Network for Greening the Financial System

Technical document

Climate macroeconomic modelling handbook

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Central Banks and Supervisors
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Foreword

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As climate change and the transition to net zero begin to affect macroeconomic outcomes, not just over the medium-to-longer term, but also over the two-three year horizon, it becomes a relevant consideration for monetary policymakers. Central banks have identified a range of challenges in modelling these impacts, and while some aspects may require them to take on novel approaches, others can be addressed by making use of existing toolkits with suitable modifications.

Since it is clear that there is no modelling "silver bullet", central banks should develop a toolkit that incorporates different models. This handbook provides practical guidance for central banks at various stages of their modelling journey.

The handbook draws on an in-depth survey of the work done by academics and policymakers to identify modelling approaches in the areas of greatest importance for central banks. It assesses the relative strengths and use cases of different approaches for determining physical and transition impacts. It also focuses on how different aspects of climate uncertainty can be incorporated in modelling.

This handbook is one of a suite of reports being published by the NGFS focused on assessing and understanding the macroeconomic effects of climate change and implications for monetary policy. Together, these reports provide an analytical foundation which allows central banks to better understand how climate change impacts on the achievement of their price stability mandate.

We are grateful to the NGFS members, observers and the NGFS Secretariat for contributing to this work. In particular, we would like to thank the co-leads of the subgroup on macro-modelling – Elías Albagli (Banco Central de Chile) and Stephen Murchison (Bank of Canada) – for leading the efforts in putting together this report. We hope the handbook will be useful to assist NGFS members whether they are beginning to consider climate impacts in their modelling for the first time or are seeking to enhance their capabilities further.

Executive summary

Climate science has shown that the rapid increase in the concentration of atmospheric CO_2 and other greenhouse gases (GHG) since the Industrial Revolution has resulted in climate change. The physical impacts of climate change will have significant economic consequences due to direct consequences on the productivity of sectors such as agriculture and livestock farming, mining, tourism, and of industries located in areas more exposed to physical impacts. At the same time, the world is already in a transition – albeit an increasingly delayed one – to reduce its dependence on fossil fuels and other carbon-emitting activities.

As explored in dedicated NGFS reports[1], physical and transition impacts will jointly have significant effects on the macroeconomy and macroeconomic variables relevant for monetary policymakers. The purpose of this document is to provide technical guidance to central banks and regulators in this area. This report is motivated by the desire expressed by the NGFS membership (see NGFS, 2023a).

This document is based on an in-depth survey of the work done by academics and policymakers on these issues, with a focus on structural macroeconomic modelling. The document is tailored to help NGFS members at different levels of development and engagement – whether they are beginning to consider climate change modelling, or whether they have already begun efforts and are in the process of choosing next steps.

The core of the document is laid out in two sections.

The first section deals with the advances made in modelling and quantifying physical impacts of climate change (i.e. changes in the distribution that governs weather patterns and events along several, interrelated dimensions). Most climate change effects can be categorised into chronic and acute impacts. Chronic impacts originate from changes in the means of the different dimensions of the climate distribution. Arguably, they can be thought of as affecting the economy in more predictable ways (i.e. through average temperature or sea level rise). Acute impacts originate from the realisation of the tails of the climate distribution (i.e. extreme weather events, such as droughts, floods, wildfires and hurricanes).

The bulk of the literature reviewed in this section uses Integrated Assessment Models (IAMs), which combine economic and climate modules to understand the effects of climate change in the economy. This handbook namely expands upon the fact that it is better to have different models for different questions, as the level of complexity that can be managed by any single model is limited.

In particular, to understand and model chronic impacts, this handbook suggests that its users favour IAMs based on a computable general equilibrium structure (CGE), which assumes perfect foresight. This is useful because the simplification gained by dropping uncertainty allows the inclusion of other features, such as non-linearities, or more layers of sectoral and geographical disaggregation. Naturally, the user should be wary that supposedly chronic impacts can also accelerate, and cause either non-linear damages or exacerbate harm along other climate dimensions. Uncertainty would also be absent in these models.

On the other hand, if the user wants to understand the effects of higher frequency, acute climate events, IAMs based on a Dynamic Stochastic General Equilibrium (DSGE) structure which are better equipped to deal with stochastic events. Furthermore, DSGE models are used to evaluate policy scenarios, particularly with regard to conjunctural policies such as monetary and fiscal policy. The drawback of this approach includes model structures that often feature a high level of aggregation and therefore do not allow to consider sectoral developments properly which is the benefit of multi-sector CGEs.

In short, different questions benefit from different methodological approaches, whose merits and limitations should be understood so as to make them work as effective complements.

The climate and the economic modules of IAMs are often linked by damage functions, which assess the channels

1 See Acute physical impacts from climate change and monetary policy (NGFS, 2024a) and The green transition and the macroeconomy: a monetary policy perspective https://www.ngfs.net/en/green-transition-and-macroeconomy-monetary-policy-perspective (NGFS, 2024b).

through which climate change affects the economy[2]. The damage functions reviewed usually use mean temperature rise as the main climate stressor. While this is a prototypical choice, this handbook stresses the importance, and gives examples, of work that includes stressors arising from other climate dimensions (e.g. sea level rise). This emphasis responds to need to better accommodate the most pressing climate change manifestations of different countries.

This first section on physical impact ends with an analysis of the uncertainty inherent in climate change modelling. It distinguishes between the uncertainties faced by the modeller, from those faced by economic agents. The first type of uncertainty includes the specific structure of a model, the value of parameters used in it, and so on. The second type of uncertainty, which is faced by economic agents within a particular model, refers to how physical impacts may affect agents' behaviour – for instance, risk aversion affecting investment and precautionary saving, giving rise to additional transmission channels. Generally, the stochastic and dynamic environment of IAMs with DSGE models lends itself better to understand this second type of uncertainty.

The second section of the handbook surveys advances in the work on transition impact modelling. The work reviewed here studies the macroeconomic dynamics that arise during the phasing out of fossil fuels and the adoption of more energy efficient and less polluting technologies, often motivated by changes in polices (i.e. carbon pricing, regulation).

This section discusses different technical approaches and presents several suggestions. There is an emphasis on the supply side of the model including firms that cannot easily substitute among production inputs, at least in the short term. It delves into the importance of including more realistic production structures in which consumption and investment goods are made using intermediate green[3] and carbon-intensive inputs. Importantly, the handbook presents examples on how to model technological change, which can play a relevant role in speeding up the transition.

This section also discusses the role of uncertainty. As before, there is uncertainty with the economic structure and parameters, but this section also highlights how uncertainty in transition policies themselves can affect incentives driving firms and households' decisions – for instance, through irreversible investments whose returns may be affected by changes in policies brought about by the political cycle.

Besides these two main sections, this handbook includes boxes that complement the main discussion. Box 1 summarises how to better use the document. Box 2 discussed important considerations that, due to their complexity, are mostly absent from current models, but are promising avenues for future research. They include damage functions with multiple stressors, and where damages from acute impacts can accumulate; climate systems with non-linearities and tipping points; and complex socio-economic interactions of climate change such as mass population movement and social conflict. Finally, Box 3 stresses the importance of considering multiple models in order to understand different aspects of climate change and provides illustrations of such cases.

The report has three key takeaways for modellers at central banks and financial regulators:

1. Modelling climate change is paramount to understanding both the coming physical damages and the economic disruptions inherent in transition policies tailored to mitigate them. All of the articles reviewed in this handbook dealt with issues related to these topics, and included macroeconomic relevant mechanisms and quantities. Although the levers for the climate transition are outside of central bank mandates, if the impact of climate change is relevant at the macroeconomic level, central banks will need to understand and incorporate their effects with their macroeconomic modelling.
2. Modelling climate change is difficult. Models have improved, but there is no silver bullet. Central banks should confront these challenges not as a single project, but rather as a research agenda which gradually incorporates and adapts different models into a broader analytical toolkit. Such toolkits can then be used to provide more robust answers to the different, interrelated questions that the coming change in climate will pose to economic decision makers.

2 Although IAMS often feature a damage function it is by no means an essential model component. See, for example, the discussion about cost-effectiveness vs. cost-benefit IAMs (section 3.1) in Drudi *et al.* 2021.

3 "Green" in the context of this report refers to activities which are more closely aligned with the transition to a net zero economy. This may include low-carbon assets, as well as assets that help with the "greening" of traditionally carbon-intensive activities (as part of the provision of transition finance).

3. Modelling climate change requires addressing several dimensions of uncertainty that differ between physical and transition impacts.

   For physical impacts, the key uncertainty is about how a process interacts with the economies. Here the challenge is improving the modelling of climate change and its impacts, which are highly multidimensional, non-linear, and subject to tipping points.

   For transition impacts, there is uncertainty on how new technologies may accelerate changes in industries and the speed of convergence towards net zero. But perhaps more importantly, both firms and households face the crucial uncertainty about whether climate change policies may be reversed due to the political cycle, which can have important implications for resource allocation in economies.

Introduction

Climate science has shown that the rapid increase in the concentration of atmospheric CO_2 and other greenhouse gases (GHG) since the Industrial Revolution has resulted in climate change (a change in the distribution of weather events). This change in climate includes an increase in the average temperature of the planet, which, according to the IPCC (2023), will most likely exceed +2 °C within the 21st century under the currently committed Nationally Determined Contributions (NDCs)[4]. The shift in climate is affecting seasonal weather patterns, leading to more frequent and severe extreme weather events that will hit ecosystems that have already become less resilient due to their general degradation and loss of biodiversity[5]. Most worrying is the possibility of crossing multiple, interdependent planetary tipping points[6]. Science indicates that without further mitigation actions, mean temperature, the frequency and severity of extreme events, and the probability of crossing these catastrophic thresholds will increase.

The physical impacts of climate change will have significant economic consequences due to both direct and indirect impacts. Direct impacts will manifest through changes in the productivity of sectors like agriculture and animal husbandry, mining, tourism, and of industries located in areas more exposed to physical impacts. Indirect impacts will arise via the broader economy because supply, demand, and financial channels amplify and propagate the effects of the initial shock (NGFS, 2024a). These effects are likely to be particularly severe in emerging market and developing economies (EMDEs), often in geographical areas that are already suffering from the impacts of climate change. In addition, other sectors of the economy will be impacted by the indirect effects via interconnected supply and production chains among firms (Stern, 2007; Arent *et al.,* 2014). These impacts are already being felt by the effects of a slow but steady increase in temperature or by more severe and frequent extreme weather events. Private and public wealth and capital in real estate and infrastructure projects are threatened by both sea level rise and the increase in the probability of extreme events (e.g. wildfires, tornados, etc.), which is increasingly being reflected in higher insurance costs or reduced availability of insurance.

At the same time, the world is already in a transition – albeit an increasingly delayed one – to reduce its dependence on fossil fuels and other carbon emitting activities. The phasing out of fossil fuels and other polluting activities will significantly affect the global production structure through the emergence of new technologies and industries, as well as significant changes in existing ones: energy, food production, sustainable mining, manufacturing, and construction. These transformations will imply a reallocation of economic activities across sectors and geographic regions, with wide ranging implications for macroeconomic dynamics and economic growth (NGFS, 2024b).

Jointly, physical and transition impacts will have significant effects on the macroeconomy and macroeconomic variables relevant for monetary policymakers. Firstly, mitigation policies such as the introduction of carbon pricing, subsidies, and regulations will affect energy production and energy consumption by households and firms. This could affect key variables such as productivity, growth, as well as inflationary pressures. Moreover, how policies are financed also affects output and inflation (NGFS, 2024b). Secondly, sizeable investments will be required. These include investments in green energy generation and transmission, the transformation of industrial processes intensive in emissions, investments in adaptation to cushion the impacts of physical damages as well as the expenditures needed for reconstructing infrastructure and productive capacity in the aftermath of extreme weather events. The scale of these investments are likely to exert a relevant influence on the cost of capital worldwide. Moreover, both the direct disruption associated with physical impact and the sectoral transformations implied in the transition will likely affect inflationary dynamics, as well as the demand for different types of capital and labour. These elements could

4 See IPCC (2023) which describes the Sixth Assessment Report.

5 See IPBES (2019).

6 See OECD (2022).

also potentially affect key structural variables, such as the natural interest rate and potential output[7]. Some of these impacts are already happening, and many will strengthen within the next decades. In short, climate change is already affecting macroeconomic variables that are of key interest for central bankers, and these effects will only intensify in coming years.

How should central banks respond to the very challenging task of quantifying the physical and transition impacts of climate change on their economies? This is surely a formidable question. Indeed, assessing the market and non-market impacts of climate change "continues to be thorniest issue in climate change economics" (Nordhaus, 2010). The purpose of this document is to provide technical guidance to central banks and regulators on how to start approaching these complex and interrelated issues in a systematic way and reflects the interest that NGFS members expressed in the 2022 membership survey (NGFS, 2023a). This technical note surveys the work that has been done on these issues, with a focus on structural macroeconomic modelling, and presents the material to help guide central banks as they begin or continue to deal with these questions. The specific ordering of modelling priorities will likely differ among central banks, depending on (i) the most pressing concerns for its particular economy (i.e. whether physical or transition impacts are dominant), (ii) the time horizon of interest (e.g. should long-run growth models with limited room for stochastic processes be emphasized, or rather adapt short-term models to include some of these issues, for example employing a New Keynesian framework?), (iii) the level of knowledge and expertise on climate issues and data that is available, and (iv) the resources that the organisation can devote to these broad and complex topics. The purpose of this note is to help central banks choose their next (or first) steps depending on where they fall in the above characteristics.

Central banks already deploy a range of modelling tools to understand the macroeconomic effects of different shocks, trend shifts and policy developments on their economy. Modelling the impacts of climate change on the economy brings a new set of challenges for central banks to consider and requires an expansion to toolkits that can better express the challenges associated with both physical natural phenomena (such as heatwaves, flooding etc.) and mitigation measures that are being pursued to achieve a reduction in CO_2 emissions. This expansion includes moving beyond traditional frameworks used in macroeconomic research to incorporate insights and techniques from the models used in climate change sciences (such as Integrated Assessment Models, or IAMs). This process will involve collaborations across disciplines, as well as involvement with other organisations and academic institutions.

This guide mainly covers the broadly categorised IAMs used to estimate and understand the physical and transition impacts of climate change. The main characteristic of IAMs is that they link an economic model with the biosphere and atmosphere in one framework. Usually, the economic modules embedded in IAMs are either from Computational General Equilibrium Models (IAM-CGE) or from Dynamic Stochastic General Equilibrium Model (IAM-DSGE). The modelling approaches presented in this guide vary significantly in the questions and time horizons being studied, as well as the methodologies used to calibrate the models. Although there has been a surge in the literature that studies the effects of climate change, more progress has been made in modelling transition effects since macroeconomic models regularly used in central banks, such dynamic general equilibrium New Keynesian models, are better prepared to analyse the effect of policies, such as taxes and subsidies, and in accounting for changes in technologies and preferences. For instance, the effect of policies can be readily adapted by introducing carbon pricing and green subsidies, while technology and preference changes can be implemented by borrowing from the literature on endogenous growth theory. This guide seeks to address both the modelling challenges associated with physical impacts of climate change and transition impacts of mitigation policies.

7 See Burke, Hsiang and Miguel (2015).

Table 1 **Comparison between CGE and DSGE models**

	CGE	DSGE
Characteristics	• Deterministic • (Typically) Static • Parameters are calibrated • Large model	• Allows for stochastic, exogenous shocks • Dynamic • Parameters are calibrated or estimated • Can be small scale or large scale
Economic features	• Perfectly competitive markets	• Allows for monopolistic competition in markets • Allows for nominal, real and financial frictions giving rise to business cycle dynamics. Gives role to monetary policy
Sectoral Detail	• Multisectoral models allowing for spillover among sectors	• Frequently limited number of sectors
Expectations Formation	• In deterministic environment, the rational expectation corresponds to the future outcome	• In stochastic environment, the rational expectation corresponds to the mean of the distribution of future outcomes
Solutions	• Using computer programs such as GAMS, MPSGE and GEMPACK	• Include Bayesian estimation, generalized method of moments and maximum likelihood. The estimation can make the model fit the data well

The key differences between CGE and DSGE models are highlighted in Table 1.

