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The Macroeconomic Implications of Climate Change for Central Banks

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Abstract

Climate change is one of the most significant issues affecting the global economy. As a small open economy, Ireland is particularly vulnerable to economic spillovers from the international impact of climate-related risks. In recognition of the potential of these risks to affect their ability to maintain both price and financial stability, many central banks, including the Central Bank of Ireland, have started to embed these risks in their analytical and modelling frameworks. In this *Article*, we explore the key challenges presented by climate change for central banks. We first examine the economic implications of the risks associated with continuing climate change and abrupt mitigatory actions. We then review how these risks could affect the transmission of monetary policy through conventional channels. Finally, we discuss how the Central Bank's analytical framework needs to adapt and suggest that a suite-of-models approach offers the most practical and effective way of addressing these issues.

¹ Irish Economic Analysis Division. The views expressed in this article are solely the views of the author and are not necessarily those held by the Central Bank of Ireland or the European System of Central Banks. The author would like to thank James Carroll, Mark Cassidy, Thomas Conefrey, Sharon Donnery, Neil Lawton, Martin O'Brien, Gerard O'Reilly and Gillian Phelan for helpful comments.

1. Introduction

Climate change is one of the most significant structural forces affecting the global economy (Lane, 2019). In particular, meeting the goals set by the Paris Agreement, and the associated requirement of achieving net zero emissions, will necessitate a deep, and in some cases disruptive, shift in production processes and consumer preferences away from carbon-intensive goods and production methods towards more sustainable alternatives. At the same time, the rising frequency and severity of extreme weather events raises uncertainty about the future distribution of economic shocks hitting the economy.

The economic analysis of the potential impact of climate change focuses on two types of risks: 'physical' and 'transition'. Physical risks relate to economic costs and financial losses that stem from higher temperatures and more frequent and extreme climate events (BCBS, 2021).² In terms of long-term warming, the global average near surface temperature has risen by over 1.1°C relative to pre-industrial levels and the continued anthropogenic emissions of greenhouse gases (GHGs) are projected to lead to further increases in temperature over the next century (Kaufman et al, 2020).

The ongoing rise in average temperatures will likely lead to more regular occurrences of heavy precipitation, higher sea levels, and potentially more severe Atlantic storms that could generate storm surges and extreme waves (IPCC, 2014).³ These events could significantly increase flooding risks in countries like Ireland and thereby raise the economic costs of climate change by damaging property and infrastructure.⁴ Figure 1 shows that the cost of flooding and other extreme climate-related events over that last four decades has been sizeable across the euro area. In the case of Ireland, the cumulative costs are close to 2.3 per cent of modified GNI.

To mitigate global warming and reduce the severity of the impact of climate change, economies need to transition to a low-carbon economy by reducing GHG emissions (IPCC, 2014). However, addressing the risks from

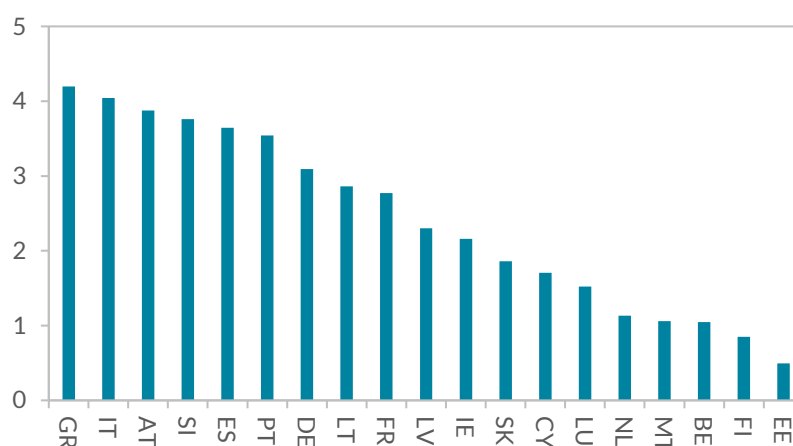
² These include tropical cyclones and hurricanes, extra tropical cyclones, convective phenomena such as tornadoes and severe thunderstorms, mesoscale phenomena such as polar lows, floods, drought, and heatwaves (Stephenson, 2008).

³ For example, Met Éireann projects that the frequency of heavy precipitation events during autumn and winter months in Ireland could rise by 20 per cent (Nolan et al, 2017).

⁴ These economic costs are in addition to the harm to human health and well-being, cultural heritage, and the environment that is caused by these events.

climate change is particularly challenging due to the so called “tragedy of the horizon” which posits that while mitigation policies may lead to output losses in the medium term, the benefits accrue over the longer term due to the avoidance of much greater damage from climate change over that longer horizon (Carney, 2015). The long term nature of these risks differs from the typical planning and risk management horizons of consumers, firms, governments and policy organisations. Accordingly, as climate-related risks have a different frequency and temporal distribution compared to other types of macroeconomic and financial risks, tackling these risks from a policy perspective requires concerted effort and leadership (Lane, 2019).

Figure 1: Cumulative GDP losses due to extreme weather and climate-related events 1980-2019 (% of 2019 GDP)



Source: European Environment Agency, AMECO, Drudi et al (2021)

Notes: Losses for Ireland are calculated in terms of modified GNI (GNI*).

In response to the risks posed by climate change, countries representing 70 per cent of global emissions and GDP have set targets for net zero emissions by 2060 at the latest (IEA, 2021). Both the European Commission and Irish government have announced plans to reach net zero emissions by 2050. These plans include policy measures that will increase the price of carbon, stimulate innovation and enhance the energy efficiency of firms and households. However, the process of adjustment towards a low-carbon economy can give rise to certain risks (‘transition risks’). Several factors could slow or disrupt the transition, and adversely affect the economy and financial system (BCBS, 2021). For example, abrupt or uncoordinated carbon pricing policies could lead to large cost increases for carbon-intensive firms and to a sharp depreciation of assets values of firms in carbon-intensive sectors. The resulting fall in the

collateral values of these ‘stranded’ (or unusable) assets could significantly reduce investment and generate financial stability concerns. Risks may also arise from unanticipated technological breakthroughs that lead to structural shifts in production processes and render carbon-intensive technologies obsolete. Finally, short-term transition risks can stem from sudden changes in the expectations of consumers, firms or financial markets about future policies or technologies, which can lead to a spike in risk premia for firms in the affected sectors (Vermeulen et al, 2018).

There is therefore considerable heterogeneity in the exposure of sectors to transition risks.⁵ Table 1 illustrates this heterogeneity for Ireland. It shows that Irish emissions, whether in terms of all GHGs or just CO₂, are mainly driven by a small number of sectors including agriculture, electricity and manufacturing.⁶ With the exception of manufacturing, these sectors also represent a relatively small share of total gross value added.

Table 1: Irish Sectoral Emissions and Energy Intensities in 2018

Sector	GVA Share (%)	GHG Share (%) ⁷	CO ₂ Share (%)	GHG Intensity (Kg/€)	CO ₂ Intensity (Kg/€)	Energy Intensity (%)
Agriculture, forestry, and fishing	1	43.1	4.8	7.2	0.4	18.7
Transportation and Storage	2.1	6.8	12.3	0.5	0.5	52.1
Electricity, gas, steam, air con. Supply	1.1	19.9	35.3	3.1	3.0	53.9
Manufacturing	35.4	16.1	29.1	0.1	0.1	1.5
Water supply, sewerage, waste mgt.	0.4	3.9	3.3	1.5	0.7	12.8
Wholesale and retail trade	7.8	2.5	4.7	0.1	0.1	2.9
All sectors	100	100	100	0.2	0.1	3.2

Source: CSO and own calculations

⁵ While this analysis focuses on sectoral vulnerabilities, there is also substantial heterogeneity in exposures to transition risks at the household level. For example, Tovar Reanos and Lynch (2019) show that the share of expenditure on heating and lighting for the lowest quartile income households in Ireland is almost three times that of the highest.

⁶ The emissions data are adjusted for non-territorial activities to calculate emissions on a territorial basis. See Conefrey et al (2022) for further details.

⁷ GHGs emissions include emissions from carbon dioxide (CO₂), methane, nitrous oxide, hydro-fluorocarbons, perfluorocarbons, nitrogen trifluoride and sulphur hexafluoride in CO₂ equivalents.

