THE GOOD, THE BAD AND THE HOT HOUSE WORLD: CONCEPTUAL UNDERPINNINGS OF THE NGFS SCENARIOS AND SUGGESTIONS FOR IMPROVEMENT

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Irene Monasterolo, María J. Nieto
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Irene Monasterolo (**)

EDHEC BUSINESS SCHOOL, EDHEC-RISK AND CLIMATE IMPACT INSTITUTE (ERCII)

María J. Nieto (***)

BANCO DE ESPAÑA

Edo Schets (****)

BLOOMBERG

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(**) Monasterolo (irene.monasterolo@edhec.edu).
(***) Nieto (maria.nieto@bde.es).
(****) Schets (eschets@bloomberg.net).

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Abstract

Climate mitigation scenarios are an essential tool for analyzing the macroeconomic and financial implications of climate change (physical risk), and how the transition to a low-carbon economy could unfold (transition risk). The Network for Greening the Financial System (NGFS) has co-developed a set of climate mitigation scenarios for climate financial risk assessment. Despite the important role that these scenarios play in climate stress tests, the understanding of their main characteristics and limitations is still poor. In this paper, we contribute to filling this gap by focusing on the following issues: comparison of the process-based Integrated Assessment Models (IAMs) used by the NGFS with alternative models; the role of Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs) in shaping the scenario narratives, and their shortcomings; the interpretation and sensitivities of carbon price pathways; and, comparison with other climate mitigation scenarios. We then draw lessons on how to increase the relevance of the NGFS scenarios. These include updating the SSP narratives; considering the potential trade-offs between different types of climate policies; assessing acute physical risks and their compounding; integrating physical risks within transition scenarios; and, taking into account the role of the financial sector and investors' expectations.

Keywords: NGFS scenarios, climate finance, climate transition risks, climate physical risks, integrated assessment models, carbon pricing, climate financial risk assessment.

JEL classification: Q40, Q50, Q54, Q55, Q58.

Resumen

Los escenarios de mitigación climática son una herramienta esencial para analizar las implicaciones macroeconómicas y financieras del cambio climático (riesgo físico), y cómo podría desarrollarse la transición hacia una economía baja en carbono (riesgo de transición). La Red para la Ecologización del Sistema Financiero (NGFS, por sus siglas en inglés) ha desarrollado un conjunto de escenarios de mitigación climática para la evaluación del riesgo financiero climático. A pesar del importante papel que desempeñan estos escenarios en las pruebas de estrés climático, la comprensión de sus principales características y limitaciones aún es escasa. En este documento contribuimos a llenar este vacío centrándonos en: la comparación de los modelos de evaluación integrados (IAM, por sus siglas en inglés) utilizados por la NGFS con modelos alternativos; el papel de las rutas de concentración representativas (RCP, por sus siglas en inglés) y las rutas socioeconómicas compartidas (SSP, por sus siglas en inglés) en la configuración de las narrativas de los escenarios y sus deficiencias; la interpretación y las sensibilidades de las trayectorias del precio del carbono, y la comparación con otros escenarios de mitigación climática. En este trabajo extraemos lecciones sobre cómo aumentar la relevancia de los escenarios NGFS. Estos incluyen actualizar las narrativas del SSP, considerar las compensaciones potenciales entre diferentes tipos de políticas climáticas, evaluar los riesgos físicos agudos y su agravamiento, integrar los riesgos físicos dentro de los escenarios de transición, y tener en cuenta el papel del sector financiero y las expectativas de los inversores.

Palabras clave: escenarios de mitigación climática, Red para la Ecologización del Sistema Financiero (NGFS), riesgos climáticos de transición, riesgos climáticos físicos, modelos integrados de clima, precio de las emisiones de carbono, riesgos financieros derivados del riesgo climático.

Códigos JEL: Q40, Q50, Q54, Q55, Q58.

Contents

1 Introduction

A growing stream of research has highlighted the negative implications of unmitigated climate change on human health (Naumann et al., 2020), ecosystem services (Carpenter et al., 2009), biodiversity loss (World Bank 2022), infrastructures and economic activities (Burke et al., 2015, Coronese et al. 2019, Dunz et al. 2021), and inequality (Hsiang et al., 2017, Diffenbaug et al., 2019). Recently, several financial authorities have recognized that climate change represents a new type of risk for finance and could impair financial stability (Battiston et al. 2017, NGFS 2019, Allen et al. 2020, Mandel et al. 2021, Alogoskoufis et al. 2021, Clerc et al. 2021, Vemeulen et al. 2021, Bressan et al. 2022).

According to Climate Action Tracker (2021), current climate targets for 2030 would put the world on track for a 2.4°C temperature increase by the end of the century, and achieving the 1.5°C goal requires halving annual Green House Gas (GHG) emissions measured in terms of CO_2-equivalent in the next eight years. If climate policies are introduced late, they could give rise to a disorderly transition (ESRB 2016) and could affect financial stability at the individual and systemic level (Roncoroni et al. 2021).

Climate mitigation scenarios provide forward-looking trajectories of economic output consistent with a given (e.g., 1.5°C or 2°C-aligned) carbon budget (i.e. how much we can still emit conditioned to temperature targets and physical conditions). Climate mitigation scenarios are generated using process-based Integrated Assessment Models (IAMs), which include detailed representations of the energy sectors and various other energy-intensive sectors. The relatively long projection horizon of process-based IAMs (until 2100), the integration of climate change, emission pathways, and the economy, and the amount of sectoral detail make process-based IAMs useful tools for quantifying future risks to, and opportunities for, global economies. However, IAMs are not the only models that are used to study economic questions around climate change. Table 1 compares the models used in the literature for assessing the economic impact of climate change.

Recently, the climate scenarios generated by process-based IAM have been used by finance researchers, investors and financial institutions that compose the Network for Greening the Financial Stability (NGFS), for climate stress tests. Given the important role that climate mitigation scenarios play in climate economic and financial risk assessment, and in the context of stress testing, it is crucial to understand their conceptual underpinnings, their characteristics, applicability, and current limitations.