IAMs

Integrated Assessment Models (IAMs) are frameworks that integrate knowledge from two or more domains into a single framework, in this case, climate science and economic theory. They developed from the theoretical work of Nordhaus[8] and the first wave of IAMs were spurred by the creation of the IPCC. The economic core of these models is that of a neoclassical growth model (see particularly Solow, 1970). In this economic approach, agents reduce consumption today to invest in capital, education, and technologies to increase consumption tomorrow. The IAMs extend this approach by including GHG concentration as "negative" capital. IAMs can link an emissions pathway to macroeconomic impacts via the use of a damage function (see Pindyck, 2013 for the six key elements of IAMs). For tractability, IAMs often do not include high frequency shocks such as extreme weather events, nor do they include more extreme and less tractable climate events such as the crossing of planetary tipping points. They also abstract from more complex socio-economic interactions such as climate-induced conflict, population movement, etc. These omissions naturally lead to an underestimation of the macroeconomic (and more generally, welfare) implications of climate change (see Box 3).

Early IAMs faced many challenges in terms of data availability and computational ability, and came under considerable constructive criticism (e.g. Ackerman, Stanton and Bueno, 2010; Pindyck, 2013, Pindyck, 2017; Ackerman and Stanton, 2012; Stern, 2013). Aggregate damage functions were considered "the most speculative element of the analysis" of the economics of climate change (Pindyck, 2013). Damage functions in early IAMs were calibrated based on top-down, cross-section regressions of GDP levels and temperature, which faced significant identification challenges in disentangling temperature effects from other factors.

In recent years, IAMs have become much more sophisticated and several approaches to improve the calibration of damage functions have been developed. For example, the Dynamic Integrated Climate-Economy model (DICE) has been adapted to include endogenous growth and catastrophic damages (Dietz and Stern, 2015) and a DSGE extension of DICE seeks to model climate tipping points (Lemoine and Traeger, 2014; Cai *et al.,* 2015; Lontzek *et al.*, 2015). Researchers have sought to improve the identification strategy to isolate the impact of temperature on output, which has lifted the estimated economic damages. This includes using cross-sectional regression or panel data methods to estimate the parameters of the damage function (e.g. Burke, Davis and Diffenbaugh, 2018; Kalkuhl and Wenz, 2020), including bottom-up estimates of the effects of weather variations on agricultural output and labour productivity (see Dell, Jones and Olken (2014) for

8 See Nordhaus and Yang (1996) and Nordhaus (2018).

a survey). However, some aspects of climate change – such as its uncertain impacts and risks – remain challenging to capture within the optimisation framework embodied in IAMs (Stern, Stiglitz and Taylor, 2022).

IAMs vary greatly with regards to sectoral and geographical granularity (Batten, 2018). Many of the models include only one aggregated production sector – often on a global scale – or use very coarse geographic units. Others give detailed descriptions of several different sectors in the economy and take advantage of developments in spatial models to give results at high geographical resolution. Given that climate change will have largely heterogeneous effects both across geographies and sectors, at least some degree of disaggregation is necessary for addressing relevant monetary policy analysis. It may also be useful to use different IAMs for different applications (e.g. starting in 2020, the NGFS climate scenarios have been produced using three different IAMs).

Currently, IAMs are used to calculate the main global climate change scenarios by leading institutions. In particular, a cost-effective analysis approach is adopted by the IPCC[9] and the NGFS, where a carbon budget is imposed to match a climate target. The model then calculates the optimal mitigation pathway using its abatement options. In cost-benefit analysis (CBA), IAMs discount climate change damage, which enables them to compare it with mitigation costs, which then lead to the optimal decarbonisation strategy. An example of this is the calculation of the social cost of carbon.

As previously mentioned, IAMs contain an economic module that captures the effect of climate change in the economy. The next section briefly explains the main types of economic models that are usually included in IAMs: CGEs and DSGEs.

CGE Models

Computable General Equilibrium (CGE) models are a class of micro-founded general equilibrium models. A CGE model is a large system of simultaneous, non-linear equations fitted to historical data. These models feature utility-maximizing households, profit-maximizing firms and market clearing. In addition, since these models assume that agents behave rationally, they are less subject to the Lucas Critique (Lofgren, Harris and Robinson, 2002) presents a standard CGE model in detail[10].

In CGE models, agents optimise their decisions within a deterministic environment. Consequently, the models can more easily accommodate non-linearities and capture complex relationships among the variables, including occasionally binding constraints and Leontief functions. In addition, the solution methods used in these models allow the user to construct large scale models with many sectors. This sectoral approach makes CGE-style models good candidates for modelling the macroeconomic effects of climate change and the transition because it is possible to introduce an energy sector, differentiate sectors by their emissions profile, or refine the linkages to GHG emissions from production. Furthermore, this style of model sets the stage for the study of sectoral policies at both an aggregate and granular level. For calibration of the elasticities of substitution and production technologies, these models use either the Social Account Matrix or the Input-Output Matrix. Depending on the available data the modeller can then calibrate the sectors that are included in the framework.

CGE models can be static or explicitly model dynamic adjustment pathways towards a steady state. As different steady states can be solved for, CGEs can be useful for studying structural changes in an economy arising from both the physical and transition impacts of climate change. Examples of climate policy CGE models are the OECD ENV-Linkages Model, which links economic activity to GHG emissions to identify least-cost mitigation policies, and the World Bank ENVISAGE model, which incorporates an emissions and climate module that directly links economic activities to changes in global mean temperature.

DSGE Models

The other class of models, which are extensively used within central banks, are Dynamic Stochastic General Equilibrium (DSGE) models.

DSGEs have similarities to CGE models, in that households seek to maximise utility while firms maximise profits, both subject to constraints. A key difference is how expectations

9 See IPCC (2023).

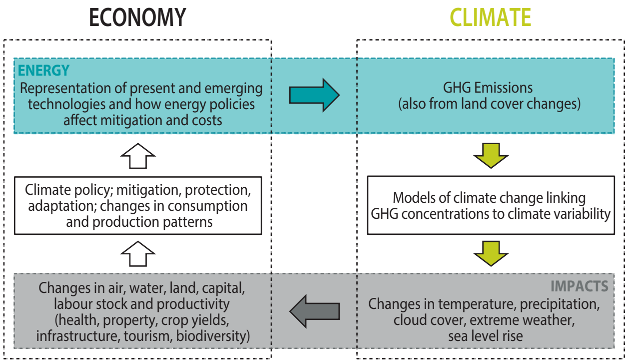
10 Although agents in these models behave rationally, there are different solutions strategies that can have important consequences in the behaviour of the agents. In particular, models can be solved using an inter-temporal optimisation or recursive dynamics.

are formed: while in DSGE models agents form expectations within a stochastic environment because of the presence of aggregate or idiosyncratic shocks, CGE models assume a deterministic environment.[11] Having uncertainty adds a layer of complexity[12] and thus require researchers to simplify other dimensions of modelling to retain tractability. For example, limiting the size of the model by simplifying production structures and/or reducing the number of state variables. Even with a simpler approach, the solution methods for DSGE models remains more complex, prompting researchers to rely on linearizing the equations when solving for the equilibrium and dynamics which is problematic when dealing with large shocks. Model linearization gives rise to certainty equivalence. In other words, even though the economic environment is stochastic, agents behave (make the same decisions) as they would in a deterministic environment. As a result, the distinction between expectations in CGE and linearised DSGE models is greatly reduced. In addition, while DSGE models often assume one representative household and sector, it is still possible to introduce some degree of granularity through nested production structures that add further richness to the model, along the lines of CGEs.

Despite some of these shortcomings, DSGE models provide several advantages over other models, especially when describing transition dynamics and acute weather shocks. First, the dynamic stochastic setting leads to potentially important uncertainty effects when the model is used in its non-linear form. Second, particularly in the context of transition dynamics, they include several frictions that allow them to better replicate the data and create out-of-steady-state dynamics. These frictions are typically on the nominal and real side of the economy. Some examples of the former friction type include price and wage rigidities, while real frictions include labour and investment adjustment costs. Nominal frictions are useful for central banks since they allow to analyse the response of monetary policy to different climate change scenarios, including mitigation paths. These features provide a perspective that the other models cannot capture.

Third, many central banks have already developed in-house the DSGE machinery for medium-term economic projections. As such, it is possible to adapt existing models to include damage functions or climate change modules by adding a climate block to a pre-existing setup. An example of an environmental dynamic stochastic general equilibrium (E-DSGE) model is the Environmental Multi-Sector DSGE model EMuSe, developed by the Deutsche Bundesbank.[13] In this model, emissions are a by-product of production, proportional to the output of a given sector, and a damage function can be introduced to account for negative pollution externalities.

Figure 1 **Climate-economy dynamics with four modules: economy, climate, impacts and energy**



Source: Diagram from Nikas, Doukas and Papandreou (2019).

Figure 1 exemplifies a minimal set of modules that are needed to comprehensively integrate economic and climate dynamics, highlighting how the structure should allow for two-way feedback between climate policies (such as adoption of new technologies), impact on GHG emissions and other climate variables (such as precipitations) and in turn effects of such variables on the macroeconomy (for example through changes in capital and labour productivity).

The topics of the document are presented in the form of a literature review. The distinguishing feature of each paper is presented so that each researcher can easily find the attribute that they are looking for and then refer to the cited paper for a deeper analysis of the topic.

The document is divided in two main sections. Section 1 describes the modelling of physical impacts, detailing the importance of damage functions and the important difference between studying chronic impacts versus those from acute weather events (whose probability, intensity and duration are also changing with the shift of the overall climate distribution). A schematic view of this section can be seen in Table 2.

11 DSGE models can also be used to simulate the transition from one steady state to another steady state. Although this transition occurs without idiosyncratic shocks, these models can be referred as DGE as they still capture complex dynamics not present in CGE models.

12 Specifically, rational expectation corresponds to the mean of the distribution of future outcomes, which involves numerically approximating an integral.

13 See Hinterlang *et al.* (2023).

Table 2 **Schematic view of the contents of Section 1 (modelling the physical impacts of climate change)**

		Physical impacts				
		Sectoral Disaggregation		Uncertainty		
		Aggregated Global GDP	**Disaggregated** Local production, individual sector	**Carbon cycle dynamics**	**Climate temperature dynamics**	**Economic damage functions**
Chronic	Climate stressor: temperature, sea level, precipitations, droughts, etc.	Highlight non-linearities (CGE/IAM) Simple long term damage function	Highlight several sectors (CGE/IAM) Complex sectoral damage functions	Explicit	Explicit	Explicit
Acute	Climate stressor: floods, precipitations, wildfires, etc.	Highlight stochastic aspect (DSGE) Damage function over aggregated productivity	DSGE with limited sectoral disaggregation Damage function for specific sectors	Implicit/ not modelled	Implicit/ not modelled	Explicit

Section 2 describes the modelling of transition impacts. It highlights the importance of incorporating at the very least a more detailed modelling of the energy sector, and more broadly, the use of multisector models and CES[14] functions. This section also deals with advanced features in sectoral disaggregation as well as uncertainty. A schematic view of the section can be seen in Table 3.

Table 3 **Schematic view of the contents of Section 2 (modelling the transition impacts of climate change)**

	Transition impacts		
	Economic structure		Uncertainty
	Basic features	Advanced features	
Modelling the phasing-out of fossil fuels use	**CES production functions** • Minimum of two sectors (clean and dirty) • Non-unitary elasticity of substitutions and differentiated shares (DSGE, CGE, IAMs) **Limited sectoral disaggregation** (medium/large scale DSGE, CGE, IAMs)	**Multi-stage production structures, international trade linkages and I/O features** (DSGE, CGE, IAMs) **Detailed sectoral disaggregation:** • Energy and other economic sectors • Network theory • Interconnectedness and spillovers (medium/large scale DSGE, agent-based models, IAMs) **Idiosyncratic Shocks:** • Assumption of power laws distribution for firms' size (medium/large scale DSGE, IAMs) • Idiosyncratic shocks (HANK models)	**Investing today versus waiting, using:** • Time-to-build lags • Smooth investment cost functions • Discontinuities in investment, such as irreversibility (DSGE model, dynamic programming)
Modelling of green policies	**Carbon taxation** (DSGE, CGE, IAMs)	**Directed economic (industrial) policies** (medium/large scale DSGE, IAMs)	**Implementation and timing of new policies** (small scale DSGE model, dynamic programming)
Modelling of technological progress	**Exogenous technological change** (DSGE, CGE, IAMs)	**Endogenous technical adoption/directed technical change** (medium/large scale DSGE, IAMs)	**Speed and timing of adoption of new technologies** (small scale DSGE model, dynamic programming)

14 Constant Elasticity of Substitution.

Box 1

Beginning modelling: how to use this guide for choosing priorities and designing a broader climate change research agenda

The process of including climate change in economic modelling is, generally, not different than any other modelling project. Two general options are available: (i) question driven and (ii) method driven. In a question-driven approach, the researcher can start with specific questions. They can then explore the related literature to understand the theory and the methods, empirical and theoretical, that have been used to answer similar questions. This approach may save some time and guide the researcher faster to an appropriate methodology to tackle the initial question. While useful for exploring specific questions and methods, such an approach may leave out broader questions and methods. It is thus a better fit for researchers with a clear set of initial questions in mind.

The method-driven approach works in reverse. First, the researcher starts by familiarising themselves with the different methodologies used to study climate change implications more generally. After the researcher has understood the main features of the available methodologies and how each fits better for a particular set of questions, they can focus on more specific questions as well as on the method to frame and study them. Conversely to the question-driven approach, this option requires more ground to be covered and is therefore more time consuming, at least in the beginning. However, it may be a good fit for central banks that have less clarity on either the most pressing questions, and/or those that intend to tackle climate change issues within a broader and longer research agenda.

Whichever method is preferred, the main difficulty in dealing with climate change in economics is the multidisciplinary nature of the exercise, involving areas such as earth sciences, physics, chemistry, ecology, and potentially many others, some of which will need to be included explicitly in models, whether microfounded with the fundamentals of a particular discipline, or through more reduced-form approaches. Even in models where climate is presented in reduced form, the researcher needs to be familiar with at least some aspect of these disciplines. For example, in modelling chronic physical impacts, the researcher needs to understand what the basics of the carbon cycle and the relationship between GHG concentrations and its impacts on temperature and other climate dimensions. When studying the implications of transitioning to a greener electric grid, the researcher needs at a minimum to know how electricity is generated, transmitted and distributed to firms and households.

1. Modelling the physical impacts of climate change

1.1 Main takeaways

This section presents a survey of the toolkits used in the literature to model the physical effects of climate change on the economy. The section covers the difference between chronic and acute impacts, what damage functions are, extreme weather impacts and how to model them in different sectors of the economy. The main takeaways of this section are:

- Physical impacts originating from climate change can be roughly categorised in two types:
  - **Chronic climate change impacts:** gradual effects of global warming affecting the economy primarily associated with a shift in the mean of the climate distribution;
  - **Acute climate change impacts:** unexpected shocks to components of supply and demand stemming from extreme weather events, predominantly affecting the economy in the short to medium run (associated with a shift in the tails and/or overall shape of the climate distribution).
- Within the IAM tradition, models have evolved to explore different questions, mechanisms, levels of aggregation, and other complexities. The macroeconomic model underpinning the framework tends to fall in one of two categories:
  - **CGE models:** solved deterministically, they are a better fit for studying macroeconomic effects of chronic impacts;
  - **DSGE models:** their stochastic nature allows them to better model the impacts of higher frequency, acute climate events.
- Damage functions relate the physical impacts of climate change to economic variables by using a climate stressor. The vast majority of models consider only one climate stressor, with temperature change being the most commonly used one. This means that any direct and/or additional impacts associated with other climate stressors, such as changes in precipitation, rising sea levels and extreme events are omitted. The estimated damages will therefore not capture the full extent of the impacts (i.e. the estimates have a downward bias[15]).
- It is difficult for a single model to appropriately capture the various dimensions and horizons of the physical impacts of climate change. Policymakers should stay open to using multiple models to address different policy questions or different aspects of physical impacts. While it is currently beyond the scope of most models, further efforts to include multiple stressors and their reinforcing feedback will be important in future work to ensure impacts are better captured.
- There are several dimensions of uncertainty involved in modelling the economic effects of physical climate change impacts. For the modeller, these include model uncertainty (both within the model, i.e. specific structure and parameters, and between models, i.e. underlying structure, climate stressors). But there is also climate uncertainty faced by economic agents within models, which may lead to endogenous responses such as precautionary behaviour (including self-insurance). Some of these uncertainties can be dealt with making use of techniques from other economic fields (e.g. stochastic shocks, time varying moments, etc.), while others require more complex models (e.g. non-linearities to explicitly consider the role of uncertainty in decision-making). The dominant source of uncertainty for the modelling of physical impacts is the specification of damage functions. Specifically, it is difficult to include multiple stressors and to model their interactions. In addition, this uncertainty is augmented by the fact that ecosystem integrity and resilience, to both chronic and acute climate change, depends on the severity and spacing between damaging events, which ultimately defines thresholds for the crossing of tipping points at both local and global scales.