The energy and emission intensities of production in these sectors can be used to indicate the potential vulnerability of each sector to policy- or regulatory-induced changes in the price of emissions.⁸ Although manufacturing accounts for between 12 and 18 per cent of sectoral emissions, its energy and emissions intensities are close to the mean for all sectors. In contrast, the water supply, sewerage and waste management sector accounts for a relatively small share of emissions but has an energy and emissions intensities well above the average. Output in agriculture has the highest GHG emission intensity due to its emissions of methane, while its carbon dioxide emissions intensity is low.⁹ The transportation and energy generation sectors have the highest energy intensities. This suggests that these sectors, together with the emissions intensive agriculture and water and waste management sectors, could be the most affected by transition risks in the short to medium term

While fiscal authorities control the primary policy instruments that can mitigate climate-related risks, there is a growing recognition among central banks that these risks could affect their ability to meet price and financial stability objectives (Lagarde, 2021). Moreover, the broad-ranging impact of climate change, as well as the important role that central banks can play in financing the transition, places it firmly in the bailiwick of central banks (Makhlouf, 2021).

In this context, although there is broad acknowledgement that climate-related risks could have an increasingly adverse impact on the economy, relatively few studies examine the particular channels through which these risks affect the conduct of monetary policy, or the implications of these risks for central banks' analytical frameworks.¹⁰ In this *Article*, we explore these issues. We first outline the main channels through which physical and transition risks affect output and inflation, and consider the key policy interventions that can mitigate these risks. We then examine how climate change presents analytical challenges for assessing the short-to medium-term trajectory of the economy and how this, together with its impact on the natural rate of interest, may complicate the calibration of the monetary stance. We also consider how climate change may alter the transmission of

⁸ The energy intensity of production is calculated as the share of the sector's energy expenditure in its GVA. The GHG and CO₂ emissions intensities of production are calculated by dividing emissions in kilograms by gross value added in constant prices.

⁹ See Conefrey et al (2022) for a discussion of the carbon intensity of employment across sectors in Ireland.

¹⁰ Notable exceptions are Batten et al (2016) and Drudi et al (2021).

monetary policy through conventional channels, which could change how central banks respond to aggregate economic shocks.

Finally, we discuss the conceptual and technical challenges of incorporating climate risks in the models typically used by central banks for policy and scenario analysis. These challenges stem from the long-term and persistent nature of the shocks arising from climate change, the global nature of the climate change externality, uncertainty about the stability of economic relationships, and the potential for non-linearities to amplify the impact of climate-related shocks. (Batten, 2018).

The focus of our analysis is on the macroeconomic impact of climate change. We therefore abstract from the important impact of climate change on the stability of the financial system. The interaction between climate and financial stability risks is examined in Donnery (2019), Lane (2019) and Madouros (2020), while the impact of climate change on bank supervision is discussed in Sibley (2021). This *article* accordingly tries to complement their analysis by providing a macroeconomic and monetary perspective on the broader implications of climate change for central banks.

The remainder of this article is structured as follows. Section 2 outlines the current policy and institutional context framing the transition to net zero. Section 3 presents an overview of the channels through which physical and transition risks can affect the economy, and examines the role of different transition policies. Section 4 discusses how these risks could affect the calibration and transmission of monetary policy, while Section 5 considers how they can be incorporated in the macroeconomic models typically used by central banks. Section 6 concludes.

2. Policy and Institutional Context

Carbon pricing policies represent a key component of the EU's strategy to combat climate change. Since 2005, the Emission Trading System (ETS) has regulated the emissions of entities involved in power and heat generation, energy intensive industrial activities, and aviation, which combined comprise 41 per cent of the EU's total emissions.¹¹ This 'cap-and-trade' system sets regulatory limits, or 'caps', on the total amount of certain GHGs that can be emitted in a

¹¹ The European Commission is currently considering proposals to include road transport, shipping and buildings in EU ETS.

given year by these entities. Emissions permits are then issued that are consistent with that cap and these can be traded or auctioned between firms. The cap is reduced over time so that emissions fall. Since the introduction of the ETS, total emissions of the in-scope sectors have fallen by almost 43 per cent.

In addition to the ETS, European Commission has adopted a series of legislative proposals, as part of the 'European Green Deal' outlining how it intends to achieve net zero emissions in the EU by 2050. Through the 'fit-for-55' proposals it has also established an intermediate target of a minimum 55 per cent reduction in GHG emissions *relative to 1990 levels* by 2030 (European Commission, 2021). One of the primary policy vehicles achieving these targets and for financing the transition is the €750 billion Next Generation EU (NextGenEU) fund. At least 37 per cent of the resources available through NextGenEU are ring-fenced for climate and biodiversity projects.¹²

While Ireland is subject to EU emissions regulations such as the ETS, it has also announced its own plan to combat climate change. *Climate Action Plan 2021* documents the Irish government's strategy for achieving a 51 per cent reduction in GHG emissions *relative to 2018 levels* by 2030 and reaching net zero emissions by 2050 (DECC, 2021). Table 2 outlines the emission reduction requirements and key policies proposed for each sector under the plan.

Table 2: Climate Action Plan: Emissions Reductions Targets and Policies

Sector (reduction)	Policy/Targets
Energy (62-81%)	• Increase renewable electricity – wind and solar up to 80% • Support scheme for micro-generation (plus feed-in tariffs) • New connectors/interconnections to Northern Ireland, Great Britain, and the EU • Complete the phase-out of coal and peat-fired electricity generation
Transport (42-50%)	• Increase the number of EVs to circa 1 million by 2030 • Enable 500,000 daily sustainable travel journeys by 2030

¹² Ireland will receive approximately EUR 500 million for climate-related initiatives including the retrofitting of public buildings, electrification of commuter rail and rehabilitation of peatlands (DEPR, 2021a).

	• Expansion of rail services, and cycling and walking infrastructure • Increase the use of biofuels in transport
Business (29-41%)	• Introduce new obligation to ensure energy for heat comes from renewable sources • Prioritise longer-life and lower-carbon cement blends in public contracts • 80% of cement energy needs will come from alternative fuels and waste recovery • 50-60% of the total fuel demand for heating will be met by carbon-neutral heating.
Buildings (44-56%)	• Blend low-cost loans with SEAI grants to make retrofits affordable • Retrofit 500,000 homes to B2 BER / cost optimal equivalent or carbon equivalent • Install 400,000 heat pumps in existing homes and 250,000-280,000 in new homes • Roll out district heating scheme

Source: Climate Action Plan 2021

With the proposed introduction of carbon budgets, emissions in each sector would be required to fall by prescribed amounts by 2030, including by up to 81 per cent in the energy sector. The plan also includes a wide-ranging set of mitigation policies and regulatory changes. These include measures to boost energy efficiency through a large-scale retrofitting of the housing stock and commitments to raise the proportion of renewable electricity to 80 per cent by the end of the decade. An important driver of the decarbonisation process will be the legislated increase in the carbon tax, which will rise from its current level of €41 per tonne to €100 per tonne by 2030. The climate action plan is complemented by the €165 billion *National Development Plan 2021-2030*, which, through the electrification of transport and construction of low-carbon infrastructure, could facilitate a shift in the long-term energy mix of production and consumption towards sustainable alternatives (Krogstrup and Oman, 2019; DEPR, 2021b).

From a policy perspective, the intersection of climate change with areas of competency other than those of governments' is now widely recognised. In this context, the European Central Bank and the European System of Central Banks recently completed a monetary policy strategy review, which included an exploration of the channels through which climate change interacts with their collective primary and secondary mandates of, respectively, maintaining price stability

and supporting the policies of the European Union.¹³ It also published an action plan outlining its goals in terms of assessing the vulnerability of financial institutions to climate-related risks, augmenting its modelling frameworks to incorporate the impact of these risks on the economy, and adjusting its collateral operations and asset purchase programmes to include climate change criteria (ECB, 2021).