Our paper contributes to this understanding, focusing on the climate mitigation scenarios provided by the NGFS (2021a). First, we analyze the NGFS climate scenarios, considering the underlying mitigation policies. We discuss their relation to process-based IAMs on which the NGFS scenarios build, the output trajectories, and the two sets of uncertainties on which such IAMs are constructed (the Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs)). Further, we discuss the limitations of the socio-economic narratives of the reference scenarios, represented by

Table 1

COMPARISON OF CLIMATE ECONOMIC MODELS

	Dynamic Stochastic General Equilibrium DSGE	Computable General Equilibrium CGE	Stock Flow Consistent SFC	Process based-Integrated Assessment Models	Aggregated Integrated Assessment Models
Representation of the Economy	Detailed calibrated on sector data at country and regional level. Market clearing prices, representative agents with forward-looking expectations. Finance treated as exogenous frictions	Varied Dynamic CGEs calibrated on granular sector data at country and regional level. Market clearing prices, representative agents with forward-looking expectations. No finance	Detailed dynamic balance sheet assessment with endogenous shocks. Agents' heterogeneity and adaptive expectations. Out of equilibrium dynamics. Financial agents and markets, macro-financial feedbacks	Aggregated Ramsey-style long-term economic growth model, representative agents, market clearing prices. No finance	Aggregated Ramsey-style long- term economic growth model, representative agents, market clearing prices. No finance
Representation of Non-economic Systems	No Some models might embed GHG emissions from production	No Some models might embed GHG emissions from production	Yes Agriculture, energy	Yes Agriculture, land-use, energy, water and climate systems	Limited Climate system
Price of Carbon	Exogenous/ assumed	Exogenous/ assumed	Endogenously generated	Marginal Abatement Cost	Social Cost of Carbon (SCC)
Use for Cost Benefit Analysis	No Used to build economic intuition	Yes	Yes Comparison of policy costs (socio-economic, financial) and co-benefits	No Climate damages calculated separately	Yes
Geographic Resolution	Global-Regional-Country	Regional-Country	Regional-Country	Global-Regional Country available through additional downscaling	Global-Regional
Explicit Accounting for Carbon Budget	No	No	No	Yes	No
Sector Granularity	Limited Energy sector	Yes Full sectoral disaggregation of the economy	Yes For high/low-carbon, labor/capital intensive sectors in the economy	Yes Several energy intensive sectors and several technologies	No
Bibliography	Xiao et al. (2022)	Babatunde, Begum and Said (2017), Carbone and Rivers-2017	Caversasi and Godin (2015), Dafermos et al. (2017), Monasterolo and Raberto (2018), Dunz et al. (2021)	Calvin et al. (2013); McCullum et al. (2018); Rogeli et al. (2019); Kriegler et al. -2013	Nordhaus (1993, 2018); Anthoff and Tol, (2014); Hope et al. (1993)

SOURCE: Own elaboration.

the SSPs, that withstand the IAMs trajectories. Moreover, we highlight some differences of the NGFS transition scenarios with other relevant scenarios, such as those produced by the International Energy Agency (IEA) and those published by International Panel for Climate Change (IPCC). We then analyze the characteristics and current limitations of the NGFS consideration of physical risks. Finally, we discuss the implications of current scenarios' characteristics for the analysis of climate financial risks and opportunities.

The remainder of this paper is structured as follows. Section 2 introduces climate mitigation scenarios used by the NGFS considering: (i) the narratives underpinning the RCPs and SSPs; (ii) the interpretation and sensitivities of carbon price pathways as well as the limitations; (iii) the comparison of trajectories of the NGFS scenarios with the IEA and IPCC climate mitigation scenarios. Section 3 presents the representation of physical risks and discusses its limitations. Section 4 concludes and highlights some areas of improvement.

2 Climate transition risk scenarios

The NGFS scenarios were designed to provide financial institutions and authorities a common set of scenarios to work from for the purpose of climate financial risk assessment, thereby promoting some harmonization in the scenario assumptions used, and increasing comparability of scenario analysis results and disclosures (NGFS 2021a). The scenarios are increasingly being used in climate scenarios exercises, including in Allen et al. (2020), Clerc et al. (2021), and Bank of England (2022).

The NGFS scenarios bring together a harmonized set of transition pathways, physical climate change impacts and economic indicators that have a global coverage and integrated assessment of risks. The transition pathways are generated by three process-based IAMs, which are also models vetted by the IPCC: GCAM (Calvin et al., 2019), MESSAGE-GLOBIUM (Rogelj et al., 2021), and REMIND-MAgPIE (Kriegler et al., 2012). The use of three models allows users to compare outcomes, hence providing insight into the uncertainty around long-term model projections, e.g., in terms of carbon emissions and temperature increases. The emissions pathways projected by the IAMs are used to estimate global temperature outcomes using the MAGICC model (Meinshausen et al., 2011), which are downscaled to the regional level. Based on these temperature estimates, the NGFS scenarios provide estimates of aggregate GDP impacts from physical risk following a damage function based on Kalkuhl and Wenz (2020), as well as more granular physical risk data derived from the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP database).[1] Further, a macroeconomic model (NiGEM) is used to complement the economic variables provided by the IAMs.[2]

The time horizon of the NGFS scenarios is up to 2100 (NiGEM projections run until 2050). There are six NGFS reference scenarios (table 2), including two scenarios which incorporate the policy goal of net-zero CO_2 emissions by 2050. Each scenario is produced with each of the three IAMs for a total of 18 model runs. The main scenarios assume a one-way link between GHG emissions and climate change, and do not include feedback effects from physical risks on the GHG emissions trajectory. However, the NGFS did publish an additional subset of scenarios where such feedbacks are included.[3]

The regional coverage differs between the models used by the NGFS. The MESSAGEix-GLOBIOM and REMIND-MAgPIE models both have 11 native model regions, whereas the GCAM model has 32 native model regions. For the purposes of the NGFS scenarios, all IAM native model regions were downscaled to 132 individual countries (NGFS, 2021b). NiGEM has 52 native model regions. As this exceeds the number of regions available in the IAMs, the downscaled results were used to inform the NiGEM projections.

1 Detailed information about the model settings and characteristics used for each ISIMIP simulation round and Output Data table can be found at https://www.isimip.org/impactmodels/ (accessed 10th October, 2022).

2 The supporting models have been developed by an academic consortium from the Potsdam Institute for Climate Impact Research (PIK), International Institute for Applied Systems Analysis (IIASA), University of Maryland (UMD), Climate Analytics (CA), the Swiss Federal Institute of Technology in Zurich (ETHZ), and the National Institute for Economic and Social Research (NIESR).

3 The additional scenarios with physical feedbacks are produced with REMIND-MAgPIE, following the methodology in Schultes et al (2021).

Table 2
OVERVIEW OF THE SIX NGFS SCENARIO NARRATIVES ACROSS THE ORDERLY, DISORDERLY AND HOTHOUSE WORLD CATEGORIES

Type	Scenario	Description
Orderly	Net Zero 2050	Climate policies are implemented immediately with sufficient stringency to reduce global CO2 emissions to net zero around 2050, yielding a 50% chance of limiting end-of-century global warming to 1.5°C
	Below 2°C	Climate policies are implemented immediately and gradually intensified such that there is a 67% chance of limiting end-of-century global warming to below 2°C
Disorderly	Divergent Net Zero	Climate policies are implemented immediately with sufficient stringency to reduce global CO2 emissions to net zero around 2050. Policy differentiation across sectors leads to higher transition costs and a quicker phase out of fossil fuels.
	Delayed Transition	Climate policies are not implemented until 2030, but intensify rapidly thereafter to ensure that there is a 67% chance of limiting end-of-century global warming to below 2°C
Hot house world	Nationally Determined Contributions (NDCs)	Only climate targets and policies that have been officially submitted by countries to the United Nations Framework Convention on Climate Change (UNFCCC) secretariat are assumed to be achieved. Expected end-of-century global warming is circa 2.5°C
	Current Policies	No further climate policies are implemented after December 2020. Expected end-of-century global warming is circa 3.0°C

SOURCES: NGFS (2021a) and NGFS (2021b).

