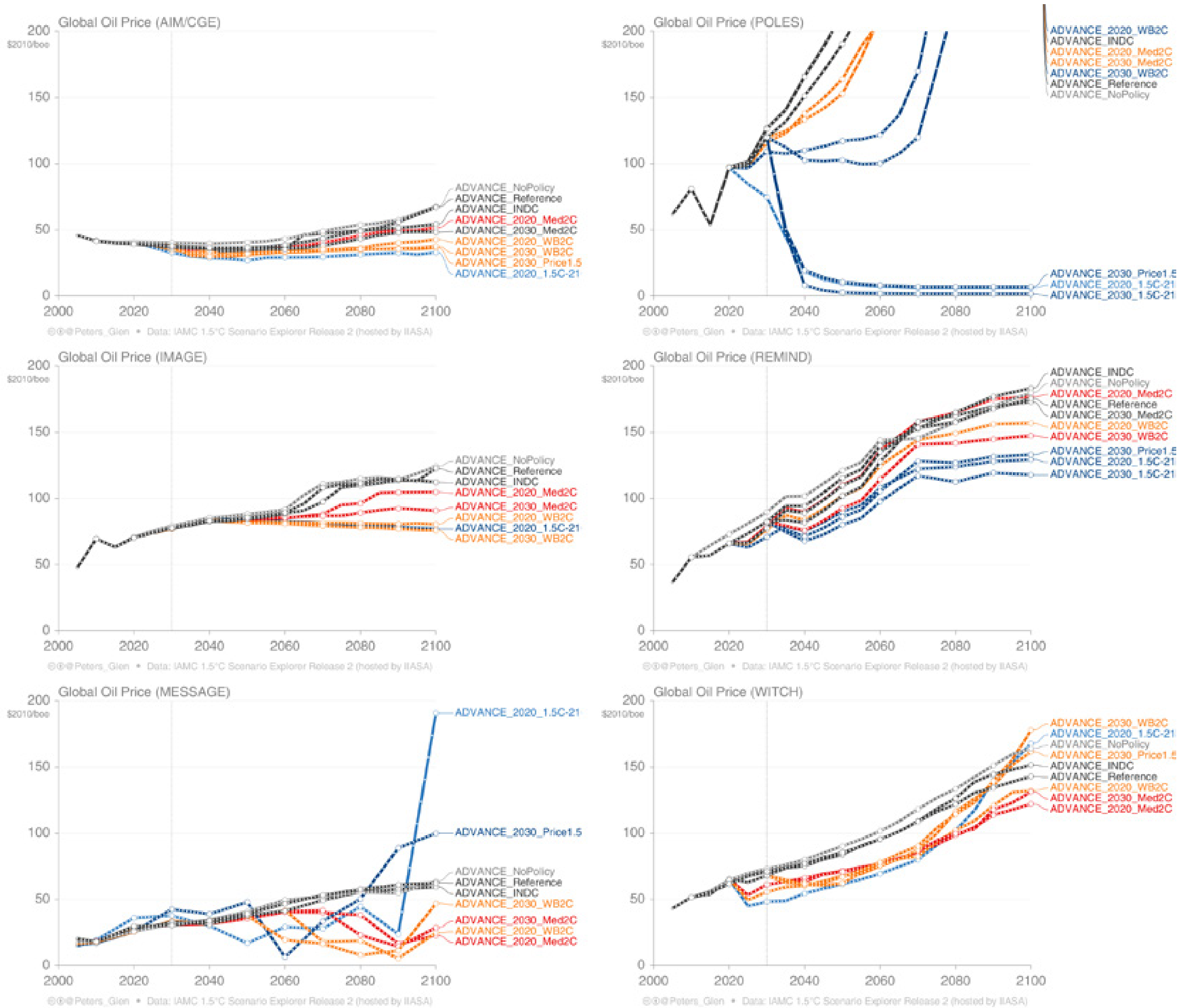


Figure 14: Oil prices in six different IAMs involved in the ADVANCE model inter-comparison study

The grey lines are baseline scenarios, the red lines 2°C scenarios, and the blue lines 1.5°C scenarios. Each set of scenarios has additional variations, which will not be discussed here.

Unmodeled factors and tipping points

In addition to the type of climate policy (whether this is a uniform carbon price or a technology-specific subsidy), many other factors have an impact on future demand for fossil fuels. Many of these factors are poorly represented in IAMs. Some of these factors may lead to rapid shifts in supply, demand, asset values, and even tipping points in the climate and/or technology systems. IAMs should therefore be considered in conjunction with uncaptured factors to ensure that such shifts and tipping points are not ignored.

Continuing our narrative:

Technology learning leads to cost reductions for new technologies, such as renewables, when deployment increases. This is known as the experience curve effect. This means that new technologies generally become more competitive over time. Although technology learning is included for some technologies in some IAMs (including REMIND, MERGE-ETL, and WITCH), most IAMs have a limited representation of technology learning and tend to model technology cost reductions exogenously, which means that deployment and climate policy has no impact on technology costs over time. By not modelling technology learning, IAMs might underestimate cost reductions of new technologies and therefore also their future deployment. For the same reason, IAMs might then also overestimate the future deployment of legacy fossil fuel technologies.

In addition to technology learning – which means technology costs decrease with experience – the type of policy also matters for technology deployment. Most IAMs use economy-wide carbon pricing, but real-world climate policies such as renewable energy support and subsidies, tend to speed up cost reductions and deployment more than what an economy-wide carbon price tends to do. Learning effects again imply that this might move technologies further down their learning curves, which can have a self-reinforcing effect, thus accelerating deployment further. This means that IAMs that do not model technology learning and that use carbon prices as a proxy for climate policy, may significantly underestimate the future deployment of low-carbon technologies. Experience from past modelling gives reason to believe this is, at least in part, the case: IAMs failed to predict the expansion of wind and solar energy seen in the last decade.

Technologies are chosen in IAMs primarily according to least-cost to the system over the time horizon of the IAM. But technology deployment is not determined by cost alone. In addition to costs, IAMs also assume maximum technology deployment rates. These rates are mostly based on historical rates, where these are available. History might, however, not be the best guide to the low-carbon transition, which differs in important ways from previous technology transitions. While past energy transitions were primarily driven by reductions in costs, technological inventions, and improved functionality, the low-carbon transition is primarily driven by directed efforts at moving from an energy system based on fossil fuels to an energy system based on renewable energy. The rate at which technology changed in the past might thus not be a good guide to the rate at which technologies might change in the coming decades.