The challenge presented by climate change for central banks' ability to achieve their mandate is highlighted in the Central Bank of Ireland's new *Strategy* for the 2022-2026 period (CBI, 2021). In particular, the strategy emphasises the importance of being 'future-focused' in terms of anticipating how climate-related risks could inhibit its ability to meet its mandate, and adopting a 'safe-guarding' approach to monitoring and mitigating the potential impact of these risks on price and financial stability. The latter includes the development of analytical frameworks that capture appropriately the implications of both physical risks and primary policy mitigants on the economy. To operationalise this strategy, the Central Bank has implemented or participated in a number of initiatives including the establishment of a Climate Change Unit as a central hub for coordinating the Bank's work on climate change and becoming a member of the Network for Greening the Financial System (NGFS).¹⁴

3. Climate-Related Risks and the Transition to Net Zero

Physical and transition risks can be the source of significant shocks to the economy. In this section, we outline the channels through which these risks are transmitted and discuss how the shocks generated by the risks differ in their timing and persistence. We then examine the mix of climate-related policies that can minimise the economic cost of the transition to net zero emissions.

¹³ See Corbisiero and Lawton (2021) for a discussion of the key findings from the *Strategy Review*.

¹⁴ The NGFS is a consortium of central banks and supervisors that was formed in 2017 to "help strengthen the global response required to meet the goals of the Paris Agreement and to enhance the role of the financial system to manage risks and to mobilise capital for green and low-carbon investments" (NGFS, 2019a).

3.1 Transmission Channels of Climate-Related Risks

Table 3 summarises how the shocks associated with each type of climate risk affect both the demand and supply sides of the economy.

Extreme events reduce output by damaging the productive capacity of the economy and causing disruption to the supply of intermediate goods.¹⁵ These phenomena can lower consumption and investment by damaging household and firm assets, respectively. For example, if insurers consider these risks uninsurable, the losses arising from these events will have a larger impact on the balance sheets of firms and households, and likely reduce their ability to borrow due to lower collateral values (Donnery, 2019). Inflation levels (and volatility) may rise due to goods shortages.

Gradual warming is likely to have a negative impact on output, with higher temperatures reducing labour supply, labour productivity and investment being diverted towards adaptation technologies (such as air conditioning or insulation) and away from potentially more productive areas that could stimulate innovation (Fankhauser and Tol, 2005; Dell et al, 2014). For example, current evidence suggests that labour productivity falls by 2 per cent per degree above humans comfort temperature of between 18°C and 22°C (Heal and Park, 2016). The shift in consumer preferences towards low-carbon products and the change in comparative cost advantages across countries is likely to result in changes in relative prices. Rising sea levels, along with other geophysical changes, could also alter trade patterns by disrupting existing trade routes.

Transition risks arising from uncertainty about the trajectory of future policies reduce consumption and investment. In addition, cross-country differences in the stringency of climate policies can cause shifts in comparative cost advantage and thereby affect trade in intermediate and final goods. The supply potential of an economy might also be adversely affected by asset stranding and worker displacement in carbon-intensive sectors.

¹⁵ While productivity may increase if firms in the reconstruction phase invest in newer technologies, the empirical evidence on the recovery of economies from extreme events suggests productivity growth does not recover to its previous trend in the aftermath of the event (Von Peter et al, 2012; Hsiang and Jina, 2014).

Table 3: Macroeconomic risks from climate change

Shock	Variable	Extreme Events	Gradual warming	Transition Risks
Demand Shocks	Investment	Reconstruction. Investment delays from uncertainty about climate risks.	Change in preferences towards greener products	Crowding out' from climate policies. Uncertainty about transition path.
	Consumption	Uninsured damage to property could cause permanent decrease in wealth.	Change in preferences towards greener products	Crowding out' from climate policies. Shift towards greener consumption.
	Trade	Change in food prices. Disruption to trade flows.	Trade routes disrupted due to geophysical changes.	Distortions from asymmetric climate policies.
Supply Shocks	Labour Supply	Loss of hours worked due to natural disasters	Loss of hours worked due to extreme heat. International migration	Unemployment due to sectoral composition changes.
	Energy, food and other inputs	Food and other input shortages. Disruption to transport and production chains.	Decline in agriculture productivity and yields.	Risks to energy supply.
	Capital stock	Damage due to extreme weather.	Diversions of resources from productive investment to adaptation	Resources diverted to mitigation activities. Stranded assets.
	Technology, Productivity	Destruction of capital and infrastructure. Diversion of resources from productive investment to adaptation capital	Diversions of resources from innovation to adaptation capital. Lower labour productivity due to heatwaves.	Uncertainty about the rate of innovation and adoption of clean energy technologies.
Aggregate impact on Output and Inflation	Output	Physical destruction of capital. Supply chain disruption. Crop failures.	Investment diverted to mitigation. Lower labour productivity.	Frictions from distortive transition policies. Policy uncertainty.
	Inflation	Increased inflation volatility, particularly for food, housing and energy.	Relative prices changes due to shifting consumer preferences and changes in comparative cost advantages.	Prices affected by transition policies, policy uncertainty, technological changes and shifts in consumer preferences.
Timing of Impact		Short to medium run	Medium to long run	Short to medium run

Source: Adapted from Batten (2018) and Drudi et al (2021)

A key variable that determines the stance of monetary policy is the natural rate of interest, denoted r^* . The natural rate of interest represents the real interest rate that is consistent with output equalling potential and stable inflation (Woodford, 2003; Laubach and Williams, 2003). When r^* is low,

central banks have less room to provide monetary accommodation through conventional monetary policy and thus face a higher probability of hitting the effective lower bound on interest rates (Mertens and Williams, 2019). The economic disturbances precipitated by climate-risks could put persistent downward pressure on r^* . First, the reduction in the effective supply of labour from emigration, and higher morbidity and mortality, raises the amount of capital per worker and reduces its marginal product over the long term.¹⁶ This would lower r^* . Second, the decline in productivity growth from shocks driven by physical and transition risks could increase savings and reduce the natural rate, as shown in the Ramsey growth model (Ramsey, 1928). Third, uncertainty about future climate-related risks can lead to higher risk premia, which can lower r^* by increasing the propensity to save, and the demand for safe assets, while reducing willingness to invest in risky assets (Caballero and Fahri, 2018; Bansal et al, 2019).

As discussed below, however, the downward pressure on r^* from the impact of climate change could be mitigated by higher government spending. In addition, while the diversion of resources from innovation towards adaptation may lower productivity growth and thus r^* , this could be outweighed by higher productivity growth arising from investment in green technologies. In this case, the a priori impact on r^* is ambiguous.

Table 3 also shows how the timing of the impact of economic shocks varies according to each type of risk. As discussed in the next section, the differential timing and persistence of economic shocks driven by climate-related risks presents particular analytical challenges for central banks. Extreme weather events happen unexpectedly and therefore affect the economy in the short to medium run through the channels outlined above. In contrast, the economic impacts from global warming tend to manifest more slowly, with the full severity of its impact on the productive capacity of the economy arising over the medium to long run.

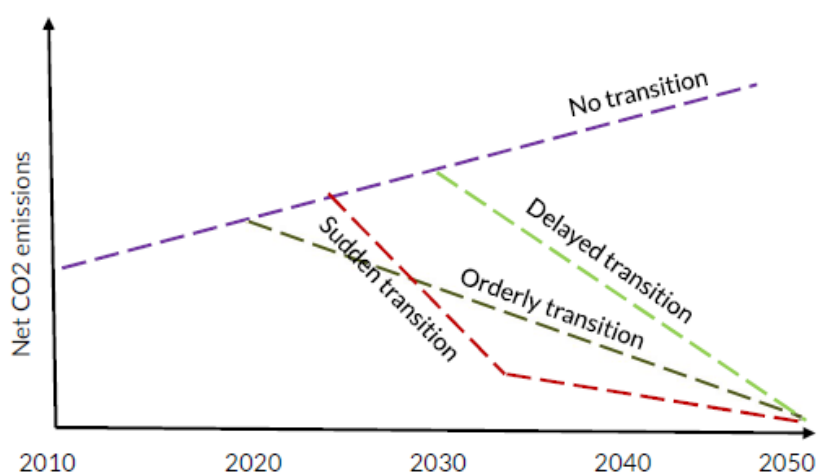
For transition risks, the sequencing of policy actions and pace of technological progress will heavily influence their impact on the economy. Figure 2 depicts the case of an 'orderly' or gradual transition, in which the gradual rise in the price of carbon, allows firms sufficient time to reduce the carbon-intensity of their production processes, while technological progress increases the availability of low-carbon substitutes and mitigates

¹⁶ The impact on r^* from migration is clearly heterogeneous across countries, as capital per worker would fall in those countries that receive migrants.

any sharp rise in energy prices. However, we can also consider scenarios in which the transition to a carbon-neutral economy is ‘disorderly’. Figure 2 also shows two variants of the latter: a ‘sudden’ transition scenario in which the rapid shift away from carbon-intensive production leads to a spike in energy prices and a reduction in the supply of energy, and a ‘delayed’ transition scenario in which climate action is postponed until 2035 before highly stringent mitigation policies are introduced resulting in a sharp adverse productivity shock.