The NGFS scenarios are characterized by their level of physical and transition risk. Risk drivers are scenario-specific characteristics that may increase transition or physical risks. The NGFS considered five characteristics that may influence the severity of a given scenario. One risk driver pertains to physical risk severity, while four risk drivers to transition risk severity (NGFS 2021a), including:

— Level of policy ambition, whether the temperature objectives are consistent with the Paris agreement (1.5°C, 2.0°C) or higher, which would yield higher physical risk;

— Timing of the policy response, which is either immediate or delayed. The more delayed the policy action, the smaller the remaining carbon budget for any level of policy ambition, leading to greater transition risk, especially for high ambition scenarios (1.5°C);

— Level of policy coordination across countries and the effects of different carbon prices across economic sectors. The more variation in regional or sectoral policies, the greater the transition risk;

Figure 1
REPRESENTATION OF THE RISK DRIVERS IN THE NGFS SCENARIOS

		Physical risk	Transition risk			
Category	**Scenario**	**Policy ambition**	**Policy reaction**	**Technology change**	**Carbon sequestration***	**Regional carbon price variation**
Orderly	Net Zero 2050	1.5°C	Immediate	Fast	Medium	Low
	Well-below 2°C	1.8°C	Immediate	Moderate	Medium	Low
Disorderly	Divergent Net Zero Policies	1.5°C	Immediate	Fast	Low/Medium	Medium
	Delayed 2°C	1.7°C	Delayed	Slow/Fast	Low	High
Hot House World	Nationally Determined Contributions (NDCs)	2.5°C	NDCs	Slow	Low	Limited
	Current Policies	3°C+	Current policies	Slow	Low	Limited

Macro-financial risk level
Low
Medium
High

SOURCE: NGFS (2021a).

— Pace of technological change. The faster technologies evolve, the larger the economic disruption experienced by incumbent firms. In turn, technological developments also make it easier to reach global climate goals;

— The availability of carbon sequestration and CO_2 removal technologies (CDR) would translate into less deep emissions cuts, reducing transition risk. However, the feasibility of massive negative emissions has been increasingly questioned by the scientific and policy community.

Figure 1 represents the risk drivers included in the NGFS scenarios along with an indication of the implications for the level of macro-financial risk. Table 2 summarizes the role of each of these risk drivers in the six NGFS scenarios.

2.1 Key uncertainties in the NGFS scenarios

In process-based IAMs uncertainties emerge from the socio-economic developments (SSPs) and level of climate change (RCPs) that will prevail (Figure 2 shows the relation between these key uncertainties and the NGFS 2022 scenarios).

SSPs and RCPs are central in the scenario-based literature informing the Assessment Reports of the IPCC, including the current sixth assessment cycle (AR6).[4] The SSPs describe alternative socioeconomic futures in the absence of climate policy intervention on climate

4 The IPCC process has resulted in four generations of emission scenarios. Only the fourth comprises the RCPs and SSPs, which informed Phase 5 and 6 of the Climate Model Intercomparison Project (CMIP5/CMIP6). The RCPs have been used in scenario-based literature informing the IPCC Fifth Assessment Report (AR5), while a combination of SSPs and RCPs has been used for the IPCC Sixth Assessment Report (AR6) published in 2021 (Pedersen, et al 2020).

Table 3

RCPs AND THEIR ASSOCIATED FORCING LEVELS, EMISSIONS CONCENTRATIONS, AND TEMPERATURE ANOMALIES

RCP	Radiative forcing (W/m^2 in 2100)	CO_2e (ppm)	Temperature anomaly (°C)	Pathway
RCP8.5(a)	8.5	~980	~4.9	Rising
RCP7.0	7.0	~850	~4.0	Rising
RCP6.0	6.0	~690	~3.2	Stabilization without overshoot
RCP4.5	4.5	~575	~2.7	Stabilization without overshoot
RCP2.6	3 W/m2 before 2100 declining to 2.6 W/m^2 by 2100	~475 before 2100 declining to ~425 by 2100	~1.9 before 2100 declining to ~1.7 by 2100	Peak and decline

SOURCE: O'Neill et al. (2016).
NOTE: CO_2e is CO_2 equivalent.

a General view now is that RCP8.5 is not realistic Business As Usual (BAU) given policies in place throughout the world, and slowing emissions.

mitigation or adaptation. The narratives include sustainable development (SSP1), the already mentioned middle-of-the road development (SSP2), regional rivalry (SSP3), inequality (SSP4), and fossil–fueled development (SSP5) (O'Neill et al., 2017; Riahi et al., 2017).[5] SSP assumptions, which include projections for GDP and population, can have a considerable bearing on the level of transition and physical risk, because they inform projections of energy demand and countries' ability to absorb adverse shocks.

RCPs standardize the temperature outcomes estimated by process-based IAMs and are measured in terms of radiative forcing levels (expressed in Watts per square metre, W/m2). The link between radiative forcing and global temperatures is somewhat uncertain and time-dependent, so radiative forcing levels (which can be linked to GHG emissions concentrations) is a more unambiguous anchor for climate change projections. "Representative" means that each RCP provides only one of many possible scenarios that would lead to the specific radiative forcing characteristics captured by the RCP. The term pathway highlights that not only the long-term concentration levels matter, but also the trajectory taken over time to reach that outcome (Moss et al., 2010). RCPs usually refer to the portion of the concentration pathway extending up to 2100, for which IAMs produce corresponding emission scenarios (Table 3).

5 The NGFS scenarios are anchored around the SSP2 middle-of-the-road developments that imply "the world follows a path in which social, economic, and technological trends do not shift markedly from historical patterns. Development and income growth proceeds unevenly, with some countries making relatively good progress while others fall short of expectations. Global and national institutions work toward but make slow progress in achieving sustainable development goals. Environmental systems experience degradation, although there are some improvements and overall the intensity of resource and energy use declines. Global population growth is moderate and levels off in the second half of the century. Income inequality persists or improves only slowly and challenges to reducing vulnerability to societal and environmental changes remain" (https://www.carbonbrief.org/explainer-how-shared-socioeconomic-pathways-explore-future-climate-change/ accessed 10th October, 2022).