The rate of technological change is key to predicting how the low-carbon transition may unfold, and thus also for financial stress testing. The diffusion of electric vehicles, for example, if continuing to grow at an accelerating pace, might reduce future oil demand faster than expected. Furthermore, rapid deployment of electric vehicles for passenger cars may have technological spillover effects on other forms of transportation (such as freight), and local microgrid deployment, further accelerating a drop in oil demand. Few IAMs, however, have a detailed representation of technology diffusion. Non-monetary preferences, whether related to power generating technologies such as nuclear and wind, or whether related to transportation choices, such as between internal combustion engine (ICE) cars, electric vehicles, public transport, or bicycles, are generally poorly represented in IAMs. This, in addition to the poor representation of technology learning and specific policies beyond carbon prices, means that there is a lot of uncertainty around the technology deployment rates depicted in IAMs. For some technologies, things might happen a lot faster, for others, it might happen a lot slower.

Finally, new practices for considering climate risks in the financial sector might themselves have an impact on the speed of the low-carbon transition. New risk considerations might lead to fossil fuel divestment and reallocation of financial resources into clean energy projects by companies and investors. This process is happening in a number of markets, triggered by the coronavirus pandemic and leading to asset revaluation and write downs at the world's largest fossil fuel companies. Financial institutions and market regulators are reassessing the speed of the energy transition, which may have self-reinforcing effects. The possibility of investors and regulators recalibrating their financial risk models to more fully incorporate climate change and energy transition risks, and the potential for more rapid behavioural change in the financial sector are not yet represented in IAMs.

6. Bank assessments of climate scenarios (Case Studies)

6.1. Overview of UNEP FI transition risk approach used for bank case studies

This section discusses climate scenarios at a sectoral level. Although the granularity and extensiveness of scenario outputs varies by model, there are still common themes across scenarios that can be identified and explored. This section aims to show the strengths and limitations of existing climate scenarios for conducting financial risk analyses within major sectors. This analysis from CICERO and UNEP FI is complimented by a set of case studies conducted by bank participants in UNEP FI's TCFD banking program. These case studies provide bank perspectives on the granularity, severity, and economic assumptions contained in selected scenarios.

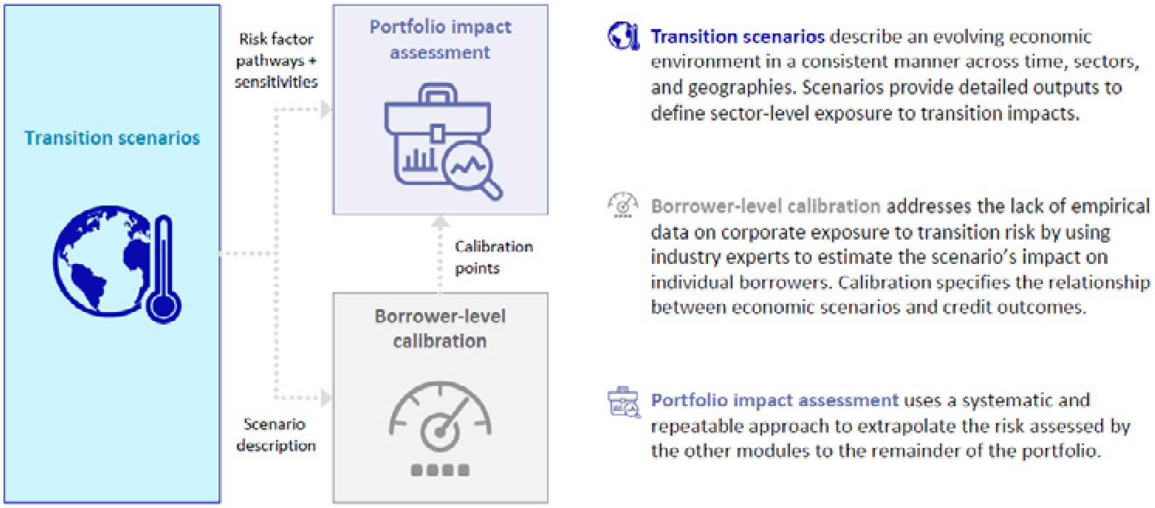
To produce these case studies, the contributing banks applied the transition risk methodology developed in Phase I of the TCFD banking program. While extensive details about the methodology can be found within UNEP FI's Extending Our Horizons report, the following methodological overview is provided to orient the reader (UNEP FI & Oliver Wyman 2018).

During Phase I, UNEP FI and a consortium of 16 banks collaborated with Oliver Wyman, a global management consulting firm, to develop an approach for evaluating corporate lending portfolio exposure to transition risk across various climate scenarios.

The program engaged with leading climate modelers to identify suitable climate scenarios for inclusion in the model. Through an evaluative process, the group selected the integrated assessment models (IAMs) produced by the Potsdam Institute for Climate (PIK), REMIND-MAgPIE, and the International Institute for Applied Systems Analysis (IIASA), MESSAGE-GLOBIOM.

The methodology incorporated the best available science through partnership with these globally recognised climate modelers. The three-step approach (see Figure 15) integrated climate scenario data and borrower-specific information to produce a portfolio-level view of transition risk. This dynamic methodology allowed for application to different sectors and geographies. By applying the pilot approach to their portfolios, banks were then able to better implement the TCFD recommendations to assess and disclose their climate risks.

Figure 15: Transition risk methodology from Phase I of the UNEP FI TCFD Banking Program



Initially, this methodology was implemented in an Excel workbook. However, to support the widespread exploration of climate scenarios and the application of the transition risk methodology, a webtool was developed with Oliver Wyman. This webtool, called Transition Check, provided a user-friendly interface for conducting scenario analysis. Participants submitting case studies used either the Excel workbook or Transition Check to generate their results. In a few instances, banks adapted the methodology described above for their case studies. These adaptations are described within the case studies themselves. However, the primary focus of the case studies is not on the methodology applied, but on the scenarios themselves.

6.2. Bank case studies and perspectives on climate scenarios

Banks are the largest providers of regulated capital in the world, so their views on climate change and the energy transition are important in establishing lending criteria across all sectors of the economy. As the world's largest commercial banks and members of the UNEP-FI convened Principles for Responsible Banking (PRB) begin to integrate IAMs into their risk modelling and regulatory reporting work, the field is rapidly evolving. Prudential regulator engagement with banks on climate risk reporting and regulators' questioning of the climate stress-testing models used should help to drive greater consistency in the use of IAMs for both regulatory reporting and internal risk monitoring purposes. The case studies below provide insights into the thinking of banks who are piloting climate risk scenario modelling.

General perspectives on the use of climate scenarios

A North American bank provided perspectives on the use of climate scenarios in the financial industry along with suggested areas for future enhancement of those scenarios.

Case study 1: North American bank perspective

Developing a suite of standardized reference scenarios is a positive step forward and will help facilitate more consistent disclosure.

