Network for Greening the Financial System
Technical supplement
to the First comprehensive report

Macroeconomic and financial stability
Implications of climate change

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1. Introduction

Climate change is one of many sources of structural change affecting the economy and financial system. However it has several distinctive characteristics that mean it needs to be considered and managed differently. These include:

- **Far-reaching impact in breadth and magnitude:** climate change will affect all agents in the economy (households, businesses, governments), across all sectors and geographies. The risks will likely be correlated and, potentially aggravated by tipping points and non-linear impacts. This means the impacts could be much larger, more widespread and diverse than those of other structural changes.
- **Foreseeable nature:** while the exact outcomes, time horizon and future pathway are uncertain, there is a high degree of certainty that some combination of increasing physical and transition risks will materialise in the future.
- **Irreversibility:** the impact of climate change is determined by the concentration of greenhouse gas (GHG) emissions in the atmosphere and there is currently no mature technology to reverse the process. Above a certain threshold, scientists have shown with a high degree of confidence that climate change will have irreversible consequences on our planet, though uncertainty remains about the exact severity and time horizon.
- **Dependency on short-term actions:** the magnitude and nature of the future impacts will be determined by actions taken today, which thus need to follow a credible and forward-looking policy path. This includes actions by governments, central banks and supervisors, financial market participants, firms and households.

The risks from climate change arise from two sources: physical and transition.

Physical impacts are those that could arise from climate and weather-related events, such as droughts, floods and storms. They comprise impacts directly resulting from those events such as damage to property. They can also have wider systemic, as well as firm-level impacts, for example through disruption to global supply chains. Longer term progressive shifts in the climate (such as changes in precipitation, extreme weather variability, sea level rise and rising mean temperatures), and adaption to these changes, may also have implications for the economy, such as on productivity, migration and the reconstruction and replacement of infrastructure.

These changes could also potentially result in large financial losses. If losses are insured, they can directly affect insurance and reinsurance firms through higher claims. If losses are uninsured, the burden can fall on households, corporates and governments. This can impair asset values, reduce the value of investments held by financial institutions and increase credit risks for banks and investors. Since the 1980s, the annual number of registered weather-related loss events has tripled. Overall losses amount to four times the size of insured losses on average and the protection gap continues to widen (Geneva Association, 2014).

Transition impacts are those that relate to the process of adjustment towards a low-carbon economy. Emissions must eventually reach "net zero" to prevent further climate change. The scale of the economic and financial transformation required for this transition is considerable. For example, the Global Commission on the Economy and Climate (2018) estimated that globally around $90tn will need to be invested in infrastructure in the urban, land use and energy systems until 2030.

This transition will also be relevant to the financial system. Changes in climate policies, technological innovations or market sentiment could prompt a reassessment of the value of a large range of financial assets as changing costs and opportunities become apparent. The speed at which such re-pricing occurs is inherently uncertain but, given the scale, its impact could well be important for financial stability and the safety and soundness of financial firms.

The assets which could be impacted are not just limited to sectors involving the production or distribution of fossil fuels, such as coal, oil, or gas. They also include utilities, heavy industry,

petrochemicals, cement, transportation (including aviation and shipping), real estate, and agriculture – essentially all sectors that are energy, or otherwise emissions-intensive and could therefore be affected by policies to reduce GHG emissions. Investment in emissions-intensive assets today has the potential of locking in a certain amount of future GHG emissions. Power plants, for example, have an operational life of several decades. These assets could be at risk of stranding if they are retired before the end of their productive lifespan, for example due to policy change.

Understanding macro-financial changes is a core part of central banks' and financial supervisors' responsibilities. This paper aims to summarise the academic work done to model the impact from climate change on the economy and on the financial system, to set out indicators that can be used to monitor these risks (see Annex 1) and identify some of the areas for further research (see Annex 2). While the ranges of estimates from models are sensitive to the assumptions used, they do describe significant transformations across different sectors of the economy to either mitigate or adapt to the risks. These changes could also manifest as risks to the financial system, particularly if the transition to a low-GHG economy is disorderly.

The paper also sets out a menu of options for central banks and supervisors to assess the risks. In particular, it sets out some preliminary views on how scenarios can be used to simplify the analytical exercise by providing a plausible narrative to anchor model inputs and assumptions and so help size the economic costs and financial risks from climate change.

2. Macroeconomics and climate change

As the macroeconomic consequences of climate change could be significant, central banks, supervisors and macroeconomic policymakers should consider quantitatively assessing the physical and socio-economic impacts of climate change. As pointed out by Stern (2007), the economic analysis of climate change must be global, focus on long-term consequences, appropriately account for risk and uncertainty and examine the possibility of major, irreversible and potentially non-linear changes. Climate change affects economic outcomes while, in turn, economic activity through GHG emissions and production of waste generates changes in climate. Thus, feedback loops between the climate and the economy must be fully incorporated into analyses.

2.1. Modelling approaches

2.1.1. First generation Integrated Assessment Models (IAMs)

During the last decades, the economic assessment of climate change has relied on Integrated Assessment Models (IAMs).[1] IAMs combine a climate science module, describing how emissions derived from economic activity affect temperature, and an economic module, describing economic outcomes that are potentially affected by rising temperatures. Initially, these analytical tools aimed to quantify the economic damages posed by climate factors and provide a cost-benefit analysis of mitigating the ecological risks due to climate change. As such, they provide an estimate for the social costs of GHG emissions and determine optimal mitigation policy, explicitly incorporating both transition and physical risks. More recently, IAMs have been designed to analyse which sets of policies are needed to generate a given level of climate change mitigation (scenario based policy evaluation). These models focus on transition risks.

The level of complexity varies across IAMs, with some versions incorporating regional differences and tackling cooperation issues, and others providing greater detail on specific sectors. But at their core, they all typically include five main features. Each of these models describe (i) the emissions pathway, (ii) the mean temperature, (iii) a society's welfare measure, (iv) an emission

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[1] A non-exhaustible list includes DICE (Nordhaus, 1994), PAGE (Hope et al., 1993), RICE, (Nordhaus and Yang, 1996) and FUND (Tol, 1997).

abatement cost function, and (v) a representation of how changes in temperature affect economic activity (also known as the damage function). Although IAMs are used in, amongst others, the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2014) and the Stern Report (Stern, 2007) and by several governments in their economic assessment of climate change policies, they also received criticism questioning their suitability for policymaking (see Pindyk, 2013).