In these disorderly scenarios, investors may shift their portfolios away from ‘brown’ sectors resulting in the assets of firms in those sectors becoming ‘stranded’ or suddenly depreciating in value. Higher relative prices for carbon-intensive products may also lead to customers substituting away from these goods towards ‘greener’ alternatives.¹⁷ These sudden adjustments could lead to a significant fall in aggregate output in the short to medium term.

Figure 2: Orderly and Disorderly Transition Paths to Net Zero



Source: Allen et al (2020)

3.2 Primary Policy Actions for the Transition to Net Zero

Transition risks associated with the path to a carbon-neutral economy can be mitigated through the expeditious implementation of a range of policies aimed at initiating changes in behaviour and facilitating green innovation.

¹⁷ As discussed below, asset stranding can also lead to a rise in corporate insolvencies and increased risks to financial stability.

Carbon pricing is widely seen as one of the key policy responses to achieving an ‘orderly’ transition.¹⁸ By internalising the climate change effects associated with carbon emissions, carbon pricing incentivises household and firms to switch from high- to low-carbon activities (de Mooij et al, 2012; Drudi et al, 2021).¹⁹ Moreover, predictable and gradual increases in carbon prices provide a signal to investors to shift resources from ‘brown’ to ‘green’ sectors and can therefore spur investment in low-carbon technologies and infrastructure (Aghion et al, 2009).

The sectoral shifts in production that are integral to the transition to a low-carbon economy can lead to worker dislocation in the short term. Higher carbon prices can also reduce real household incomes and can have a proportionately larger impact on low-income households (De Bruin et al, 2019b). Accordingly, recycling carbon tax revenues in the form of transfers to the most affected households and supports for labour market adaptation can help reduce the economic cost of the transition for those that are proportionately most affected (Black et al, 2021). Carbon revenues could alternatively be used to lower more distortionary taxes such as those on wages and profits, potentially yielding a ‘double dividend’ of reducing emissions while boosting growth (Bovenberg, 1999).

As policy instruments aimed at reducing GHG emissions, carbon taxes and cap-and-trade schemes with full coverage are broadly equivalent as both can achieve the same carbon price. While carbon taxes generate a more stable trajectory for carbon prices, the associated reduction in emissions is less predictable due to uncertainty about the future technologies and abatement costs (Drudi et al, 2021). In contrast, as cap-and-trade schemes impose regulatory ceilings on emissions that fall over time, they tend to lead to more stable emissions paths but more volatile carbon prices (Aldy and Stavins, 2012).

One concern that frequently follows the introduction of carbon pricing policies is that, in the absence of international coordination, higher domestic carbon prices could adversely affect a country’s

¹⁸ Carbon pricing policies also include the removal or phasing-out of fossil fuel subsidies. See De Bruin et al (2019a) for an analysis of the impact on the Irish economy of policies that simultaneously lower fossil fuel subsidies and raise carbon taxes.

¹⁹

competitiveness.²⁰ This is a corollary of the ‘pollution haven’ hypothesis, which posits that carbon-intensive production could shift to countries with less stringent climate policies, resulting in ‘carbon leakage’. This relocation of production if on a large scale could create pollution havens in the host economies (Levinson and Taylor, 2008). Empirical estimates of the pollution haven effect for EU countries suggest that emissions rise by up to 30 per cent in the rest of the world for each unit of EU emissions avoided, with leakage rates highest for emissions-intensive and trade-exposed industries such as cement, aluminium, steel and iron (Chen et al, 2020).

Carbon leakage can be mitigated via the implementation of a carbon border adjustment mechanism (CBAM), whereby countries impose tariffs on imports from countries with less stringent environmental policies (Parry et al, 2021). However, challenges to implementing a CBAM include the difficulty in measuring the emissions embodied in imports due to data constraints, the administrative burden, and the potential for retaliation.²¹

Effective carbon pricing regimes typically have several core features (IMF, 2019). First, the carbon price covers a broad range of emissions, as well as other environmental costs including traffic congestion and local air pollution.²² Carbon prices should also reflect co-benefits or additional economic benefits that stem from climate policies, including their impact on innovation, resource allocation and productivity growth (Batten et al, 2020). Second, the trajectory of carbon prices over time should be gradual and predictable to spur investment in low-carbon technology. Third, the revenue generated from carbon pricing policies should be used efficiently, while some redistribution may also be needed to protect the real living standards of low-income households (Drudi et al, 2021).

²⁰ An alternative view, as encapsulated in the ‘Porter hypothesis’ (Porter, 1991; Porter and van der Linde, 1995), is that environmental regulations could lead to gains in international competitiveness by providing incentives for ‘green’ innovation that would not have happened in the absence of these regulations. However, there is little empirical evidence to support this view (Dechezlepretre and Sato, 2014).

²¹ An alternative approach to reduce leakage would be for large economies to establish a “Green Club”, which would set an international floor on carbon prices (Chen et al, 2020).

²² An important feature of co-benefits is that they can be realised in the medium run, while the impact of mitigation policies on climate change likely only materialises in the long run (Batten et al, 2020).

However, carbon pricing policies are only one of the necessary components of a successful transition to a low-carbon economy. Governments also have a key role in supporting the transition through complementary structural policies that facilitate the shift away from carbon-intensive activities. Investment in public transportation and urban infrastructure is particularly important as this type of public expenditure can lock in the long-term energy mix for the economy and embed behavioural changes initiated by higher carbon prices (Krogstrup and Oman, 2019).

Governments can influence the speed and timing of the transition through policies aimed at expediting the diffusion of green technologies, worker retraining, and supporting research and innovation. Governments may also have a role in the development of clean technologies, as the knowledge produced in development process is only partially excludible so its social benefits are not fully captured (Batten, 2018).²³ Similarly, the uncertain returns, large sunk costs, network effects and long time-horizons associated in particular with the development of these technologies rationalise government intervention (Acemoglu et al, 2016; Mazzucato and Penna, 2016; Hotte, 2020). Government support can then be withdrawn once the technologies are sufficiently mature (Acemoglu et al, 2012).

As discussed above, the economic shocks generated by climate-related risks could put downward pressure on the natural rate of interest, r^* . However, fiscal policy related to the transition could offset some of these forces. By increasing investment in innovation and ensuring an orderly transition, governments can mitigate the uncertainty-driven rise in risk premia and boost future productivity growth. In addition, recycling carbon tax revenues to increase transfers to low-income households and reduce other distortionary taxes could spur consumption and investment. Both of these measures would mitigate the potential decline in r^* from physical and transition risks.

²³ Dechezlepretre et al (2017) find that knowledge spillovers, as measured by patent citations, are significantly higher for 'green' compared to 'brown' technologies. They suggest that the knowledge spillover effect of low-carbon technologies is comparable to that from information and communications technologies (ICT).

Finally, there are some concerns that the increase in transition-related government investment, together with the reconstruction and adaptation costs from global warming and more extreme weather events, will have significant implications for the stability of public finances, particularly in fiscally weaker countries (Darvas and Wolff, 2021; Zenios, 2021). In terms of the likely scale of expenditure, the European Green Deal assumes that additional (public and private) investment of close to two per cent of GDP per annum over the next decade will be needed to meet the EU's 2030 climate and energy targets. The extent to which the required increase in government spending will be financed by debt is uncertain (Pisani-Ferry, 2021). A key issue is how revenues from carbon taxes are recycled. If these revenues are ring-fenced to finance higher investment, support innovation, and reduce distortionary taxes, growth effects could help mitigate risks to fiscal sustainability (NGFS, 2021).

4. Climate Change and Monetary Policy

Central banks adopt a forward-looking approach to assess the key risks to meeting their primary objective of price stability over the medium term. Consequently, the calibration of the monetary stance requires identifying the nature, persistence and magnitude of shocks affecting the economy. As economic shocks can originate from climate-related risks over the time horizon that the stance is assessed, these risks could increasingly be of concern to monetary policymakers. We now examine how climate change could affect the conduct of monetary policy and the ability of central banks to achieve their primary mandates.

