
Are Climate Finance Models Fit for Purpose?

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1 Introduction

1.1 Background information on climate finance models

Banks and other financial institutions have long incorporated climate finance models into their risk assessment processes; the models allow financial institutions to evaluate the creditworthiness and financial stability of businesses and projects in sectors vulnerable to climate risks. Many climate-related investments, including infrastructure projects, renewable energy initiatives, and climate adaptation programs all utilize climate finance models. The models help identify potential climate-related impacts on loan portfolios, and help insurers determine appropriate premium rates, coverage limits, and much more.

1.2 Overview of climate-related risks

In "A call for action: Climate change as a source of financial risk"[1], the Network for Greening the Financial System (NGFS) outlines how environment and climate-related risks, such as transition risks arising from changes in policies and regulations, causes both microeconomic and macroeconomic effects. Individual firms and households are susceptible to various consequences at the micro-level, including property damage, disruptions to business operations, income loss, alterations in demand, and devaluations of assets due to asset stranding. On a larger scale, the macroeconomy can experience changes in prices, changes in productivity, socioeconomic transformations, and labor-market frictions, which can have significant impacts. This report focuses on how different stakeholders utilize results from climate financial models to manage risk, and whether this practice serves its intended purpose or not.

1.3 Discussion of the role of climate finance models in addressing climate risk

Climate finance models help stakeholders, including insurers, financial institutions, policymakers, and investors, make informed decisions on managing climate risks, allocating resources, pricing financial products, and supporting sustainable investments. Using these models, stakeholders can enhance their understanding of the financial implications of climate change and develop strategies to mitigate risks and seize opportunities in a changing climate landscape. Financial impacts associated with climate-related risks and opportunities depend on not only an organization's level of exposure and planned responses, but also on how effective its responses

are in realizing targeted opportunities and mitigating or otherwise managing risks. To effectively plan responses, an organization should assess its climate-related risks and opportunities within the context of its businesses, operations, and physical locations in order to determine potential financial implications with the aid of a climate finance model.

2 Climate-Related Risks

2.1 Identification and explanation of climate-related risks faced by financial institutions

2.1.1 Banks

Banks are exposed to climate-related risks and opportunities through their lending and other financial intermediary activities as well as through their own operations. As financial intermediaries, banks may assume exposure to material climate-related risks through their borrowers, customers, or counterparties. Banks that provide loans or trade the securities of companies with direct exposure to climate-related risks (e.g., fossil fuel producers, intensive fossil fuel consumers, real property owners, or agricultural/food companies) may accumulate climate-related risks via their credit and equity holdings. In particular, asset-specific credit or equity exposure to large fossil fuel producers or users could present risks that merit disclosure or discussion in a bank's financial filings. In addition, as the markets for lower-carbon and energy-efficient alternatives grow, banks may assume material exposures in their lending and investment businesses. Banks could also become subject to litigation related to their financing activities or via parties seeking damages or other legal recourse. Investors, lenders, insurance underwriters, and other stakeholders need to be able to distinguish among banks' exposures and risk profiles so that they can make informed financial decisions. [4]

2.1.2 Insurance companies

For insurance companies, climate-related risks and opportunities constitute a key topic affecting the industry's core business (e.g., weather-related risk transfer business). The scientific consensus is that a continued rise in average global temperatures will have a significant effect on weather-related natural catastrophes and will account for an increasingly large share of natural catastrophe losses. Users of climate-related financial disclosures are specifically interested in how insurance companies are evaluating and managing climate-related risks and opportunities in their underwriting and investment activities. Such disclosure will support users in understanding how insurance companies are incorporating climate-related risks into their strategy, risk management, underwriting processes, and investment decisions. This guidance applies to the liability (underwriting) side of insurance activities. [4]

2.1.3 Asset Owners

Asset owners are a diverse group that include public- and private-sector pension plans, re-/insurance companies, endowments, and foundations and invest assets on their own behalf or on behalf of their beneficiaries. Asset owners invest according to a mandate or investment strategy set out by their oversight body or their beneficiaries. Asset owners have various investment horizons that influence their risk tolerance and investment strategies. Many asset owners have broadly diversified investment portfolios across investment strategies, asset classes, and regions and portfolios with thousands of underlying individual company and government exposures. Asset owners may hire asset managers to invest on their behalf. Whether asset owners invest directly or through asset managers, asset owners bear the potential transition and physical risks to which their investments are exposed. Similarly, asset owners can benefit from the potential returns on the investment opportunities associated with climate change. Asset owners sit at the top of the investment chain and, therefore, have an important role to play in influencing the organizations in which they invest to provide better climate-related financial disclosures. Disclosure of climate-related risks and opportunities by asset owners allows beneficiaries and other audiences to assess the asset owner's investment considerations and approach to climate change. This may include an assessment of the asset owner's integration of appropriate climate-related financial information into its investment activities in various ways, for example, in setting investment strategy, making new investment decisions, and managing its existing portfolio. By encouraging climate-related financial disclosures by asset owners, beneficiaries and other stakeholders will be in a position to better understand exposures to climate-related risks and opportunities. Further, climate-related financial disclosures by asset owners may encourage better disclosures across the investment chain—from asset owners to asset managers to underlying companies—thus enabling all organizations and individuals to make better-informed investment decisions. [4]