2.1.2. Criticisms of first generation IAMs

The main criticisms of IAMs are centred on (1) the climate sensitivity, which determines the link between GHGs and temperature, (2) the welfare representation, particularly regarding the discount rate as the effects of climate change typically only materialise in scale in the long-run, and (3) the specification of the damage function. Using the DICE (Dynamic Integrated Climate-Economy) model (Nordhaus, 1994), a well-established IAM, Dietz and Stern (2015) show that the social cost of carbon changes substantially when the discount rate, the climate sensitivity and the damage function are altered (Auffhammer, 2018). Moreover, as discussed by Pindyck (2013), despite the important progress made on the science of climate change and the analysis of its economic impact, the selection of parameter values and functional forms for the damage functions used in IAMs still relies on arbitrary choices.

Another criticism of first generation IAMs relates to the assessment of how the economic variables are likely to change under different policy interventions. The initial IAMs, by assuming that the rate of economic growth is exogenous, ignored this channel. Recent IAMs that focus on scenario based policy evaluation incorporate some version of endogenous growth (see Farmer et al. (2015) and references therein). Studies that focus on the effects of endogenous growth on the social cost of carbon and optimal mitigation policy are less common. As discussed by Acemoglu et al. (2012), incorporating the path dependencies and complementarities in technological diffusion and adoption might be

crucial to measure the economic cost of transition to a carbon-neutral economy.

A third type of challenge regards the treatment of uncertainty. IAMs are typically recursive dynamic general equilibrium models solved deterministically. However, there is inherent scientific uncertainty in the increase in temperature due to GHG concentration (Roe and Baker, 2007). How the economy will be affected by a rise in temperatures is also uncertain, possibly involving non-linearities, catastrophic outcomes and irreversible damage. Instead of introducing some randomness in the model, most IAMs try to account for that by reporting simulations under a range of different parameters. However, this approach does not reflect the impact of uncertainty on decision making. As a result, more recent dynamic stochastic general equilibrium (DSGE) models that integrate climate and economic conditions have been developed.[2] Cai et al. (2013) show that IAMs that discard uncertainty significantly understate the benefits of abatement policies, confirming the need to explicitly tackle uncertainty. Although DSGE models are able to account for uncertainty, they are normally smaller, abstracting from some of the complexity included in the large IAMs.

2.1.3. Second generation integrated assessment models

The difficulty in specifying a damage function and the recent commitments on targeting a cap in temperature increase motivated the creation of IAMs for scenario based policy evaluation. These are energy-economy models that produce scenarios of how a *given level* of climate change mitigation (e.g. achieving "well below 2°C") can be achieved with a given level of probability, (e.g. 66%). This includes modelling what policies would be needed for a desired target and what their impact on different sectors of the economy would be (IPCC, 2014). These models focus on transition pathway scenarios and attempt to represent many of the most important interactions among technologies, relevant human systems (e.g. energy, agriculture, the economic system), and associated GHG emissions in a single

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[2] A non-exhaustible list includes Kelly and Kolstad (1999), Cai et al. (2013) and Golosov et al. (2014).

integrated framework. Because of the multitude of relationships estimated, second generation IAMs tend to be solved numerically.

2.2. Macroeconomic impacts of physical risks

The academic literature broadly agrees that the physical manifestation of climate change could have a substantial impact on gross domestic product (GDP), particularly after mid-century. However numerical estimates of these impacts depend on the underlying assumptions and modelling techniques, can vary significantly across regions and do not usually consider the possible non-linearities and tipping points.[3]

2.2.1. Transmission channels

There are a number of supply and demand channels through which increased temperature can have an impact on the macro-economy, and which are similar for the two types of physical risks: extreme weather events and gradual global warming. On the *demand* side, losses deriving from extreme climate events such as floods and storms could reduce household wealth and therefore private consumption. Business investment could also be reduced by uncertainty about future climate risks. Extreme weather events have also been found to affect international trade (Gassebner et al., 2010, Oh and Reuveny, 2010). On the *supply* side, natural disasters can destroy infrastructure; disrupt economic activity and trade, creating resource shortages; and divert capital from technology and innovation to reconstruction and replacement. Moreover, extreme temperature may impair firm performance, due to reduced labour productivity from heat exposure (Pankratz, 2018).

Gradual global warming can also cause economic losses. On the *demand* side, expectation of future losses could change current preferences, for example towards greater precautionary saving. Business investment could also be reduced by uncertainty about future demand and growth prospects. On the *supply* side, global warming could have a large impact on the potential of the economy to grow in the future, by reducing labour and agricultural productivity (Dell et al., 2014), and

Table 1 **Theoretical channels through which examples of physical risks can affect the macro-economy**

	Type of shock	From gradual global warming	From extreme weather events
Demand	Investment	Uncertainty about future demand and climate risks	Uncertainty about climate risks
	Consumption	Changes in consumption patterns, e.g. more savings for hard times	Increased risk of flooding to residential property
	Trade	Changes in trade patterns due to changes in transport systems and economic activity	Disruption to import/export flows due to extreme weather events
Supply	Labour supply	Loss of hours worked due to extreme heat. Labour supply shock from migration	Loss of hours worked due to natural disasters, or mortality in an extreme case. Labour supply shock from migration
	Energy, food and other inputs	Decrease in agricultural productivity	Food and other input shortages
	Capital stock	Diversion of resources from productive investment to adaptation capital	Damage due to extreme weather
	Technology	Diversion of resources from innovation to adaptation capital	Diversion of resources from innovation to reconstruction and replacement

Source: adapted from Batten (2018).

[3] Defined by the IPCC as a critical threshold when global or regional climate changes from one stable state to another stable state, which may have significant and irreversible impacts. For example, after 1.5-2°C of temperature increase, the melting of the Greenland and Antarctic ice sheets may irreversibly accelerate, increasing sea level rise.

diverting resources from investment in current productive capital and innovation to climate change adaptation. Table 1 presents some examples of the channels from physical risks to the different components of GDP.

2.2.2. Range of estimates

Quantitative estimates for how the physical impact of climate can affect GDP usually consider a timeline up to 2100. Earlier studies summarised in Tol (2009, 2014) found small effects of increased temperatures on GDP, even at high levels of Global Mean Surface Temperature (GMST) warming (relative to 1981-2010).