We understand that the general equilibrium integrated assessment models continue to be updated and refined. We support the development of a suite of standardized reference scenarios to facilitate comparability of scenario analysis processes and results across institutions. However, we offer the following observations on how scenario utility can be improved to support financial risk analysis

- The scenarios were not originally designed to support financial risk analysis and disclosure
  - The climate models used to generate the scenarios are complex and difficult to explain within a conventional financial risk context.
  - The scenarios were created to inform policy, shape climate goals and focus on constraining / mitigating climate change rather than being designed to support risk management and strategic decision-making in banks.
- Scenarios are not easily applied across different industries and countries and appear to generate risk parameterization that is challenging to understand and substantiate. Similar to stress testing scenarios, it would be helpful if scenarios reflected:
  - Sector-specific linkages to sector drivers to assess changes in asset prices
    - Changes in supply / demand by industry
    - Drivers and changes in costs / margin / prices (e.g., there are different demand and emission drivers across metals and mining business segments)
  - Country-specific / regional macro trends including stage in economic cycle
  - Country-specific carbon / green investment policy
  - Shorter time horizon ▯ lending book turns over ~ 3 years

Sector specific case studies

The following case studies were provided by CaixaBank, Intesa Sanpaolo, Danske Bank, Mitsubishi UFJ Financial Group (MUFG), and KBC Group, a Belgian bank. The case studies cover the oil and gas, power generation/utilities, and metals and mining sectors as PRB members have focused on the high-emitting sectors in the first phase of their work.

Case study 2: CaixaBank

CaixaBank has applied the transition risk methodology provided by UNEP FI and developed by Oliver Wyman to assess the change in Expected Loss in the Oil & Gas and Power Utilities sectors. The exercise has been carried out by calibrating the tool with a sample of different companies from CaixaBank's Energy portfolio for different regions according to portfolio segmentation (World, Europe, Latin America, Middle East and United States).

Practical implementation of the methodology at CaixaBank

CaixaBank has calibrated the tool using the REMIND 1.5°C Low-CDR (Carbon Dioxide Removal) scenario developed by the Potsdam Institute for Climate Impact Research (PIK), as proposed by UNEP FI. As detailed in the Phase I report (Extending our Horizons), the methodology involves several steps (portfolio segmentation, developing a qualitative risk analysis, gathering internal risk data and giving an estimation of the evolution of credit rating for the different companies in the sample). As per CaixaBank's experience, adjusting the credit rating estimate has proved to be the most challenging step of the exercise.

CaixaBank has developed a special-purpose tool that translates the qualitative assessment of transition risk into financial figures for the different companies in the sample. The tool uses the different Risk Factor Pathways (RFPs) derived from the REMIND 1.5°C Low-CDR scenario and modifies them according to a specific scoring system to bring in the expert opinions from specialists of the different internal departments (Climate Risk Analysis, Credit Decisions, Environmental Risk Assessment, Rating, Strategy). These modified RFPs are then translated into changes in the main credit risk factors (EBIT, EBITDA and revenues) that can be introduced in the bank's internal rating system in order to obtain a transition risk-adjusted rating for the companies, given their decarbonization and transition strategies.

Key drivers of transition risk in the Oil & Gas and Power Utilities sectors

For the assessment, CaixaBank considered the following drivers of transition risk in the energy sector:

- Evolution of carbon prices
- Future energy mix
- Business transformation
- Existence and valuation of stranded assets
- Evolution of new technologies

Gaps identified in the existing IAMs for the evaluation of transition risk

The evaluation of climate transition risk of the companies in the sample entails a significant degree of expert judgment to be built around the assumptions of the underlying Integrated Assessment Models (IAM) chosen for the analysis. Therefore, the correct understanding of the narrative behind the model used is key, as are the assumptions made for each of the variables.

Following the exercise, CaixaBank found that, for the climate risk assessment to be more precise, further work would be needed in the following 6 areas:

- **Carbon prices.** Most IAMs assume an extremely high carbon price. In addition, these price assumptions are mostly the same across geographies. This is because carbon prices are modelled as the only policy tool available to systematically enable an energy transition. However, the high price levels needed to achieve the temperature objectives might, in most cases, be difficult to justify and therefore difficult to use as an input for internal evaluation. A more realistic carbon price pathway would be helpful, considering that carbon prices are a key factor to accelerate the transition to a low carbon economy. A more realistic carbon price assumption would enable considering carbon prices directly in a company's assessment instead of using them as an indicator of price increases for a qualitative evaluation.
- **Electricity sector composition:** the models used during the pilot define RFPs for several sectors. For Power Utilities, "renewable sector" and "electricity sector" are displayed as separate segments in Transition Check. However, additional granularity for the underlying energy mix and the emissions produced by each (e.g. renewables vs. conventional technologies) would help model users to better understand the evolution of the variables. This would then determine the necessity of establishing additional internal assumptions. The consideration of a separate non-renewable power utility sector segment would also be a good alternative, since this would allow the calibration of the transition risk for a group of fully non-renewable companies.

- **Carbon Capture and Storage (CCS):** the assumptions behind CCS uptake under different 1.5°C scenarios are not obvious and a deeper understanding of these, with a focus on the underlying cost/quantity relationship assumptions, would be helpful. The Low-CDR scenario we have used in our calibration assumes that CCS technologies are not yet developed enough to create negative emissions. Further insight into the CCS technology pathways across markets could help us judge whether the capital expenditure needed for this kind of CCS technology is lower than that needed to capture carbon emissions from the atmosphere - direct air capture (DAC) which would, in turn, have different implications for the evolution of the companies evaluated.
- **The role of electricity storage (batteries) in the models:** batteries are only included in the low carbon CAPEX RFP for the transmission and distribution segment of the electricity sector. This assumption should be made explicit since it has a non-negligible effect on the sector, as well as on other market segments that would displace significant amounts of fossil fuels, including transport and building heating and cooling. In future modelling exercises, it would be useful to incorporate the option of allocating batteries in other segments and even in other sectors, since it is unclear where batteries will finally fit.
- **Sector transformation:** CaixaBank assessed the capability of businesses to transition to lower carbon activities in order to evaluate their probability of succeeding in the new economy. The evaluation of each of the companies would benefit from understanding the "standard" degree of adaptation from the sector to the low carbon transition. This shows in variables such as the amount of emissions, whose decrease could come for example from either a transformation of the most intensive sectors (through the uptake of low emission technologies to provide the same service) or from the effective disappearance of the sector. This is key to understand what the evolution of a particular sector could imply for a company in that sector and whether its transformation strategy places the company over or below the average level of transition readiness for that sector.
- **Underlying assumptions:** certain assumptions underlying most of the variables in the models are unknown, while internal evaluation of a company would differ depending on these baseline data. A better understanding of model construction would help identify what we need to consider in our evaluation in addition to what is taken into account in the standard RFP. Examples of these in the Oil & Gas sectors are:
  - **Reputation:** Understanding the extent to which reputational considerations are included in the model would impact the basis for evaluation. Having these already included in a clearly defined manner in the Oil & Gas demand curve would imply not including them as an add-on in our own internal assessment.
  - **Stranded assets:** the transition of the economy away from fossil fuels is likely to result in stranded assets that suffer from unanticipated premature write-downs. Some companies are taking actions that implicitly acknowledge the existence of stranded assets and a deeper understanding of the model's assumptions on this topic will help in assessing whether the company should be over or under rated compared to the average company in the sector.