1.2 Modelling physical impacts

1.2.1 Chronic and acute climate change impacts

When assessing the effects on the economy, physical impacts originating from climate change can be roughly categorised in two types:

- **Chronic climate change impacts:** these originate from ongoing global warming affecting the economy in a somewhat predictable way (e.g. shifts in the mean

15 Some papers that use additional climate stressors include Nordhaus (2010) and the Policy Analysis of Greenhouse Effect (PAGE) IAM (see Yumashev, 2020).

of the new climate distribution). Examples of these impacts include the detrimental effects of temperature rise and land use-change on agricultural and labour productivity, or savings effects from uninsurable property, etc.;

- **Acute climate change impacts:** these effects originate from extreme and unpredictable weather events that predominantly affect the economy in the short to medium run (e.g. associated to the shifts in the tails of the climate distribution). Examples include droughts, floods/landslides, wildfires, and seasonal plagues, which have direct effects on harvests and livestock, timber production, mining, water, and energy provision, among other industries. Their frequency, intensity and duration have already increased, and are projected to do so further.

The nature of the climate impacts and the specific questions at hand determine the appropriate type of model to be used. It is important to note that in general it is difficult for a single model to appropriately capture the various dimensions of physical impacts of climate change. Therefore, policymakers should stay open to using multiple models to address different policy questions.

Considering both types of models presented in the introduction, CGE and DSGE based IAMs, it is important to highlight the differences between them.

CGE models are usually solved in a non-stochastic environment which allows the model to incorporate non-linearities, multiple stressors, and to address longer-term issues. This makes them better suited for analysing **chronic climate change impact**, as non-linearities become more relevant when trying to understand the consequences of climate change for longer periods of time (i.e. decades). Although many of these models lack the short-term inflation and business cycle dynamics relevant for monetary policy analysis, they are useful to assess the long-term effects on the economy from changing climate conditions which is an important input into monetary policy decision-making.

On the other hand, DSGE models are solved in a stochastic environment, usually linearising the model around a deterministic steady state. The stochasticity of the model allows the environment to surprise the agents with unanticipated shocks which leads to reactions different to anticipated shocks. Therefore, these models are better suited for analysing the effects **of acute climate impacts**.

1.2.2 Supply-side effects

The physical impacts of climate change often first affect the supply side of the economy. Global warming can affect labour productivity, as well as potential labour supply as rising temperatures and sea levels generate population flows from one region to another. Policy responses to address the impacts from chronic warming – be it, for example, via investment associated with adaptation or mitigation measures, will also affect an economy's capital stock.

Acute weather events, can also affect the supply side of the economy. For example, droughts, floods or wildfires destroy physical capital, which materialise as temporary lower productivity, lower potential output and can also affect financial intermediation. Destruction of crops and energy infrastructure can increase volatility in food and energy prices, leading to significant price hikes. Given that these disasters are expected to increase in frequency and severity over time, DSGE models can accommodate these events by incorporating non-linearities (Fernández-Villaverde and Levintal, 2018) give an overview of different solution methods that address these issues).

1.3 Acute effects (stochastic)

1.3.1 Extreme weather shocks

A generalised approach to incorporating the effects of extreme weather events into a central bank's modelling toolkit tends to consist of adding a natural disaster shock directly into the macroeconomic framework.

Incorporating a natural disaster event into an existing model used by the central bank can be a relatively straightforward way to highlight two of the most important transmission channels from acute physical shocks: the destruction of physical capital and the decrease in TFP. This approach is also flexible to different kinds of extreme weather events. However, models that use a representative firm limits the analysis to aggregate effects and does not allow for potential spillover effects between different sectors. Nevertheless, it is still a useful first step to integrating physical impacts into a relatively simple modelling framework.

To address some of the more specific transmission channels, more sectoral detail must be added to the model. For instance, to assess the effects of droughts on agricultural output and productivity and the transmission to other sectors of the economy, Gallic and Vermandel (2020) add a weather-dependent agricultural sector to a small-open economy DSGE framework. In their study, agricultural productivity is modelled as an autoregressive (AR) process, allowing droughts to have persistent negative effects on the production process of agricultural goods through lowering land productivity. The effect of weather conditions of agricultural production is modelled using a simple damage function, similar to the IAM literature. Unlike most models that are simply calibrated to match empirical estimates or data, the authors estimate their model using weather data as an observable variable in the estimation. The transmission of weather shocks in the model is also validated using a SVAR.

By assessing physical impacts in a small-open economy framework, the model approach used in the Gallic and Vermandel (2020) adds an important transmission channel through which extreme weather events can affect the economy and the real exchange rate. For example, when the economy is hit by a weather shock, agricultural production and domestic farmer competitiveness decrease, which could lead to a trade deficit. This leads to a real depreciation of the domestic currency, restoring some of the competitiveness of the agricultural sector and potentially increasing the competitiveness of other export sectors.

The destruction of physical capital can also affect the economy through impaired financial intermediation. By the introduction of a financial accelerator mechanism, the destruction of physical capital is allowed to affect the credit supply to firms (see Hashimoto and Sudo, 2022). The destruction of physical capital leads to impaired balance sheets and lowers retained earnings. This increases the expected probability of default and raises borrowing rates faced by the goods producing sector in the economy. In turn, this leads to lower investment and to a larger decrease in economic activity. The model also introduces the role of insurance, which can potentially mitigate some of the negative balance sheet effects. The financial accelerator mechanism can be a useful addition to the modelling framework, especially if insurance markets are incomplete or non-existent (NGFS, 2024a).

Extreme weather events can also affect infrastructure related to energy supply and production. Evgenidis, Hamano and Vermeulen (2021) extend a small open economy framework with a simple energy sector, by introducing electricity as an intermediate input in production alongside labour. This allows for an electricity supply shock stemming from the disruption of energy production due to natural disasters.

Cantelmo, Melina and Papageorgiou (2023) introduce the role of public capital, where the government is allowed to invest in costly capital resilient to natural disasters, decreasing the loss of physical capital when the disaster strikes, financed through increased taxes. Resilient capital is defined as a perfect substitute to normal public capital but is not damaged by natural disasters. However, this capital is produced at a higher cost capturing the potential trade-off between investing in costly adaptation or bearing the costs of higher damages from physical impact.

In addition to thinking about the detail, it can also be helpful to step back and look at aggregated impacts of extreme weather events on the supply side of the economy. Keen and Pakko (2011) allow the disaster shock to affect the economy in two ways. First, by destroying a share of productive capital; second, by generating a temporary decline in total factor productivity. The disaster shock is modelled as a two-state Markov switching process and is calibrated to match the observed effects from hurricane Katrina. The authors also consider how monetary policy should respond following natural disasters, both with a simple Taylor rule and by introducing optimal monetary policy. The findings suggest that the standard Taylor rule is unable to produce the optimal policy response to a natural disaster shock. Still, both the Taylor rule and an optimal policy rule produce an increase in the nominal interest rate.

A similar approach is adopted in Cantelmo (2022) where TFP is modelled as a combination of a stationary and a permanent component. This framework allows natural disasters to have both short and long-term effects on productivity and on potential output. The disaster shock is modelled using a dummy variable, where the shock occurs with a certain exogenous probability. The model is calibrated using data of natural disasters from OECD countries.

1.3.2 Uncertainty in economy-climate models

In climate economics, the modeller is faced with uncertainties along several dimensions. There is model (or "between-model") uncertainty which refers to how different model choices for the economic and the geoscientific inputs can yield different results. Moreover, there is parameter (or "within-model") uncertainty related to the specific structure and the specification or parameter choices in a given model. Looking at the interaction between economic and climate systems, the modeller faces model and parametric uncertainty related to the following three channels:

- *Carbon cycle dynamics:* mapping carbon and GHG emissions into atmospheric GHG concentration;
- *Climate/temperature dynamics:* mapping atmospheric GHG concentration to temperature changes ("climate sensitivity") and other parameters of the climate distribution;
- *Economic damage functions:* map the impact on productive capacity from changes in temperature and other climate parameters ("shape of the damage function").

Uncertainties in carbon cycle and temperature dynamics have been partially quantified from ensembles, of climate models by collectively running multiple model simulations. The exercises assess the robustness of results based on alternative models and parameterisations. Barnett, Brock and Hansen (2022) provides a more detailed overview of such exercises and a way to quantify and assess them. Typically, to quantify uncertainty in the carbon cycle and climate dynamics, the standard approach relies on pulse experiment results across various carbon cycle and climate dynamics models (see Joos *et al.*, 2013; Heal and Millner, 2014). To capture uncertainty in the carbon cycle, modellers first use a set of alternative Earth System models to characterise cross-model variation in the responses of atmospheric carbon concentration to emission pulses. Second, to assess the uncertainty pertinent to climate dynamics, 16 alternative climate dynamics models are used to quantify the between-model variation (uncertainty) in the temperature response to all the alternative carbon concentration estimates. While this approach helps to quantify the uncertainty surrounding the geoscientific model choices, Barnett, Brock and Hansen (2022) also introduce a simple stochastic specification of the temperature response which serves as a precursor to model uncertainty more formally.

The climate-economy literature also suggests that uncertainty in the climate system's dynamics could create fat-tailed distributions. This means that the probability of extreme warming, while small, is larger than under a standard normal distribution (e.g. Ackerman, Stanton and Bueno, 2010; Weitzman, 2011; Wagner and Weitzman, 2018).

Moreover, translating carbon emissions to economic damages is also subject to uncertainty. Estimates of damages are uncertain, and probably underestimated. This introduces large uncertainty about non-linear responses and the thresholds defining tipping points. While damage functions are simplifications that render the model solution and analysis feasible there remains considerable uncertainty as to their specification. Stern (2007) was one of the first to illustrate the importance of the damage function exponent. Consequences of changing the shape of the damage function are also discussed in, for example, Ackerman, Stanton and Bueno (2010) and Barnett, Brock and Hansen (2022). Finally, Carleton and Greenstone (2021) provide an extensive discussion of damages and what is missing from simple damage function specifications. They propose three criteria that damage functions should fulfil (i.e. damage functions should be empirically derived and plausibly causal, capture local-level non-linearities for the entire global population, and be inclusive of adaptation).

1.3.3 Modelling uncertainty: higher-moment shocks in DSGE models

DSGE models allow for the analysis of uncertainty and risks in dynamic environments. As such, they lend themselves naturally to not only assess the economic impacts of weather events (level shocks) but also the uncertainty surrounding them. As discussed earlier, weather shocks can be thought of as unexpected shocks to components of supply and demand that affect the economy. For example, on the supply side, a loss of hours worked due to an extreme weather event could be modelled as a shock to labour supply, while physical damage due to flooding or wildfires could be modelled as a shock to the capital stock.

Considering the relationship between climate change and the frequency, duration and severity of weather events, climate change can be thought of as a slow shift in the distribution of weather. The changes could be variance-preserving mean shifts or higher-order changes to the distribution. Empirically, higher-moment changes in the distribution of weather have been documented in, for example, Ferro, Hannachi and Stephenson (2005); Cavanaugh and Shen (2014); Gadea Rivas and Gonzalo (2020); Diebold and Rudebusch (2022). Thus, to estimate the effects of weather events in an economic model, one might want to allow for changes in the higher-order moments of these shocks. Currently, there is little work to draw on that directly models higher-order effects of climate events in DSGE models. However, the literature in DSGE modelling has well-established concepts and methods that could be readily applied in the context of climate. For example, uncertainty shocks (second-moment shocks) could be used to model the effects of uncertainty surrounding physical impacts (such as weather shocks) and rare disaster risk approaches could be used to model the effects of extreme and weather events. To study the effects of rare natural disasters, models with time-varying disaster risk can assess the impact of shocks from the tail of the distribution which is particularly useful. Modelling these higher-order effects in DSGE models requires non-linear solutions or higher-order approximations and gives rise to additional transmission channels such as precautionary savings behaviour.

1.3.4 Modelling uncertainty: endogenous transmission channels

The work by Justiniano and Primiceri (2008), Bloom (2009), and Fernández-Villaverde *et al.* (2011, 2015) has shown that uncertainty shocks, i.e. increases in the standard deviation of the shocks that affect the economy, can explain aggregate fluctuations. There is an extensive literature on how to model uncertainty shocks in DSGE models and their economic mechanisms that can be leveraged in the context of climate changes[16]. Uncertainty can be linked to aggregate fluctuations in economic models through, for example, precautionary behaviour in the form of savings or pricing decisions. Uncertainty can also affect the production decisions of the firm via the Oi-Hartman-Abel effect[17] or via real rigidities such as non-convex adjustment costs in investment[18].

In a DSGE model, uncertainty shocks are generally modelled as changes in the standard deviation of the structural innovations generated by stochastic volatility, GARCH processes, or Markov regime switching.

Specifically, let x_t be a random variable, e.g. productivity, and σ_t its time-varying volatility. Assuming a simple AR(1) process, x_t follows:

$$x_t = \rho x_{t-1} + e^{\sigma_t}\varepsilon_t,\ \varepsilon_t \sim N(0,1)$$

An example of modelling stochastic volatility, i.e. AR(1) in logs, is given below:

$$\sigma_t = (1 - \rho_\sigma)\sigma + \rho_\sigma \sigma_{t-1} + (1 - \rho_\sigma^2)^{1/2} v_t u_t, \qquad u_t \sim N(0,1)$$

Here u_t refers to the uncertainty shock and ε_t to the first moment (level) shock. There are several alternatives of how to model the volatility. For studying uncertainty shocks in dynamic macroeconomic models, stochastic volatility specifications dominate GARCH processes. Another possible specification is using a Markov regime-switching structure. An advantage of using stochastic volatility in the context of climate shocks such as extreme weather events is that this specification allows for a separation between uncertainty and level shocks. At the same time, one can correlate the level and second-moment shock, which is particularly relevant for modelling extreme weather shocks since changes in mean and variance of their distribution are likely linked.

1.3.5 Modelling rare disasters and higher-moment shocks

Some extreme weather events can be classified as rare natural disasters which occur with relatively low probability (such as crossing multiple tipping points) and have large economic impacts. Time-varying disaster risk introduces large non-linearities in the solution of the model. A mechanism that makes the rare disaster approach work from a modelling perspective is the large precautionary behaviour responses induced in normal times by the probability of a tail event. An overview of the literature and solution methods are discussed in Fernández-Villaverde and Levintal (2018).

Rare disasters are usually modelled as a reduction in TFP and capital destruction (productivity and capital depreciation shock). When a disaster occurs, technology and capital fall immediately. Modelling rare disasters captures severe disruptions in production, such as those caused by war or a large natural catastrophe, and therefore, is a suitable candidate to assess the impacts of large and rare natural disasters related to climate change. One such application is by Cantelmo (2022) who calibrates a model with time-varying disaster risk to natural disasters in OECD countries based on data since 1960 from the Emergency Events Database (EM-DAT) considering natural disasters (droughts, extreme temperatures, floods, fog, landslides, storms and wildfires).

16 For summaries of the literature, see, for example Bloom (2014) or Fernández-Villaverde and Guerrón-Quintana (2020).

17 See, for example, Fernández-Villaverde and Guerrón-Quintana (2020).

18 See, for example, Bloom (2009).

The bulk of the literature on rare disasters is focused on the economic effects of shocks from the tail of the distribution where the probability and severity of such events is time-invariant. However, as climate change is expected to increase the frequency and severity of extreme weather events, the probability of the occurrence and the severity of such events will change. This situation will require additional research efforts to model the probability of these events. The framework in Gabaix (2012) provides a tractable way to do so (in the context of asset pricing) by allowing for stochastic probability and severity of disasters. One can also think about the change in the probability of a natural disaster as a change in the skewness of the distribution of shocks. Thus, skewness shocks could be modelled to capture the higher-moment changes in the distribution of weather that yield to an increased probability of extreme events. However, this is an area of dynamic macroeconomic modelling that remains largely unexplored. One exception is the model of Salgado Ibáñez, Guvenen and Bloom (2019) that considers shocks to skewness of firm's productivity.