2.1.4 Asset Managers

Asset managers, also known as investment managers, are hired by clients to invest assets on their behalf. In this role, asset managers act as fiduciaries. Asset managers invest within the guidelines specified by their clients for a given mandate set out in an investment management agreement or product specification. Importantly, the investment results, whether positive or negative, belong to the client. Asset managers' clients, as owners of the underlying assets, bear the major portion of the potential transition and physical risks to which their investments are exposed. Similarly, asset managers' clients will benefit from the potential returns on the investment opportunities associated with the transition to a lower-carbon economy. The relevance of climate-related risks and opportunities to an asset manager and its asset owner clients will depend on a number of variables, including its investment styles and objectives, the asset classes in which it invests, the investment mandates, as well as other factors. In the case where an asset manager is a public company, it has two distinct audiences for its climate-related financial disclosures. The first audience is its

shareholders, who need to understand enterprise-level risks and opportunities and how these are managed. The second is its clients, for whom product-, investment strategy-, or client-specific disclosures are more relevant. Asset managers' clients rely on reporting from asset managers to understand how climate-related risks and opportunities are managed within each of their portfolios. [4]

2.2 Analysis of the potential financial impacts of climate-related risks

After assessing its exposure to climate-related risks and opportunities, an organization needs to choose how to respond to the identified risks and opportunities, including the following: [5]

1. the risk management actions it plans to undertake (i.e., mitigate, transfer, accept, or control);
2. capital expenditures (CapEx) on new technology or facilities that may be warranted; and
3. R&D expenditures that may be necessary.

These are largely strategic and financial planning decisions around the operating and capital expenditures the organization plans to undertake in response to climate-related risks and opportunities. In some cases, these responses may be directly motivated by specific climate-related issues, and in other cases, climate-related issues may be an additional, but not exclusive, motivational factor around other business drivers. It is important for an organization to recognize that accepting climate-related risks (i.e., “no response”) may also carry potential financial implications, such as a loss in revenue, reduced asset valuations or write-offs, or increased costs.

2.3 Importance of regulation of climate-related risks

After the global financial crisis of 2007-2008, the Basel Committee on Banking Supervision revised its minimum international standards (the Basel III Agreement). The revisions included a reform of the minimum level of regulatory capital for banks (Pillar I). Post-crisis, this minimum level was deemed insufficient for banks to ensure stability when under significant market stress. Basel III then specified a more robust framework with a strengthened capital adequacy ratio to increase banks' resilience and address the flaws identified during the crisis. This capital adequacy ratio should ensure that banks have the minimum capitalization level to deal with unexpected losses as the ones suffered the banks in the financial crisis of 2007-09. However, in spite of these recent revisions, climate-related risks are not yet incorporated in the risk-weighted assets of a bank. “The current Basel Capital Accord does not take explicit account of, and therefore only marginally addresses, these [environmental risks] issues”.[6] More specifically, the CISL report notes: “Pillar 1 [...] does require banks to assess the impact of specific environmental risks on the bank's credit and operational risk exposures, but these are mainly transaction-specific risks [...]”.

[6] Besides not fully considering environmental risks, some authors even claim the Basel Agreement can be adverse to green financing. These authors point out that the Basel Agreement gives a more rigorous prudential treatment to long-term loans. This characteristic can then negatively impact the lending to green infrastructure projects which are highly important for the transition to a low-carbon economy but are by nature long-term projects. [9] The under-capitalization of Climate Risk by the Financial Sector is a growing risk, given only a minimal portion of Climate Risk is currently covered by Banks' core capital: physical risk as far as it impacts banks' daily operations (e.g. flooding). In short, the financial impacts of climate-related risks could result in losses for banks and possible financial instability. [3]

When considering possible regulatory adjustments, the first question is whether current rules already capture climate-related financial risks. If that were not the case, regulators would need to consider supplementary actions through modifications to Pillar 1 instruments (such as risk weights), Pillar 2 requirements (eg supervisory review processes and capital add-ons) or Pillar 3 disclosure obligations. Indeed, the BCBS, as the international standard-setting body for banks, has announced a roadmap to identify gaps in the Basel framework, so that they can develop measures to address them.

Pillar 2 offers more possibilities to deal with climate-related risks. Under the supervisory review processes, authorities have a larger variety of tools that can be deployed to ensure adequate management of climate-related risks. Supervisors could use their assessments of firms' exposure to such risks to seek – within a reasonable period of time – changes in how supervised firms identify, monitor, measure and control them. That is likely to prove more helpful than direct capital requirements to mitigate the impact of climate-related risks on banks' financial positions. Sectoral concentrations limits could also be used under Pillar 2 if deemed appropriate.

As a starting point for any prudential measures, granular taxonomies are needed to support the assessment of banks' vulnerabilities, especially for corporate exposures. Moreover, these assessments need to be based on comprehensive scenarios including climate developments and the policy responses. In addition, standardised regulatory returns need to be developed that contain sufficiently detailed information on the relevant climate-related risk exposures.

Fortunately, the international community is already working to fill the current gaps in information and analysis. For example, some national authorities are seeking to develop practical taxonomies for evaluating risks for different sectors and classes of entities. The Network for the Greening of the Financial System (NGFS) has developed a suite of plausible scenarios. These are already in use by regulators to analyse the vulnerabilities of their supervised institutions.

The FSB has also made progress in developing guidance for climate-related disclosures, which is now being adopted in many jurisdictions. These efforts are complemented by initiatives under way at the international accounting standard-setting bodies (eg the IFRS Foundation) to establish public financial disclosure standards on sustainability.