4.1 Analytical Challenges

As outlined in Table 3, climate change can affect the nature, timing and persistence of economic shocks hitting the economy. While climate-related shocks can affect both the demand and supply sides of the economy, disentangling one from the other is particularly challenging from an analytical perspective. Moreover, little is known about how these shocks interact and whether there are amplification mechanisms in these interactions that generate non-linear impacts on the economy.

From a monetary policy perspective, climate-related risks can have differing implications for how a central bank should respond depending on how they affect the economy. For example, physical risks such as extreme weather events that affect the supply side of the economy will tend to lower output and raise inflation.

Accordingly, and in contrast to demand side shocks, central banks face a trade-off between stabilising inflation and boosting economic activity. The typical monetary response in this case is calibrated based on the magnitude and persistence of the shock (Drudi et al, 2021). Central banks will tend to ‘look through’ shocks that are expected to be transitory but intervene in response to those that are likely to be persistent and feed back into inflation expectations. Climate change, by increasing the frequency, severity, and persistence of supply shocks, could therefore require a recalibration of central banks’ monetary reaction functions to incorporate the potential impact of these shocks on price stability over the medium term (Boneva et al, 2021).²⁴

In addition to physical risks, transition risks can also have implications for price stability. For example, higher carbon prices arising from carbon taxes or cap-and-trade schemes will tend to raise inflation in the short-term as low-carbon substitutes may not be readily available.²⁵ The dynamic effect of carbon policies on inflation will ultimately be determined by the transition path. For example, in an orderly transition, carbon prices rise steadily and predictably over time, thereby raising the price of carbon-intensive goods. Investment in green technologies increases the availability of low-carbon alternatives, which allows consumers to substitute away from increasingly expensive carbon-intensive goods. Therefore, the net impact of higher carbon prices on inflation should dissipate over time as the share of these goods in consumption falls. However, a persistent rise in inflation over the medium term due to carbon pricing policies may lead to tighter monetary policy in order to limit feedback to inflation expectations (Schnabel, 2022).

²⁴ The monetary policy rate typically influences economic activity over the short to medium term. However, if climate change shocks have a duration longer than the typical horizon of monetary policy, central banks may be unable to fully reverse their impact on the economy (Coeure, 2018; Villeroy de Galhau, 2019).

²⁵ See Kanzig (2021) for evidence on the impact of carbon price shocks on inflation.

In the case of the euro area, differences in exposure to physical and transition risks suggests that climate change is likely to have heterogeneous effects across member countries. The diverse climate systems across the euro area imply differential regional vulnerability to physical risks. For example, the main physical risk affecting countries in the Northern Europe is higher precipitation which could lead to more frequent episodes of flooding. In contrast, countries in Central and Southern Europe are most vulnerable to higher temperatures and drought (European Environment Agency, 2017). While euro area countries are members of the EU's emissions trading scheme (EU ETS) which covers approximately 40 per cent of the EU's GHG emissions, differences in other transition policies and initial levels of emissions, could lead to considerable cross-country heterogeneity in the impact of transition risks.

4.2 Potential Impact on Monetary Transmission Channels

Table 4 from Drudi et al (2021) outlines how each type of climate-related risk could interact with the main transmission channels of monetary policy.²⁶ As the relationship between climate change and monetary policy is a nascent area of research, the discussion here focuses on the conceptual issues and abstracts from the potential strength of the impacts on each channel. In the context of the euro area, it is also important to note that there is likely to be considerable cross-country heterogeneity in the impact of climate-related risks on these channels due to differences in countries' exposures to each type of risk.

The *interest rate channel* captures how a change in policy rates directly affects money-market rates and, indirectly, banks' lending and deposit rates. The change in short-term rates will also tend to raise long-term rates through the expectations hypothesis. As discussed above, the increase in risk aversion and uncertainty that stems from both physical and transition risks can lead to higher precautionary savings by households and lower investment by firms. A given change in interest rates will consequently have a smaller impact on the real economy, all else equal. The potential fall in the interest rate sensitivity of aggregate demand would therefore imply

²⁶ See Beyer et al (2017) for an overview of the transmission channels of monetary policy.

a weakening of one of the key transmission channels of conventional monetary policy.

The *credit channel* reflects the importance of banks' balance sheets for the transmission of monetary policy. A policy-induced fall in interest rates increases borrowers' net worth by increasing the net present value of their assets, thereby raising the collateral values of such assets and increasing borrowers' ability to obtain credit.

Climate-related risks can weaken the transmission of monetary policy through the credit channel via their impact on borrower creditworthiness and collateral values, which raises borrowing constraints for firms and households. In addition, if banks' balance sheets become impaired due to higher rates of borrower default, lending risk premia may rise. Both the decline in collateral values and rise in risk premia could then lead a contraction in the supply of loans to the real economy.

As discussed above, climate-related risks could lead to a lowering of equilibrium interest rates over the longer term. In addition to other factors that have been suppressing long-term rates, this could further lower net interest margins and bank profitability. As retained earnings are a key source of capital for banks (Cohen and Scatigna, 2016), this would weaken the ability of banks to expand their balance sheets and provide credit to the real economy.

Table 4: Impact of Climate Change on Monetary Policy Transmission

	Physical Risks From more common extreme weather events and persistent warming	Transition Risks From carbon pricing and reducing emissions
Interest rate channel	Non-interest cost factors become more relevant, lowering investment and saving response to interest rate changes.	Uncertainty about timing and speed of policy response raises risk premia and volatility. Natural rate of interest affected.
Credit channel	Financial losses reduce borrower net worth and bank collateral. NPLs constrain credit supply.	Financial losses reduce borrower net worth and bank collateral. NPLs constrain credit supply.
Asset price channel	Physical risks destroy capital and residential property. Financial losses lower firm valuations.	Demand shifts across sectors and regions. Stranded assets.
Exchange rate channel	Devaluation incentive for short-term competitiveness gain. Higher volatility.	Border carbon adjustment may disrupt trade routes and global value chains.

Expectations channel	Monetary policy less predictable since shock persistence uncertain, blurring supply/demand.	Time-consistent transition policies reduce monetary policy credibility and effects.
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Source: Drudi et al (2021)

The *asset price channel* captures how changes in policy rates affect the economy through changes in asset values. Climate-related risks could affect the transmission of monetary policy through this channel in several ways. More frequent extreme weather events could lead to greater volatility in financial markets due to their impact on the values of insurance companies, banks and non-financial firms. Physical risks can also reduce the value of residential and commercial property in exposed areas, which would lower the net worth of households and firms in those areas. Sudden changes in transition policies or in investor sentiment can lead to asset stranding and large write-downs in firms' capital values. These shocks to net worth are likely to adversely affect investment and consumption.

The *exchange rate* channel captures how an increase in domestic policy rates relative to policy rates in other countries can lead to a real appreciation of the domestic currency and reduce net exports. However, the increase in uncertainty and economic volatility due to climate change can weaken the transmission of monetary policy through the exchange rate channel. As climate-related risks can disrupt trade and alter the international pattern of production, the elasticity of demand with respect to a change in the exchange rate may fall over time.

Finally, the *expectations channel* captures the impact of monetary policy on expectations of future interest rates and inflation. Expectations of future interest rates are a key component of important economic decisions that have a long-term horizon such as fixed capital investment and durable consumption.²⁷ As climate change raises uncertainty about the future distribution of economic shocks, central banks' ability to guide private sector expectations about the future path of policy rates may also weaken and lead to higher inflation volatility.²⁸ In particular, the difficulty of

²⁷ See Blinder et al (2008) for a discussion of the role of expectations in the conduct of monetary policy.

²⁸ See Weitzman (2009) for a discussion of the potential distribution of climate risks.

differentiating between shocks according to their nature and persistence could lead to policy errors, which would further complicate communication of the medium-term policy stance. Similarly, climate-related risks could further affect the expectations channel if, for example, carbon pricing policies are projected to generate persistently higher inflation or if the downward pressure on r^* is likely to constrain future monetary policy.

5. Challenges for Macro-Modelling

This foregoing discussion has highlighted the potential impact of climate-related risks on the economy and the conduct of monetary policy. From an analytical perspective, this implies that central banks' forecasting and macro-modelling frameworks need to be modified to account for these risks. In terms of forecasting, there is evidence that including weather variables and changes in carbon prices significantly improves the performance of nowcasting and short-term forecasting models, particularly in relation to food and energy prices.²⁹ In this section, however, we focus on structural models that can be used by central banks for policy-relevant scenario analysis. We assess how traditional workhorse macroeconomic models can be augmented to capture the transmission to climate-related risks to the economy and financial system.³⁰ We also consider the role of integrated assessment models and outline how they could be combined with structural macroeconomic models to provide a comprehensive toolkit for assessing the impact of climate change.