1.4 Long-term effects

1.4.1 Gradual global warming

While DSGE models are useful for analysing the effects of acute weather events in the short to medium run, the chronic effects of global warming can appear gradually over decades. To study these chronic effects, the literature has deviated from IAMs based on DSGEs. The economic core can vary depending on the model class (Nikas, Doukas and Papandreou (2019) give an overview of the different types of models available).

Examples from the literature

Cruz and Rossi-Hansberg (2021) assess the heterogeneous effects of global warming by employing a highly disaggregated spatial general equilibrium assessment model. The high degree of spatial disaggregation is an important feature, as the effects of climate change are expected to have highly heterogeneous effects across different countries and regions depending on their geography and climate conditions. Changes in local temperatures are allowed to affect both productivity and amenities from living in certain areas. This is incorporated by estimating the damage functions directly on productivity and amenities, instead of aggregated variables such as GDP. These damage functions depend not only on the change in temperature, but also on current temperature, allowing for heterogeneous geographical responses to temperature changes. By including costly labour movement and trade, innovation, and fertility, many of the transmission channels from chronic climate change to the economy can be assessed.

Conte *et al.* (2021) extend the Cruz and Rossi-Hansberg (2021) framework by introducing multiple sectors. More specifically, the authors model an agricultural and a non-agricultural sector (comprising of manufacturing, services, etc.), to account for the fact that the productivity in the agricultural sector is more sensitive to changes in temperature. This gives a more realistic development in sectoral specialisation around the world, with the agricultural sector becoming more spatially concentrated in the presence of climate change. The extension to multiple sectors is important, as certain sectors are more prone to the effects of global warming.

Desmet *et al.* (2021) adopt a similar modelling framework, but with a focus on the effect of sea level rise on economic activity. Land density in each location varies in time due to the dependence on sea level. As coastal flooding only affects certain areas, high spatial granularity is important. Taking the local sea level projections as given, the role of adaptation to reduce flooding is ignored. The focus is instead on the endogenous economic adaptation mechanisms through population movement, changes in trading patterns and technological investment and the role of clustering of economic activities.

Focusing instead on investment in adaptation capital, Fried (2022) quantifies the interactions between climate change and adaptation by using a general equilibrium heterogeneous agent model. The damage from climate change is modelled as the realisation of idiosyncratic shocks, differing from the standard climate damage function used in most of the literature. The realisation of storms damages the productive capital of affected households (housing) and firms. The agents can invest in adaptation capital to reduce the damage from storms. The effect of climate change is captured in the increase in the probability and severity of storms in different temperature scenarios.

Although the models most frequently used to assess the effects of gradual global warming vary greatly from the models normally used in the forecasting and policy framework at central banks, they offer alternative mechanisms and perspectives regarding the long-term effects of climate change. Thus, they are a useful addition to central banks´ model portfolio to conduct scenario analysis or similar analytical work, particularly over longer horizons (e.g. a decade or more).

1.4.2 Overview of damage functions

Damage (or impact) functions relate the physical changes in the climate distribution to economic variables. They are used to assess the direct or indirect damages and systematic impacts caused by climate change, in terms of a simplified relationship between economic effects and various climate stressors, such as atmospheric temperatures, sea levels and climate extremes (Nordhaus, 2014). Damage functions are also widely used to arrive at estimates of the social cost of carbon[19].

Damage functions can reflect different characteristics and these need to be determined when selecting the appropriate modelling approach. The main ones are described below:

1.4.2.1 Which climate stressor?

Most damage functions in existing models are temperature-denominated (i.e. they are functions that estimate economic damages per unit of temperature change[20]). This is because climate policies and frameworks currently focus on specific temperature change thresholds and scenarios, and because temperature change is a fairly good statistic to capture overall effects of climate change. Indeed, the IPCC's *Reasons for Concern* framework (O'Neill *et al.*, 2017) aggregates global risks into five categories as a function of global mean temperature change, primarily because temperature change is closely correlated with other climate stressors.

However, the focus on the direct effects of temperature alone can also be a drawback because other stressors, such as increased precipitation, rising sea levels or extreme weather events (i.e. floods and heatwaves) can have economic effects beyond those caused by higher temperatures. These other stressors are often not explicitly considered when quantifying the economic impacts of climate change *via* models because of tractability concerns. It is important to keep these additional stressors in mind, not just because each additional dimension of climate stress "adds" directly to economic damages, but also because different climate stressors can have indirect effects through mutually reinforcing feedback loops (see Box 2). In addition, standard damage functions have been mostly used to model chronic impacts. As these damage functions typically do not model acute weather events or tipping points, they can only provide meaningful results over a limited range of temperature increases. For example, the latest iteration of the DICE model (DICE-2023) has been calibrated for chronic damage estimates in the range of global mean surface temperature being 1-4 °C higher than pre-industrial levels, which encompasses the temperatures in the different IPCC scenarios for the first 100 years (Barrage and Nordhaus, 2024).

Nevertheless, even when the damage function is temperature-denominated, other climate stressors can be used to inform the estimation and calibration of the damage function, thereby taking a step toward capturing some of the impacts associated with these other stressors. Models can also contain multiple damage functions that link economic effects to different climate stressors. For instance, the original damage function in the Regional Integrated of Climate and Economy (RICE) model was updated to include an explicit representation of damages from both sea level rise and temperature increase (Nordhaus, 2010). Similarly, sea level rise is modelled explicitly in the Policy Analysis of Greenhouse Effect (PAGE) Ice, Climate, Economics (PAGE-ICE IAM) (Yumashev, 2020).

A notable exception is presented by Kotz, Levermann and Wenz (2024) where the authors present a global model with 1600 regions. The authors use a damage function that depends on each regions' mean temperature, temperature variability, annual precipitation, number of wet days and extreme daily rainfall. Another interesting characteristic of this function is that it allows for weather impacts to spillover to neighbouring regions.

The majority of IAMs do not account for tipping points because of the higher-than-usual uncertainty associated with quantifying their economic effects, making them difficult to model. However, there have been some efforts

19 Recent estimates using the Greenhouse Gas Impact Value Estimator (GIVE), a new IAM developed by researchers at Resources for the Future and UC-Berkeley, suggest that the social cost of carbon estimates for the United States should be significantly higher, at 185 USD per tCO_2, which is 3.6 times higher than the U.S. government's current value of 51 USD per tCO_2. The estimate is based on regionally disaggregated damage functions for four sectors. The main contributors to the higher estimate of the social cost of carbon is the use of a lower near-term discount rate (compared to the DICE model) and updated damage functions (Rennert *et al.*, 2022). Bilal and Känzig (2024) obtain a social cost of carbon of 1,065 USD per ton.

20 There are also damage functions based on the level of temperature, but using the change in temperature is the most common approach.

to incorporate them in IAMs, albeit in a highly stylised manner (Dietz *et al.*, 2021) present a literature review and a meta-analytic IAM with eight tipping points). For example, in a DSGE extension of the DICE model, a hazard function is used to model the instantaneous risk of the tipping point being reached at each time period, as a function of temperature increase (Lontzek *et al.*, 2015). The probability distribution for the hazard function is derived from expert surveys for several climate tipping points. The PAGE-ICE model explicitly models arctic feedbacks, while other socio-economic (such as pandemics, mass population movements) and tipping points are modelled through a discontinuous jump in damages when temperature thresholds are breached (Yumashev *et al.*, 2019; Yumashev, 2020).

1.4.2.2 Coverage and degree of aggregation of the damage function

Aggregated damage functions treat the global economy as a single region to model damages to global GDP, such as in the first-generation IAMs. Aggregate damage functions have the advantage of being comparatively simpler to model, but also face the criticism that the reduced-form relationship is not grounded in data or theory, which tends to downplay or provide misleading quantification of their economic effects (Pindyck, 2017).

Another approach is to use disaggregated damage functions at the region or sectoral level, which can then be more representative of specific and more localised impacts. In some cases, disaggregated damage functions have resulted in negative damages (i.e. there are positive impacts from climate change) for certain economic sectors or for colder regions which may enjoy positive effects from a warming planet. Another example of negative damages is road infrastructure that experiences damage from freeze-thaw cycles, which can be reduced from a moderate rise in temperatures (Neumann *et al.*, 2020). But overall, damages are mostly positive.

Recent literature shows that modelling more granular damages, such as local-scale impacts, is important as it can significantly affect aggregate damages at the regional and global level (Cultice, Irwin and Jones, 2023). Even the globally aggregated damage function in the DICE model, which is considered the pioneering IAM, has been calibrated such that it matches the sum of climate damages in all ten regions represented in the regional version of the model (RICE). The damage function in the Climate Framework for Uncertainty, Negotiation and Distribution (FUND) model (Tol, 2002) is even more detailed and includes the impact of climate change on wide range of sectors such as agriculture, forestry, water resources, energy demand, biodiversity and human health.

1.4.2.3 Shape of the damage function

In the modelling of the damage functions, the researcher is using a two-step approach, either implicitly or explicitly. The first step consists of defining a framework that relates GHG concentrations and changes in temperature. The second step relates the change in temperature to the damages created over the economy. Therefore, the key parameters that determine the damages to economic activity are the climate sensitivity parameters assumed by that IAM. A polynomial damage function is the most common specification, as can be seen as follows:

$$D_t = \alpha_1 T_t + \alpha_2 T_t^{\alpha_3}$$

where D_t are the damages at time t due to changes in the climate stressor such as temperature or precipitation (T_t) with respect to a reference period. α_1 and α_2 are fixed slope parameters that are fitted based on the climate sensitivity, which describes by how much rising levels of greenhouse gases affect the Earth's temperature. The climate sensitivity parameter is usually exogenously derived from large climate models and is itself subject to estimation challenges and uncertainty. The IPCC's Sixth Assessment Report estimates that climate sensitivity is higher than previously thought, and there is lower uncertainty around the latest estimate[21]. Usually, the climate sensitivity parameters are the same for all warming trajectories and are path-independent, which means that tipping points might not be well accounted for.

A common modelling choice is to assume that the damage function has quadratic form (the exponent, α_3, is equal to 2) since it fits the data the best and according to surveys results in reasonable predictions. It also has nice modelling properties by allowing for non-linear damages,

21 The Sixth Assessment Report (IPCC, 2022) concludes that there is a 90% or more chance (very likely) that the equilibrium climate sensitivity (ECS) is between 2 °C and 5 °C. The ECS is defined as the long-term global warming caused by a doubling of carbon dioxide above its pre-industrial concentration. This represents a significant reduction in uncertainty compared to the Fifth Assessment Report (IPCC, 2014), which gave a 66% chance (likely) of ECS being between 1.5 °C and 4.5 °C.

is well-behaved (first differential is linear) and makes the model more tractable. However, the quadratic damage function also faces some criticism as it is seen as having too low of a curvature, thereby generating implausibly low future damages (Weitzman, 2012). In practice, the damage function is usually calibrated to take a functional form that allows the model to be tractable, where the calibration is informed by empirical historical relationships between environmental conditions and economic responses (using aggregated or sectoral data and studies) and/or expert judgement. As with all models, these calibrated parameters need to be regularly updated to reflect the latest data and findings from climate science.

Examples from the literature

Estrada, Tol and Botzen (2019) present a new damage function in which both the climate sensitivity and adaptation capacity of the climate system are dynamic and explicitly modelled. The authors depart from earlier models where large damages for high levels of warming are generated by assuming highly non-linear functional forms. Instead, their damage function generates large economic damages because of the time-varying effects of past climate impacts on the adaptation capacity of the system, which is modelled as the sum of both autonomous adaptation by natural and human systems as well as planned adaptation based on a deliberate policy or investment decision. By modelling climate sensitivity as dynamic, this damage function provides an alternative mechanism for describing the highly non-linear economic impacts of climate change (Ackerman, Stanton and Bueno, 2010; Dietz, 2011; Weitzman, 2012).

In Hassler and Krusell (2018), the authors present a model to understand the effects of increasing temperature in the economy. The model connects the environment module and the economic module using two alternative damage functions where a higher temperature depresses GDP. The first specification defines the remaining share of GDP after climate damages from increased temperatures as the function $\Omega_t(T_t) = \frac{1}{1+\theta_1 T_t + \theta_2 T_t^2}$, where T_t is the temperature above pre-industrial levels. Another formulation states the remaining GDP share $\Omega_s(S_t)$ after controlling for the current concentration of carbon in the atmosphere above preindustrial level is given by $\Omega_s(S_t) = 1 - e^{-\gamma(S_t - \bar{S})}$. It is important to note that the climate module presented in Hassler and Krusell (2018) is very simple and so can be regarded as a useful starting point for modellers looking to understand the impact of temperature on the economy. A more complex climate module is presented in Hassler, Krusell and Smith (2016), where the authors introduce, among other features, the effect of the ocean as carbon sinks on global temperatures.

In Hashimoto and Sudo (2022), the authors use a DSGE model to quantitatively assess the indirect effects of floods on the real economy and the financial system. The model incorporates exogenous depreciation of the capital stock and public infrastructure to account for the damage of floods. In addition, the authors incorporate an exogenous decrease in total factor productivity (TFP) due to flood shocks.

Another model that studies physical impacts in a two-country New Keynesian framework is introduced by Faccia, Parker and Stracca (2021), where heat plays a relevant role for productivity and inflation. In modelling climate, the authors assume that the temperature in both countries are subject to common shocks, but each the temperature in each country is also subject to idiosyncratic shocks.

In Gallic and Vermandel (2020), the authors incorporate natural disasters into a two-sector New Keynesian DSGE model consisting of agriculture and other industries and estimate the model using data from New Zealand, including a drought index. They use this index to model an explicit agricultural sector that is directly affected by droughts.

1.4.2.4 Discount rate

Given that the timing of damages from climate change is uncertain, and under the assumption of relative climate stability (i.e. the climate system does not reach tipping points until further in the future), the discount rate used to calculate present-value or total damages can give rise to a wide range of impacts. The chosen discount rate is usually more material when modelling chronic physical impacts that are slow-moving and where impacts accumulate over time. There is considerable debate on what the appropriate discount rate is for the social planner. Some have argued for discount rates that are lower than market or private discount rates, even close to zero, so that the welfare of future generations is given greater regard, especially when time horizons are long (Stern, 2007; Acemoglu *et al.*, 2012).

Box 2

Current limitations in climate damage functions modelling

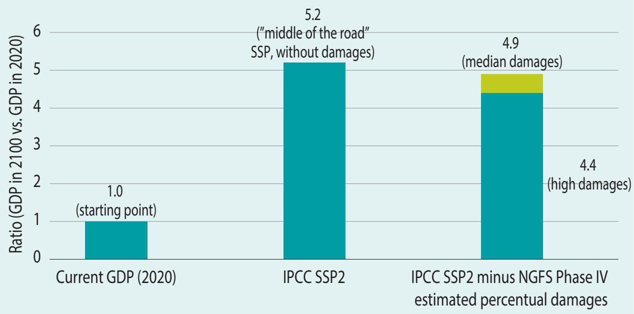
While there have been important advances in modelling climate damages, some limitations of the current analysis need to be considered when assessing quantitative results[1]. Standard IAMs have traditionally found small effects of climate change on GDP over the long-term. For instance, Barrage and Nordhaus (2024) estimate that a 3 °C increase in temperature decreases the level of GDP by about 1.6% by 2100.

Several rounds of modelling phases at the NGFS have progressively added features to standard IAMs. In 2021, NGFS scenarios included an assessment of chronic physical impacts, and in 2022 they were updated to include model uncertainty[2]. The latest phase IV scenarios (see NGFS, 2023b) use multiple models (REMIND-MAgPIE, MESSAGEix-GLOBIOM, and GCAM), which on average find damages of about 5% in a "current policies" scenario with 3 °C warming by the end of the century, which increases to 15% in the 95th percentile of the damage distribution.