Case study 3: Intesa Sanpaolo S.p.A.

Case study objectives and implementation

One of the objectives of the UNEP FI Phase II project was to pilot a scenario-based assessment on different sectors, using Phase I 2018 scenarios and then the latest PIK/IIASA's scenarios (focusing on the different hypotheses of +1.5°C) to develop a more complete understanding of potential transition risks to credit quality.

Intesa Sanpaolo estimated the impact on a portion of its loan portfolio, referring to the oil & gas sector in the European Union, with the aim to compare the differences between orderly and disorderly transition scenarios, assessing the "climate-adjusted" probability of defaults (PDs) and proposing next steps to improve the analysis. To conduct the exercise, we brought together enterprise and credit risk teams with the support of the Corporate Social Responsibility department. The participation of the various teams was essential to provide the appropriate skills, as well as to share knowledge on transition risk measurement across the bank.

The first step in the process was the selection of appropriate climate scenarios. Among the various possible combinations, we chose to analyze the following scenarios (both REMIND and MESSAGE models under SSP2 hypothesis):

- **Phase I +4°C (Baseline):** business as usual, no climate policies are adopted;
- **Phase I +1.5°C:** general implementation of climate policies;
- **Phase II – No Climate Policy (Baseline):** baseline scenario for Phase II (lowest transition risk), very similar in structure to the Phase I +4°C scenario;
- **Phase II – Nationally Determined Contributions (NDC):** implementation of NDCs by 2030, but no further intensification of emission reduction after 2030;
- **Phase II – Immediate +1.5°C:** collective action is taken now, very similar in structure to the old +1.5°C scenario;
- **Phase II – Delayed +1.5°C:** aggressive action only begins after 2030 (first candidate for disorderly transition scenario);
- **Phase II – Immediate +1.5°C low Carbon Dioxide Removal (CDR):** aggressive action begins now but limited use of negative emissions (second candidate for disorderly transition scenario).

The second step was to calibrate the model for each company we were assessing. The sample included several oil & gas companies assessed segment-by-segment (conventional gas on/offshore, transportation and storage, and gas and oil refining being the most significant segments), representing more than 70% of the European bank's total exposure to this sector.

The third step in the case study process extended these modelled impacts to the rest of the oil & gas portfolio in the EU, using the specific heatmap/sensitivity analysis provided during the project.

Assessment of the oil & gas sector creditworthiness

We measured five different through-the-cycle PDs (TTC PDs) for the sample companies. For each of the five scenarios, we performed a single model run relative to baseline scenarios (respectively Phase I 4°C and Phase II No Climate Policy), thus obtaining interesting and reasonable results in terms of PD, expected loss and net income changes.

As expected, the PD impact on the oil & gas sector is related to the previously mentioned sensitivities, attributed by segments. The NDC scenario, assuming no further intensification of emission reduction beyond2030, appears to be the least affected (1.46x change in average PD by 2040). For Phase II and Phase I 1.5°C scenarios the impacts are on average between 1.87 and 1.91x, higher than candidates for disorderly scenarios (Phase II Delayed and low CDR), where the increases are on average 1.52 to 1.70x.

These results seemed counterintuitive, since we expected higher transition risk for disorderly candidates. However, for the Phase II Delayed scenario, narratives might explain these effects: climate policies, acting late or without immediate commitment reduce the feasibility of keeping warming below the 1.5°C by 2040, consequently reducing transition risk in the first half of the century. The main results are summarized in the following table:

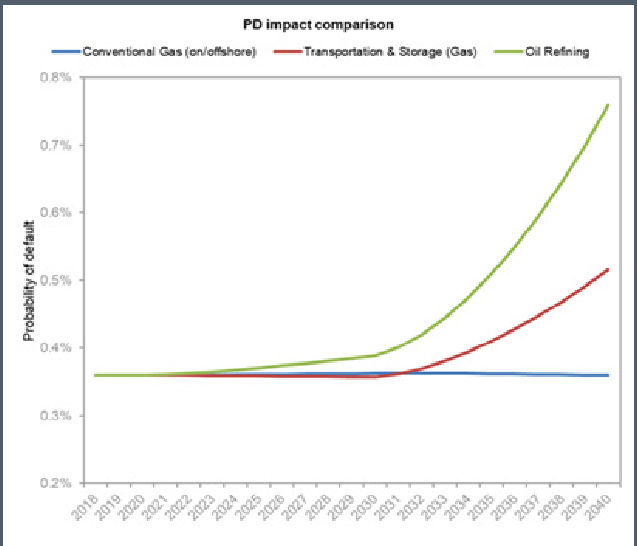
Scenario results: PD change and rating impact (by 2040)

		Phase I	Phase II			
		1.5°C	NDC	Delayed 1.5°C	1.5°C low CDR	Immediate 1.5°C
REMIND	PD average change (weighted by exposure)	1.91x	1.46x	1.52x	1.70x	1.87x
	Rating average impact	2 notches	1 notch	1 notch	1 to 2 notches	2 notches
MESSAGE	PD average change (weighted by exposure)	see Phase II	1.11x	N/A	1.74x	1.72x
	Rating average impact	see Phase II	0 to 1 notch	N/A	1 to 2 notches	1 to 2 notches

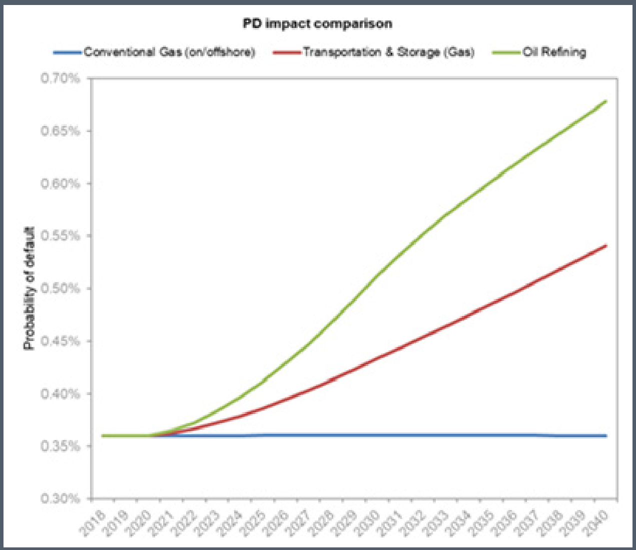
Note that these results also allow for a bank-by-bank customization. Drilling-down exposures and projections by each segment, analysts could check consistency and hypotheses, especially for material segments. For example, we checked:

- **conventional gas on/offshore and transportation/storage gas:** in comparison to other segments, the impact is considered relatively low since gas demand is expected to reduce but not at the same rate as oil;
- **oil refining:** though refining is emissions intensive, this activity is necessary for all types of upstream production. However, oil demand under the scenarios will face a consistent reduction which will impact all forms of crude oil and associated infrastructure.