3 Understanding Climate Finance Models

3.1 How modelers create usable climate finance models

Initially, modelers set a foundation by outlining research questions and objectives. This is followed by defining the modeling scope, encompassing sectoral coverage, time frame, and relevant metrics. Identifying the modeling framework involves assessing strengths and weaknesses to align with research goals. The modeler then details the reasons for choosing the modeling scenarios, including reference scenarios and policy connections. Pre-gathered data are cleaned to address anomalies and biases before being put into the model. The modelling results are then analyzed with an emphasis on uncertainties and sensitivity. It is worth noting that the communication of results, tailoring formats to suit objectives and audiences, and addressing modeling limitations are essential. Lastly, elucidating process aspects, such as team information, peer-review processes, and transparency measures, contributes to the credibility and clarity of the results.

3.2 Overview of different types of climate finance models

The models used are typically Integrated Assessment Models (IAMs), which these models fall into five broad categories, with some overlap: welfare optimization, general equilibrium, partial equilibrium, simulation, and cost minimization.

Welfare optimization models tend to be fairly simple, which adds to their transparency. Production causes both emissions and consumption. Emissions affect the climate, causing damages that reduce production. The models maximize the discounted present value of welfare (which grows with consumption, although at an ever-diminishing rate) across all time periods by choosing how much emissions to abate in each time period, where abatement costs reduce production. The process of discounting welfare (or “utility,” which is treated as a synonym for welfare here and in many models) requires inputting speculative values to non-market “goods” like ecosystems or human lives, as well as assigning a current value to future costs and benefits. Dynamic optimization models – including all of the welfare optimization and cost minimization models reviewed here – solve all time periods simultaneously, as if decisions could be made with perfect foresight.

General equilibrium models represent the economy as a set of linked economic sectors (labor, capital, energy, etc.). These models are solved by finding a set of prices that have the effect of “clearing” all sectors simultaneously (that is, a set of prices that simultaneously satisfy demand and supply in every sector). General equilibrium models tend to use “recursive dynamics” – setting prices in each time period and then using this solution as the beginning point for the next period (thus assuming no foresight at all). There is a possibility of multiple equilibria, and when this occurs general equilibrium models yield indeterminate results which may depend on details of the estimation procedure.

Simulation models are based on off-line predictions about future emissions and climate conditions; climate outcomes are not affected by the economic model. Rather, a predetermined set of emissions values by period dictates the amount of carbon that

can be used in production, and model output includes the cost of abatement and cost of damages. Simulation models cannot, in and of themselves, answer questions of what policy makers should do to maximize social welfare or minimize social costs. Instead, the simulation models estimate the costs of various likely future emission paths.

Cost minimization models are designed to identify the most cost effective solution to a climate economics model. Some cost minimization models explicitly include a climate module, while others abstract from climate by representing only emissions, and not climatic change and damages. [7]

4 Evaluating Climate Finance Models

4.1 Assessment of the effectiveness of climate finance models in measuring climate-related risks

Reference scenarios provide a counterfactual of what is most likely to happen in the absence of any further intervention. These scenarios are often also called business-as-usual or baseline scenarios. Many assumptions go into the construction of the reference scenario. It is important to be aware of them — especially when comparing two studies based on different models — because the choice of assumptions can have a greater effect on the outcome than the choice of modeling methodology. Ideally, each assumption in a model should be justified by adequate backing studies or expert opinions. Below we include some key modelling assumptions and different questions to be asked about the assumptions.[2]

KEY MODELING ASSUMPTIONS

Variable	Explanation	Questions to Ask about the Assumption
Population	Changes in population drive the need for new buildings, transportation, industrial activity, and food production, among others.	<ul style="list-style-type: none"> Are the population projections clearly stated? What source was used to generate them (externally supplied or within the model)? Do the projections include subnational details? Are they broken down by working age, urban/rural, educational attainment, or income level?
Gross domestic product (GDP) and economic growth	Aggregate economic activity, quantified as GDP, depends on population, productivity, and factors of production such as labor, land, and industrial machinery. When economic activity is an exogenously provided parameter, it is a driver of model results. For some models, it can also be an output.	<ul style="list-style-type: none"> Are the GDP projections clearly stated? What source was used to generate them (externally supplied or within the model)? Is GDP provided at the subnational and sectoral level? If the model provides GDP estimates, how were these projected? Are growth rate assumptions disaggregated by sector?
Policies and actions	Existing policies and actions may be explicitly represented in the model. Sometimes studies explicitly include only policies and actions implemented before a certain cutoff year. Studies should clarify what assumptions are used for policies and how they are translated into the model framework.	<ul style="list-style-type: none"> Which policies and actions were included in the baseline scenario? Are any policies excluded from the report? If so, explain why they were excluded? What is the policy cutoff year (the last year for which existing policies were considered)? How are the impacts of existing policies estimated and represented in the model?
Availability and build rates of new technologies (the rate at which these technologies can be built)	Assumptions on constraints (such as land-use constraints) and build rates of new technologies (such as renewable energy sources and carbon capture and storage [CCS]) may be included in the model. They are useful for assessing whether enough of these resources can be deployed in time or enough space is available for multiple competing land uses (for example, for bioenergy and food crops).	<ul style="list-style-type: none"> Does the model provide information on the price and price variation over time of technologies such as wind, solar, and hydropower; biomass; electric vehicles; batteries; and CCS? Is the information disaggregated by region? Are there explicit assumptions about build rates (in gigawatts or carbon mitigated per year)?
Technological learning rates	The learning curve usually leads technology prices to taper over time.	<ul style="list-style-type: none"> What learning rates are assumed for technologies such as solar, wind, batteries, and CCS?