While these effects are larger than other estimates, they still look small when compared to the projected rise in GDP levels over the next eight decades. Indeed, the "middle of the road" shared socio-economic pathway (SSP2) used by the IPCC to inform climate change outcomes assumes that global GDP will increase about five-fold towards 2100. Thus, even using the large estimates from the NGFS phase IV scenarios (95th percentile) implies that GDP will "only" grow about 4.4-fold in a +3 °C world (see Figure 2) – damages comparable to the cumulative effects of a couple of financial crises. These magnitudes are hard to square with the perception – shared by many earth scientists and economists alike – that a +3°C world would approach the realms of catastrophe.

The literature has identified several features that may bias impact estimates downward. First, IAMs mostly focus on chronic effects, omitting the impacts of extreme weather events. Moreover, even when these are included, they are treated as isolated shocks. But ecosystem science suggests damages from extreme events are path-dependent processes, since integrity can be diminished if extreme events become too frequent relative to the speed at which ecosystems can recover – especially if resilience is diminished by reduced biodiversity (IPBES, 2019)[3].

Figure 2 **GDP losses relative to "middle of the road" SSP**



Notes: The "IPCC SSP2 minus NGFS Phase IV estimated percentual damages" is calculated scaling down the IPCC SSP2 (OECD-ENV) projections using the average losses estimated from REMIND-MAgPIE, MESSAGEix-GLOBIOM, and GCAM (median and high damages). These average losses are inferred by comparing the current policies (median and high chronic physical risk damage) scenarios with the corresponding no-damages counterfactuals. Note that while IPCC SSP projections (OECD-ENV) are based on GDP in PPP (billion USD 2017), the projections of the NGFS assume GDP PPP (billion USD 2010).

Sources: NGFS (2023b) and authors' calculations.

Second, while climate change implies a simultaneous shift in the distribution of weather along multiple dimensions, most IAMs are able to manage at most a handful of climate stressors. This is important because (i) different biomes differ as to which stressor is dominant in causing physical damages; and (ii) climate stressors and other dimensions of nature tend to mutually reinforce each other[4], further amplifying the inherent non-linear effects along each dimension.

Third, IAMs have difficulties dealing with tipping points – persistent changes of equilibria brought about by chronic damages and/or repeated acute events. Recent studies

1 See Pindyck (2013, 2017); Auffhammer (2018); Stern (2023); and references therein.

2 Specifically, NGFS scenarios combine the transition pathways of IAMs, the MAGICC climate module and the damage by Kalkuhl and Wenz (2020) to provide estimates of chronic damages (see NGFS, 2023b – NGFS Scenarios Technical documentation V4.2).

3 The latest round of NGFS scenarios explicitly account for both chronic and acute impacts on economic activity and financial stability through multiple channels (NGFS, 2023b). These results indeed reach larger damages, but due to the added complexities, the analysis extends only to 2050.

4 See Rockström *et al.* (2009); Richardson *et al.* (2023).

in earth sciences document the delicate interactions of global tipping points, such as the Amazon dieback, the Arctic sheet meltdown and the collapse of ocean circulation in the north Atlantic (AMOC). They suggest that the crossing of these tipping points may be closer in time than previously thought[5], and would have catastrophic implications for vast regions of the world[6]. Recent research in tipping points within economic-nature models include extensions of DICE models featuring differentiated temperature – CO_2 feedback responses, or the collapse of ocean circulation systems beyond critical thresholds[7], while some study the effects of crossing such thresholds on broader dimensions of nature and natural capital[8].

Fourth, while there is a growing empirical literature about the broader socio-economic and geopolitical impacts of climate change and ecosystem degradation[9], these dimensions are too complex to be handled in current models. Moreover, even the empirical estimates, often based on relatively short datasets, may underestimate the importance of such dimensions due to the paucity of extreme climate events when compared to the sharp, region-wide, and multi-decade events that have shaped the course of global history[10].

Beyond suggesting profitable directions of future research, this box stresses two key takeaways:

(i) Current assessments of physical damages from climate change are not only uncertain; they are likely to be biased downward (perhaps severely so) due to the omission of complex elements and their interactions;

(ii) Many important socio-economic aspects of the interaction of climate, economics and human wellbeing are hard (maybe impossible) to model. Nevertheless, historical research suggests socio-economic channels, including massive population displacement, are among the most relevant disruptions linked to severe climate change throughout human history. These aspects can be explored through alternative analytical approaches, such as "scenario narratives" informed by academics and policymakers in joint efforts across multiple disciplines[11].

5 See Dasgupta (2021); Ditlevsen and Ditlevsen (2023).

6 See Lenton *et al.* (2019); McKay *et al.* (2022).

7 See Lemoine and Traeger (2014); Cai *et al.* (2015).

8 See Batini and Durand (2024).

9 See Hsiang, Burke and Miguel (2013); Carleton and Hsiang (2016); Missirian and Schlenker (2017); Carleton *et al.* (2022); and numerous references therein.

10 See Tainter (1988); Diamond (2011); Ellenblum (2012); Harper (2017); and the comprehensive compilation in Brooke (2018).

11 See Swart, Raskin and Robinson (2004); Lempert *et al.* (2006); Kosow and Gaßner (2008).

2. Modelling the transition impacts of climate change

2.1 Main takeaways

This section surveys recent modelling frameworks used by macroeconomists to analyse the economic impact of transitioning toward a low carbon economy. These studies typically embed one or more climate policy instruments in otherwise standard general equilibrium models. Overall, these frameworks are designed to study the macroeconomic dynamics that arise during the phasing out of fossil fuels and the adoption of more energy efficient and less polluting technologies in response to the incentives generated by policy changes.

The main takeaways of the section are that modelling of transition requires dealing with multiple sectors. Depending on the question the researcher wants to answer, basic or advanced features may be included.

Basic features:

- Account for multiple economic sectors and technologies, which can be modelled using representative firms.
- Key questions involve: (i) degree of sectoral disaggregation, and (ii) production linkages.
- Use a **multistage process**: a practical example is the use of nested **Constant Elasticity of Substitution** (CES) functions that combine production factors (inputs) that are then used in the subsequent production stages.
- Allow for **trade flows**: for example, by quantifying how many imports are needed to create the aggregate intermediate materials.
- Use **I-O models** and data to help inform the structure, calibration and/or estimation of key parameters (elasticities; shares).

Advanced Features and Policy Exercises:

- Allow for **endogenous technological progress,** *via* directed technical innovation towards clean inputs.
- Introduce **fiscal instruments** (CO_2 pricing and subsidies to green energy and technologies) to quantify macroeconomic transitional effects, including costs (inflation), distributional effects, etc.
- Introduce production networks, granularity, and spillovers.

Some modelling suggestions arise from the survey of the literature, such as:

- **Move away from Cobb-Douglas** and its assumption of unitary elasticity of substitution among inputs. In reality, it is not easy replace one input with another without incurring additional costs or sacrificing efficiency.
- Distinguish between energy and non-energy sectors and allow for heterogeneous degrees of elasticity of substitution.
- Enhance spillover analysis by exploring non-mainstream macroeconomic modelling tools such as **stock-flows consistent** models. These allow for heuristics in decisions within a complex economic structure and are stock-flow relevant, in the sense that they are built upon a "realistic" description of how an economy works (Carnevali *et al.*, 2019)[22].

Uncertainty is pervasive in economic decision-making. Applications to climate change transition modelling include:

- **Uncertainty in the economic structure**: Uncertainty over parameters governing the economies, such as price elasticities and elasticities of substitutions will influence the optimal policy mix that is required to achieve climate objectives.
- **Uncertainty in climate policies**: Climate change transition policies require public acceptability and can thereby encounter resistance by certain sectors of society, especially so when they are implemented in an overly disruptive manner. This may lead to low predictability/temporal consistency of climate policy, generating uncertainty that might lead the private sector to postpone investments.
- **Uncertainty in technology:** Some green technologies are at their early stages of development and their viability and scalability remains highly uncertain.
- In contrast to physical impacts, an important source of uncertainty of transition impacts may not be related to the economic structure of the model itself (common to policy analysis in general), but rather the uncertainty associated with climate policy and the scaling up of different technologies[23].

22 While DSGE are also stock-flow consistent, they are less stock-flow "relevant" (Carnevali *et al.*, 2019).

23 Although the choice of the modelling structure would still play a role (e.g. frameworks that rely only on modelling the transition *via* (proxy) carbon pricing would not be able to fully capture the dynamics that may result from other policy mixes).

2.2 Analysis of transition dynamics using deterministic or stochastic models

As studying transitional dynamics is a relatively uncommon exercise within central banks, it is useful to begin highlighting the two main approaches available. Specifically, transitional dynamics can be studied by assuming either perfect foresight or uncertainty regarding the future. The first approach draws from much of the economic growth literature and has the advantage of being computationally tractable but potentially less realistic in its prescriptions, while the second approach finds its roots in stochastic dynamic programming, and while richer and more realistic, it also requires more effort from the researcher.

In the case of perfect foresight, the first step involves determining the specific economic structure and calibrating (or estimating) the deep parameters of the model such that, for given values of the exogenous variables, the initial steady state reflects the current economic system. The second step consists of calibrating (or estimating) the model in such a way as to reflect the long run steady state of the economy, after the transition has been completed.

Since the agents in the economy have perfect foresight, the entire transition path is known from the first period, and the numerical solution boils down to a set of (possibly) non-linear equations. Ljungqvist and Sargent (2018) describe how the path of the endogenous variables can then be computed using a "shooting algorithm", which allows for a possible time-varying path of (exogenous) government policies.

In DSGE models, which can be either medium-sized or scaled up to produce quantitative predictions, the common approach is to assume that economic agents make their decisions based on all the information available in the present (rational expectations). The typical solution method consists of first calculating a deterministic steady state and then approximating the equilibrium in response to shocks using log-linear methods (that is, using a first-order perturbation methods around the steady state[24]).

Linear approximation methods have the advantage of allowing the modeller to characterise complex economies relatively easily, but they are less suited to answering questions related to alternative stochastic environments, including very large or permanent shocks. Notably, Kim and Kim (2003) showed how, when comparing utility functions under the assumption of a linear approximation, welfare results are spuriously higher under autarky than under full risk sharing, because second and higher order elements of the equilibrium welfare are not captured when linearising the model. For these reasons, when studying transition policies, which are by their very nature permanent and with large impacts, the researcher should consider that the accuracy of the approximation solution deteriorates the further the economy diverges from its initial steady state. To reflect this challenge, some of the works presented in the next sections make use of higher order of approximations when finding the solution (see Schmitt-Grohé and Uribe, 2004) or the use of numerical methods based on dynamic programming (see Sargent and Stachurski, 2023).

As an alternative to higher-order approximations, the modeller could periodically update the linearisation of the model throughout the simulation. For example, if the transition simulation is *x* periods long, they can begin by linearising the model around its deterministic steady state and then re-linearise around the same interval, say *x/y* periods, based on the simulated values in period *y*-1.

2.3 Economic models with multiple sectors

A key feature of modelling the transition to a low carbon economy includes understanding how the effects of a policy will vary across different areas of the economy. This requires, at a minimum, abandoning the assumption of having only one economic sector, to include some degree of heterogeneity. When studying the effects of the climate transition, the most basic sectoral models include only two sectors: a pollutant sector and a non-pollutant sector. More sophisticated models can have a variety of sectors, such as transport, manufacturing, agriculture, electricity generation, etc. These types of settings usually require that each sector has its own production structure. This heterogeneity is key since it allows to highlight

24 See for example Kydland and Prescott (1982).

how the resulting equilibrium changes depending on the economic policies in place and the advancement of sector-specific technological progress. This section reviews a selection of parsimonious models sharing these features, highlighting both the main characteristics and their potential applications. In the following sections, this handbook reviews a selection of models that integrate some basic degree of heterogeneity, distinguishing between frameworks with and without nominal rigidities, the former being particularly useful when studying the inflationary impact of the green transition.

2.3.1 Basic aspects of multiple sectors in economic models

2.3.1.1 Models with flexible prices

Golosov *et al.* (2014) is one of the first frameworks to add fossil fuels (oil and coal) inputs into an otherwise standard DSGE model to study transition policies. It builds over a parsimonious, yet articulated, economic structure, which offers great didactic value from a modelling perspective. The model assumes that the production of the final consumption good relies on, aside from the usual capital and labour inputs, several fossil energy inputs, which are drawn from an exhaustible stock of resources. Finally, the model allows varying efficiency across energy sources through sector-specific parametrizations of the production functions.

With this setup in place the researcher can evaluate the impact from introducing a variety of transition policies, such as a time varying tax on the energy resource itself; for simplicity the tax can be assumed to generate a lump-sum rebate for the (representative) households, but more sophisticated forms of revenues recycling could be easily added. In the case of Golosov *et al.* (2014), the optimal tax can be shown to be exactly equal to the marginal externality cost of emissions (as a proportion of GDP). The authors also expanded the model by allowing for a process of endogenous technological change that depends on an intermediate input expenditure that has both a private return for the firm investing in it but also for the economy at large through knowledge spillovers.

Another application of sectoral models consists of allowing for a variety of (partially) substitutable inputs to be used in the production of a single final good. A good example of this type of models is presented by the two sector model of Acemoglu *et al.* (2012). The authors build on a strand of research that uses growth models to analyse and assess the extent to which reliance on exhaustible resources for production can eventually pose a limit to growth (see Dasgupta and Heal, 1974; Stiglitz, 1976). This class of frameworks is tractable enough to allow for a transparent depiction of the channels at play during a transition, and for the endogenous response of different types of technologies to environmental policy changes.

A key feature of Acemoglu *et al.* (2012) is to allow for one economic sector to generate environmental degradation. In this context, technology can be directed by profit maximising researchers who, by "using" the stock of previous innovations, can improve the quality of the machines in one or another section. The sectors in which innovations eventually materialise depends on both the market size and the relative prices of each sector. In turn, this depends on the elasticity of substitution among sectors, the relative levels of development of the technologies and on whether the carbon-intensive technology uses an exhaustible resource. When the sectors are highly substitutable, the environmental challenge can be easily addressed through sectoral policies that incentivise production in the sectors that do not exploit the resource. Importantly, in this case, the policies only need to be set in place temporarily to allow for the clean sectors to expand. Once the clean sectors have reached a sufficiently large size, enough technological advancement will optimally flow to them to ensure long run economic sustainability.

Critically, a key takeaway for policymakers from this modelling set up is that implementing policy early on avoids further increasing the initial technological gap between the sectors, which would make an eventual future convergence costlier. A lower degree of substitutability might require permanent policies, while the complementarity of the inputs implies that growth will stop.

An important modelling assumption when including multiple sectors in economic models is the use of Constant Elasticity of Substitution (CES) functions in production. This type of production function allows modellers to account for the (imperfect) complementarity or substitutability among inputs in production, such as energy and non-energy inputs. This contrast with Cobb-Douglas (CD) production functions, which assume a unitary elasticity of substitution between inputs. Cobb-Douglas is often an unrealistic representation, especially in sectors where energy and other inputs like labour or capital are highly complementary, since, in such scenarios, it is not easy to replace one input with another without incurring additional costs or sacrificing efficiency.

Hassler, Krusell and Olovsson (2021) provides an example highlighting the importance of this aspect: if energy and non-energy inputs are highly complementary, policies that aim to reduce energy inputs (e.g. fossil fuels) could have significant implications for the productivity of other inputs (such as labour and capital). One key takeaway from the study is that the short-run complementary relationship between energy and capital/labour, as observed in aggregate U.S. data, can morph into a relationship of imperfect substitutability in the medium and long run, depending on how technological change is directed toward certain types of inputs. For instance, according to the authors, the oil shocks of the 1970s triggered an acceleration in energy-saving technological advancements, which, when paired with imperfect substitutability in the long run, allowed the economy to (partially) substitute away from oil. The paper estimates that, due to this directed, energy-saving technological change, the long-term dependence on fossil energy for the United States is less than 10% of the factor share. Absent the targeted technological innovation, the paper estimates that the dependence would have risen to 100%, indicating a complete reliance on fossil energy.

The complementarity between inputs and role of technological innovation highlighted in this study is relevant for the design of climate change policies as it underscores the role that directed technological change can play as a mechanism for reducing fossil fuel dependency and, consequently, greenhouse gas emissions. From a modelling standpoint, capturing the evolving degree of substitutability among inputs becomes crucial when modelling transition policies, which is another reason why incorporating CES production functions into modelling is necessary. For instance, while in the early stages of a transition to a low-carbon economy, renewable energy might be a poor substitute for fossil fuels in some cases and applications, however, as technologies adapt, the substitution to greener energy inputs should become easier. A CES model, by capturing these dynamic changes, can offer a more accurate representation of the economy over the transition period.