5.1 Structural Macro Models

Structural macroeconomic models including Dynamic Stochastic General Equilibrium (DSGE) and macroeconometric models are typically the workhorse models used by central banks for policy and

²⁹ See Huurman et al (2012) and Guorio (2015) for evidence on how including weather conditions in forecasting models of output and inflation can significantly improve the accuracy of their forecasts.

³⁰ The discussion in this section focuses on how central banks' workhorse structural macroeconomic models can be augmented to incorporate climate-related risks and how climate-economy models such as IAMs could be used as satellite models in this existing macro-modelling framework. See NGFS (2019b) for a discussion of how other types of models such as, computable general equilibrium (CGE), agent based (ABMs), stock-flow consistent (SFC), network and overlapping generation (OLG) models, could also be used to assess the economic impact of climate change.

scenario analysis.³¹ As the integration of physical and transition risks in these models is still in its infancy, a common approach to modelling these risks has not yet emerged. We now explore how these models can be augmented to incorporate the relevant transmission channels to the domestic economy.³²

Climate policy instruments such as carbon taxes affect the economy through their impact on relative energy prices and resemble a classic supply shock. To incorporate their impact on the supply side of the economy, the production function in the models needs to be modified. This can be achieved in several ways. The approach taken in Yoda (OECD, 2017) and GEM (CISL, 2015) is to allow carbon taxes, and thus energy prices, to affect total factor productivity (TFP).

An alternative approach is to include energy directly as a separate factor of production. In the NiGEM model, potential output takes the form of a production function in which a constant elasticity of substitution (CES) bundle of capital and labour is nested in a Cobb-Douglas function with energy and labour-augmenting productivity. The energy component is further decomposed into the output intensity of fossil fuels and renewables (NIESR, 2021). By modelling production in this way, disorderly transition scenarios can be generated in which the share of renewables rises abruptly due, for example, to an improvement in technology.³³ However, a key challenge that arises with this approach is the difficulty of specifying and calibrating a functional form for the substitutability between renewables and non-renewables due to data constraints. A further complicating factor is that this substitutability is likely to be influenced by technical innovation over time.

On the demand side of the model, carbon taxes affect consumer prices. As a change in the effective carbon tax rate is analogous to a

³¹ See Clancy and Merola (2016), Conefrey et al (2018), Lozej et al (2018) and McNerney (2020) for details on the Central Bank's existing suite of structural macroeconomic models.

³² While the discussion here focuses on semi-structural or macroeconometric models, the modelling challenges presented by climate-related risks are similar for DSGE models. In terms of the latter, see Golosov et al (2014) for an early DSGE model with environmental features and Drudi et al (2021) for a discussion of recent advances in environmental DSGE (E-DSGE) modelling.

³³ This shock to the share of renewable energy can be coupled with a write-down of the existing capital stock to represent the "stranding" of the capital assets of fossil-fuel intensive sectors. Vermeulen et al (2018) examine the impact of such a scenario on financial firms in the Netherlands.

change in the indirect tax rate, pre-existing transmission channels in the model for the latter can be modified to incorporate the impact of carbon price policies. The implied change in the indirect rate can therefore also quantify the impact of a carbon tax change on government tax revenues. Different expenditure rules for carbon tax revenue can also be implemented to highlight the dependency of transition paths on the composition of fiscal policy (NGFS, 2021).

Section 3 outlined how physical risks could be transmitted internationally through trade channels, while international heterogeneity in climate policies could lead to shifts in the spatial pattern of production. Transition paths could vary across countries due to differences in existing capital stocks, productivity, socioeconomic conditions, and economic structure. In addition, transition risks that lead to higher risk premia and tighter credit conditions could be transmitted through international macro-financial linkages. Accordingly, structural models should be able to capture international spillovers from climate shocks, particularly for small open economies which are most exposed to these spillovers.³⁴ As discussed below, one approach would be to use a global model such as NiGEM as a satellite model to a more detailed country model. The latter is important in providing more detail on the domestic macro-financial impact of climate-related shocks and capturing potential heterogeneity in the transmission of these shocks across sectors.

Perhaps the most conceptually challenging aspect of using structural macroeconometric models to assess the impact of climate change is that unlike typical quantitative risks assessments, the probability distribution of risks derived from historical data may be uninformative about future climate change risks (Allen et al, 2020). As climate change may generate significant structural shifts in the economy, economic relationships that held in the past, and which are embedded in the models, may not continue to hold in the future (Drudi et al, 2021). In this context, scenario analysis could be used to address these limitations (Bolton et al, 2020). This allows central

³⁴ Incorporating international transmission channels is also important for analysing issues related to 'carbon leakage' and the introduction of a carbon border adjustment mechanism. For example, in NiGEM, countries that have implemented carbon taxes can form a "Green Club" that imposes a carbon adjustment tax on imports from non-members (NIESR, 2021).

banks to incorporate model and parameter uncertainty through a range of assumptions about the long-term impact of physical risks, the timing and stringency of transition policies, the rate of technological progress, and potential shifts in consumer preferences.

5.2 Integrated Assessment Models

Integrated Assessment Models (IAMs) have been used extensively to inform policymakers and make important contributions to the economic assessment of climate change policies in several recent reports of the IPCC (IPCC, 2014, 2018). These models typically include climate, energy and economic modules, which makes them particularly useful for modelling physical and transition risks.

IAMs can be used to generate the most cost-effective path for the economy to meet an exogenous climate or emissions target and therefore do not need to specify a ‘damage function’ (Drudi et al, 2021).^{35, 36} These models simulate the changes in energy demand, land use and policy that would be needed to meet a particular temperature or emissions trajectory (NGFS, 2021). One of the key variables in IAMs is the (shadow) price of emissions, which is defined as the marginal abatement cost of an additional tonne of GHG emissions (Batten, 2018). This price is an important indicator of transition risk and is determined by the stringency and coverage of policies (‘policy intensity’), the availability of clean technologies, and consumer preferences for carbon-intensive goods.

Transition trajectories will also depend on assumptions made about the availability of carbon capture and storage (CCS) and carbon dioxide removal (CDR) processes. These processes allow for the removal or capture of carbon from the atmosphere through, for example, afforestation, soil sequestration and bioenergy crops (Batten, 2018). For similar reasons, the agriculture, forestry and land modules in IAMs provide important information on how adaptation in these sectors could lead to significant reductions in emissions intensity through carbon sequestration.

³⁵ The discussion here focuses on ‘cost effectiveness’ IAMs. These models differ from ‘cost-benefit’ IAMs in that they take the global warming target and corresponding trajectory for emissions as given rather than solving for these values endogenously.

³⁶ A damage function specifies the impact of higher temperatures on GDP and productivity and thus enables these models to capture the feedback loop between economic activity, emissions, and global warming.

Incorporating physical risks in IAMs changes the optimal transition path by raising carbon prices in short to medium term and lowering the rate of increase in the longer term (NGFS, 2021). Physical risks will also affect the transition paths of other key variables including energy use and investment. The impact of chronic physical risks on the economy can be quantified through a damage function, although there is considerable uncertainty about how to appropriately specify and calibrate these functions (Pindyck, 2013, de Bruin and Krishnamurthy, 2021).³⁷

5.3 A Suite-of-Models Approach

As IAMs and structural macroeconomic models have different strengths in terms of elucidating the channels through which climate change affects the economy, an optimal strategy for central banks from a modelling perspective might be to adopt a ‘suite-of-models’ approach that utilises the output of both types of models in a single analytical framework. In this type of modular framework, satellite IAMs and workhorse structural macroeconomic models could also be combined with Input-Output models to facilitate a sectoral analysis of the economic impact of climate change, and with loan-loss models to allow for the stress testing of banks’ balance sheets under different climate risk scenarios.³⁸

Following NGFS (2021), Figure 3 illustrates how climate-related risks could be incorporated in central banks’ macro-modelling framework through a suite-of-models approach. This framework has three components. The IAM generates scenarios for the relevant climate and economy variables including mitigation costs, carbon prices, land use, energy system characteristics, and energy-related technological progress that are consistent with a given emission pathway. The implied physical risks arising from each scenario can also be simulated post-recursively using an IAM damage function.