KEY MODELING ASSUMPTIONS (CONTINUED)

Variable	Explanation	Questions to Ask about the Assumption
Energy and fuel prices	Prices for fuels such as oil, gas, and coal determine many model results. Sometimes electricity prices are also supplied exogenously, although in many cases they are computed as an output by the model. High fuel prices can lead to faster adoption of energy efficiency measures; high prices of carbon-intensive energy carriers can lead to a shift to more renewable energy.	<ul style="list-style-type: none"> What are current and future prices of oil, gas, coal, electricity, and any other fuels used? Are they expressed in a clear currency, and are they in real or current terms? Are fuel prices responsive to demand for fuels?
Trade	A country's consumption depends partly on international trade.	<ul style="list-style-type: none"> Is trade included in the analysis? For which commodities and with which other regions is it modeled? Are electricity imports and exports included?
Emissions factors	Emissions factors indicate the extent to which emissions are embedded in each unit of emissions-producing activity or emissions per unit of fuel. The choice of emissions factors affects a study's results.	<ul style="list-style-type: none"> What emissions factors are assumed for different electricity-generation technologies, industries, transport, and agriculture? What is the source of the emissions factors? Are the factors country specific or regional/global?
Discount rate	A social discount rate is typically used to reduce ("discount") the value of costs and benefits occurring in the future. It reflects the fact that people tend to value the future less than the present. The value of this parameter can be highly subjective and controversial. It can have strong effects on the results of models and the implications drawn from them. This choice can affect whether to make an investment. In addition to the social discount rate, which affects the analysis of costs and benefits for society, there are also private and corporate discount rates for private citizens and companies.	<ul style="list-style-type: none"> What are the assumptions about social, household, and corporate discount rates?
Price elasticities and elasticities of substitution	The higher an elasticity, the stronger the response to price change. For example, a high gasoline price elasticity means that consumers will use much less gasoline if the price increases. They might switch to other fuels (such as biofuels), change the activity that requires gasoline (use public transport instead of a car), or cease engaging in an activity altogether. Price elasticities of substitution characterize the change in consumption of alternatives to a good when the price of that good changes (e.g., switching from a coal-based power supply to natural gas or renewable energy sources). Tuning parameters like these can give modelers power over the study's outcomes. This information should therefore be transparent and the assumptions justified by empirical studies.	<ul style="list-style-type: none"> What are price elasticities for commodities such as gasoline, oil, natural gas, and coal? Does the model provide information about whether consumers switch fuels based on prices? If so, at which price does the switch occur? Do consumers choose more efficient technologies (for cars and appliances, for example) in response to fuel and electricity price increases? Do consumers consume less in response to fuel and electricity prices (driving less or using less electricity, for example)?
Exchange rates and year of currency value	Exchange rates between currencies can fluctuate significantly. In order to compare studies from different times, it is important to account for these differences.	<ul style="list-style-type: none"> What year is used for currency values? What exchange rates between currencies are assumed for trade?
Other	These are variables that more specialized models use to reflect more refined sectoral or behavioral analysis.	<ul style="list-style-type: none"> Are there any changes in land-use practices? Do weather conditions affect model parameters (e.g., heating and cooling degree days)?

Source: WRI authors.

4.2 Examination of climate finance models for risk management strategies

In 2023, the European Central Bank released a new stress testing model framework at the firm level. The firm level model used in this framework as outlined in (ECB, 2022), this has a dynamic model of the firm's assets, liabilities, costs and revenue lined to current internal assets and leveraged as outlined below. Asset growth is driven by macro-economic drivers rather than specific market demand predictions

(for example the demand for energy). Unlike (Cormack et al., 2020), the model does not utilise a full balance sheet, cashflow evolution for the firm. A firm was defined as failed if, for two consecutive years, (a) its cash flow did not cover its financial expenses (cash flow insolvency), and (b) its leverage was above 90% (approximating accounting insolvency; see Cornell Law School (2020) for reference) [10]

Market Modelling Within the ECB model framework a number of assumptions are made about changes in Gross Value Add (GVA) for firms based on anticipated investment for the different climate scenarios. The challenge to such statements needs to be qualified in the sense that if firms cannot raise capital due to increased cost from inflationary pressures or, the GVA predictions will be incorrect. There is no mechanism within this framework to viably stress such price shocks given the costs are exogenously driven. In their framework, it was assumed that corporates would maintain the same capital structure over time, meaning that total assets, liabilities and equity would all grow at the same rate (and given that total assets = total equity + total liabilities). *Note in the following equations the superscript i denotes the firm, t the time (year), c the country and d the sector.*

Corporate Credit Risk The ECB model uses a number of dynamics to model the growth in assets of the firm. Specifically the total assets for firm i , Total assets $_t^i$ at time t are taken to evolve as follows:

$$\begin{aligned} \text{Total assets}_t^i = & \alpha + \beta_1 \text{Total assets}_{t-1}^i + \beta_2 \text{GVAGrowth}_t^{c,d} \\ & + \beta_3 \text{Inflation}_t^c + \beta_4 \text{SizeDummy}_t^i + \epsilon_t^i \end{aligned}$$

where $\beta_1, \beta_2, \beta_3, \beta_4$ are obtained from a linear regression using firm-level data from the Orbis Database. The estimation sample consisted of more than five million firms and spanned from 2010 to 2020. This period encompassed two major Europe-wide economic and financial crises (the European sovereign debt crisis and the COVID-19 pandemic), therefore making it possible to model historically defaulted firms based on their financial information. To estimate a firm's probability of default, the authors ran a logistic regression using this model:

$$PD_t^i = \alpha + \beta_1 \text{leverage}_t^i + \beta_2 \text{profitability}_t^i + \epsilon_t^i$$