2.3.1.2 Sectoral models with nominal rigidities

When the modeller's interest is on the impact of environmental mitigation policies on price dynamics, the researcher should start by amending a standard dynamic macroeconomic model by introducing frictions in product and/or labour markets (for example by assuming adjustment costs on prices or downward nominal wage rigidity). These frictions open the door for the analysis of inflation by making equilibrium prices sticky (see Galí, 2015).

Ferrari and Nispi Landi (2022) is an example of an analysis studying the inflationary impact of a green transition. The authors first develop a two-period New Keynesian model, which offers a useful setup to distil the main channels at play. The model is very close to the three equations model of Galí (2015) and allows for a sharp characterisation of permanent policies; the first period corresponds to the short run while the second period to the long run. The model is amended with the usual assumption that emissions are proportional to production and that they can be reduced investing in abatement technologies. Abatement spending is convex in the fraction of emissions (see Heutel, 2012), which is a standard assumption in the literature. The two periods model is complemented with a medium-scale two sector framework, based on Ferrari and Nispi Landi (2023), which allows for a more quantitative assessment of climate policies.

One feature of the Ferrari and Nispi Landi (2022) model is that the simulations also consider the possibility that households form expectations non-rationally, a deviation from standard modelling practice. Non-rational household expectations can be readily integrated within standard DSGE models by assuming that the current forecast of economic variables is an exponentially weighted moving average of past observed values of the forecasted variable. In the approach the weight parameter can then determine the extent to which households employ a single random walk or an adaptive-learning type of process (see Gelain *et al.*, 2019). It is then possible to build a model where the intertemporal first order condition is a hybrid, weighted by the average of the two forecasts (e.g. rational expectations forecasts and adaptive learning forecasts, with the weight given by the share of households following each type of expectations). In the context of Ferrari and Nispi Landi (2022) these insights are applied to both households and firms (see the aforementioned paper for the specific implementation details).

The work of the Ferrari and Nispi Landi (2022) offers a useful benchmark for thinking through how to model environmental policies together with their long-run macroeconomic impact. However, since its primary focus is on carbon taxation, modellers who want to study different policy instruments, including their impact on the transmission of conventional business cycle shocks, might find a useful reference in Annicchiarico and Di Dio (2015). Another option is Annicchiarico, Di Dio and Diluiso (2024), where the authors contrast the macroeconomic effects of carbon taxes and cap-and-trade system by also accounting for short-run uncertainty over climate policies and non-fully rational agents.

In Annicchiarico and Di Dio (2015), the first E-DSGE model to incorporate nominal rigidities, the authors extend a standard New Keynesian model with price rigidities *à la* Calvo, by adding climate features borrowed from Heutel (2012) and assuming that emissions are costly to producers due to environmental regulations in place. The model therefore only deviates from a standard macroeconomic framework through the modelling of emissions and an abatement function that the firm can invest into to produce less emissions. In this sense the model proposes a very direct way to embed green policies.

Firms in the Annicchiarico and Di Dio (2015) setup, optimally choose between paying abatement costs or paying a price on emissions, which opens the door for a rich variety of instruments, such as emissions caps (i.e. an exogenous limit on emissions), emissions intensity targets (i.e. an exogenous limit on emissions per unit of output) or a tax policy.

The researcher can then compare outcomes of a transition policy according to the selected instruments and potentially to a combination of instruments; this is particularly useful to the extent that each policy has different implications for the transition path. For instance, a cap policy is generally seen as a natural stabilizer for business cycles, as the price of emissions as well as abatement effort becomes procyclical under such policy[25]. On the other hand, a policy of emissions intensity targets generates more volatility over the business cycle, and the volatility becomes more pronounced the more rigid prices are. As an interesting exploration, the paper also describes how monetary policy should optimally respond to each environmental policy regime, depending on whether environmental quality is considered part of the household utility function[26].

Using a simple setup, Airaudo, Pappa and Seoane (2023) offers the basic ingredients to study a variety of transition events with a focus on price dynamics using a minimalistic setup. The model builds on a typical Home-Foreign goods environment, with a nominal friction *à la* Rotenberg. The Home good is assumed to be an aggregate of both value-added inputs (e.g. capital and labour, aggregated using a constant return to scale Cobb-Douglas production function) and an energy input. Importantly both inputs have distinct efficiency-augmenting, non-stationary productivity factors and there is a non-unitary elasticity of substitution between the value-added and energy input, following Hassler, Krusell and Olovsson (2021). Critically, each firm employs a fixed stock of "researchers", and these researchers either work to improve the efficiency of the energy input or the productivity of capital and labour. This creates a trade-off for the firms, which need to decide how to optimally allocate the researchers between the two sectors used in production. This trade-off in turn affects the degree to which the transition impacts output and inflation.

Integrating macroeconomic models with detailed sectoral models has emerged as essential for understanding the impacts associated with transitioning to a more sustainable economy, especially in the domain of climate change mitigation strategies. Strategies such as carbon pricing do not just have isolated impacts. They generate effects across various sectors, including energy, agriculture, and transportation, while also shaping connections among these sectors themselves. This interconnection among sectors is well presented in Del Negro, Di Giovanni and Dogra (2023), who augment a New Keynesian model by allowing for an input-output structure that differentiates between "green" and "non-green" firms. Their framework highlights how a carbon tax affects both "green" and "non-green" activities and inflation through interlinkages[27].

25 Discussing relative merits of cap-and-trade versus price mechanisms is complicated; for example, even though cap-and-trade schemes are generally seen as stabilizing output over the business cycle, empirical evidence suggests that they generate greater volatility in headline CPI inflation potentially complicating the conduct of monetary policy (Santabárbara and Suárez-Varela, 2022).

26 Another reference worth mentioning is Annicchiarico and Di Dio (2017), which explicitly analyses optimal climate and monetary policy.

27 Other useful references to analyse the inflationary impact of the green transition include Diluiso *et al.* (2021) and Olovsson and Vestin (2023).

Adopting highly granular multisectoral models allows policymakers to pinpoint which areas of the macroeconomy will be most affected by climate change transition. In this way, policymakers can craft focused policies that can have more traction and efficacy in greening the economic and financial system. Overall, by highlighting how changes in one sector can affect other sectors, this class of models allows for more effective risk management and planning and would be a valuable part of the toolkits used by central banks around the world for financial stability purposes.

2.3.2 Advanced aspects of multiple sectors in economic models

Macroeconomic modelling has traditionally placed less emphasis on integrating microeconomic structures and production networks. The reason being that in an efficient economy, and under assumptions such as linearity, macroeconomic shocks can be decomposed as the sum of weighted microeconomic shocks, where the weights can be taken as exogenous and constant. This result is often referred to as the Hulten's theorem. However, in the context of green transition policies, the first order approximation of the economy is inadequate because the analysis of non-linear dynamics is essential.

Several studies have shown how microeconomic shocks can matter for macroeconomic outcomes. Gabaix (2016) emphasises that many economic realities (such as cities, firms, and the stock market) are characterised by power law distributions, which break down the intuition that idiosyncratic shocks should cancel each other in the aggregate. Baqaee and Farhi (2019) demonstrate that moving away from the Cobb-Douglas specification for the production function is key to endogenise the weights, making the whole input-output matrix responds endogenously to shocks. One of the key findings of the authors is that the macroeconomic impact of microeconomic shocks depends on the ability of production factors to relocate across production units, which gives centre-stage to questions related to geography and mobility of labour.

Two relevant examples of models that include multistage production are in Antosiewicz and Kowal (2016) and Antosiewicz *et al.* (2020). These papers present a multisector large-scale DSGE model (MEMO). This framework embeds an Input-Output (I-O) structure that allows for a granular specification of the economic sectors and their inter-relationships. Firms in the model are organised into several sectors based on the NACE Rev.2 symmetric input-output. These firms utilise a multistage production technology based on nested Constant Elasticity of Substitution (CES) functions.

Another example is the Bundesbank's environmental multiregion multisector DSGE model EMuSe, detailed in Hinterlang *et al.* (2023), which features several production sectors that are interconnected via input-output linkages. Specifically, in contrast to prototypical production technologies used in DSGE models, it is assumed that in addition to labour and capital, a bundle of intermediate inputs is needed. This bundle combines output from all sectors using a constant elasticity of substitution production technology, which implies that the extent to which various inputs are substitutable is limited. Considering sectoral linkages across all sectors allows to capture a detailed production network.

Aguilar, González and Hurtado (2023) develop a general equilibrium model of the Spanish economy to simulate green transition scenarios by highlighting the impacts that could stem from unexpected changes to the policy instrument (carbon pricing/caps) (e.g. shocks to the price and coverage of GHG emission allowances). The authors rely on cross-sectoral relationships, with different degrees of elasticity of substitution across the production structure to reflect the interlinkages that appear in the input-output matrices of the Spanish economy.

Importantly, by modelling each sector as a separate entity, the authors can account for the different shares of energy in the production functions of the various industries, their emissions intensities, and the interrelations between them, which is essential to answer the questions at hand. At the same time, the authors maintain the assumption of inter-sectoral labour mobility, which can downplay the impact of transition policies in the short run.

Another framework that highlights interlinkages and multisector production is presented by Del Negro, Di Giovanni and Dogra (2023), who develop a 396-sector New Keynesian model. The high level of granularity allows for a refined, sector-specific, degree of price stickiness (empirical evidence suggests that sectors with higher CO_2 emissions relative to value added tend to change prices more frequently). In addition, the network structure that emerges from the model allows users to account for the impact of monetary policy and relative price shocks. Specifically, since the non-green sector is an input to the output of the green sector, and a carbon tax directly increases the marginal cost of non-green firms, the inter-relation across sectors will also result in an increase in marginal costs in the green sectors. Finally, the structure provides a means to analyse how results vary depending on whether the environmental policy is applied upstream or downstream along the production supply chain. A key feature of the model is the ability to understand how inflationary introducing a tax on the non-green sector can be, which depends on the price stickiness of the non-green sector relative to the green sector. In this respect, the authors also highlight that the implications for inflation depend on the adopted policy instrument (e.g. a tax on the non-green sector versus a subsidy to the green sector).

In parallel to the modelling of interlinkages and networks, central banks could find useful integrating insights from the heterogeneous agent macroeconomic literature that, starting from the seminal papers of Bewley (1977) and Aiyagari (1994) among others, introduced idiosyncratic uninsured risk and market incompleteness in otherwise standard macroeconomic models. The relevance of these ideas is immediate in the context of climate change where each household and firm are fundamentally different in their exposure to possibly aggregate events such as rising temperatures, extreme weather episodes, and in their ability to insure their assets and livelihoods against the realisation of such shocks. Applications could easily extend to scenarios, where idiosyncratic human capital accumulation is intertwined with aggregate climate events, trailing some of the original ideas from the work of Krebs (2003) (who links human capital and business cycle risks). One first effort in this direction is Bakkensen and Barrage (2018) who, while maintaining the representative agent assumption, allow for human and physical capital shocks to be correlated. The authors then study how cyclones risks can affect investments and savings decisions of the agents, ultimately leading to potential changes in economic growth and welfare.

2.4 International effects of climate transition: trade and international spillovers

If researchers are interested in exploring international spillovers and trade linkages under different transition policies, then models of transition impacts can extend the main ideas of sectors and networks to the international context, by allowing for inter-countries trade and financial flows. This modelling strategy will help in understanding how shocks that originate in one country can propagate across other countries. For example, how will the unilateral implementation of a carbon tax or the introduction of a carbon border adjustment mechanism (CBAM) affect the rest of the world?[28] Moreover, how should the rest of the world respond to such unilateral actions? These issues are especially topical in the context of policies that are applied by large countries (such as the United States) or blocks of countries (such as the European Union), which when combined can have large effects on the global economy[29]. The modelling strategy of international spillovers can follow the same economic structure and logic presented in Baqaee and Farhi (2019), with the emphasis that, in this context, the assumption of lack of labour and capital mobility across countries is of primary relevance.

To better appreciate how unilateral climate policies can spillover into the domestic economy, consider a simple stylised case of two countries, A and B. Assume that country A, as part of its transition goals, reduces its imports of coal from country B. The effect on country B is twofold, first there is a reduction in coal extraction, production and exports, and the profitability of its fossil firms. In addition, the reduction of exports and profits decreases its fiscal revenues, affecting its sovereign bond rates and sustainability. Quantitatively evaluating spillovers, will need to, at a minimum, consider all of these channels, and possibly also allow for a larger number of countries and feedback effects that reverberate in the country that originally implemented the policy.

Carattini *et al.* (2023) develop a standard multisector, multi-country, dynamic general equilibrium model following the seminal works of Backus, Kehoe and Kydland (1992) and

28 Ernst *et al.* (2023), for example, use a three-region version of the EMuSe model to assess the implications of carbon border adjustment mechanisms and climate clubs.

29 See Fournier *et al.* (2024) for a discussion of the literature on the effects that climate policies have on the macroeconomy including across borders, and the presentation of a global CGE model that integrates recent climate packages from the U.S., Canada and Mexico.

Corsetti, Dedola and Leduc (2010). The framework provides a platform to study the role of climate policies, including carbon tariffs, and macroprudential policies, and the role that a domestic financial regulator can play when faced by financial spillovers effects originating from transition policies abroad. The key assumptions of this modelling strategy are the distinction between emission-intensive tradable sectors and green non-tradable sectors and the ability of the government to observe the banks' exposure to green and carbon-intensive assets (reflecting the increase in mandated disclosure of climate risks and the increasing popularity of climate stress tests).

Other works worth mentioning and that follow the mainstream macroeconomic approach include Moro and Nispi Landi (2024), who develop a two-country, two sectors (green and carbon-intensive) DSGE model with incomplete financial markets to study the global implications of carbon taxation with a specific focus on the strategic interactions among countries, including possible cooperation. Along the same lines, Ferrari and Pagliari (2023) develop a three country, two sector DSGE model. The three-country structure allows for a richer analysis of cooperation in climate policies. Finally, the reader interested in analysing how specific shocks interact with climate policies should refer to Annicchiarico and Diluiso (2019) who build a two-country model to study the international transmission of shocks, highlighting how trade patterns, complementarity between goods, and monetary policy reactions might affect the extent of spillovers.

An alternative and complementary modelling strategy, suited to understanding how production networks and spillovers interact, departs from the DSGE literature to follow the principles of Stock-Flow-Consistency. This line of research emphasises making use of balance sheet entries, calibrated on actual data, and the correspondence between stocks and flows circulating in an economy. Specifically, this class of models assumes that agents' behaviour adapts "period-by-period" depending on changes in their balance sheets. Agents also adopt behavioural rules based on expectations and heuristics, which allows modellers to break away from the usual forward-looking assumption[30]. This could be especially fruitful from a modelling point of view as it allows for the possibility to explicitly include the analysis of "out-of-equilibrium" states of the economy, together with amplification effects[31].

A useful reference of a stock-flow model that accounts for spillovers across countries is the work of Gourdel, Monasterolo and Gallagher (2022) in which the authors build a fully-fledged stock-flow consistent model to study climate transition spillovers and sovereign risk, calibrated for Indonesia. Among the specific model features are: (i) the distinction between workers and capitalists, which allows to quantify the distributional impact of climate policies; (ii) the assumption of buffer-stock savings (see Deaton, 1991; Carroll, 2001); (iii) the differentiation between renewable and fossil fuel producers; (iv) the inclusion of an oil and mining sector; (v) the assumption that the households have an inelastic demand of energy, and; (vi) the presence of a detailed financial sector, where commercial banks make loans and receive deposits and where there can be allocations characterised by credit rationed firms. All these features add to the realism of the exercise hence providing a coherent framework to study the questions at hand.

2.5 Transition impacts using large scale models

The models discussed so far generally follow a parsimonious approach when describing the economy and are therefore useful for deriving key insights regarding the interaction between economic policies and climate outcomes. These frameworks provide valuable qualitative assessments (especially regarding the cross-section of the economy) but may be less suited for generating economic projections such as those produced by central banks in support of monetary policy. Since accuracy of economic forecasts is crucial when making monetary policy decisions, the development and modification of large scale policy models can offer a complementary approach to more stylized representations of the economy.