The appropriateness of these hypotheses seems suitable, also in relation to the comparison of the PD profile resulting from the simulation for these segments. The graphs below show the dynamics for analyzed segments, restricted to BBB-rated companies, within the candidates for disorderly scenarios Phase II Delayed and Phase II Immediate low CDR (REMIND proposals):



Dynamics of Phase II Delayed 1.5°C by segment for BBB-rating borrowers



Dynamics of Phase II Immediate 1.5°C low CDR by segment and for BBB- rating borrowers

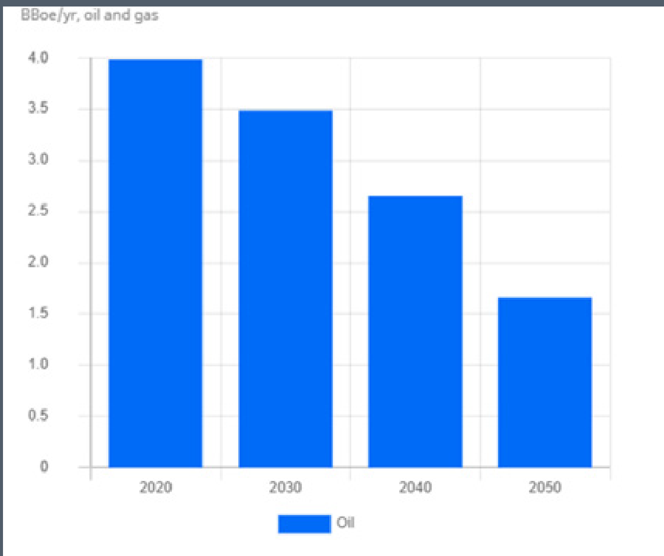
Conclusions and what is required to strengthen climate scenarios

From the point of view of interaction between climate scenarios and credit methodologies, it is true that this useful tool represents the best in class for possible implementations in internal processes of financial firms. This approach is especially important in the context of the recently published draft ECB Guide on climate-related and environmental risks4. However, during the exercise, several issues remained unresolved and have been addressed in internal discussions in a qualitative way. These include the need to:

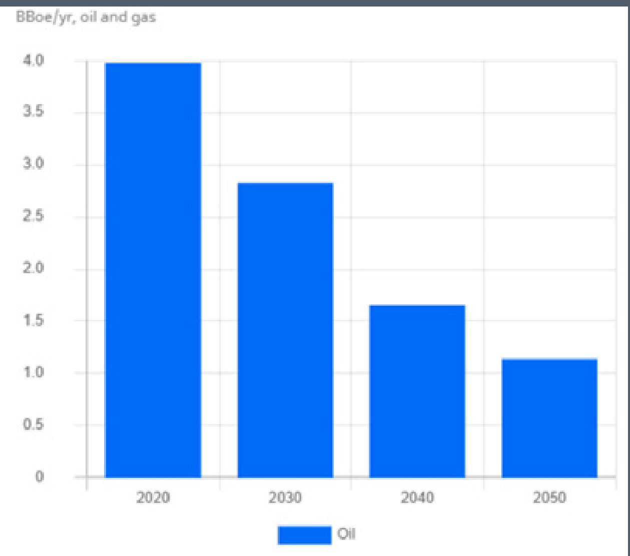
1. evaluate the **consistency of specific sensitivities** (low/moderate/high ranking scale) for certain sensitive segments;
2. choose the **correct time horizon** of the climate scenarios and risk models: PD changes by 2040 could not be informative of the total long-term effects;
3. find the **right level of data granularity** for allocating the representative borrowers' sample to the appropriate segments;
4. identify relevant KPIs and KRIs to be used for **mapping the exposures to heatmap segments:** NACE codes are not completely feasible, specifically for conglomerates where different segments should be considered; and
5. determine methodologies to assess the **adequacy of the translation** of economic impacts into financial risk metrics.

Regarding the appropriateness of climate scenarios, compared to the Phase I model, we find the development of the Delayed 1.5°C scenario an interesting step, as it seems unlikely that policy actions will be taken as early as 2020. The same goes for the Immediate 1.5°C low CDR, as we are not sure about the development of technological solutions related to CO_2 capture and storage. Both the Delayed and the low CDR predict a limited PD change, leaving us to think that these two scenarios should be further refined to be considered the right ones to use in modelling disruptive pathways.

We can argue that timely and orderly pathways should be associated with lower transition risks, while late and disorderly pathways correlate with higher transition risks. In our example for the oil & gas sector, oil demand under the Delayed and the low CDR will undergo a substantial reduction as shown below, and the associated impact on different market segments dos not fit the disorderly transition model expectations.



Phase II Delayed 1.5°C: Primary energy, oil demand



Phase II Immediate 1.5°C low CDR: Primary energy, oil demand

In disruptive scenarios, we need to understand the consequences relating to changes in consumer choices and the actions that companies will introduce to minimize reputational and market risks. The ripple effect that could be created in case investors are no longer interested or able to invest in certain sectors also needs to be considered. Furthermore, systemic risks and correlations within and across macroeconomic variables need to be better understood as part of disruptive scenario modelling. The COVID pandemic highlighted that the potential effects on GDP of systemic economic shocks were heavily underestimated and that impacts must be modelled at the sector/segment level.

The proposed climate scenarios should therefore be seen as a valid attempt to assess the potential impact of transition risks at the sector/ segment level, to be gradually refined as new elements become available:

- **uncertainty and shifts in demand:** materialization of threats in a completely unpredictable way with sharp decline in demand for certain energy suppliers;
- **expand macroeconomic consequences and analyse spill-over effects:** second-order implications across sectors and segments;
- **regional coverage and sectoral granularity:** borrower level analysis needs more information to refine and expand the scope of the analysis.