Leverage was defined as total liabilities over total assets, and profitability as net earnings (operating revenues minus operating and financial expenses) before tax over total assets. It is also worth noting that the model includes a component of green investment, whose formula is linked to the reduction of GHG emissions, which is detailed later on. The liabilities of the firm are taken to follow a proportionate model the authors assert preserves capital structure given below:

$$\begin{aligned} \text{Total liabilities}_t^{i,s} = & \text{Total assets}_t^{i,s} * \frac{\text{Total liabilities}_{t_0}}{\text{Total assets}_{t_0}} \\ & + \text{Green investments}_t^{i,s} \end{aligned}$$

Within the model, green investments in each year are given by the change in emissions scaled by the cost of mitigation, with an allocation of 50% investment forced in the first three years, and the second 50% would be raised in the remaining 15 years.

4.3 Analysis of the limitations and challenges of current climate finance models in addressing financial institutions' needs

For carbon mitigation activities, the amount of green investment that firms would have to raise would depend on their decrease in Scope 1, 2 & 3 emissions from 2022 until 2030, determined by their carbon footprint at the starting point (at firm-level) and the projected emissions pathways for each scenario until 2030 (at sector-level). For the costs of carbon mitigation activities, the authors relied on the sector-level prices derived from the IPCC (IPCC, 2022), which calibrated those costs based on the mitigation options and costs of each sector and their potential contribution to net emissions reduction until 2030.

$$\sum_{t=2023}^{2030} \text{Green investments}_t^{c,s} = \Delta(\text{Scope 1, 2, 3tCo2})^{c,s}(2023 \sim 2030) \\ * \text{mitigation cost}_j \left(\frac{EUR}{tCo2} \right) + \sum_{t=2023}^{2030} G_t^{e,s} * I_t^s$$

The ECB model provides a firm-level assessment of the impact of climate, in comparison with other firm-based models such as (Cormack et al., 2020), provides detailed asset level cost and detailed modelling on the depreciation and as firm-level capital controls are more consistent in these other frameworks where all investments are taken to be inline with current company investment constraints rather than having a green investment add-on as exits in the ECB model. Concepts such as capital and cashflow management are critical to a firm's management; hence, models of the firm undergoing such long-term term (in this case, long term is greater than 1 year) need to factor in these controls in a way that reflects risk management practices within a corporate treasury, else risk misstating risks. Similar principles must be assessed when reviewing the impact of costs and how a firm would transfer or absorb such costs.

4.3 Analysis of the limitations and challenges of current climate finance models in addressing financial institutions' needs

IAMs inevitably rely on forecasts of future climate outcomes and the resulting economic damages, under conditions that are outside the range of human experience. This aspect of the modeling effort raises two related issues: **the treatment of scientific uncertainty about climate change**, and **the functional relationships used to project future damages**.

Scientific uncertainty in climate outcomes

There are inescapable scientific uncertainties surrounding climate science, for instance in the climate sensitivity parameter (the temperature increase resulting from a doubling of CO2 concentrations). As a result, low-probability, enormous-cost climate outcomes cannot be ruled out; the response to these extreme risks is often central to policy debate, and would ideally be incorporated in economic models of climate change. Yet we found that most IAMs use central or average estimates to set parameter values. Those few models that express parameter values as distributions most often use truncated distributions that inappropriately exclude or de-emphasize

low-probability, high-cost catastrophes. Uncertainty is inescapable, despite the ever-expanding body of climate research, because there are only a limited number of empirical observations relevant to questions such as estimation of the climate sensitivity parameter. As a result, the best estimates of the relevant probability distributions inevitably exhibit “fat tails,” meaning that extreme outcomes are much more likely than a normal distribution would imply (Weitzman 2008).

In the face of such worst-case risks, it is misleading to look only at the most likely range of conditions. That approach would take for granted policy-makers' willingness to play the odds in crafting a response to rising global emissions: Suppose that we knew that there were one hundred equally likely future scenarios, of which only one or a few would experience truly catastrophic climate change. The future will happen only once. If we plan well for the most likely outcomes but instead one that we consider unlikely comes to pass, will we be comforted by our parsimonious rationality? The most common approach to uncertainty found in the IAM literature is off-line sensitivity analysis, often conducted by changing one parameter value at a time and observing the results. A more thorough treatment of uncertainty, through Monte Carlo analysis that varies multiple unknown parameters, is seen in just a few IAMs, and even then it is difficult to fully explore the parameter space, especially given the fat-tailed distributions that characterize many key climate parameters, and their poorly understood correlations.

Projecting future damages

Most IAMs have two avenues of communication between their climate model and their economic model: a damage function and an abatement function. The damage function translates the climate model's output of temperature – and sometimes other climate characteristics, like sea-level rise – into changes to the economy, positive or negative. Many models assume a simple form for this relationship between temperature and economic damage, such that damages rise in proportion to a power of temperature change:

$$D = aT^b$$

where D is the value of damages (in dollars or as a percent of output), T is the difference in temperature from that of an earlier period, and the exponent b determines the shape or steepness of the curve. Implicitly, the steepness of the damage function at higher temperatures reflects the probability of catastrophe – a characteristic that can have a far more profound impact on model results than small income losses at low temperatures. However, there are three main concerns associated with damage functions:

4.3.1 Under-explained parameters

DICE, like other models assumes that the exponent in the damage function is 2 - that is, damages are a quadratic function of temperature change. This implies that only 10.2 percent of world output is lost to climate damages at 6°C, which is clearly an underestimate. Other models, such as the GRAPE model, assert key parameters with little or no justification. According to Manne and Richels, the creators of the MERGE model, “Admittedly, the parameters of this loss function are highly speculative. With

different numerical values, different abatement policies will be optimal. This helps to explain why there is no current international consensus on climate policy.”