For example, Coenen, Lozej and Priftis (2023) add disaggregated energy blocks to the original New Area-Wide

30 At the same time, it is important to emphasise that, generally, these frameworks are not directly microfounded and hence subject to the "Lucas critique".

31 An example of how stock-flow consistent models can be applied to study the macroeconomic dynamics of global warming is given by Bovari, Giraud and Mc Isaac (2018), which follows an approach based on the Lotka-Volterra logic, allowing for an interaction between non-linear monetary dynamics of underemployment and income distribution with abatement costs.

Model (NAWM) used at the ECB. The NAWM is a large scale DSGE that consists of two symmetric countries of different sizes where international linkages arise through the trade of goods and international assets, allowing for gradual exchange rate pass-through and imperfect risk sharing. The new energy blocks of the model follow a nested CES approach. Households' consumption is assumed to be a CES bundle that includes energy and other goods. Final goods production uses a CES combining a value-added bundle of capital and labour services together with an energy composite. The energy composite is in turn also a CES of green and non-green energy inputs. The former is produced using a green input and a value-added input, while the latter is produced using fossil inputs and a value-added input. Prices of both types of energy are subject to Calvo price setting frictions. The imports of non-green inputs also adds to the current account specification. The model suggests that for the European Union to reach its net zero transition target by 2050, the price of carbon emissions needs to be raised significantly and in a timely manner. Also, the study points to moderately higher inflation from the policy, and a lasting, but contained decline in real GDP. However, it is important to highlight that some of these macroeconomic effects may be more nuanced once other complementary – and growth friendly – green policies are introduced in parallel to carbon pricing, as further suggested by the study below.

Following a similar approach, Varga, Roeger and in 't Veld (2022) build a multi-region DSGE model to simulate the transitional costs of moving to a net zero emissions economy through regulation and carbon taxes. The authors find that the costs of net zero transition can be reduced significantly when carbon taxes are used to lower other distortive taxes or to subsidise clean energy. In the model, consumption consists of a bundle of durables and non-durables. The model also includes the demand for green and non-green energy. One of their key findings is that subsidising the purchase of clean capital is the most effective policy to reduce transition costs but this hinges on both the degree of substitutability between non-green and green inputs in energy generation and on assumptions regarding endogenous growth ("learning-by-doing") in the clean sector and energy-saving technological progress.

The Bundesbank's environmental multiregion multisector DSGE model EMuSe, outlined in Hinterlang *et al.* (2023), incorporates various interconnected sectors in addition to environmental features. The model has been used to tackle various questions, such as contrasting the macroeconomic effects of disorderly and orderly transition scenarios, as well as illustrating the effects on carbon leakage from implementing unilateral climate policy measures[32]. Model versions of EMuSe, with a detailed representation of the energy sector, can be found in Hinterlang *et al.* (2022). A three-region version that considers the implications of carbon border adjustment mechanisms and climate clubs can be found in Ernst *et al.* (2023)[33].

Bartocci, Notarpietro and Pisani (2022) builds a two-county New Keynesian DGSE model with a detailed energy sector that includes energy generated from oil, coal, gas, nuclear, and a green source. Each type of energy is produced by firms under perfect competition using a CES production function for which the inputs are domestic capital, labour, and the related source of energy. The energy outputs obtained from the different sources are aggregated in a CES energy bundle and used, jointly with capital and labour, by firms that produce intermediate manufacturing goods. Moreover, the different types of energy are also assembled into a basket that enters households' final consumption jointly with (non-energy) consumption goods. The authors find that an increase in the carbon tax generates recessionary effects, but the macroeconomic impact can be limited if carbon tax revenues are used to increase subsidies on capital used to produce green sources of energy and lower labour taxes.

The National Institute Global Econometric Model (NiGEM) uses IAM outputs to produce projections of macroeconomic variables for individual countries that are connected through trade in goods and services and capital markets. The framework includes more than 7,500 variables and uses historical data from 1997 to forecast until 2052. The model is commonly used by central banks and has also been used as the macroeconomic basis for the NGFS long-term Climate Scenarios outputs (NGFS, 2023b). The model quantifies the direct impact of mitigation policy costs on potential national income and the potential national income benefits from

32 The EMuSe model, which is accessible for download on the Bundesbank's website (see Hinterlang *et al.* (2023)), allows users to tailor the number of sectors and regions to their research needs. Additionally, a MATLAB-based calibration toolkit is publicly available to specify the model's detailed sectoral parameters using data from the World Input-Output Database.

33 A multiregion version of EMuSe has also been applied in Hinterlang (2024).

avoided climate damages, showing that an orderly transition generates net benefits, when accounting for avoided chronic and acute damages. Importantly, the model has all the main ingredients needed to perform valuable scenarios analysis. First, the model has a complete demand and supply sides, with full asset structures. Second, most behavioural equations are estimated in error-correction, with the option of adding a rational expectations assumption in financial markets (and also adaptive learning), labour markets and consumption. Third, there is a supply side based on CES relationships that combine a value added bundle with oil. Fourth, the model allows for a government sector that can apply direct and indirect taxes to ensure long-run solvency[34].

Finally, some large-scale global IAMs are particularly suited to analysing the challenges in transition that can materialise for small open and resource rich economies. These models generally divide the world into several regions. Two examples of such frameworks are the Computable Framework for Energy and the Environment (COFFEE) model and the Brazilian Land Use and Energy System (BLUES) models. Both frameworks are developed by COPPE/UFRJ in Brazil and have been extended to account for changes in land-use and trade channels across regions (see Rochedo, 2016). The "land system" block is interacted with a highly detailed energy system to account for energy production and conversion technologies. The addition of a transport bloc distinguishes between passenger and freight. This level of detail can be used to study how changing demand for energy sources within and across regions will affect cropland areas, including potential competition of land use between food and energy industries.

2.6 Financial implications of climate change transition

The transition to a low carbon economy will affect the valuation of a broad range of assets. Some assets will become stranded as they will be associated with declining sectors in the new economy. This will require a high level of vigilance from supervisory and regulatory institutions due to the possible impacts on financial stability. In addition, transition policies can have a strong effect on financial market activities and allocations of funds, which can have macroeconomic effects.

This section presents a selection of conceptual frameworks that, while parsimonious, still encapsulate some of the key channels that allow modellers to integrate financial market considerations into their modelling efforts of the green transition. When analysing the effects on the financing of firms and the financial system, these models generally rely on financial frictions, so that the financial structure generates real effects. Some of the frameworks have been developed with macroprudential questions in mind, which nevertheless may still provide a useful framework for other macroeconomic applications.

Carattini *et al.* (2023) develop a standard multisector, multi-country, dynamic general equilibrium model, with the addition of financial frictions in the tradition of Gertler and Kiyotaki (2010) and Gertler and Karadi (2011). The framework provides a platform to study the role of climate policies, including carbon tariffs and macroprudential policies that shift banks' portfolio composition away from non-green assets. In the setup, climate policies can trigger a recession as bank's assets decline in value, which then causes a tightening in the credit supply. The paper explores the role that a domestic financial regulator can play when faced by spillovers effects originating from transition policies abroad. By explicitly allowing for both trade and financial flows enables a vast array of questions to be answered such as how changes in funding constraints affect foreign lending and how domestic carbon taxes targeted on domestic production can lead to a surge in foreign production, which happens as global demand shifts towards cheaper alternatives. Key assumptions of this modelling strategy are the distinction between emission-intensive tradable sectors and green non-tradable sectors and the ability of the government to observe the bank's exposure to green and non-green assets (reflecting the increase in mandated disclosure of climate risks and the increasing popularity of climate stress tests). One implication from the analysis is that ambitious climate policies need not cause a recession if coupled with appropriate macroprudential policies that reduce the financial system's exposure to non-green assets.

To understand the role of monetary policy and financial regulation during a low carbon transition Diluiso *et al.* (2021) build a simple New Keynesian model. The model also helps researchers to understand the extent to which climate policy can be a source of macroeconomic and

34 See www.niesr.ac.uk (NIESR, 2024) for an overview of the framework.

financial instability. The model introduces a financial intermediary that enters into a principal-agent relation with its borrower. The authors assume that the incentive friction is asset specific and relatively higher for the case of energy assets. This distinction is important from a modelling perspective as it gives rise to risk-adjusted leverage, which depends on how much of each asset category the bank holds in its balance sheet.

2.7 Uncertainty in transition

Uncertainty is pervasive in economic decision-making, and this is particularly true for decisions related to investments in research and development, physical and human capital. Large upfront costs, long time-to-build lags, and long lifespans for capital mean that investment decisions must be highly forward looking. Unforeseen events that fundamentally alter the payoff can occur between when the decision to invest in a project is taken and when it is actually operational.

Uncertainty related to the path to net zero can take many forms. First, there is domestic and global policy uncertainty. Despite a broad scientific consensus, the level of urgency accorded to climate action can differ substantially across the political spectrum within countries, as well as across countries and geographical regions[35]. Interest groups, election cycles and doubts about the credibility of long-term climate policies can lead investors to take a wait-and-see approach, delaying the required adjustment.

Furthermore, policymakers are themselves uncertain as to the magnitude and mix of policy initiatives that will be required to achieve climate objectives. Price elasticities and related substitution effects are not known, but rather must be estimated using historical data that may be relatively uninformative about the future. In practice, policy is likely to react endogenously based on the evolution of actual GHG emissions data relative to their projections, and the worsening climate outcomes that are implicit in current abatement promises (NDCs). This issue is intimately linked to the next source of uncertainty, the rate of technology growth.

In addition to policy uncertainty, investors and private sector companies must contend with uncertainty related to green technologies. Some key technologies such as wind or solar are already well-established and being rolled out at large scale. While other more ambitious technologies, including carbon capture and storage, storage systems for wind and solar power, extra-terrestrial solar power, fusion and hydrogen production and storage are still in early development or at the proof-of-concept stage. The viability of these technologies, and their scalability to real-world applications remains unknown.

Macroeconomic models are typically poorly equipped to deal with uncertainty effects, meaning that judgement must be used. To date, most attempts to model the transition to net zero assume no role for uncertainty[36]. Linear models (or linearisation of non-linear models) display certainty equivalence, meaning economic agents behave as if they know the future with certainty. This can be problematic for business cycle analysis, but it is an even bigger issue for scenario analysis that involves a shift from one steady state to another over the course of several decades.

Economic models also often rely on *ad hoc* assumptions like quadratic adjustment costs to match the business cycle properties of investment. In reality, there can be long time-to-build lags before capital becomes productive, and if at that time, production is not profitable, the scrap value can be a small fraction of the original outlay (irreversible investment).

As a result, there is an option value to waiting until uncertainty declines that can be followed by a flurry of investment (and the possibility of bubbles) as winners emerge. This is a very different dynamic than predicted by standard forward-looking models of business investment.

35 But it is important to emphasise that, while possible, policy mistakes have large asymmetric economic costs. E.g. It might be not very costly to have introduced an ambitious carbon tax in vain, but the opposite – having introduced a modest tax in the face of higher-than-expected climate sensitivity – is substantially more costly (see Hassler, Krusell and Olovsson, 2024) for a discussion, including simulations that quantify the costs of policy mistakes).

36 A notable exception is Kaldorf and Rottner (2024), who study the impact of climate policies on financial instability during the transition to net zero using a fully nonlinearly solved macroeconomic model.

The literature is somewhat split on the sign of the impact of uncertainty on business investment. Early models that assumed perfect competition, (near) constant returns to scale, and reversible investment suggest that uncertainty should increase investment. This stems from the fact under these assumptions, the demand for capital is a convex function of the firm's output price, and therefore greater uncertainty increases the expected payoff. More recent research that emphasises imperfect competition, irreversible investment and risk aversion obtains the opposite result. Much of this work borrows from the real-option-value literature in finance.

Modelling uncertainty effects can be done in *ad hoc* fashion, by putting judgement on endogenous variables thought to be impacted by uncertainty, although determining how much and where to put judgement can be quite difficult. In addition, this judgement would typically be specific to a particular scenario. If some aspect of the model simulation is changed, the judgement would also have to be changed.

A more promising approach is to build realistic but tractable features into the economic model, and then use non-linear techniques to simulate the model so that uncertainty effects arise endogenously.

Modelling uncertainty related to the transition to net zero is very new field, with few published papers, particularly using medium-scale policy models. IEA (2007) uses Monte Carlo methods to replicate the dynamic programming approach in Dixit and Pindyck (1994) in order simulate the effects of uncertainty associated with the net present value (NPV) of a green project. This is a good example of the real options price approach to modelling the firm's investment decision. At any point in time, the firms must make a discrete decision to invest in a project or pay a fee to maintain the option to invest later when conditions may be more favourable. Risk neutral firms will generally delay investment in projects when the level of uncertainty is high relative to the expected NPV of the project.

Bretschger and Soretz (2022) provide an excellent review of the literature in this area and develop a model with a stochastic tax rate on the non-green sector and subsidisation of the green service sector. They demonstrate the important result that stochastic taxation serves as a substitute for a green service subsidy if uncertainty decreases in the green service ratio.

Fried, Novan and Peterman (2022) consider the impact of a possible but uncertain one-time introduction of carbon price on steady-steady investment in green and non-green energy sectors and find that uncertainty reduces overall investment. Their approach also relies on dynamic programming.

A second approach is to introduce risk aversion into an otherwise standard firm problem such as in, for example, Nakamura (1999). The author shows that risk aversion is sufficient to generate a negative relationship between uncertainty and investment. However, this approach also relies on value function iteration (dynamic programming) which is very slow, even for small models.

Strict irreversibility of investment implies a discontinuity of the investment cost function at zero (see Xepapadeas (2001) for a simple example in continuous time), whereas the options price approach to investment implies a discrete choice between investing or waiting. Discreteness and discontinuities make model solution and approximation more difficult when working with medium-sized policy models.

One method that avoids these additional complications is to assume a smooth investment cost function that is asymmetric around the zero-investment point. In this setup, the costs to additional investment are small, but increasing with the size of the investments made, whereas the costs to negative investment (scraping a capital project) are large and increase rapidly in the degree of disinvestment. With this type of asymmetry, firms' investment will generally be lower if the probability of future disinvestment is high. Strict irreversibility can be considered a limiting case where the costs of disinvestment go to infinity.

In this setup, widely available perturbation methods can be used to approximate the non-linear field oriented control (FOC) for investment and thus capture this uncertainty effect, as in Murchison *et al.* (forthcoming). This work demonstrates that uncertainty about the future value of Tobin's q, which is influenced by climate policy and technology growth, reduces current investment.

2.8 Implementing multisector models

As described in the previous sections, a key feature of the models analysing the climate transition is the inclusion of many productive sectors in the economy. This section presents simple guidelines on how such modelling can be approached.

The first step involves defining the specific objectives and scope of the model, including the key research questions or policy issues that need to be addressed. These could range from the impact of carbon pricing to technological transitions in the energy sector. Subsequently, the researcher should evaluate which framework is best suited to answer the questions at hand, also verifying that appropriate data exists for the calibration and/or estimation of the parameters. As a final step, the model's performance should be evaluated, for example by comparing the framework's generated moments with those from the data, and by doing simulations over past periods that can be benchmarked against actual outcomes. The following two subsections review some implementation details, by distinguishing between DSGE and CGE frameworks.