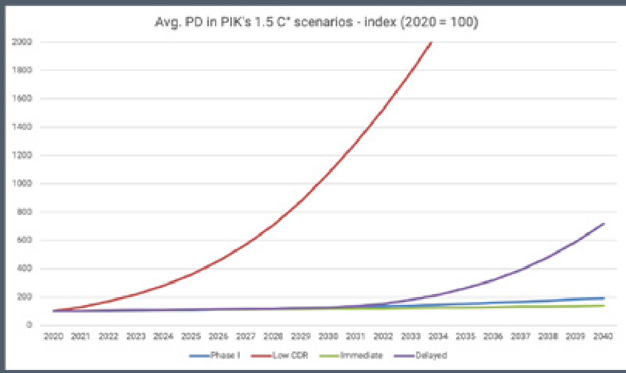
4 European Central Bank (2020), Guide on climate-related and environmental risks - Supervisory expectations relating to risk management and disclosure: https://www.bankingsupervision.europa.eu/legalframework/publiccons/html/climate-related_risks.en.html

Case study 4: Danske Bank

The purpose of the case study was to compare the impact of the new transition risk scenarios with the ones used in phase I of UNEP-FI's TCFD programme, as provided by PIK and IIASA. We chose to make the comparison from the point of view of our exploration and production (E&P) segment in the oil and gas portfolio and compare changes in probability of default (PD) across a range of scenarios. In order to expose the E&P portfolio to the most severe transition risks, we decided to compare PD results using the various 1.5 degree Celsius scenarios. For this reason, we only show results using PIKs scenarios, as the climate model from IIASA's cannot provide a solution under the low carbon dioxide removal (CDR) scenario constraints. To run the comparison, we used the transition risk tool provided by UNEP-FI, which runs out to year 2040.

In order to apply the transition risk tool, we estimated the future PD on a small representative sample of customers under the various transition scenarios. The estimated impact is used to calibrate the model implemented in the tool. We chose a small sample with a rating distribution comparable to the full portfolio. For each of the customers we extracted last year's annual results, including the breakdown of income from each of the main sources, i.e. crude oil, gas, coal, and/or refined oil products. When assessing the customer-specific impact in the sample, we focused on the projected development in demand and price for each of the fossil fuels as well as the carbon price. Using the changes in demand and price, we recalculated future income. To estimate the additional cost from an increasing carbon price, we used customers' own disclosed information on their productions carbon intensity, or, if this was not readily available, carbon-intensity statistics from IEA on the E&P industry. Combining annual production and the scenario-specific carbon prices, we estimated the future additional cost from carbon emission. Using these stressed financial figures, we re-estimated future PDs under the various scenarios. It is important to note, that this assessment assumes our customers do not change their business model or make any upgrades to their current operation.

As expected, the results show that especially the low CDR scenario is extremely harsh on the E&P segment. The average PDs double already in the year 2023 for the low CDR 1.5C scenario, whereas PIK's 1.5C scenario from phase I only sees a slight increase by the same year. This suggests that unless the international community finds a way to start implementing wide-scale carbon dioxide removal technologies in the very near future – an assumption that is inherent in many of the available transition risk scenarios – and we still aim for a 1.5C future, the oil and gas sector would come under immense pressure in a transitioning economy. When comparing the 1.5C scenario from phase I with the delayed 1.5C scenarios, it is clear that the delayed scenario would impact the E&P segment very severely after 2030. The new immediate scenario on the other hand, shows a slightly lower average PD increase compared to the phase I 1.5C scenario (see figure below for development in average PD).



From a risk management perspective, the new 1.5C scenarios clearly provide some added benefits when trying to assess the range of transition risks that different sectors will potentially face. The immediate and delayed scenarios give new perspectives on the importance of timing as well as whether or not the transition that takes place can be characterised as orderly or disorderly. The longer that the international community takes in terms of implementing the actions needed to reach the climate targets, the harsher the impact on portfolios exposed to high transition risk. Furthermore, if banks want to stress test their portfolio for the full suite of possible transition risks, the new low CDR scenarios are very useful for that purpose. Since the low CDR scenarios require immediate and large reductions in GHG emission, it also allows you to test the sensitivity of the portfolio over a shorter timeframe than most other transition risk scenarios and ensure that a wider range of potential futures is considered - one which puts less faith in the wide-scale use of carbon removal technology.

In several of the scenarios, most of the transition risks take effect in the second half of the century, suggesting the necessity of extending the financial modelling beyond 2040 in order to fully utilize the climate scenarios. Such an extension likely requires the analysis to be done in smaller separate time steps, calling for additional estimates on the sample used for calibration, and putting more focus on incorporating the different sectors adaptability into the assessment. Creating sound, repeatable, and time-efficient methods for doing such sample estimates are challenging, and more work is needed in order to translate climate model outputs into relevant financial variables to help on such methods, for instance, how prices and costs of different materials and services would be affected, as well as the value of collaterals typically used to secure loans.

Case Study 5: Mitsubishi UFJ Financial Group (MUFG)

Approach

MUFG is participating in the UNEP FI TCFD Pilot Phase II (hereinafter called "Pilot Project") and calculated the transition and physical risk based on the discussion and the methods examined in the Pilot Project. MUFG calculated the transition risk on a selection of electric power utilities and other energy sector companies which carry a high transition risk.

1. Basic Concept of Measurement Methods

i. Considering results of discussion and direction through Pilot Project, also reflecting climate change scenarios on BS/PL which is selected were developed. Moreover, the impacts on the financial condition in 2020-2050 of the companies were calculated from upgrade/downgrade transition of the credit rating using the key methodologies.

ii. Regarding scenarios, SDS scenario (equivalent to less than two degrees scenario) was mainly employed with IEA WEO scenarios which have been applied by many financial institutions.

2. Key Factors in Scenarios

There are four key factors in scenarios used to model transition risk; "energy demand", "carbon tax", "fuel price" and "renewable energy investment".

3. Parameters in Risk Factor Pathway

i. Sales and revenue are determined by electricity and energy demand in the electric utilities and energy (oil and gas) sectors.

ii. Parameters have ranges based on the discussion of which sector should bear how much of the cost of the "carbon tax", "fuel price" and "renewable energy investment cost" items.

iii. Parameters were set while ensuring the consistency across items of accounts.

4. Sectoral sensitivities

i. Impact from key four parameters on each sector is described in Figure 1 below.

ii. Under IEA WEO scenarios, sensitivity of the energy sector to carbon pricing is slightly less than that of the power utilities sector.

iii. The major difference is that fuel price has an opposite impact on the electric utilities and energy sectors (ie. higher fuel prices have a negative impact on utilities company financial performance, but a positive impact on energy companies).

Major items	Utilities	Energy
Energy demand **(+) Moving up**	Positive: Increase in sales and revenue	Positive: Increase in sales and revenue
Carbon tax **(+) Moving up**	Negative: increase in costs,	Negative: increase in costs,
Fuel price **(+) Moving up**	Negative: increase in costs,	Positive: Increase in sales and revenue
Renewable energy investment cost(*) **(+) Moving up**	Negative: increase in costs,	-

Figure 1: Major item sensitivities

*Regarding renewable energy investment cost, only the depreciation associated with capital investment and the interest burden have been considered.