More recently, Burke et al. (2015) found that climate change might reduce GDP levels by 23% by 2100 relative to a no climate change scenario. This effect is due primarily to increasing temperatures impacting GDP non-linearly through changes in labour supply and labour productivity. In this study, GDP impacts vary across different geographies.

The OECD (2015) finds that, without mitigation, GDP could be up to 12% lower by 2100.

Nordhaus' (2017) first generation IAM finds that a loss in GDP levels of 2.1% would occur by 2100 at 3°C warming and a loss of 8.5% at 6°C. This model is however known to produce low estimates of economic damages.

The large difference in estimates across these models stems from differences in assumptions that feed into the damage functions (see Section 2.1.1),

Table 2 **Range of estimates for physical impacts on the macroeconomy**

Studies	Scenario	GDP impact	Timeline
Burke et al. (2015)	5 - 6°C	-23%	2100
OECD (2015)	1.5°C	-2%	2100
	4.5°C	-10%	
Nordhaus (2017)	6°C	-8.5%	2100
Hsiang et al. (2017)	1.5°C	0.1 to -1.7%	2100
	4°C	-1.5 to -5.6%	2100
	8°C	-6.4 to -15.7%	2100

including assumptions about its functional form and the discount rate.

Hsiang et al. (2017) assume that expected annual GDP level losses for the USA increase quadratically as a function of temperature increase. Taking into account uncertainty, the very likely (5%-95%) range of expected losses at 1.5°C warming is -0.1 to 1.7% of GDP, at 4°C warming is 1.5 to 5.6% of GDP, and at 8°C warming is 6.4 to 15.7% of GDP. Specific results for agriculture show yields declining with rising GMST between 9 to 12% per °C.

2.2.3. Distribution of impacts

2.2.3.1. Geographical impacts

In terms of geographical distribution, standard approaches to valuing climate damage describe average impacts for large regions (e.g. North America) or the entire globe. However, examining local (e.g. country) level impacts reveals major redistributive impacts of climate change on some sectors that are not captured by region or global averages. Hsiang et al. (2017), for example, show that warming causes a net transfer of value from southern central and mid-Atlantic regions towards the northern regions in the US.

An important aspect of physical risk for GDP is the possibility of non-linearity of effects. In many empirical studies, productivity in developed economies appears not to respond to temperature, while productivity in developing countries tends to respond linearly. This raises the question of whether the models are fully capturing the temperature impacts, since productive elements such as workers and crops exhibit highly non-linear responses to local temperature even in developed economies. For example, Burke et al. (2015) show that overall economic productivity is non-linear in temperature for all countries, with productivity peaking at an annual average temperature of 13°C and declining strongly at higher temperatures.

Box 1 below explores a case study on the potential impacts of climate change on Malaysia.

BOX 1

The complex trade-off in emerging economies: the case of Malaysia

Malaysia has experienced warming and rainfall irregularities particularly in the last two decades, characterised by an increase in mean temperatures (under the influence of El Niño), higher occurrence of extreme weather events and variability in rainfall, and rising mean sea levels (Tang, 2019).

The impact of these events is wide-ranging, particularly on agriculture, forestry, biodiversity, water resources, coastal and marine resources, public health and energy. Weather patterns have led to, in particular, supply disruptions that saw the contraction in growth of the commodity sectors (palm oil and rubber) by up to 5% in several periods in the recent past. Fresh food production has also been affected, which in turn affected domestic food prices and livelihoods of many communities that rely on their production as a source of income. One study estimated that fishermen in the east coast of Peninsular Malaysia earned up to 32% less due to unstable weather patterns (Yaacob and Chau, 2005).

Climate change has also resulted in deterioration in air quality due to forest fires and more frequent major floods in Malaysia, resulting in property damage for both households and firms, business interruptions, displacements and higher cases of related diseases such as dengue. Based on data obtained from the Emergency Events Database (EM-DAT) over a period of 20 years from 1998, Malaysia saw a total of 51 natural disaster events. These events have affected over 3 million people, resulted in 281 deaths and at a cost of RM8bn (approx. US$2bn) (Zurairi, 2018). This has clear implications on both the supply and demand sides of the economy, the corresponding valuations of

financial assets and fiscal spending required to cope with severe economic and health consequences.

Emerging economies face the dilemma of a disproportionate impact of climate-related risks on the economy, and yet substantially higher costs of transition necessary to mitigate such risks due to limited resources and competing socio-economic priorities such as reducing poverty and income inequality.

Many emerging economies, including Malaysia, are also reliant on fossil fuels and climate-sensitive natural resources. Agriculture and mining sectors in Malaysia account for 16% of GDP. This raises concerns as to the well-being of dependent household segments given their low resilience to losses arising from climate change.

Given the overall economic structure and the development priorities, both the physical and transition impacts of climate change would affect households' income disproportionately. This would be exacerbated by the level of debt and financial buffers maintained by the vulnerable household segments. Given Bank Negara Malaysia's (BNM) broader mandate of financial inclusion, there is a need to account for the impact of climate change in the different community segments and tailor the subsequent action plans based on their specific financial needs. Emerging economies are also exposed to external factors associated with transition strategies of developed economies that could limit prospects for managing transition risks (such as the implications of the European Union's resolution relating to the palm oil industry). This could expose affected economies to further financial risks.

2.3. Macroeconomic impacts of transition risks

2.3.1. Transmission channels

Transition risks encompass all economic and financial risks that result from the transformation of the current modes of production and consumption to reduce emissions and mitigate climate change.[4] Conceptually, this transition may come at a cost as it involves investing in R&D, in new facilities and new processes, the depreciation of existing production facilities and other assets and changes in the relative prices of key inputs such as energy.

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[4] The total economic effect at different temperature levels would include mitigation costs, co-benefits of mitigation, adverse side-effects of mitigation, adaptation costs and climate damages.

Green growth and the Porter hypothesis

In his speech on the tragedy of the horizon, the Governor of the Bank of England highlighted the potential opportunities from de-carbonisation of the economy, noting that the transition implies a sweeping reallocation of resources and a technological revolution (Carney, 2015). Some researchers predict a "green race", in which countries try to improve their competitive position by implementing environmental policies (Fankhauser et al., 2013). According to the so called "Porter Hypothesis" (Porter and van de Linde, 1995), environmental regulation can have a positive impact on innovation and competitiveness that may in the long run outweigh compliance costs. Subsequently, the literature has distinguished between a 'weak' Porter Hypothesis, stating that individual sectors receive a productivity boost from climate policy through innovation[5], and a 'strong' Porter Hypothesis, stating that climate policies lead to economy-wide productivity gains.[6] However, the debate around this is not yet settled (Albrizio et al., 2014).