4.3.2 Continuity

The damage functions are often defined to be continuous across the entire range of temperature rise, even though climate change is hardly gradual and continuous. Several climate feedback processes point to the possibility of an abrupt discontinuity at some uncertain temperature threshold or thresholds. To improve on this, DICE-2007 models catastrophes in the form of a specified loss of income, which is multiplied by a probability of occurrence (given by an increasing function of temperature), to produce an expected value of catastrophic losses. This expected value is combined with estimates of non-catastrophic losses, to create the DICE damage function. This allows to incorporate some treatment of catastrophic change, while maintaining their continuous, deterministic damage functions.

4.3.3 Income damage

Damages are often modeled in IAMs as losses to income or consumption. However, other factors such as capital stocks and productivity are often undiminished. When damages are subtracted from the output, the implication is that these are one time costs that are taken from consumption, with no effects on capital, production or consumption in the next period - which is an unrealistic assumption.

5 Case Studies and Examples

5.1 Presentation of real-world examples showcasing the use of climate finance models

There are a number of commercial and in-house proprietary models that have been developed to address the challenges of climate risks within commercial banks and also by regulators. Whilst some of the methodologies have been shared as they indicate they use frameworks such as PACTA and central banks such as the Bank of England and the ECB have run exploratory stress testing exercises. As climate risk modelling is a new field and financial institutions have only just started working on determining whether they can build effective risk-based pricing, this will inevitably result in risk adjustments for a number of assets. However, a recent review has indicated that asset prices underestimated climate risks (Bank for International Settlements, 2022), it is clear that such risks if they cannot be measured cannot be reflected in risk-based pricing. Indeed, from communications with those in banking there is some reluctance where these risks have been identified to pass these fully through to price by some banks. Whilst regulations to embed these risks have been put forward (for example ECB, BoE), the delivery capital frameworks have yet to be fully defined, consequently commercial banks have typically absorbed these costs across their current balance sheet.

5.1.1 Deep Decarbonization in South Africa

Altieri, K. et al. (2015). Pathways to deep decarbonization in South Africa, explores deep decarbonization pathways that focus on development challenges, such as ways to decrease unemployment. The authors used an Energy Extended South African General Equilibrium Model (e-SAGE) which is a dynamic recursive computable general equilibrium (CGE) model developed by UNU-WIDER. The main input is the 2007 South African Social Accounting Matrix (SAM). The SAM is a set of accounts that represents all of the productive sectors and commodities in South Africa, as well as factor markets, enterprises, households, and the 'rest of the world'. The 2007 SAM has 61 productive sectors (industries) and 49 commodities. The seven factors of production include land, four labour groups disaggregated according to level of education, and there is a distinction between energy and non-energy capital (Arndt et al., 2013). The government, enterprises, 14 household groups based on their per capita expenditure, and the 'rest of the world' are all represented (Thurlow, 2004). The behavior of industries and households is governed by rational expectations (Thurlow, 2008). Industries and producers aim to maximize profits while households aim to maximize their utility subject to their budget constraint. Product and factor market equilibrium are maintained. The e-SAGE model is a dynamic recursive model, and as such has two periods, the within-period and the between period. The static part of the CGE model makes up the within period. Some variables and parameters are updated during the between period, with capital accumulation and re-allocation being determined endogenously with exogenous forecasts for population growth, factor productivity and technical change in the energy sector (Alton et al., 2014). A

key feature of the e-SAGE model is that non-energy industries can react to energy price changes during the between-period by shifting their investments to less energy intensive capital and technologies, the ease of which is specified exogenously (Alton et al., 2014). It is important to note that some exogenous changes made in the CGE model replicate policy goals in the National Development Plan: achieving a labour participation rate of 65% by 2030, an increase in South Africa's agricultural exports, and an increase in national savings to 25%. To briefly summarize, there were two scenarios represented in the e-SAGE CGE model, which were both linked to a GHG emission constrained energy system model. The goal of both scenarios was to reduce unemployment. The approach in the first scenario was to identify an economic structure that decreased unemployment while remaining within the emissions constraint. The approach in the second scenario was to simulate a large improvement in the overall skills profile of the working population, which would require a significant improvement in the effectiveness of the education sector, including training and vocational development programs. [8]

5.1.2 Barclays' methodology towards energy

Barclays' Climate Risk team was set up to develop Barclays' climate risk methodologies and manage the financial and operational risks from climate change in the portfolio. The team strengthened Barclays' approach to climate risk governance, and utilized scenario analysis methodologies and carbon modelling to create the BlueTrack™ model used for portfolio alignment and target setting. The Energy sector covers the production, processing and distribution of hydrocarbon fuels and its derivatives. Hydrocarbons are mostly used as an energy source, but they are also used in the petrochemical industry to produce plastics, solvents and other intermediate products. This sector generates emissions mainly through the combustion of fuels by end users, e.g. automotives and power generation, but also through production processes including flaring, venting and unexpected leaks that could occur across the supply chain. Barclays' estimates intensity factors by fossil fuel, separating them into **oil, gas, natural gas liquids (NGLs) and coal**.