The SSPs complement the RCPs by defining the socioeconomic challenges to adaptation and mitigation given a specific climate change outcome (Kriegler et al., 2012; O'Neill et al., 2014). SSPs and RCPs thus jointly define the framework to explore future mitigation pathways by standardizing fundamental assumptions across climate scenarios. Notably, however, modelers still exercise considerable discretion with regards to assumptions about technological development. As a result, two scenarios that are built around the same SSP and RCP combination can still yield very different results. This can be due, for instance, to differences in the projected deployment of Carbon Capture Utilization and Storage technologies (CCUS). Thus, in order to enhance comparability of scenarios, increased standardization of technological assumptions is needed.

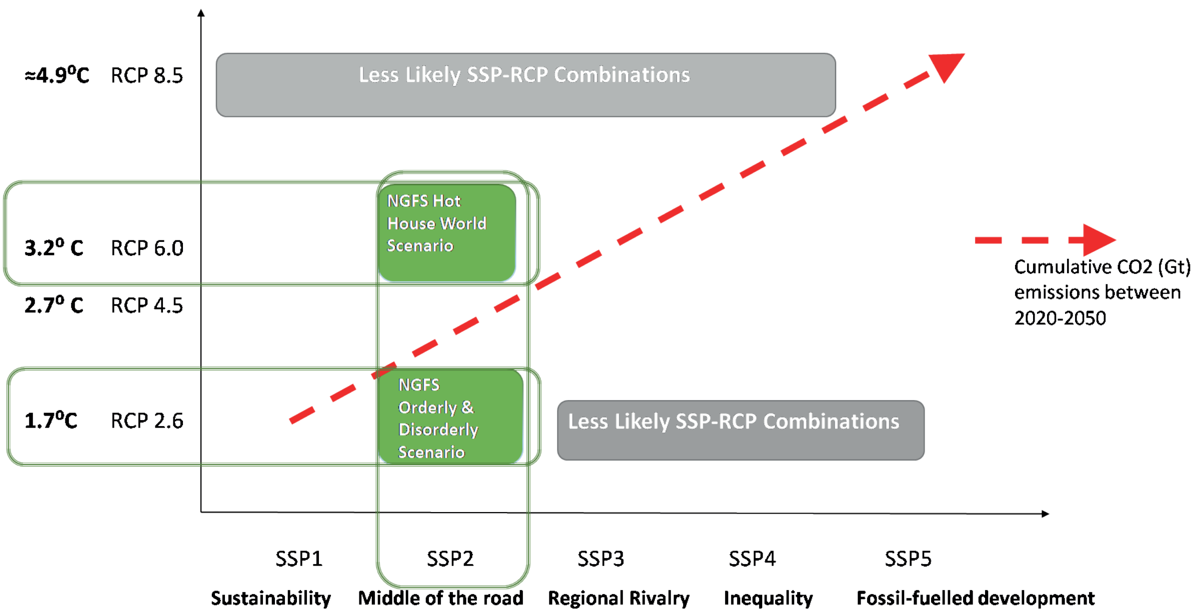
Pedersen et al. (2021) have compared long-term historical developments of key socioeconomic drivers and GHG emissions from 1990 to 2018 to determine if the SSPs are still plausible, considering the latest insights. The authors conclude that global emissions generally followed a medium-high pathway, captured by "middle-of-the-road" scenario narratives in the earlier series, and by combinations of "global-sustainability" and "middle-of-the-road" narratives in the most recent series (Special Report on Emissions Scenarios (SRES)[6] and SSP-baselines). This corresponds to the SSP narrative chosen by NGFS (more below). However, it is unclear if the socioeconomic drivers and GHG emissions continue to follow these pathways post 2018, particularly in light of recent developments such as the COVID-19 pandemic and global energy crisis.

The NGFS scenarios consider two RCPs. The orderly and disorderly transition scenarios are in the range of the low temperature scenario RCP2.6, with a projected temperature anomaly between 1.5°C and 2°C. The hot house world scenarios are close to the high temperature scenario RCP6.0 (NGFS 2021b) (Figure 2). All scenarios are currently based on SSP2, which assumes that society evolves broadly in line with past trends, global population peaks around 2070, and – when not accounting for the impacts from climate change – GDP would continue to grow in line with historical trends. The pathway for GDP as prescribed by SSP2 has been adjusted in the NGFS scenarios to account for the short-term impact of COVID-19 on growth rates (NGFS 2021b).

There are other possibilities not currently considered by the NGFS (Figure 2). On the one hand, if consumer preferences were to shift (e.g., in line with the SSP1 "Sustainability" narrative) this would relax the need for strict climate policies and could hence reduce potential transition impacts. On the other hand, if investment and economic growth trajectories would be more aligned with SSP4 such that there would be increasing inequality, the level of climate adaptation may suffer leading to higher physical risk vulnerabilities. In light of mounting geopolitical and socioeconomic uncertainties brought about by, e.g., COVID-19 and the global energy crisis, these alternative pathways become increasingly relevant for climate financial risk assessment.

6 Emissions scenarios form a key pool in the scenario-based literature informing the IPCC assessments (Pedersen et al. 2021). Historically, IPCC assessment reports has covered several generations of emissions scenarios: SRES correspond to the first vintages (Nakicenovic and Swart, 2000), while more recent scenarios developed outside the IPCC (i.e. RCPs and SSPs)

Figure 2
SSP AND RCP COMBINATIONS AND THEIR APPLICATION IN NGFS SCENARIOS



SOURCE: Authors´ analysis based on O'Neill et al. (2016), and NGFS (2021b).

Furthermore, the SSP narratives have several limitations. First, they were last updated in 2017 (Riahi et al 2017) and do not account for recent developments such as the COVID-19 pandemic. Similarly, geopolitical developments such as the war in Ukraine should ideally be taken into consideration for the revision of the SSPs. In addition, SSPs do not account for the role of finance, i.e. money and investment decisions, even though these could be a key driver of, or impediment to, climate mitigation and adaptation. For example, challenges to mitigation and adaption will be lower if firms – especially those in low-income regions and countries– have better access to capital. Hence, for the purposes of developing climate scenarios for financial analysis, four opportunities emerge: (1) implementing a regular revision cycle for SSPs to ensure the policy relevance of scenarios and their results; (2) the NGFS scenarios could incorporate alternative SSPs to better capture the complexity and uncertainty of evolving geopolitical and socioeconomic conditions; (3) the SSPs could account more explicitly for pathways of financial conditions; and (4) standardization of technological assumptions would further enhance the comparability of climate mitigation scenarios.

2.2 Climate transition risks in the NGFS scenarios

Transition risk in the NGFS scenarios is represented by the introduction of carbon pricing, which can be interpreted as a proxy for policy intensity. Carbon prices aim at internalizing negative externalities of GHG emissions such as damages to crops, human health or infrastructures. Carbon prices can also be interpreted as an implied price, which may be brought about indirectly through regulations or through other production constraints.