Indisputably, the transition to a carbon-neutral economy will require a significant scale-up of sustainable investments offering unprecedented opportunities for innovative companies and their financiers. The OECD estimates that US$6.3trn of investments will be needed each year up to 2030 in energy, transport, water and telecommunications infrastructure to sustain growth. An additional spending of US$600bn per year would likely make those investments compatible with the 2°C target (OECD, 2017). Current infrastructure spending is estimated to be around US$3.4 to US$4.4trn, leaving a significant gap towards future climate-compatible investments. The EU alone would need to raise annual investments by EUR180bn by 2030 to reach its climate and energy targets (EU Commission, 2018). Provided that mitigating scenarios were pursued, the IPCC projected in the

period until 2029 an annual increase by about US$147bn in investments in low carbon electricity supply and by about US$336bn for energy efficiency investments in transport, industry and buildings (IPCC, 2014). Aiming at halting global warming at 1.5°C would require additional energy-related investments amounting to around US$830bn annually compared to current climate policies (IPCC, 2018). While global energy demand driven by population growth and rising incomes may increase by a quarter until 2040 in the "New Policies Scenario"[7], demand for electric power may rise by 60% in the same scenario or up to 90% in a scenario where electrification accelerates even faster (International Energy Agency, 2018).

Accordingly, green finance has grown at an exponential rate over the last decade. Annual issuances of green bonds have increased from less than US$1bn to over US$170bn in 2017 and Asian countries seek to promote this growth by incentives such as grants for green bond issuance costs (Bullard and Shurey, 2018). By contrast, the EU Commission presented a far-reaching sustainable finance action plan in March 2018 followed by legislative proposals encompassing inter alia a green taxonomy and disclosure requirements (EU COM, 2018). In the U.S., green municipal bonds worth about US$30bn had been sold by Mid-2018 (Bullard and Shurey, 2018). The total climate-aligned outstanding bond universe amounts to US$1.45tn.[8]

Global green bond issuance

Source: Bloomberg NEF
Note: 2018 data through June 29.

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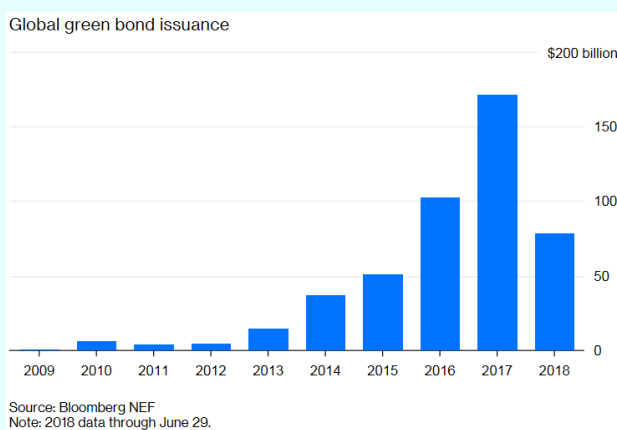
[5] Calel and Dechezleprêtre (2012) argue that positive economic effects tend to occur in single sectors or companies only, if at all.
[6] Wei *et. al.* (2017) find that a range of 22 climate policies could increase growth and employment in the Mexican state Baja California. Landa et. al. (2015) find that redistribution of revenues from a potential carbon tax can have a positive effect on GDP in a general equilibrium model. The ESRB (2016) finds that an early

and ordinary transition could stimulate innovation, job creation and lower production costs.
[7] A scenario including current as well as announced policies and targets.
[8] Climate Bonds Initiative (2018); included are also issuers pro rata where 75%-95% of revenues are derived from climate-aligned assets and green business lines as well as fully-aligned US municipal agencies.

However, these costs and the precise transition pathways will vary from country to country depending on the existing capital stock and may be more or less likely due to different political, technological and socioeconomic conditions. Moreover the costs and pathway for the transition can change over time depending on future choices made (e.g. infrastructure investment, a sudden decision by policymakers to cut subsidies for renewables energy or a sudden shift of consumers towards greener choices).

In addition, these cost estimates are not universally accepted and some argue that there could be a positive 'green growth' effect, meaning that ambitious climate policies associated with structural reforms could increase investment and could actually benefit the global economy in the short- and in the medium-term (OECD, 2017). The investment in research and energy efficiency could have a positive impact on innovation and knowledge spillovers, while creating opportunities for economic growth, job creation, and financial innovation (see Box 2 above).

2.3.2. Range of estimates

A number of studies have quantified the impact of transition risks on GDP, productivity, labour and investment. Some of the estimates are set out in Table 3. The studies suggest that the economic costs of meeting the requirements to give a likely chance of limiting global warming to 2°C would be between 1-4% of global aggregate consumption levels in 2030.[10]

The impact of the transition on GDP depends heavily on the assumptions underlying the analysis, but models generally agree that the speed and timing of the transition is crucial for macroeconomic costs: if it is *orderly and starts early,* costs can be minimised, because it allows for an orderly transition of the existing capital stock and infrastructure. A number of studies have considered the impact of delayed policy action on the cost of the transition (Acemoglu et al., 2012; Furman et al., 2015); according to Furman a one-decade delay in addressing climate change would result in a 40% increase in the net present value cost of doing so.