For oil, they use the OPGEEa (Oil Production Greenhouse Gas Emissions Estimator) and the PRELIMb (Petroleum Refinery Lifecycle Inventory Model) lifecycle assessment models to calculate Scope 1 and 2 emissions, which provides increased granularity of energy intensity, e.g. oil extracted from tar sands can be three times more intensive than the global midpoint on a CO₂e basis. OPGEE is a peer reviewed independent academic study and the model can provide estimates for CO₂ and methane both separately and on a combined (CO₂e) basis. Scope 3 CO₂ emissions factors are estimated using the annual emissions and annual production levels as reported from the IEA.

Extraction technologies for gas are less diverse and detailed studies of production intensity are less common. They use the National Energy Technology Laboratory (NETL) lifecycle assessment analysis to estimate CO₂ emissions factors which allowed them to differentiate by extraction technology (conventional, unconventional, deepwater, CBM). While NETL is a study of North American gas fields, this methodology was adopted by the team because the CO₂ component of gas extraction is

reasonably consistent across geographies. Methane and extraction technology level is estimated by using the IEA Methane Tracker. There can be a significant divergence in methane intensity at a country level and those with stronger regulations in place often observing far lower intensities than average, e.g. the intensity of Norwegian gas is on average around one hundred times less intensive than the median and around one thousand times less intensive than the most intensive country. Scope 3 CO₂ emissions factors are estimated using the annual emissions and annual production levels as reported from the IEA. The detailed description of the approach towards energy can be found here.

5.2 Evaluation of the outcomes and lessons learned from these case studies

5.2.1 Deep Decarbonization in South Africa

South Africa may aspire to zero poverty and zero emissions in the long term, but is this possible? The study examined the twin challenges of development and climate change, and found that it is technically feasible for South Africa to meet a 14 Gt CO₂-eq constraint on energy emissions while improving on key development imperatives. Meeting the peak, plateau, and decline emissions trajectory requires major transformations in the energy system. The focus of this country report was to analyze the techno-economic pathways to meet development imperatives and decarbonization pathways. This study has focused on the long term, which is important for large investments and clear policy signals. However, there are rigidities in socio-economic systems, particularly in the short term, that need to be taken into account. How much of the mitigation potential in these technologically feasible scenarios for deep decarbonization can be realized depends on economic, social and political factors. The investments required to decarbonize the electricity sector are presented, and at some stages are as high as 14% of total investment. However, the detailed and sector-specific investments required are not yet fully quantified, and the sources of finance required to make such investments affordable not examined here. This study could be expanded by the use of a more sophisticated financial model, where the financial flows and investment requirements could be fully disseminated. From a global perspective, there are certain investment flows from developed to developing countries, as well as flows among developing countries, required to support deep decarbonization in developing countries. In this case, investment includes financial support as well as technological support. The rapid decarbonization of electricity supply envisaged in this study would only be affordable if technology costs are significantly reduced. Learning rates are a function of global installed capacity, and costs need to be brought down in developed countries. South Africa faces a high opportunity cost of investment in mitigation, notably investment in the reduction of poverty and inequality through employment and education. This study suggests that unemployment can at best be halved by mid-century. There is a certain amount of cooperation and collaboration inherent in the decarbonization process that requires joint action from developing and developed countries. An important component of this cooperation lies in the realm of international trade, ensuring that global demand

for all goods and services can be met, especially with respect to energy intensive goods. The current study is based on important methodological innovations, notably linking the SATIM-E energy model to an economy-wide CGE model expanded for energy, eSAGE. Equally important is the innovation in representing changes in the economic structure, and explicitly addressing South Africa's top policy priority of employment in this context. This research can be extended through analysis of what modeled scenarios might be blocked or supported in South Africa's political economy. Much further research is needed to provide a strong evidence base for urgent action on development and climate in South Africa.

5.2.2 Barclays' methodology towards energy

Some of the most important datasets in climate change analysis are sourced externally, including climate scenarios (both transition and physical risk), emissions data and client business activity (industry codes; financial revenue or asset splits; capacity, production and volume data). There is also a significant need for robust internal data, including things like financial exposure. Where selection and use of climate scenarios is concerned, it is important that the purpose of the modelling that requires the scenario is carefully thought through. For example, for scenario analysis work, a range of scenarios may be required containing varying degrees of transition and physical risk. For portfolio alignment work, the important consideration is the temperature alignment of the scenario. Consideration also needs to be given to the datasets provided by the scenario and whether these are adequate for analysis and modelling purposes. For the portfolio alignment work, Barclays' had to quantify client emissions accurately. While company-level disclosure has improved significantly in recent years, particularly driven by the TCFD, they continue to find that the data is still not robust enough overall to be a primary source. Because of this, the methodology has to estimate company emissions by combining information from external databases with their own internal assumptions. To assess which data providers would be most suitable for their requirements, they sourced data feeds from a number of providers to cross check and increase the accuracy of the model.

5.3 Discussion of the applicability of these examples to the broader financial industry

In Barclays', a challenge has been the inherent imperfection of the tools available to design and operationalise their approach. In an industry where practitioners are so used to long-standing processes and sources of data that have stood up to challenge over many years, they have to change that way of thinking in today's ever-changing world. For example, given the much longer time horizons over which climate change occurs, with no historic data to predict a future subject to potentially huge change and uncertainty, we need to understand new information and types of data (climate science, types of emissions, scope of emissions), as well as entirely new ways of measurement and analysis (attribution of impact to bank's activities, alignment methodologies). However, some of our historical tools are still reliable, particularly

as climate risks translate into the types of risk banks have always had to manage (credit, market, operational, reputational).