5. Conclusion

i. Many participating banks expressed concerns about whether the balance sheet would survive a disruptive energy transition scenario. But the modelling did not confirm these concerns. MUFG's own modelling pilot produced similar results, confirming that the bank would be resilient to the type of disruptive transition implied by the scenario. In the scenario, centring on companies in developed countries where high economic growth cannot be expected and companies whose renewable energy ratio is extremely low, their capital efficiency gradually deteriorates as investment in renewable energy increases. Their credit ratings are also gradually downgraded as their financial strength weakens.

6. Challenges

i. The lack of standardised scenarios is an issue faced by all banks.

ii. It is difficult to calculate climate related risks in some companies with insufficient disclosure. Considering that there is no standardized climate risk database at present, it is important for us to develop such a database to calculate risks in a more systematic way.

iii. Given the range of possible real-world outcomes, the ability to carry out climate risk assessments for several scenarios is important. Meanwhile, several different scenarios are being published by different institutions. While there are still variations in the direction, coverage and granularity of these models, it is necessary to use these scenarios to assess the impact as much as possible in the future, even when the available models may not be perfect.

Case study 6: KBC Group

As part of the Phase 2 activities, KBC experimented with a model-based framework to translate risk factor pathways directly into transition adjusted PDs. It could provide an alternative for the rather manual and expert oriented borrower-level calibration of the Phase 1 methodology.

1. Modelling framework

The basis of our approach is inspired by the Basel framework in which the Vašiček model is used to transform a through-the-cycle (TTC) PD into a stressed PD via following formula:

$$PD^{stress} = \Phi\left(\frac{\Phi^{-1}(PD^{TTC}) - \sqrt{\rho}Z}{\sqrt{1-\rho}}\right)$$

where Φ represents the cumulative distribution function and ρ the correlation (reflecting the dependency of the obligor's exposure on the economic cycle). The severity of the stress is reflected by the systematic risk driver Z which we can obtain from the projected evolution of net income (the sum of the four risk factor pathways). More precisely, the change in net income under a given scenario should result in a change of equity values for a sector. Assessing this projected change in equity price within its historic context allowed us to determine the severity of the scenario and associated risk outcomes.

2. Portfolio segmentation and sensitivities

We opted to divide our Metals portfolio into 3 segments: primary processing (e.g. primary iron & steel production), secondary processing (e.g. casting of iron & steel) and manufacturing (e.g. manufacture of metal goods). The segmentation takes account of the characteristics of the underlying activities with energy intensity used as the main transition risk driver. Our qualitative sensitivity assessment to the risk factor pathways is provided in the table below.

SEGMENTS	RISK FACTOR PATHWAYS			
	Direct emissions costs	Indirect emissions costs	Low-carbon capex	Revenue
Primary processing	High	High	High	Moderate
Secondary processing	Moderately high	High	Moderate	High
Manufacturing	Low	Moderately high	Low	High

Table 1: Segment sensitivities

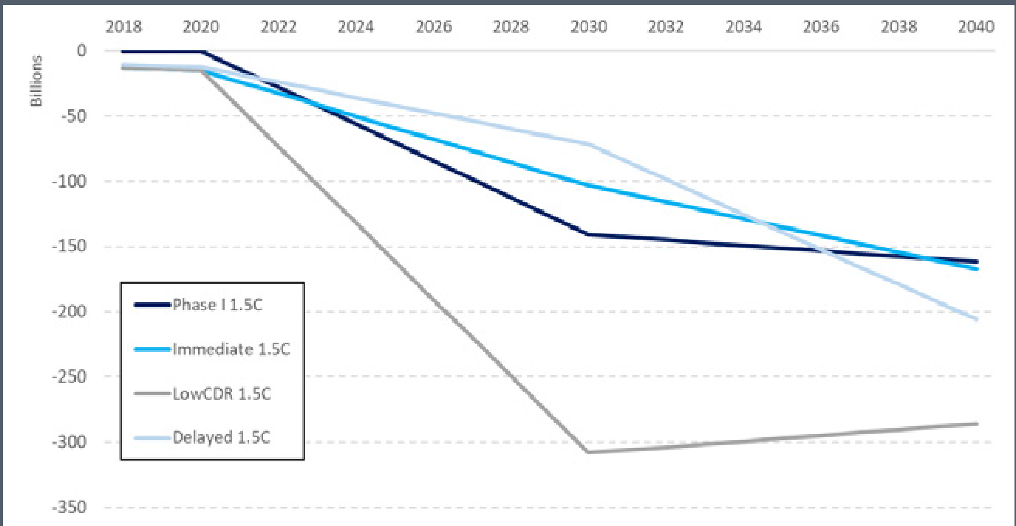
3. Scenario setup and analysis

The analysis is based on the following scenario setup within the transition risk tool:

Model:	Geography:	Sector:	Scenarios:
REMIND	EU	Industrial processes	

The difference of the sector's net income compared to the 4˚C Baseline scenario is illustrated for each of these scenarios in the figure below.

Figure 1: Change in sector net income compared to Baseline scenario



We observe that the 'LowCDR 1.5°C' is an outlier to the other three analysed scenarios. The significantly higher negative change in net income is the result of the industry's high and expected further increasing direct emissions costs while (collective) broad-scaled carbon dioxide removal actions remain absent.

The table below on selected PD ratings shows the transition adjusted ratings together with the estimated severity for the various scenarios. The latter is obtained from the computed in our Vasiček framework.

Segment	Primary processing		Secondary processing		Manufacturing	
Scenario	Phase I Delayed Immediate	Low CDR	Phase I Delayed Immediate	Low CDR	Phase I Delayed Immediate	Low CDR
Severity	1 in 4	1 in 67	1 in 3	1 in 11	1 in 2 to 3	1 in 4
BBB	BB+	B+	BBB-	BB	BBB/BBB-	BB+
BB	BB-	B	BB	B+	BB	BB-

Table 2: Scenario severity and transition adjusted PD ratings

The model indicates a significant impact on net income and PDs when targeting a max. 1.5°C temperature increase. That information should certainly be incorporated in a more in-depth strategic study of the industry which should try to determine its future financial viability including potential future mitigating factors such as a successful introduction and deployment of broad-scaled carbon dioxide removal technologies.