Process-based IAMs define the carbon price as the marginal abatement cost of an incremental ton of GHG emissions, which implies that, when this cost is internalized by producers, it creates an incentive to mitigate GHG emissions. The marginal abatement cost curve is upward sloping, such that the easiest (i.e. cheapest) to abate emissions are the ones that are addressed first. Sectors with relatively high marginal abatement costs will only be incentivized to decarbonize their production when the carbon price is high enough to match abatement costs. As a result, the pace of decarbonization differs across sectors. If the carbon price is not high enough to incentivize emissions abatement in a given sector, but it is high enough to lead to financial losses, the sector may reduce its supply in order to restore profit margins. Hence, carbon prices can have economic impacts through their impacts on production costs and prices, as well as on production volumes.

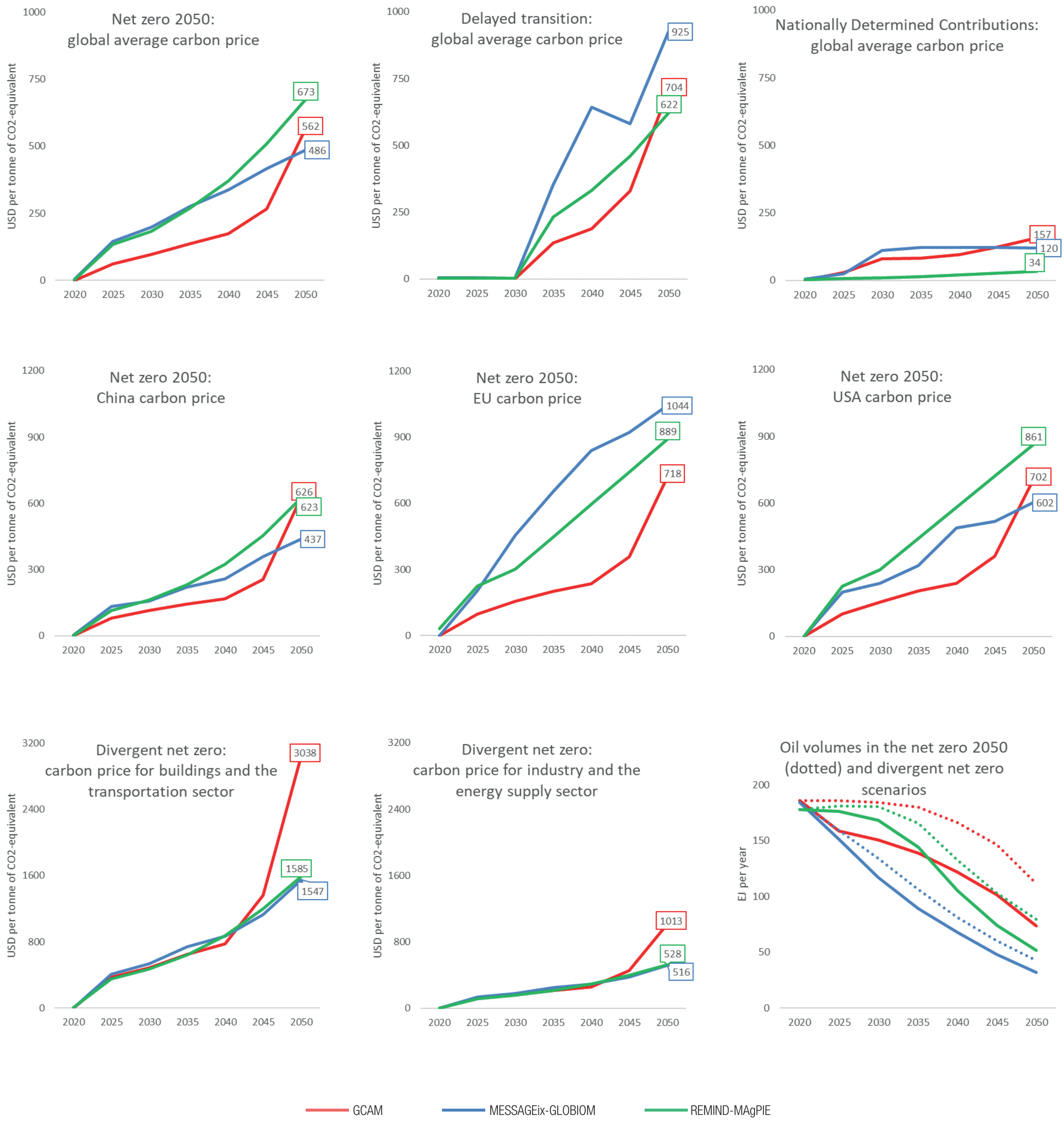
Implied carbon prices do not distinguish between levies on GHG emissions (e.g. via a tax or cap and trade system) or other environmental regulations. Process-based IAMs may therefore not capture the full impact of specific policy tools. Models that can capture the trade-offs of different climate policy tools would enable a more comprehensive insight into the potential financial and economic implications of climate mitigation scenarios. This is, for example, the approach followed by the European Commission in the design of the "Fit for 55" proposal to reach net zero emission in 2050. In the NGFS scenarios, the impact of climate policy is mitigated by an assumption that carbon prices generate fiscal revenues that are included in the general budget of each country or region (NGFS 2021b, p.19 and p.39). However, in the real world, carbon prices may not generate such revenues, and when they do, countries and regions may not want, or be able to, use those revenues.

The climate ambition, policy timing and technology assumptions in each NGFS scenario jointly determine how swiftly and by how much carbon prices need to increase. Marginal abatement costs differ across regions, with regional differences reflecting how advanced the region is in terms of abatement as well as the local cost and opportunities for deploying low-carbon technologies. In the EU, for example, progress on abatement of emissions tends to be relatively advanced (i.e. cheap opportunities for abatement have already been exhausted), and the marginal cost of abatement is higher as a result. In China, land can be utilized at a relatively low cost, e.g., to deploy carbon dioxide removal methods such as bioenergy with carbon capture and storage (BECCS) and afforestation, and that results in a lower carbon price.

The differences of carbon prices across NGFS scenarios are illustrated in chart 1(i), which shows the carbon price projections until 2050 from the three IAMs across selected scenarios. Looking across the net zero 2050 and delayed transition scenarios, it is apparent that the IAMs respond differently to a policy delay. In the GCAM and MESSAGEix-GLOBIOM models, a delay in policy response means that carbon prices need to rise higher in order to meet the climate target, even though the carbon budget in the delayed transition scenario is somewhat bigger (corresponding to a 1.8°C temperature anomaly) than in the net zero 2050 scenario (1.5°C). The impact of a policy delay is particularly strong in the MESSAGEix-GLOBIOM model, where the carbon price in 2050 is almost double that in the net zero

Chart 1

CARBON PRICES IN THE NGFS SCENARIOS ACROSS (i) SCENARIOS, (ii) JURISDICTIONS, AND (iii) SECTORS



SOURCE: IIASA NGFS scenario explorer v2.2.