Table 3 **Range of estimates for transition impacts on the macroeconomy**

Studies	Scenario	GDP impact	Timeline
IPCC (2014)	Limiting warming to 2°C (summary of 31 models and 1,184 scenarios)	1-4% of global aggregate consumption levels	2030
Finansinspektionen (2016)	Limiting warming to 2-3°C.	Up to 3%[9]	
German Federal Ministry of Finance (2016)	Limiting warming to 1.5-2°C	2-5% of GDP	
Landa et. al. (2015)	Emission cuts of 40% in 2030 and 50% in 2050 through carbon taxation	More than -4% of GDP; but positive GDP impact of around 4% if carbon tax is redistributed	2050
OECD (2017)	Limiting warming to 2°C	Positive GDP impact of 2.8%	2050
TOL (2009)		+2.5 and -4.8% on GDP	
Acemoglu et al. (2012)	Delayed policy reaction	Reduced consumption by 6% to 16%	
Nordhaus (2017)	Output is reduced by damages and mitigation costs.	By the year 2100, damages will be around 4% of global output	
CISL (2015)	Limiting warming to 2°C	3.2% higher net present value of cumulative output compared to baseline	2050
Wei et. al. (2017)	22 different GHG mitigation policies	Gross State Product (GSP) increase of $9.85bn pesos	2030

[9] Estimate based on a review and compilation of different studies.
[10] This is defined as a 66% likelihood of limiting warming to below 2 degrees. Notably, this threshold is significantly below the level set by solvency capital requirements (99.5%), which could be seen as implying a higher tolerance for risk in climate outcomes than is accepted under financial regulation.

2.3.3. Distribution of impacts

2.3.3.1. Sector impacts

The transition to a carbon-neutral economy could have varying effects across sectors, depending on how climate policy is enacted and their emissions intensity. Many studies focus on the energy transition or on stranded assets more specifically (e.g. IRENA, 2017) as being particularly exposed to transition risk. A number of transition scenarios that have been developed explore the types of economic transformations that would be required to meet particular policy ambitions, such as those set in the Paris Agreement. See for example those developed by the IEA and IRENA and representative pathways S1, S2, S5 and LED in the IPCC Special Report: Global warming of 1.5°C (2018).

This transition pathway for different sectors will depend on a number of factors, but primarily how policy and technology evolves (IPCC, 2014). The IEA and IRENA (2017) find that energy-related carbon emissions would need to peak before 2020 and fall by more than 70% from today's levels by 2050. By 2050, nearly 95% of electricity generation would be low carbon, 70% of new cars electric, the entire building stock been retrofitted and the carbon intensity of the industrial sector would be 80% lower than today. This would require significant policy changes, including the rapid phase-out of fossil fuel subsidies, carbon prices rising to unprecedented levels, extensive energy-market reforms, stringent carbon-neutral and energy efficiency mandates and global technological cooperation.

Quantifying the risk depends not only on emissions intensity, but also on firms' adaptive capacity. For example, utility companies are often emissions-intensive, but they can have more options to shift to different forms of electricity production within their existing business models.

Other 'difficult to decarbonise' sectors like steel, cement, agriculture and aviation may pose larger challenges. Real estate is also an emission-intensive sector, with transition scenarios often assuming large-scale efforts to retrofit residential and commercial real estate.

Table 4 **Sectoral impacts in different 1.5°C scenarios**

Pathways		Number of scenarios	Energy		Buildings	Transport		Industry
			Share of renewables in primary energy [%]	Share of renewables in electricity [%]	Change in energy demand for buildings (2010 baseline) [%]	Share of low-carbon fuels (electricity, hydrogen and biofuel) in transport [%]	Share of electricity in transport [%]	Industrial emissions reductions (2010 baseline) [%]
IAM Pathways 2030	1.5C-no or low-OS	50	29 (37; 26)	54 (65; 47)	0 (7; −7) [42]	12 (18; 9) [29]	5 (7; 3) [49]	42 (55; 34) [42]
	1.5C-high-OS	35	24 (27; 20)	43 (54; 37)	−17 (−12; −20) [29]	7 (8; 6) [23]	3 (5; 3)	18 (28; −13) [29]
	S1		29	58	−8		4	49
	S2		29	48	−14	5	4	19
	S5		14	25		3	1	
	LED		37	60	30		21	42
Other Studies 2030	Löffler et al. (2017)		46	79				
	IEA (2017c) (ETP)		31	47	2	14	5	22
	IEA (2017g) (WEM)		27	50	−6	17	6	15
IAM Pathways 2050	1.5C-no or low-OS	50	60 (67; 52)	77 (86; 69)	−17 (3; −36) [42]	55 (66; 35) [29]	23 (29; 17) [49]	79 (91; 67) [42]
	1.5C-high-OS	35	62 (68; 47)	82 (88; 64)	−37 (−13; −51) [29]	38 (44; 27) [23]	18 (23; 14)	68 (81; 54) [29]
	S1		58	81	−21		34	74
	S2		53	63	−25	26	23	73
	S5		67	70		53	10	
	LED		73	77	45		59	91
Other Studies 2050	Löffler et al. (2017)		100	100				
	IEA (2017c) (ETP)		58	74	5	55	30	57
	IEA (2017g) (WEM)		47	69	−5	58	32	55

Source: IPCC (2018)

Transition risks may also affect some regions and countries relatively more than others. Economies that are highly dependent on fossil fuels for export, for example, could be relatively more exposed to transition risk (Vermeulen et al., 2018). Box 3 explores the potential impacts on the Australian economy.

The recent discussion around 'just transitions' (Heffron and McCauley, 2018) has also highlighted that technological and policy changes could affect labour markets. While the absolute number of workers may not be large, they may exert considerable political influence in some instances.

BOX 3

Climate change and the Australian economy

Extreme weather patterns such as droughts and floods have had a large effect on the Australian economy for many years. The model of the Australian economy used at the Reserve Bank of Australia in the 1990s had the Southern Oscillation Index as a major determinant of Australian GDP. Today, while agriculture is a much smaller share of the Australian economy than it used to be, the effect of climate on that sector is still evident in aggregate GDP.

Given what is known about climate change, it is important to consider the impact of trends in weather, not cycles. It is also important to reassess the frequency, severity and longevity of climatic events, and to think about how the economy adapts to both the trend change in climate and the transition required to contain climate change. Both the physical impact of climate change and the transition are likely to have first-order economic effects.

Reserve Bank of Australia Deputy Governor Guy Debelle recently considered two examples of how climate change is affecting the Australian economy and the objectives of monetary policy (Debelle, 2019). These examples importantly demonstrate how climate change and the transition to a lower carbon economy have impacts that vary both across different timeframes and across different areas of the economy.

Investment in renewable energy sources

There has been a marked pick-up in investment spending on renewable energy in Australia in recent years. This spending has been big enough to have a noticeable impact at the macroeconomic level and affect aggregate output and hence the monetary policy calculus. It is a good example where price signals have caused significant behavioural change. There has been a rapid decline in the cost of renewable energy sources, in part because of extensive spending on research and development in renewable energy technology around the world, occurring both because of government policies and private actors anticipating the transition to a lower carbon economy.