The nature of the threat from climate change is so significant and new that it requires the adoption of a new mind set from many in the financial services industry – whether this be how we approach new types of risk, how we engage with clients or develop new products and services. This response also offers an opportunity to reset elements of organisational culture and to engage with a broader set of stakeholders in order to take a more sustainable, longer-term view.

6 Recommendations and Future Directions

6.1 Proposal of potential improvements to climate finance models

The 3 core IAMs (GCAM, REMIND, MESSAGE-GLOBIUM), these models provide smooth transition pathways based on a set of input assumptions linked to energy prices, technology choices and economic parameters. The sets of scenarios such as delayed choices or current policies highlight the impact at a global economic system level of the risk posed to achieve decarbonisation trajectories, however many of the models lack a rich framework for assessments of the full implications of changing energy prices, impacts to commodity price volatility, corporate earnings or the disruption to a population's ability to fund a transition. To address the issues on the oversight on income damages, it would be possible to develop an IAM that modeled climate damages as, at least in part, losses of capital stock and/or decreases in productivity. This would require a model design only slightly more complicated than the common structure of IAMs: climate damages would alter the inputs to the production function that determines output, or the parameters of that function which express productivity, rather than just reducing the amount of available output after it is constructed. It would build in “memory,” with multi-period consequences of major climate impacts, a realistic feature that could be implemented relatively transparently. It is these factors that are significant for the assessment of risk impacts for financial institutions. As it stands the utilisation of these models requires considerable engineering adaptation to map these smooth trajectories to meaningful risk scenarios for individual sub-regions, companies or assets. The stress testing paradigm from the NGFS falls into the category of general policy and expected economic impact risk and is generally too high level to be fully utilised for bank level financial exposures. Whilst they provide the potential underlying impacts of wide-scale economic shifts and hence can be used to guide corporate, commercial banking lending strategy, further layers of modelling are required to derive financial impacts to banking portfolios.

6.2 Exploration of emerging trends and advancements in climate finance models

Climate models are fundamental to understanding climate change and anticipating its risks. They provide the basis for predicting impacts, guiding adaptation decisions and setting mitigation targets. Recent studies have shown that a new generation of high-resolution models can revolutionise the quality of information available for mitigation and adaptation, from global climate and regional climate impacts, to risks of unprecedented extreme weather and dangerous climate change. Existing models have significant shortcomings in simulating local weather and climate because of available computer power. They cannot resolve the detailed structure and lifecycles of systems such as tropical cyclones, depressions and persistent high-pressure systems, which drive many of the more costly impacts of climate change, such as coastal inundation, flooding, droughts and wildfires; nor are they able to resolve ocean currents that are fundamental to climate variability and regional climate change. AR1 climate models used a horizontal grid spacing of 300 kilometres, whereas today, for IPCC AR6, climate models have a resolution of around 100 kilometres. This has been hard won with the available computing resources – each time the resolution is halved (such as from 100 kilometres to 50 kilometres), 10 times more computing power is required. Weather models are now delivering global predictions at 10-kilometre resolution, and regional forecasts at the kilometre-scale. These advances have provided indisputable evidence that resolutions nearer a kilometre are needed for accurate modelling of important weather components such as cloud systems, convection, organised monsoon rainfall belts and tropical cyclones, as well as for local extreme events.

6.3 Discussion of the importance of collaboration between policymakers and regulators in enhancing climate finance models

As many climate policies have been designed with the goal of considered change to reduce emissions over a period of 25 years or more, the objective has been to ensure that financial organisations can embed transition changes and build an improved view of physical risks to adapt their portfolios accordingly. For these organisations the business rational on providing financial facilities is defined by their current contractual obligations and their risk appetite, their views of the forward-looking risk and the risk management strategy. For example, considerations in managing a loan / financing facility for a portfolio of firms undergoing transitions requires a clear view of the clients business strategy, regional policy as well as the current wider macro-economic environment. As part of that financial institutions dynamic risk strategy they need to have a clear view on sources of uncertainty related not only to policy but the clients ability to drive change in its business model (or deliver its strategy). This requires clearly informed guidelines to these clients driven by a sufficiently rich risk framework that can provide the necessary quantitative insight to their clients. There is an argument that banks that do not have sufficiently rich climate risk as-

assessments and base choices on unclear and unchallengeable information risk treating customers unfairly if arbitrary decisions of divestment or of excessive credit limits are placed on the pool of existing clients. Choices for banks dynamic risk management need to be proportionate to the needs of the economy within the national / international policy implementations. Banks working with their clients need to be able to provide a clear view on the extent of that they would provide future financing and communicate the set of forward-looking limitations to ensure there are no abrupt liquidity shocks across important sectors such as energy. This element of risk guidelines provided by the commercial banks is something that regulators have paid some view to, however this requires an improved coherence on risk modelling and its application for risk management and its dissemination and integration into strategic planning. An incoherent view and lack of clear planning across the system of energy firms, banks, financial regulators and policy makers as fossil fuel revenues diminish under net zero transition policies, risks creating adverse shocks that could largely have been minimised through an improved view of the evolving dynamics of this economic system.

7 Conclusion

To conclude, climate finance models do provide valuable insight into future developments and potential methods to address the challenges of climate risks. Although there are certain limitations during modelling such as the inherent uncertainty in climate outcomes, and the unknown effects of climate tipping points that create much variability in the model, modellers have used different methods to compensate for possible errors as outlined in the report. We also examined two case studies in which scenario analysis and climate finance models were utilised to find viable approaches to achieve end goals or to align their portfolio. New models will also have to adapt to the new climate system and regulations that emerge under a new world.

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