7. Conclusion

IAMs are important tools for financial institutions in their attempts to identify, assess, and manage climate transition risks. They are unique in their ability to generate relatively comprehensive global and technologically detailed transition pathways for different climate targets (e.g. temperature). Their broad scope and long-term nature are valuable in assessing the trade-offs between different mitigation options across space and time. However, these same features also pose challenges as the models rely on many simplifying assumptions to generate their complex outputs. Notably, the IAMs were designed to inform climate policy making, with an often global focus in mind, rather than financial risk analysis. This initial policy focus means that some important factors required for evaluating transition risks are either not included in IAMs, or they are represented only in a stylized manner, without considering the dynamics and variability that might be of interest to financial institutions. Furthermore, most IAMs compute the theoretically optimal pathway to a given climate target, not the most likely pathway, nor necessarily the most desirable pathway. The real transition to a low-carbon future will, in all likelihood, look rather different.

IAMs, nonetheless, provide useful examples of how the transition may unfold and what the implications may be for key sectors and technologies. Given informed use, and an understanding of which IAM outcomes are robust, and which outcomes relyon uncertain assumptions, IAMs can be used to get a first order understanding of the transition risks different companies and financial institutions might face.

7.1. Next steps for climate scenarios

Climate scenario analysis and IAM calibration remain new areas for many financial institutions. Banks across all sectors are rapidly progressing in their understanding of IAMs and beginning to integrate climate risk into existing stress testing and risk modelling exercises. However, continued knowledge-building on scenarios is critical for many institutions seeking to understand the implications of climate models. Refinements will continue to occur in response to regulatory enquiries and peer learning. More and more banks are using climate scenarios, but these models are still not refined enough to produce decision-useful, standardised disclosures for internal teams, investors, or regulators. Regulators' recognition of the need for more uniform approaches to climate scenario analysis is expected to accelerate the refinement of this work. Work led by prudential regulatory members of the Network for Greening the Financial System is helping to address existing modelling gaps. Banking institutions have a wealth of knowledge and experience to contribute in addressing modelling data gaps for sector specific, geographic, time horizon and macroeconomic issues. At UNEP-FI, we are working with partners across the financial sector to develop more sophisticated and systematic models to enable more decision useful information that supports an orderly transition.

This paper has discussed the pros and cons of using climate scenarios produced by IAMs for climate-related financial risk-analysis. Based on this, the following box lists several areas of improvement. Some of these improvements might be incorporated directly into IAMs. In many cases, however, this will not be possible or feasible. Where this is the case, improvements can be made by the development and inclusion of complementary models (for instance national or sectoral models with a greater degree of detail) in the process of financial risk analysis or in the post-processing of existing climate scenarios.

Areas of improvement for the use of climate scenarios in financial risk analysis.

1. Improved sectoral granularity (as well as additional sectoral coverage)
   a. Identify the relevant risk drivers for different economic sectors
   b. Explore how these risk drivers interact with current scenario assumptions
   c. Develop sectoral assumptions/sub-models consistent with overall scenarios
2. Improved regional/national granularity
   a. Identify national policy and economic factors that will influence transitions
   b. Create national sub-models consistent with overall scenarios
3. Reconsideration of financial market dynamics
   a. Assess dynamics of major sectors under supply and demand shifts, including feedback loops for investment decisions
   b. Explore business intuition and implications behind sub-model pathways that influence final outputs
4. Incorporation of non-linear and second order effects
   a. Identify potential economic tipping points
   b. Determine cascading effects of sectoral transitions
   c. Integrate these non-linear features into certain scenarios
5. Integration of physical risk impacts
   a. Evaluate interaction effects between physical and transition risks
   b. Develop integrated scenarios with both types of risks
6. Consideration of shorter time horizons (and smaller timesteps)
   a. Assess implications of the massive economic shifts required in the short-term
   b. Consider assumptions regarding impacts of long-term solutions (e.g. CDR post-2050)
7. Inclusion of endogenous macroeconomic factors
   a. Determine how different types of transitions affect the overall macroeconomy
   b. Consider short-term scenarios with significant macroeconomic shocks
   c. Integrate endogenous macroeconomic factors into scenarios

7.2. UNEP FI's TCFD programs

The prior TCFD banking and investor pilots (and the on-going insurance pilot) have yielded valuable insights about the key challenges facing the financial sector in addressing climate risks, the needs and desires of our member institutions, and the areas where UNEP FI can be most effective. After numerous discussions with members and other financial sector participants, we have internally aligned on a path forward for our future TCFD and climate risk programs.

Since the publication of the FSB's TCFD recommendations in 2017, UNEP FI has run several pilot programs to assist its members in implementing the TCFD framework and in issuing meaningful climate disclosures. Participants in these pilots explored physical and transition risks (and litigation risks for insurers) and developed practical approaches for evaluating these risks using climate scenario analyses. Almost 100 financial institutions (banks, investors, and insurers) from all around the world have participated in these pilots. These institutions have been supported by nearly a dozen technical partners from climate modelers to climate risk experts.

For the upcoming TCFD banking sector and investor programs (launching in January 2021), UNEP FI's vision is to use the convening power of the UN to bring together financial institutions, regulators, climate researchers, and sector experts to answer critical climate risk questions for the financial sector. Climate scenario development and analysis play central roles in answering some of these questions. For financial institutions who have committed publicly to net zero financed emissions, a more nuanced approach to climate risk modelling and scenario analysis will help them to operationalise these ambitious targets. The TCFD programmes will focus on improving sectoral and regional scenario assessments, exploring macroeconomic impacts of climate risks, quantitatively comparing transition losses under different climate scenarios, and developing a framework for conducting a climate stress test.

The TCFD programs will consist of two main components:

- **TCFD reporting roadmap:** a resource-rich and highly detailed roadmap to enable institutions at all stages of the TCFD disclosure process to better understand climate risks and disclosure expectations across markets. Participants will engage with industry-leading tools, scenarios, and frameworks produced by UNEP FI and its expert partners. The structured roadmap allows institutions to plug in at any point and to use the roadmap materials to disseminate climate risk knowledge throughout their organization.
- **Targeted modules:** these modules provide hands-on and output-oriented opportunities for small groups of institutions to partner with global experts to address cutting-edge climate risk questions. These modules address the need for climate risk assessments and disclosures to become more granular and nuanced. Furthermore, best practices regarding assessment and disclosure need to be further defined and agreed upon. Achieving those two objectives demands that all relevant stakeholders across the financial ecosystem collaborate in a structured and productive way. The deep relationships UNEP FI has nurtured with climate risk leaders across the banking, pensions, and insurance sectors will enable this collaboration to occur. Each individual module will allow participants to tackle a specific climate risk challenge and produce outputs that set standards for good practice across the financial industry.

UNEP FI believes that this integrated global program will accelerate the development and deployment of advanced climate scenario development and climate scenario analysis. By fostering comparability, standardization and peer learning, these programs enable key financial sector stakeholders to better manage climate risks and play a vital positive role in the low-carbon transition.

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