2050 scenario. By contrast, the REMIND-MAgPIE model projects a slightly lower carbon price in 2050 in the delayed transition scenario, reflecting that in this model, the lower climate ambition in the delayed transition scenario compensates substantially for the impact of the policy delay. In the Nationally Determined Contributions (NDCs) scenarios, which reflects countries' official climate change commitments, carbon prices increase only slightly, reflective of the fact that NDCs represent a much lower climate ambition (2.5°C).[7] Nevertheless, even in the NDCs scenario, the IAMs vary substantially in their carbon price projections, highlighting the substantial modelling uncertainties.

The differences of carbon prices across regions are illustrated in chart 1(ii), showing carbon prices in the NGFS net zero 2050 scenario for China, the EU and USA.[8] The three IAMs project the same rank ordering of carbon prices across these selected regions, with the highest carbon price in the EU, followed by the USA and then China. This rank ordering reflects the difference in the regional marginal abatement costs. The variation across countries is largest in the MESSAGEix-GLOBIOM model (the European carbon price is more than twice the Chinese carbon price in 2050) and smallest in the GCAM model. Interestingly, the shapes of the carbon price curves projected by GCAM and MESSAGEix-GLOBIOM are similar across countries, whereas the shapes projected by the REMIND-MAgPIE model differ. Hence, these charts would suggest that the GCAM and MESSAGEix-GLOBIOM model assume that the structure of CO_2 emissions abatement cost curves is largely similar across countries. Using the REMIND-MAgPIE model, Nieto (2022) shows that China, which is expected to play a key role to reach global carbon neutrality, is by far the most highly dependent on CCUS and on CDR to reach net zero due to an energy mix dominated by fossil fuels in the 2020-2050 period. The US follows at a distance due to an energy mix that is largely dependent on oil in the 2020- 2035 period. In the EU, decarbonization is mainly driven by an increase in renewable energy and electrification.

To illustrate how carbon prices differ across sectors and IAMs, chart 1(iii) shows global average carbon prices in the NGFS divergent net zero scenario for (a) buildings and the transportation sector, and (b) industry and the energy supply sector. The divergent net zero scenario assumes that buildings (residential and commercial real estate) and the transportation sector (motor vehicles, shipping and aviation) bear the brunt of decarbonisation efforts, with sky-rocketing carbon prices in these sectors as a result. Whilst this fragmentation of policies leads to a faster phase out of fossil fuels than in the net zero 2050 scenario (the chart illustrates this for oil), the climate outcome is the same as in the net zero 2050 scenario (1.5°C) – but it comes at a higher cost and therefore brings higher transition risk.

IAMs in general, including those to support the NGFS scenarios, do not account for the role of the financial sector in climate mitigation pathways, even though there are likely to be important feedback loops between finance and the transition of the real economy. Battiston et al (2021) argue that financial markets are often considered to play an enabling role in climate mitigation pathways but they can also have a hampering role. This increases the possibility of the transition being delayed or occurring in a disorderly fashion. However, finance and investors' expectations are still excluded by IAMs and this limitation weakens the

7 Since the publication of the second version of the NGFS scenarios in June 2021, additional NDCs have been pledged which have not been incorporated in the projections shown here.

8 Given that regional definitions differ across the IAMs, this comparison is based on the country downscaled carbon price projections to ensure comparability across models.

ability of IAMs to inform policy and investment decisions. Overcoming this limitation, the authors develop a model that feedbacks climate financial risk assessment into IAM investment decisions and output trajectories.

2.3 Comparison of the Net Zero 2050 scenario across scenario providers

Besides the NGFS scenarios, financial institutions and authorities sometimes draw on scenarios by the International Energy Agency (IEA) or IPCC for the purpose of climate scenario analysis.[9,10] At present, there is no resource systematically analyzing the key differences and similarities between these various "brands" of scenarios. As such, it can be difficult to know which scenario to use, and to compare outcomes of scenario analyses from across these brands.

A framework to compare leading climate mitigation scenarios would allow users to decide more easily which brand of scenario to use for a given purpose. In addition, it would allow users to build plausible distributions of future outcomes based on a range of scenarios with comparable inputs and outputs from across scenario providers. Indeed, performing a scenario analysis based on only a single scenario is at odds with traditional approaches to quantifying financial risk that seek to account for the uncertainty around possible future outcomes.

By way of illustration, this section provides some initial points of comparison between scenario brands. Table 4 summarizes the differences among brands in terms of audience, underlying models, and scope across transition risk, physical risk and macro-economic variables. NGFS scenarios cover transition risk extensively but their coverage of physical risk is limited to chronic impacts.

Table 4
THREE BRANDS OF CLIMATE SCENARIO PROVIDERS, THEIR TARGET AUDIENCE, UNDERLYING MODELS AND SCOPE

Scenario brand	Main target audience	Models used	Transition pathways	Physical risks	Macroeconomic pathways
IPCC	Academic community	— Process-based IAMs — Climate models	Yes	Yes*	No
NGFS	Financial community	— Process-based IAMs — Climate models — Macroeconomic	Yes	Yes	Yes*
IEA	Policy makers	— Energy system model	Yes*	No	No

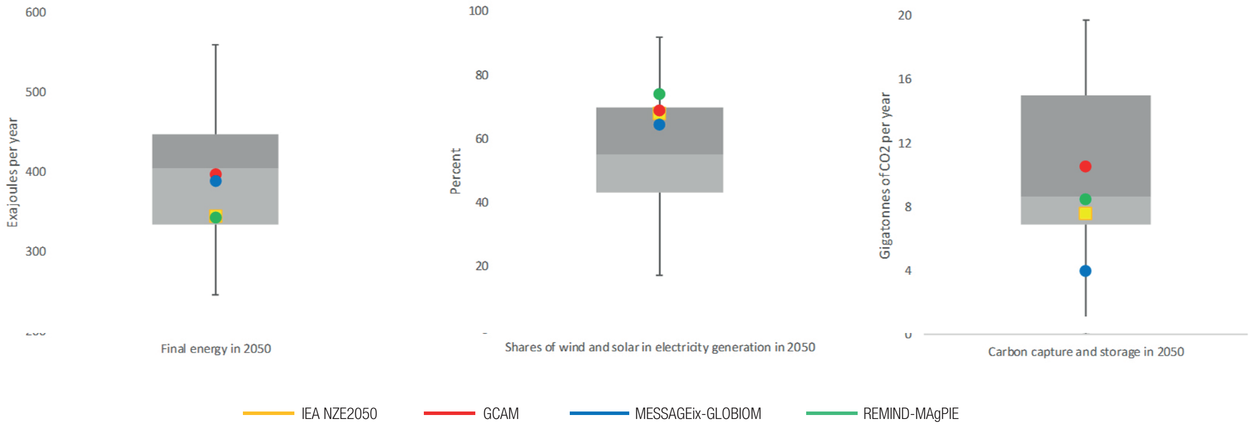
SOURCES: IEA (2021), NGFS (2021a) and Huppmann et al. (2019).
NOTE: A * indicates the scenario brand with the highest granularity in a given category.