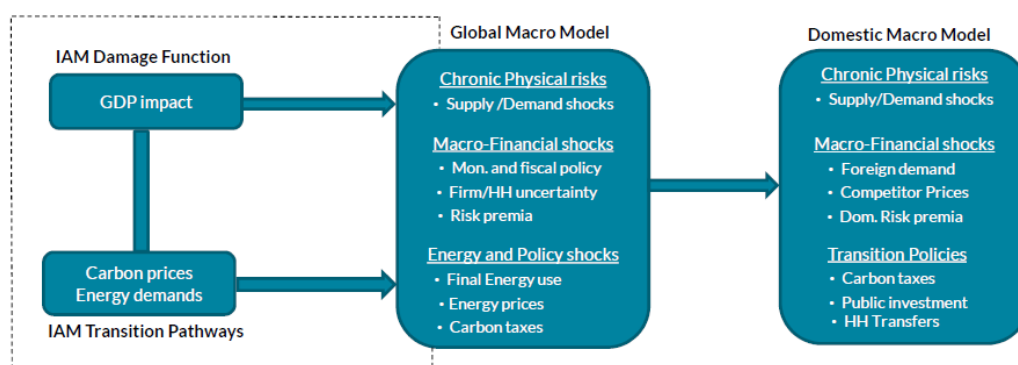
³⁷ IAMs have several limitations including their parsimonious representations of economic relations, their inclusion of only a limited number of transmission channels, and the sensitivity of results to the inclusion of particular feedback mechanisms (Batten, 2018; Dietz et al, 2021). In addition, most IAMs do not incorporate potential tipping points, non-linearities and irreversible damage from global warming and may therefore underestimate the impact of climate-related risks (NGFS, 2021).

³⁸ See Vermeulen et al (2018) and Allen et al (2020) for examples of suite-of-models approaches to stress-testing banks’ balance sheets for climate-related risks.

The second component of this framework is a global structural model. NGFS (2021) outlines how the outputs from the IAM can be mapped to a global structural model such as NiGEM in the form of shocks to supply and demand in the case of physical risks, and constraints on the trajectories of energy use, carbon prices and technological progress in the case of transition risks. As discussed above, structural macroeconomic models also need to be augmented to incorporate the transmission mechanisms through which climate-related risks affect the economy (Allen et al, 2020; Drudi et al, 2021). NIESR (2021) outlines how NiGEM has been modified to incorporate transmission channels for climate-related risks, including the impact of carbon taxes on production and consumption, changes in the energy intensity of production. Box A outlines in more detail how the NGFS has combined outputs from NiGEM and an IAM to simulate the impact of different transition scenarios on the global economy.

The final component of the framework is a structural macroeconomic model of the domestic economy. As discussed above, these models can be augmented to incorporate climate-related risks through modification of the supply, price-setting and fiscal blocks of the model. The primary advantage of integrating climate features into a model of the local economy, is the level of macro-financial detail it provides relative to a country block in a large global model, which typically is highly parsimonious and has similar specifications for each of the model's equation across countries. In contrast, a single country macroeconomic model can integrate country-specific features such as differences in the energy intensity of production or in risk premia across sectors.

Figure 3: Framework for Modelling Climate-related Risks



Source: adapted from NGFS (2021)

In Figure 3, the paths of external variables such as imported fossil fuel prices, competitor prices, and foreign demand that are generated by NiGEM can be imposed on the domestic model. These variables capture the spillover of international climate risk shocks to the domestic economy. Similar to the approach in NiGEM, physical risks can be incorporated through supply and demand shocks that are calibrated from the IAM. Finally, domestic transition risks can also be simulated through shocks to investment premia, carbon taxes and fiscal policy instruments.

Box A: The Economic Impact of Different Transition Scenarios

In this Box, we illustrate the economic impact of different transition scenarios designed by the NGFS. We focus on the international impact of each scenario to highlight the potentially large spillovers to Ireland that may arise from transition policies in other countries. These simulations can also provide insights into the key channels through which climate-related risks can affect the Irish economy and can accordingly be used to inform the ongoing process of incorporating these risks in the Central Bank's macroeconomic models. Moreover, they highlight the importance of modifying these models so that the relative importance of different transition risks can be assessed. This would then aid policymakers on how fiscal and macroprudential policies could be recalibrated to mitigate the impact of these risks on the economy and financial system.

As mentioned above, NGFS (2021) outlines how the outputs of IAMs can be combined with those of a global model such as NiGEM model can be used to estimate the impact of these scenarios on the global economy. The IAMs determine the pathways of energy, land, climate and economic systems that are consistent with a given trajectory for carbon emissions. The outputs of these models are then used as constraints on the baseline paths of GDP, population and primary energy consumption in NiGEM. Each scenario in NiGEM subsequently incorporates transition and physical shocks consistent with the IAM pathways. The former mainly comprise of shocks to carbon taxes, energy intensity and risk premia, while the latter include shocks to domestic demand, labour productivity and trend capacity.

We focus on three scenarios: a scenario reflecting an 'orderly' transition, *Net Zero 2050*, and two scenarios reflecting a 'disorderly' transition, *Divergent Net Zero* and *Delayed transition*. Table A outlines the key assumptions underlying each scenario. The policy target indicates the degree of physical risk incorporated in the scenario, with those scenarios that achieve net zero emissions by 2050 and limit global warming to 1.5°C above pre-industrial levels having the lowest physical risks. The remaining columns of

Table A indicate the degree of transition risk associated with each scenario across several dimensions. The timeliness, stringency and coverage of climate policies is a key determinant of the economic disruption generated by each transition pathways. The *Net Zero 2050* scenario will thus have significantly lower transition risks than the other scenarios as it assumes that the implementation of these policies is immediate and smooth. Similarly, while technological change in terms of the development of low-carbon technologies is also important to minimising the economic costs of transition, sudden or abrupt changes in the availability of these technologies can lead to significant disruption by rendering existing production processes obsolete and precipitating a sharp depreciation in the asset values of firms in carbon-intensive sectors.

Table A: Scenario Assumptions

Scenario	Policy Target	Policy Reaction	Technology Change	Carbon Removal	Regional Variation	Carbon Prices ³⁹
Net Zero 2050	1.5°C	Immediate and smooth	Fast change	Medium use	Medium variation	US\$3 to US\$673 (2020-2050)
Divergent Net Zero	1.5°C	Immediate but divergent	Fast change	Low use	High variation	US\$3 to US\$783 (2020-2050)
Delayed Transition	1.8°C	Delayed	Slow/Fast change	Low use	Medium variation	US\$2.50 to US\$623 (2030-2050)

Source: NGFS (2021)

Table A shows that technological change in the scenarios is mainly assumed to be fast, which accordingly contributes to higher transition risks in the short to medium term. The scenarios are also differentiated according to the assumed availability of carbon dioxide removal (CDR). CDR, through for example afforestation, lowers transition risks as it reduces the need for abrupt changes in other parts of the economy in order to achieve a given emissions target. Transition risks also increase according to the degree of policy heterogeneity across regions and sectors. A high degree of policy asymmetry, can lead to disruptive shifts in the composition of production, trade and consumption. The final column of Table A shows the increase in carbon prices in each scenario, which is a function of each of the transition risks in the table. Carbon prices rise steadily from 2020 onwards in the *Net Zero 2050* and *Divergent Net Zero* scenarios, although at a slightly higher rate in the latter. In contrast, carbon prices in *Delayed transition* scenario

³⁹ Carbon prices are reported in terms of 2010 US dollars/tonne CO₂.

remain flat until 2030, after which they increase at a much steeper average rate than in the other scenarios.

To assess the economic effects of different transition paths, we simulate the three scenarios in NiGEM up to 2050.^{40, 41} The baseline scenario against which we benchmark the results is assumed to be ‘climate neutral’ and thus does not incorporate the impact of physical or transition risks on the economy. It also assumes that population and productivity growth continue in line with past trends, while the pathway for GDP is adjusted to account for the short-term impact of COVID-19 on growth rates.