As a result of the price decline, the investment cost-benefit analysis has changed and continues to change quite rapidly.

Changes in behaviour in response to these price changes are now occurring within the time horizon relevant to monetary policy, of around two years into the future. Hence it is important to gain a better understanding of what is driving those changes and what is in prospect to affect future changes. Available data on capital expenditure intentions show there is more investment in renewables in prospect over the next two years in a way that has a noticeable influence on the aggregate business investment profile.

How these price and investment developments evolve over the coming years is something the Reserve Bank of Australia is playing close attention to, given the importance of the cost of electricity in inflation both directly to households and indirectly as a significant input to businesses.

The policy environment of major trading partners

Environmental concerns have been elevated in the current Chinese five-year plan. There has been a policy directive to move to cleaner sources of energy. This trend has provided benefits to Australia in the short term, as Australian coal tends to be of higher quality. A long held Chinese policy aim has been to gradually reduce overall coal usage. This illustrates that the time frame, the policy incentives and the transition path are important influences on the actual effect on the Australian economy. As China transitions away from coal, natural gas is expected to account for a larger share of its energy mix, and Australia is well placed to help meet this increase in demand. More generally, Australia is also benefitting from the increased demand for battery inputs (especially lithium) and other metals that are used intensively in renewable generation.

3. Financial stability and climate change

3.1. Modelling approaches

The modelling toolbox for financial stability risks is less canonical than the macroeconomic approaches. Broadly speaking, academic and institutional literature uses either (i) balance sheet analysis; (ii) scenario based approaches and (iii) case studies (mainly in physical risk space). Most of these do not take into account second-round and other feedback effects.

Energy sector models and IAMs are also used to assess the impact of climate-related risks on the financial system. Modelling approaches differ strongly between physical and transition risks. Studies of physical risks are either in the form of case studies (e.g. in the insurance industry) or they build on ad hoc assumptions leveraging on climate impact literature.

3.2. Financial stability impacts of physical risks

3.2.1. Transmission channels

The consequences of climate change, i.e. single catastrophic events combined with a long-term alteration and mostly deterioration of climatic conditions, can affect financial institutions in numerous ways. The main categories of transmission channels include:[11]

- **business risk** including operational risk from disruption to the financial sector (e.g., flooding of servers or damage to office buildings and/or collateral) and reputational risk from investing in brown assets, which could have implications for banks, asset managers as well as other financial institutions and non-bank lenders.
- **credit risk** including counterparty risk. The climate change-driven alteration of projected earnings

and expenses can affect the debt repayment capacity and collateral values of borrowers (Stenek et al., 2011), including sovereigns (Kraemer and Negrila, 2014).

- **underwriting risk** for insurance and reinsurance undertakings. Insurance liabilities, in particular in property and business interruption insurance, will significantly rise as more frequent and more severe weather events occur. [12] This could pose a risk to insurers if the insurance liabilities are not adequately priced. If insurers raise premia or restrict coverage in response this could transfer more of the risks to households, companies and their lenders.
- **market risk** for financial institutions and investors. The physical and transition impacts from climate change could affect an investment's valuation and are thus relevant for projecting returns on equity and planning exit strategies for equity investments (Stenek et al., 2011).The use of derivatives and catastrophe bonds to hedge climate risks is another potential link between physical risks and the financial industry.
- **legal risk** including liability risk that arises when parties are held accountable for losses related to environmental damages caused by their activities.

Feedback loops characterise the pattern through which climate-related risks reach the financial system and swing back to the macro economy. These are modelled sometimes through an exogenously determined damage function that affects macroeconomic growth and then feeds into the financial system affecting credit rationing, which in turn reflects on macroeconomic activity and investment decisions (Dafermos et al., 2017). For example, damage to assets serving as collateral could create losses that prompt banks to restrict their lending in certain regions; this could put downwards pressure on property values, further exacerbating the financial impact of physical events (Scott et al., 2017).

The potential impact is wider than equity and debt instruments. The value of financial assets related to

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[11] These categories follow the work of the Green Finance Study Group. However we have left 'underwriting risk' as a separate category because we view it as a fundamentally different kind of

risk, which is modelled differently and affects different sides of the balance sheet.
[12] DNB (2017, p.19), ESRB (2016), p. 7; Finansinspektionen (March 2016), p. 4.

the market prices of commodities and several climate-sensitive services, agricultural, forestry, and energy sectors could be substantially affected by rising temperatures (Finansinspektionen, 2016). Over-specialisation of the financial system, in particular with regard to the vulnerable agricultural sector, could make it susceptible to climatic shocks in some areas (Hornbeck, 2009). Weather derivatives, designed to cope with scarce resources that are sensitive to climate change (e.g. water) may also imply a shift in risk from the real economy to the financial system.[13]

The breadth and scale of impacts across multiple asset classes increase the potential for the losses of individual financial institutions to lead to a wider market downturn. This can lead to wider financial contagion given the second order effects on other financial assets that are only indirectly exposed. These feedback loops are considered, in some papers, the decisive factor for creating major systemic shocks (German Federal Ministry of Finance, 2016).

A stable financial system with liquid markets may more easily provide the financial resources that are necessary to mitigate climate change (Finansinspektionen, 2016) and to rectify the damages caused by extreme weather events. Certain development indicators, inter alia the depth of financial markets, are associated with a lower GDP loss from a given climate-related disaster (Noy, 2009). Some even suggest that bigger banks, which branch across regions, are better suited to offset temporary regional losses from natural disasters with earnings in other regions (Landon-Lane et al, 2009).

3.2.2. Range of estimates

The insurance industry is most experienced in assessing potential losses from extreme weather events, though these studies are focussed on specific sectors and geographies, rather than system wide. Maynard et al. (2014), for instance, finds that the approximately 20 centimetres of sea level rise at

the Battery since the 1950s, with all other factors remaining constant, increased Hurricane Sandy's ground-up surge losses by 30% in New York alone.