9 For example, the IEA Net Zero Emissions by 2050 scenario is mandated by the European Banking Authority as a benchmark for emissions reduction targets in the Final draft implementing technical standards on prudential disclosures on ESG risks in accordance with Article 449a CRR.

10 A third set of scenarios sometimes used in this context are the New Energy Outlook transition scenarios produced by BloombergNEF. These scenarios are similar in scope to those produced by the IEA and incorporate state-of-the-art modelling of key transition technologies such as solar energy, CCUS, etc. Due to the proprietary nature of these scenarios they are not included here.

Chart 2

COMPARISON OF THE NGFS NET ZERO 2050 SCENARIO, THE IEA NZE2050 SCENARIO AND THE PROJECTIONS FOR "1.5°C WITH NO OR LIMITED OVERSHOOT" USED FOR THE IPCC SPECIAL REPORT ON 1.5°C (ROGELJ ET AL., 2018) ACROSS SELECTED VARIABLES

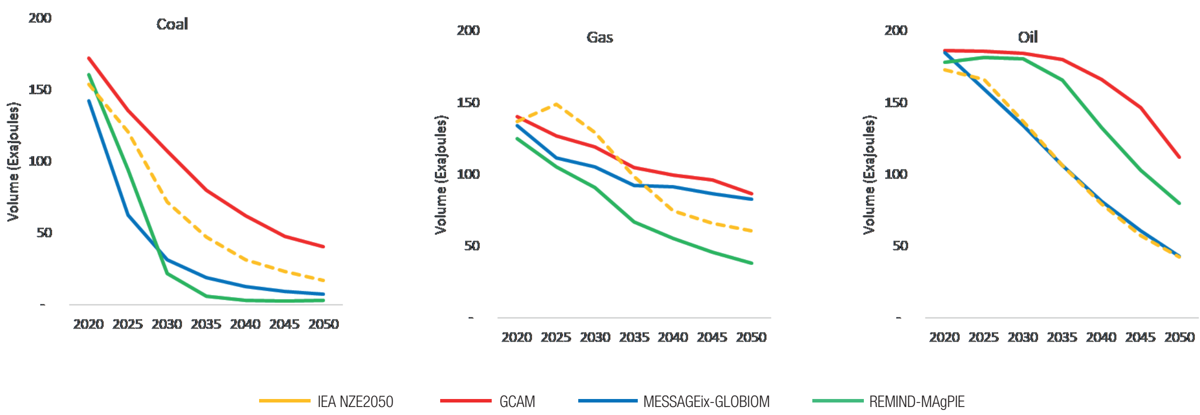


SOURCES: IEA (2021), IIASA NGFS scenario explorer v2.2, Huppmann et al. (2019) and authors' own elaborations.
NOTE: Boxplots indicate the range of projections from the IPCC report.

Despite these conceptual differences between the brands of scenarios, the actual scenario pathways often align fairly closely. Chart 2 shows results from the NGFS Net Zero 2050 (NZ2050) scenario alongside the IEA Net Zero Emissions by 2050 (NZE2050) scenario and the full distribution of results of the '1.5°C with no or limited overshoot' scenarios used for the IPCC Special Report on 1.5°C (2018). In terms of final energy demand, the three IAMs sit well within the IPCC range, with GCAM and MESSAGEix-GLOBIOM projecting final energy demand in 2050 to be just below the IPCC median. With regard to the importance of solar and wind derived energy in 2050, all three IAMs project a relatively high share for these renewables, implying that these technologies are assumed to be relatively cost-efficient in the NGFS scenarios. Projections for the role of CCUS are more varied, ranging from an extraction of about 4 Gigatonnes of CO_2 through CCUS in 2050 in the MESSAGEix-GLOBIOM model (less than the 25th percentile given by the IPCC models), to about 11 Gigatonnes of CO_2 in the GCAM model (more than the median). The IEA NZE2050 scenario sits centrally between the IAM results in terms of wind and solar derived energy and bioenergy. For CCUS, the IEA NZE2050 scenario sits just above the 25th percentile given by the IPCC and falls within the range provided by the NGFS scenarios. In terms of final energy demand, the IEA NZE2050 scenario corresponds to the REMIND-MAgPIE projection, i.e. at the lower end of the IPCC projections.

Chart 3 shows the similarity between the NGFS NZ2050 scenario and the IEA NZE2050 scenario with regard to the projections for the phasing out of fossil fuels. The demand for coal rapidly declines across all three IAMs used in the NGFS scenarios and is virtually negligible by 2050 in the MESSAGEix-GLOBIOM and REMIND-MAgPIE projections. The IEA NZE2050 scenario sits between these projections. With regards to gas, a more gradual decline is projected than for coal. The IEA NZE2050 projects a higher demand for

Chart 3
FOSSIL FUEL VOLUMES IN THE NGFS NET ZERO 2050 AND THE IEA NZE2050 SCENARIO



SOURCE: Authors' own elaborations.

gas in the short term than the NGFS scenarios, but this is followed by a rapid decline from about 2030 onwards. REMIND-MAgPIE is the only IAM that projects a lower demand for gas than the IEA NZE2050 scenario across the full time horizon. With regards to oil, the IEA NZE2050 scenario projects an immediate and consistent decline in the demand for oil, while two of the IAMs used by the NGFS (GCAM and REMIND-MAgPIE) assume that oil demand is stable in the short run and declines only from 2030 onwards. The MESSAGEix-GLOBIOM model, however, is roughly aligned with the IEA NZE2050 scenario in terms of its projection of oil demand.

3 Climate physical risks scenarios

Climate physical risks are referred to as either chronic or acute impacts.[11] Chronic impacts refer to the persistent economic losses brought about by climate change, such as reduced labor productivity and agricultural yields. Acute impacts refer to the costs created by extreme weather events, which generally increase in frequency and magnitude as a result of climate change. Both chronic and acute impacts affect the economy through their impacts on business disruptions, investments, profitability, economic growth, employment, wages, and household wealth.

NGFS scenarios represent so far the macroeconomic impacts from chronic physical risk, which are derived with a damage function based on Kalkuhl and Wenz (2020). With an econometric model, the authors establish a relationship between climate variables (temperature and precipitation) and regional GDP, and this relationship is used to inform the implications of higher temperatures for GDP losses in the NGFS scenarios. Importantly, these estimates are based on the historic relationship between temperature and GDP (using data at the subnational level for the years 1900–2014), and they primarily capture impacts on labor productivity, land productivity (agricultural yields) and depreciation of capital – i.e. chronic physical risks. They do not account for possible future impacts of climate change that are not captured in historical data. Moreover, damages from sea level rise are excluded from the analysis, and non-market damages such as loss of life, conflicts and violence, biodiversity and ecosystem damages are also not captured.