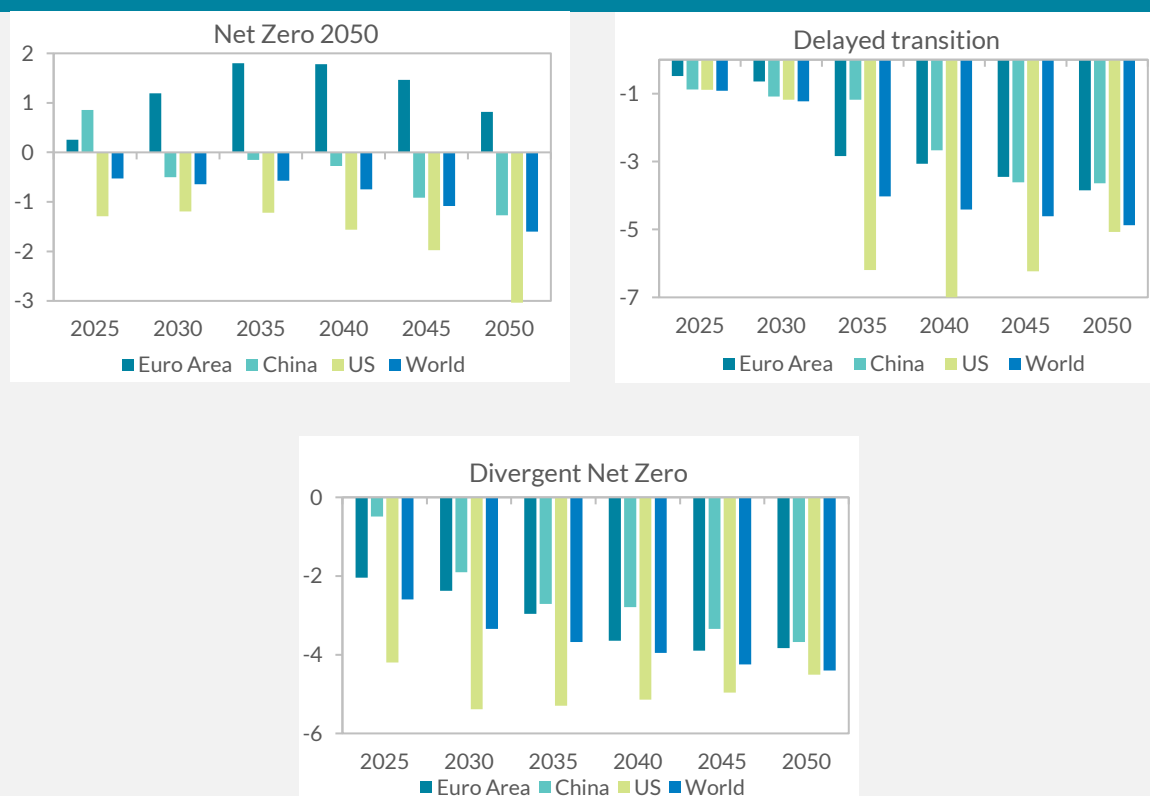
Figure A shows the impact of each scenario on GDP in the Euro Area, China, US, along with the global weighted-average. In the case of the *Net Zero 2050* scenario, the impact on Euro Area GDP is positive as the negative impact on demand from higher carbon prices and energy costs is more than offset by the use of carbon tax revenues to boost government investment and to reduce distortionary (mainly labour) taxes. In contrast, the impact on China and the US is negative in the medium to long term, reflecting the greater intensity of fossil fuels in production in those countries compared to the Euro Area.

The more severe impact on GDP in the *Delayed* relative to the *Net Zero 2050* scenario highlights the benefits of the early introduction of mitigation policies. The sharp rise in energy prices from the sudden implementation of stringent carbon pricing policies increase in carbon prices leads to higher production costs for firms and reduces households’ real incomes. The delayed policy response generates uncertainty about the future trajectory of climate policies, which dampens private investment through higher risk premia. In addition, lower government spending and the reduced availability of CDR technologies increase the cost of transition relative to the orderly scenario. The delay in implementing mitigation policies also leads to an increase in physical risks, which have a negative impact on both the supply and demand sides of the economy. In this scenario, each economy experiences a sharp drop in output, with Euro Area output almost four per cent below baseline by 2050.

⁴⁰ The underlying scenario files were obtained from the National Institute for Economic and Social Research.

⁴¹ NGFS (2021) uses three different IAMs to generate the transition pathways: GCAM, MESSAGEix-GLOBIOM and REMIND-MAGPIE. These models differ according to several features including whether they are partial or general equilibrium, their regional and sectoral granularity, and whether agents have perfect foresight or backward-looking expectations. The results we use in our scenarios are from REMIND-MAGPIE, which is a general equilibrium, perfect foresight model.

Figure A: Impact on GDP of Orderly vs Disorderly Transitions (% deviation from baseline)



Source: author's calculations, NIGEM.

The *Divergent* scenario shows a slightly smaller impact relative to the *Delayed* scenario but with adverse effects occurring much earlier. A key driver of the negative GDP impact in the *Divergent* scenario is the asymmetry in climate policies across sectors. In particular, carbon prices for the transport and building sectors are assumed to be three times those in the industry sector. As shown in Table A, aggregate carbon prices also rise more steeply than in the orderly scenario. As carbon tax revenues are assumed to be used to reduce government debt rather than raise government investment as in the orderly scenario, the negative impact of higher carbon taxes is not offset by government stimulus. Moreover, the sectoral divergence in climate policies generates higher uncertainty, which raises risk premia and lowers private investment.

Figure B illustrates the contribution of transition and physical risks to determining the overall impact on Euro Area GDP. The results for the *Net Zero 2050* scenario highlight the role of governments can play in supporting the transition. While the impact of carbon taxes is negative, this could be offset, depending on the size of multipliers, by recycling the revenues from the tax into higher investment and lower labour taxes. In the *Delayed* and *Divergent* scenarios, the key drivers of fall in output relative to baseline are higher carbon taxes and physical risks. However, the impact of these shocks is not mitigated by expansionary fiscal policy as it is in the *Net Zero 2050* scenario. Instead, carbon tax revenues are used to reduce government debt. Although this reduces

sovereign risk premia, it has a much lower stimulatory effect on the economy in the model than fiscal expansion through, for example, higher investment.

Figure B: Decomposition of Impact on Euro Area GDP (% deviation from baseline)



Source: author's calculations, NIGEM.

Notes: 'C tax' are carbon taxes, 'Other T.' are other transition risks excluding carbon taxes, 'Fiscal' are fiscal policies, 'Bus' are investment risk premia shocks, 'Phys' are physical risks, and 'Tot' is total impact.

It is important to emphasise that, while our analysis focuses on the economic (output) impact of different transition pathways as a proxy for welfare, there are other dimensions of the transition such as biodiversity losses, environmental damages, and distributional issues that influence welfare. Accordingly, our results thus have the narrow interpretation that transition pathways that are characterised by the delayed or uncoordinated implementation of climate policies, tend to have a more negative impact on the economy than those that are characterised by an orderly and expeditious implementation of policies.

6. Conclusion

In this *Article* we discuss the challenges that climate-related risks present for central banks from both an analytical and policy perspective. Physical and transition risks generate economic shocks that affect both the supply and demand sides of the economy. Differences in the timing and

persistence of these shocks can complicate an assessment of the cyclical position of the economy, and thus the calibration of the monetary stance.

Climate-related risks could affect the transmission of monetary policy through a number of channels. For example, if banks' balance sheets become impaired due to losses arising from these risks, the transmission of monetary policy through the credit channel may weaken. Climate change could also affect the conduct of monetary policy through its impact on the natural rate of interest. In particular, uncertainty about the future distribution of climate-related risks could put downward pressure on the natural rate by increasing risk aversion and precautionary saving. This would reduce monetary policy space and increase the likelihood of hitting the effective lower bound.

Finally, we highlight the importance for integrating climate-related risks in central banks' short-term forecasting and macro-modelling frameworks. Forecasting models, particularly those for food and energy prices, can be augmented with weather and climate policy variables to improve their accuracy. Structural macroeconomic models can also be modified to incorporate the transmission channels for different types of climate-related risks. However, we also emphasise the benefits of a suite-of-models approach, in which the output of models with detailed climate-economy interactions such as IAMs could be combined with that of a structural macroeconomic model. As part of this approach, the Central Bank is currently augmenting its macro-modelling framework to include the key channels through which climate-related risks could affect the Irish economy and banking system.

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