Aggregate impact on assets. There is an emerging literature on the systemic financial impacts of physical effects of climate change. CISL (2015), for instance, finds that, for a portfolio with 40% equities, losses of 25% could be incurred if no action to prevent climate change is taken, using IPCC scenarios and high-level relationships to physical damages. According to The Economist Intelligence Unit (2015), the discounted value at risk (in the sense of a permanent loss and not just market volatility) for private investors through the unmitigated impacts of climate change is estimated at $4.2tn. This equals 3% of current assets. However, climate modelling is based on probability distributions. In an extreme (tail) scenario of 6°C of global warming, present value losses in assets under management would amount to $13.8tn (equal to 10% of current assets). The public sector could incur present value damages of $13.9tn on average and up to $43tn in a 6°C scenario (Economist Intelligence Unit, 2015). The capital stock underpinning many of the managed financial assets is estimated to decline due to climate change by 9% by 2100 on average and up to 28% in the extreme scenario of 6°C global warming (Economist Intelligence Unit, 2015).

Scott et al. (2017) state that by some estimates the annual losses from natural disasters could amount to $1tn on a 1-in-100 year basis. A summer as hot as 2003 caused losses of $300 million for the French electricity producer EDF due to the shut-down of 14 nuclear power plants and losses of approximately $15bn for European agriculture. Such a summer used to be a 1-in-1000-years event, but will occur every second year by 2040 and will be cooler than the average summer by 2060 (Stenek et al., 2011).

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[13] The development of new financial instruments could also help hedge against risk if they are well-designed and the risks are well-understood, for example catastrophe bonds. However it is important to keep in mind some of the concerns related to

financial innovation and credit derivatives, i.e. making sure the market is transparent and investors understand the risks associated with the instrument.

3.2.3. Distribution of impacts

3.2.3.1. Sector impacts

The insurance and reinsurance industry will face increasing claims for damages (DNB, 2017; Finansinspektionen, 2016), while simultaneously being exposed to physical (and transition) risks threatening their asset side (Carney, 2015). The number of registered weather-related losses has already tripled since the 1980s with inflation-adjusted insurance losses increasing from approximately $10bn to around $45-50bn on average annually over the past decade (Carney, 2015; Scott et al., 2017). Total losses are around four times the size of insured losses (Scott et al., 2017). ESRB finds that losses from natural disasters have increased fourfold over the past thirty years (ESRB, 2016). While the development is still largely driven by an increase in the value of insured assets, the significance of climate-related damages is advancing (Finansinspektionen, 2016; Scott et al., 2017). Indeed, insured losses in 2017 amounted to a record high of $135bn (with total losses of $330bn), largely caused by extreme weather events such as hurricanes and wildfires in the US, late frost in Europe, and heavy monsoon in Asia (MunichRe, 2018).

Non-insured weather-related losses may also affect the value of the financial assets of financial institutions besides insurers, such as banks and pension funds. Potential channels include damage to real estate (including mortgage portfolios), losses to companies, and losses to governments (who may as part of disaster relief have to increase spending, potentially affecting their credit rating). Company losses may result amongst others from impacts on facilities, supply chains and markets (EBRD and Global Centre of Excellence on Climate Adaptation, 2018). Modelling commissioned by DNB on severe flood scenarios in the Netherlands show that floods with return periods in the range of 1 in 200 to 1 in 1000 years can result in economic losses worth €21-58bn. Such scenarios are estimated to lead to additional credit losses in the affected area for financial institutions of at least €1-2bn (DNB, 2017). Second-order effects may occur due to deteriorating macroeconomic conditions as well as due to increasing risk-premiums for weather-related losses in the future.

Further examples are set out in Annex 3.

3.2.3.2. Geographical impacts

Asia is acutely vulnerable to the physical effects of climate change. Without mitigating action, temperature over some parts of Asia is expected to rise by 6°C by 2100, causing inter alia more frequent and more extreme flooding (Asian Development Bank, 2017). In China alone, land inhabited by 145 million people is ultimately threatened by sea level rise in a 4°C scenario (Strauss et al., 2015). Also due to sea level rise in combination with storm surge, a number of high value, long-lived capital assets in the oil and gas sector are at high risk of flooding in the Guangzhou region (including the megacity Shenzhen) (Lewis et al., 2017).

Coastal areas are particularly exposed to sea level rise and floods. Real estate worth between $238bn and $507bn in the US could be under water by 2100 as sea level rises (Economist Intelligence Unit, 2015). At the same time, economies where GDP is reliant on scarce water resources are also vulnerable. Kenya lost 16% of its GDP in 1998-2000 due to floods and droughts and drought-induced electricity rationing in Brazil caused economic losses of approximately $20bn in 2001 (Stenek et al., 2011).

Unsurprisingly, climate change poses a growing concern for sovereign risk, both from the impacts of gradual warming and extreme weather. Gradual warming could have an impact on countries whose economies are heavily dependent on agriculture (Kraemer and Negrila, 2014), for example, and natural disasters could result in an increased demand for government spending or reduced inflows. For example, there is some evidence that natural disasters increase the probability of sovereign debt default (Klomp, 2017), and the country's level of adaptive capacity is strongly linked to its ability to effectively recover (Laframboise and Loko, 2012).

3.3. Financial stability impacts of transition risks

Effective mitigation of the physical risks from climate change requires a long-term structural change of the economy, which is likely to affect all sectors, including the financial sector. It is likely that such a

structural transformation will produce winners and losers among owners of capital assets, and may affect owners of commodity reserves in particular (Finansinspektionen, 2016).

As in the macroeconomic models, the timing of the transition is key with regards to financial stability aspects of the transition. As detailed in the following sections, the literature suggests that a 'smooth and early' transition minimises financial stability risks, while a 'late and sudden' transition sharply increases financial stability risks.

3.3.1. Transmission channels

Four financial risk categories are considered in most transition risk models (GFSG, 2017): (i) business risk including operational risk and reputational risk from investing in brown assets, (ii) credit risk including counterparty risk, (iii) market risk arising from movement in prices for both green and brown assets, and (iv) legal risk including liability risk that arises when parties suffer losses related to environmental change. Furthermore, transition and physical risks may amplify each other.

A lot of the literature on the financial stability impact of transition risk considers the potential for stranded assets to create credit or market risks. Assets can become "stranded" from changes in demand and thus revenues, as a result of the transition to a carbon-neutral economy. This may cause them to become unexpectedly devalued or needing to be written down (IRENA, 2017; Carbon Tracker, 2013). We can differentiate between "stranded capital" and "stranded value" (see Table 5). "Stranded capital" refers to transition risk-related losses of capital spending that went into a project (e.g. the amount invested in oil field exploration). "Stranded value" represents the transition risk-related losses of financial *valuation* of a firm (or a project), this is the forward looking impact on future discounted cash flows which would have been generated by the firm or project.