The NGFS scenarios currently do not incorporate acute physical risks within the economic projections, and estimates of acute impacts are provided only for tropical cyclones (see e.g. chart 2). The NGFS scenarios do provide data on specific climate hazards at the subnational level in a separate database.[12] This data is derived from (i) an ensemble of climate impact models that participated in international model intercomparison initiatives, gathered in the open access databases produced by the ISIMIP, which consider the impact of climate-related hazards on agricultural yields; and (ii) the CLIMADA disaster risk model, which considers the impact of river floods and tropical cyclones on the aggregate GDP of regions and countries. Uncertainty ranges are also provided.

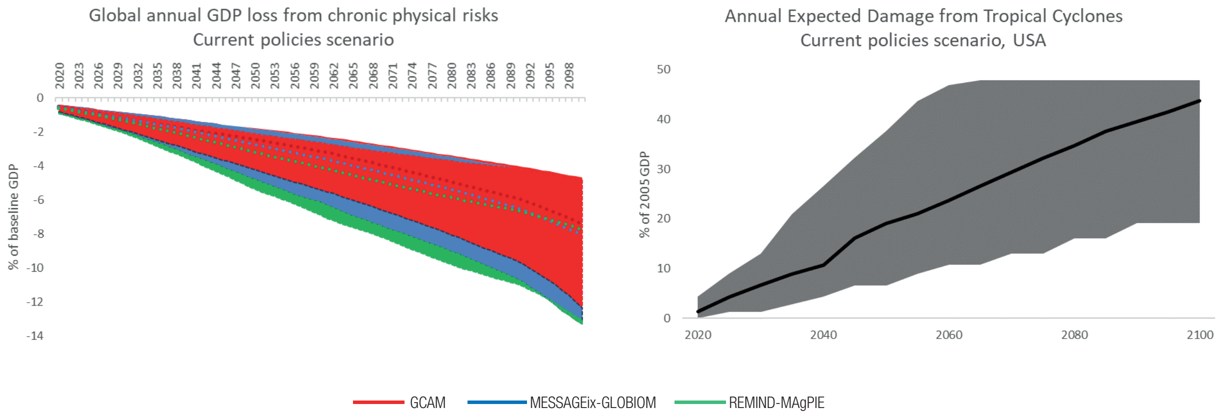
Physical risks are most pronounced in the NGFS current policies scenario (Table 2), which assumes that no further climate policies are implemented from 2020 – leading to a rise in global mean temperatures of circa 3°C by the end of the century relative to pre-industrial levels, with significant tail risk (i.e. the 95th percentile of warming is between 4.5°C-5°C). Chart 4 (left) shows that the chronic impacts of physical risk can rise to more than 13% of global GDP by the end of the century. Chronic impacts can be amplified by acute impacts.

11 Cf. NGFS (2021a).

12 This data can be explored via the Climate Impact Explorer: http://climate-impact-explorer.climateanalytics.org/ . (accessed 10th October, 2022). Note that the NGFS (2021b, p.47) caveats this data noting that “use of global datasets means regional representations are not consistently evaluated and can show deviations from other datasets used in risk assessments focused on the regional, national or subnational level.”

Chart 4

CHRONIC (LEFT) AND ACUTE (RIGHT) PHYSICAL RISK IN THE NGFS SCENARIOS



SOURCE: : IIASA NGFS scenario explorer v2.2 (left), Climate Impact Explorer (right).
NOTE: Lines indicate expected values, áreas indicate uncertainty bands.

Chart 4 (right) shows the example of tropical cyclones, which in the USA alone could lead to further losses equal to about 50% of its 2005 GDP.

The NGFS scenarios need to strengthen the representation of acute risks, considering more hazards beyond river floods and tropical cyclones (e.g., wildfires, droughts) and their potential compounding, and impacts beyond aggregate GDP and agricultural yields. This, in turn, would provide larger economic shocks, and potentially recessions, already in a shorter time frame, making the analysis more relevant for financial risk assessment and management. Including acute physical risks would provide a powerful tool for analyzing tail losses from the largest climate physical risks (Ranger et al., 2022). Furthermore, although standardized climate-relevant information at plant level has just started to be provided, consolidated information at global level is still missing (Bressan et al., 2022). Filling these gaps would enable a better assessment of the costs and benefits of climate mitigation pathways across regions and sectors.

4 Conclusions

The NGFS scenarios are increasingly used by central banks and financial supervisors, as well as by investors, for climate financial risk assessment (NGFS, 2021c). An important contribution of the NGFS scenarios is to translate the climate scenario landscape into six scenario narratives for broad use by the financial community.

By building on process-based IAMs and considering the limitations discussed above, the NGFS scenarios provide a comprehensive and robust framework for climate financial risk analysis. However, to ensure that these scenarios are used appropriately and in the right context, it is crucial to understand the characteristics and assumptions of the models that generated them, and their implications for financial risk assessment. This is the contribution of this paper.

Our analysis highlighted the following avenues for further scenario development in the context of climate financial risk assessment:

— **Assumptions:** The input assumptions to the NGFS scenarios follow SSPs. Given the continuous changes in economic and demographic developments, it is important to regularly update and revise these socioeconomic pathways. For example, the NGFS scenarios use adjusted GDP pathways to account for the short-term impact of COVID-19, which is not captured in the SSPs. In addition, in light of mounting geopolitical and socioeconomic uncertainties, it would be useful to explore a broader set of socioeconomic pathways in addition to the current SSP2 within the NGFS scenarios. Further, the SSPs could account more explicitly for pathways of financial conditions, as these can be an important factor in determining challenges to climate mitigation and adaptation. Lastly, standardization of technological assumptions would help to further enhance the comparability of climate mitigation scenarios

— **Climate policy:** Process-based IAMs rely on carbon prices as the key transition policy lever, which can usefully serve as a proxy for different configurations of actual climate policies, but may not capture the full impact of specific policy tools (i.e. price based versus environmental regulation). Models that can more precisely capture the trade-offs of different climate policy tools, including their potential implications for fiscal costs and revenues, would enable a more comprehensive insight into the financial and economic implications of climate mitigation scenarios.

— **Scenario provider comparison:** Despite conceptual differences between the brands of scenarios, the actual scenario pathways often align fairly closely, however, it is not always clear why and how the NGFS scenarios differ from other prominent scenarios, such as those produced by the IEA and IPCC. A framework to compare leading climate mitigation scenarios would allow users to decide more easily which brand of scenario to use for a given purpose. In this paper, we set out some key points of comparison.

— **Physical risk:** There has yet to be a climate mitigation scenario that captures acute and chronic physical risks in one integrated economic framework. Such a scenario framework would provide a powerful tool for analyzing tail losses from largest climate physical risks that current models cannot capture now.

— **Financial sector:** Process-based IAMs do not account for the role of the financial sector in climate mitigation pathways, even though there are likely to be important feedback loops between finance and the transition of the real economy. Going forward it will be paramount to integrate these feedback loops in modelling frameworks, especially in the context of climate financial risk analysis.

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