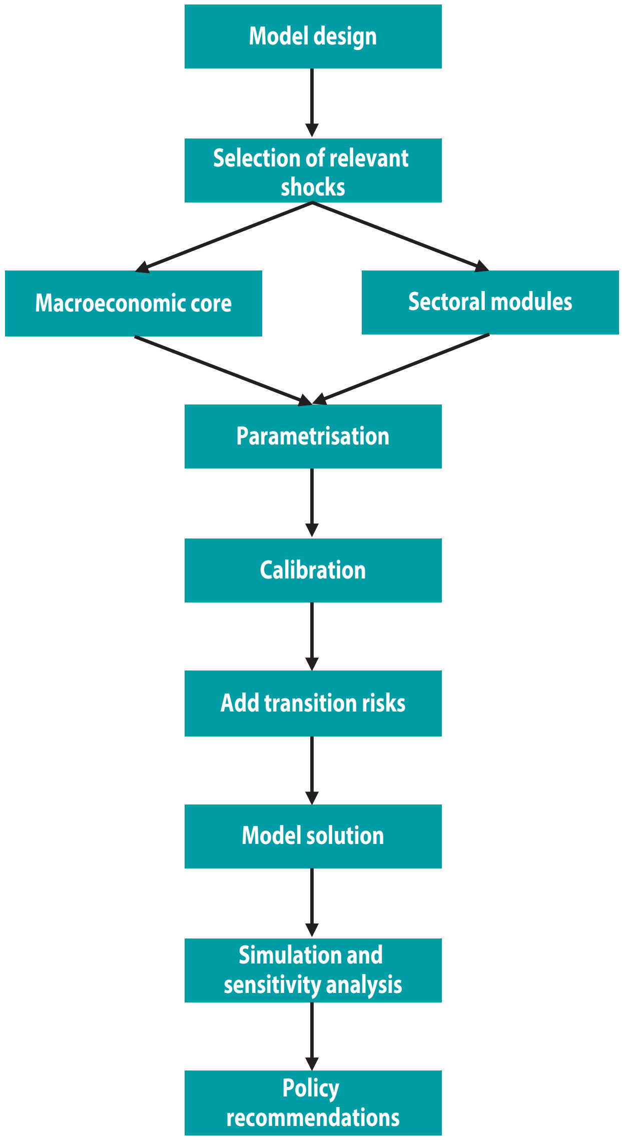
2.8.1 Implementing a multisector DSGE model

A multisector DSGE framework can be especially valuable for understanding sector-specific shocks, resource reallocation across sectors, endogenous technology adoption, and the transmission of policies (see Antosiewicz, Lewandowski and Witajewki-Baltvilks, 2016; Antosiewicz *et al.*, 2020, 2022; Frankovic, 2022; Carton *et al.*, 2023; Hinterlang *et al.*, 2023; Matsumura, Naka and Sudo, 2023).

Designing a framework for a multisectoral DSGE model involves several steps (see figure 3). First, the researcher needs to design the macroeconomic core and identify which relevant economic shocks to include. The macroeconomic core consists of the fundamental components that capture the key dynamics of the economy, including economic agents such as households, firms, and the government, as well as markets for goods, services, and labour. Key economic variables such as GDP, unemployment, and sectoral activity are endogenously determined.

The relevant shocks to be included can arise from policy changes such as the implementation of carbon taxes, input versus output taxation, and various revenue allocation scenarios such as lump-sum distribution, energy price subsidy, and labour tax reduction. Fluctuations in global commodity prices and technological advancements can also serve as shocks.

Figure 3 **Stylised framework for designing a multisectoral DGSE model**



Source: authors' own work.

The researcher should include the sectoral modules to reflect the economic interactions of interest. These sectors may include agriculture, raw material production, industry, energy, construction, transport, market services, and public services. Each sector features representative firms utilising multistage production technologies based on CES functions, which describe how substitution among inputs varies with price changes.

The parameters of the model can be calibrated based on empirical data and academic references and on transitional risks related to decarbonisation. The calibration step can be performed using Input-Output (IO) tables and granular databases such as Eurostat[37], the World Input-Output Database (WIOD)[38], and EXIOBASE[39]. Transition risks, including shifts in employment, wages, and economic activity under varying carbon tax scenarios, are integrated into the model.

Modelling the transition path itself as a stochastic process is one of the approaches that allow for the introduction of unexpected shocks that can affect the probability of different transitional paths. Another technique involves making some of the usually constant parameters time-dependent. For example, a carbon tax rate that increases over time could be modelled as a non-stationary stochastic function, reflecting uncertainty about future tax rates.

For more granular frameworks that consider multiple sectors, each sector might have its own stochastic shock, layered on top of economy-wide shocks. This creates a complex but more accurate representation of how shocks can propagate across an economy undergoing a transition. Finally, as the economy moves away from its initial steady state, the properties of shocks themselves may evolve, requiring different stochastic modelling approaches. Extending DSGE models to be multisectoral and rich in detail introduces computational challenges, especially when the model has a large state space. The larger the state space, the more difficult it is to solve the model due to the "curse of dimensionality". This is particularly true if sectoral investments are considered with their own adjustment processes, depreciation rates, etc.

2.8.2 Implementing a multisector CGE model

Similar to the construction of a DSGE model, the first step includes designing the macroeconomic core and the sectoral modules. In this case, models do not have stochastic components so there is no need to define shocks.

Once the core and sectoral modules are designed, the CGE models are usually calibrated using Social Account Matrix or the Input-Output Matrix. In particular, the economic data that is used to calibrate production functions, input-output relationships, and price elasticities is gathered alongside environmental data such as emissions levels, abatement costs, and climate vulnerabilities. All these inputs need to be harmonised, ensuring compatibility in terms of units, geographical scope, and time frames.

In the study of economic systems, CGE models are often integrated with Partial Equilibrium (PE) models to provide a more comprehensive analysis (Delzeit *et al.*, 2020). CGE and PE models are two types of economic models that provide unique yet complementary insights into economic systems. CGE models offer a macroeconomic perspective, analysing how different sectors of an economy interact with each other and how various policy measures can affect the entire economy. On the other hand, PE models offer a more focused view, often concentrating on a specific sector such as agriculture or energy, to analyse the economic dynamics and policies affecting it.

When it comes to the integration of the two models, there are generally two types of linkages: one-way and two-way linkages, which can be modelled using either a top-down or bottom-up approach (Wene, 1996; Britz *et al.*, 2012). The concepts of one-way and two-way linkages characterise the degree of interconnection within the model, while the top-down and bottom-up approaches refer to the directionality of the data and how the model is constructed.

Best practices for linking models depend on the specific research objectives. If the aim is to offer a broad, economy-wide view based on predetermined sectoral pathways or constraints, then a one-way linkage between models may be sufficient. However, if the objective is to achieve a more integrated and coherent analysis, incorporating both economic and environmental elements, then a two-way linkage is advisable. Delzeit *et al.* (2020) provides a relevant example by discussing the coupling of ENV-Linkages, an economic model, and IMAGE (Integrated Model to Assess the Global Environment), a model focused on environmental systems.

37 See Eurostat (2024).

38 See WIOD (2024).

39 EXIOBASE is a global, detailed Multi-regional Environmentally Extended Supply-Use and Input-Output database. See EXIOBASE (2024).

Box 3

Multimodel approach to understand the macroeconomic impacts of climate change

There is no silver bullet to modelling the effects of climate change in the economy: different questions are answered using different models – and often, a single question may require alternative approaches to reach robust results. Indeed, the IMF, the NGFS and the ECB, for example, use different approaches. This box briefly surveys the models used by these institutions.

The IMF uses the IMF DIGNAD Model and IMF Multi-Country Stochastic Growth Model for the study of physical impacts[1]. The IMF DIGNAD Model is used to study the impact of natural disasters on the economy by modelling the impact of a single natural disaster on households, firms, and the government. The economy is affected by the destruction of public infrastructure and private capital, and the decline in total factor productivity (coming for example from damaged physical capital and lower labour efficiency) which ultimately affects production and growth, as well as government debt and spending. The IMF Multi-Country Stochastic Growth Model is used to study the long-term effects of climate change – *via* changes in temperature and precipitation – on measures of economic activity across countries (labour productivity and GDP per capita).

For the study of transition impacts the IMF uses the IMF GMMET Global Macroeconomic Model and the IMF-World Bank Climate Policy Assessment Tool (CPAT)[2]. The former is a multi-country, multisector E-DSGE (Environmental Dynamic Stochastic General Equilibrium) model designed to analyse the short- and medium-term macroeconomic impact of curbing GHG emissions. The IMF-World Bank CPAT is an IAM used to estimate the impacts of climate policies on the macroeconomy. The CPAT model contains a series of different and interconnected modules to (i) understand the effects of energy price changes on inflation; (ii) estimate the impact of air pollution on mortality; (iii) assess how transport is affected by energy price changes, and; (iv) a macroeconomic energy module (underpinning all modules).

The NGFS, together with its academic consortium, currently relies on three major models (GCAM, MESSAGEix-GLOBIOM and REMIND-MAgPIE) that combine macroeconomic, agriculture and land-use, energy, water, and climate systems into a common quantitative framework that enables the analysis of complex and non-linear dynamics[3]. These models, together with NiGEM, form the basis of the long-term scenarios published and regularly updated by the NGFS (NGFS, 2023b).

The ECB has developed several models that are deployed to understand the macroeconomic effects of climate change. For example, Nakov and Thomas (2023) use a canonical New Keynesian model with climate externalities to study the implications of climate change and the associated mitigation features for optimal monetary policy. Coenen, Lozej and Priftis (2023) add a disaggregated energy block to the original New Area-Wide Model (NAWM) used by the ECB to distinguish between green and carbon-intensive energy production. In addition, as part of its future agenda, the ECB plans to integrate climate risks and impacts into their workhorse models with a view to assessing the impact on potential growth, to conduct scenario analyses regarding transition policies and to model the implications of climate change for the transmission of monetary policy[4].

1 IMF (2024b).
2 Carton *et al.* (2023); IMF (2024a).
3 GCIMS (2024); IIASA (2024); Potsdam Institute for Climate Impact Research (2024).
4 ECB (2024).

Conclusion

This handbook reviewed several structural methodologies that can help inform climate modelling in central banks. The discussion emphasises the distinction between (i) physical impacts that arise from both chronic and acute climate events that affect supply and demand, and (ii) transition impacts that materialise as economies around the world adjust their development paths to reduce their dependency on fossil fuels and other emitting activities. The handbook reviews how advances in both academia and policy institutions can support the development of new analytical tools to better understand, analyse and quantify the effects of climate change by central banks. The content covers topics from the modelling of the impact of climate shocks on business cycles and the role of transition policies on price dynamics and adjustments, to the modelling of long-term patterns, including the role of transition policies designed to achieve sustainable development.

The **physical impacts** section explains how to model the effects of climate change on the economy using damage functions. The section highlights how most of the papers in the literature use a single climate stressor to link climate change and the economy, but it underscores the importance of using alternative climate stressors to account for changes in environmental variables other than temperature increases and explains how they can be integrated into standard macroeconomic frameworks. It also emphasises the importance of differentiating between the impacts of chronic (predictable effects of global warming trends) and acute (extreme weather events) climate change. The section highlights the relevance of using different analytical approaches, aiming at building a battery of models to answer different questions at hand. In addition, the section explores the modelling of the supply side economy, putting emphasis on the non-linearities that can generate from climate shocks. The section also expands on the role of the uncertainty involved when studying the economic effects of climate change, contrasting between-model uncertainty (uncertainty about the appropriate economic structure, which differs across models) and within model-uncertainty (related to the specific structure and the parameter choices in a given model).

The **transition impacts** section highlights the relevance of accounting for multiple sectors when quantifying the economic impact of transitioning toward a low carbon economy. In this respect, the section suggests that to incorporate in-modelling multistage production processes (for example using a nested CES function) and trade flows, close attention should be paid to how I-O models are built and calibrated. The section also discusses more advanced modelling features such as the inclusion of production networks and spillovers effects across countries (i.e. those arising from the unilateral adoption of a tax on emissions intensive imports) and touches upon less mainstream frameworks of analysis that allow for agents to not be fully rational (as done in the stock-flow consistent literature). This second part of the handbook also reviews modelling aspects that allow for a meaningful study of transition policies, such as the inclusion of endogenous technological change, which can help in directing innovation towards sustainable economic sectors. Finally, particular emphasis is put into describing various challenges that arise when accounting for uncertainty in transition policies, with a focus on (i) the timing and adoption of climate policies, as well as (ii) the ability to scale-up present and future technological breakthroughs that are necessary for sustainable economic growth.

The report suggests (i) moving away from the Cobb-Douglas function to allow for a richer range of elasticities of substitution among production inputs; (ii) distinguishing between energy and non-energy sectors; (iii) allowing for inputs-outputs linkages; (iv) exploring less standard frameworks of analysis that allow, for example, taking into account heterogeneity and not fully rational behaviour; (v) taking uncertainty seriously by, for example, describing the evolution of carbon taxes as a stochastic process.

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Appendix

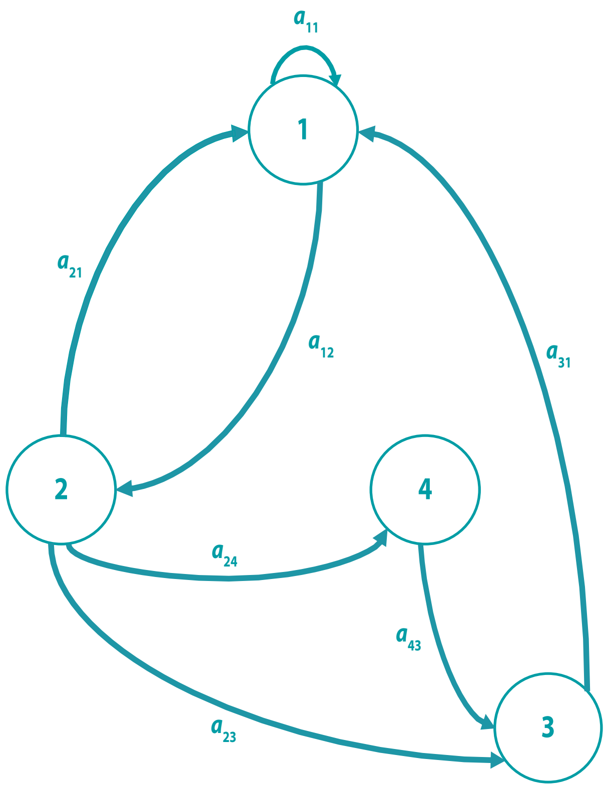
Modelling of Production Structures and Network Theory

Production structures are highly heterogeneous in terms of GHG emission volumes and intensity, making their exposure to the green transition a complex task that requires evaluating both direct and indirect policy impacts. The latter arise from each firm or sector's relationship with other firms and the sectors belonging to the same production network. This appendix reviews the modelling foundations required to properly account for production networks, sectoral linkages, and spillovers in macroeconomic modelling, also reviewing current applications to the effects of the green transition.

The modelling of production networks hinges on several ingredients: the inclusion of an input-output structure and the use and application of key concepts from graph theory, such as direct graphs ("digraphs"), communication and connectedness. A direct graph simply refers to a set of vertices connected by direct edges while the concepts of communication and connectedness refer to the properties characterising how the vertices are related to one another and the strength of such relationships. These concepts can help answer salient questions such the size of the aggregate multiplier effect from one extra dollar of demand in a given industry, the role of sectoral productivity shocks on output, and also which financial institutions (or other economic actors) are more sensitive to the effects from a negative shock. These answers could then inform how to frame green policies such as subsidies or "green" asset purchases programmes[40].

To emphasise the challenges that integrating production structures can generate from a modelling perspective, consider a Leontief Equilibrium model where the researcher is interested in tracing back the effect of a final demand shock on the different sectors of an economy. The production structure is represented by the simplified network as shown below (from Sargent and Stachurski, 2022), where each circle represents a production structure (vertex) and the interconnectedness is described by arrows representing the flows of inputs. Then, as a thought experiment, consider a positive demand shock that arises in sector 3, which in the context of the economic transition could be interpreted as a "green sector"; the increase in demand necessitates more output from the suppliers, described by sectors 2 and 4, but at the same time more production in sector 2 requires more output from sector 1, which necessitates more output from sector 3, where the shock originated. This in turn will require more output from sectors 2 and 4, and so on, in an infinite loop.

Figure 4 **A simple production network**



Sources: Sargent and Stachurski (2022).

Overall, while this type of framework provides realistic representations of the world, they may sometimes fall short in fully capturing complex sectoral interactions and supply chain dynamics. For instance, production network models generally offer a more detailed and complex view of inter-sectoral linkages. By building upon existing work, Frankovic (2022) shows how these frameworks can be adapted to explore the macroeconomic consequences of energy pricing strategies, such as the impact of both global and local carbon pricing. This research relies on the World Input-Output Database (WIOD) to calibrate trade between seven regions across 56 sectors. On the climate side, EXIOBASE's sectoral greenhouse gas emission accounts are used to calibrate emission costs for different carbon prices.

40 See Sargent and Stachurski (2022) for a comprehensive presentation of the theoretical foundations of the discipline of networks theory, together with some economic application that highlight the importance for economic modelling.

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