However this is not necessarily a complete picture of potential financial stability impacts, for example, some research suggests that the transition could particularly affect some countries (see Section 3.3.3), which could affect market and business risks, but could also manifest as lower macroeconomic growth, which interacts with other financial stability concerns (see Section 4.3). As noted in Section 3.1.2, there may also be second-round effects and feedback loops to consider, whereby relatively small exposures or seemingly small impacts become amplified.

3.3.2. Range of estimates

3.3.2.1. Estimates based on energy sector models: early and smooth transition

Investigating an early transition scenario, and other assumptions being equal, IRENA (2017) finds that there could be about $10tn of stranded value. IEA (2017) on the other hand, finds about $320bn of stranded capital worldwide over the period to 2050 in terms of fossil fuelled power plants that would need to be retired prior to recovering their capital investment. In both studies, the assumption of an early and smooth transition results in the significant reduction of potential risks. The differences between the two overall numbers result from a difference in methodology (see Table 5).

If the ambition is raised – as stated in the Paris Agreement – to well below 2°C, stranded asset numbers could grow significantly, both in a smooth and early or in a late and sudden transition scenario.

3.3.2.2. Estimates based on energy sector models: late and abrupt transition

Numbers on stranded assets differ greatly. IEA (2017) estimates that stranded assets could be about $2.3tn. IRENA (2017), however, estimates a potential for stranded assets of $18tn. Both estimates assume a late and abrupt transition

Table 5 **The concepts of stranded capital and stranded value**

	Concept	Drivers
Stranded capital	Capital invested in a project, at risk from the transition	Driven by the cost of equipment, labour costs and other inputs needed for the project
Stranded value	Market valuation of a firm or project, at risk from the transition	Driven by expected future profits from the project(s)

scenario. Differences in estimated losses stem mainly from two sources.

Firstly, the IEA estimates stranded *capital* while IRENA estimates stranded *value*. For instance, in the upstream oil and gas sector, the IEA considers investments that oil and gas firms have made into exploration, which may not be recouped. IRENA, on the other hand, considers the potential priced-in market value of explored reserves, which, as one might expect, is higher than the cost of exploration.

Secondly, IRENA (2017) finds more than $9tn stranded value in the *buildings sector*, while the IEA assumes there are no stranded assets in buildings.[14] Underlying IRENA's assessment of the buildings sector is the insight from 2°C models that significant retrofitting of the existing buildings stock is needed in order to reduce the carbon footprint of buildings. These required investments, in turn, reduce the value of the buildings compared to a scenario where they are not needed. They argue that the low stock turnover rate of buildings means that stranded assets (i.e. buildings with an inefficient building envelope, and equipment, among others) cannot be avoided, even if all *new* buildings are constructed to the highest of standards in terms of energy efficiency and with integrated renewable energy systems.

A study conducted by Mercure et al. (2018) estimates an amount of stranded *capital* that is similar to the IEA (2017) estimates. Using a second generation IAM, they estimate potential stranded fossil fuel assets to be equivalent to $1 to $4tn loss to global wealth, depending on whether or not climate policies are implemented. They also find significant global variation between countries in terms of impact.

3.3.2.3. Exposure analysis

A separate set of studies considers financial sector exposures explicitly. Weyzig et al. (2014) estimates that exposures to firms holding fossil fuel reserves and fossil fuel commodities are approximately 5% of total assets for EU pension funds, 4% for EU insurance companies and 1.4% for EU banks.

Similarly, DNB (2016) reports that fossil fuel producers make up less than 6% of Dutch pension fund portfolios, about 1% of Dutch insurers' portfolios and about 2% of Dutch bank portfolios. The PRA (2015) finds that carbon-intensive companies equal one third of the $2.6tn global leveraged loan market.

When taking a broader view of all sectors affected, exposure numbers are larger. Although direct exposures to fossil fuel producers may be limited and may not in themselves pose a systemic threat to the financial sector, indirect exposures, such as exposures to sectors which use a lot of fossil fuels in production, are much larger and could potentially pose a systemic risk. For instance, the German Ministry of Finance (2016) found that emissions-intensive companies account for nearly half of the DAX30 from the chemical (20%), industrial goods and services (13%), automotive (14%) and utilities (3%) sectors. They find that if the equity funds were required to pay for the emissions they had financed in the oil, gas, utilities, commodities and industrial sectors, the costs could total up to €4bn (based just on current carbon prices), equivalent to 4.5% of investment in these sectors.

3.3.2.4. Studies that combine exposure data and scenarios

Battiston et al. (2017) analyses the effects that a full write-down of companies in climate-sensitive sectors would have on the equities held by the 50 largest listed banks in the EU. Within the climate context, they pioneer the modelling of second-round feedback effects, stemming from indirect exposures through other financial institutions. They find about 13% of equity exposures are to firms in energy-intensive sectors. If all energy-intensive firms lost all their value and second round effects (exposure via other financial institutions) were accounted for, the maximum loss is estimated at 28% of banks' equity holdings.

Hayne et al. (forthcoming) find that high-carbon power, automobile and fossil fuel exposures make up approximately 8% in both global equity and

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[14] The value of these stranded assets is estimated by the difference between the cost of retrofit and the additional cost to construct a new energy efficient and fossil-free building in lieu of conventional buildings.

bond portfolios. They investigate what a transition to a 2˚C scenario would mean for these exposures if it was to take place in 2030. The increase in transition risk can be visualised as the difference between business as usual and the 2˚C scenario (Chart 1). The authors find that about a quarter of the high-carbon exposures could be at risk, leading possibly to a 3.5% or $2tn equity shock in 2030 (Chart 2). Their study does not include indirect exposures via other financial institutions and thus does not include feedback effects.

CISL (2015) find that the value of a typical investor's portfolio could be 50% lower in a scenario without climate change mitigation as compared to a 2°C scenario. Vermeulen et al. (2018) conduct a top-down stress test of Dutch financial institutions in which financial losses are brought about by disruptive policy measures, technological breakthroughs, or a drop in consumer and investor confidence. They estimate losses of up to 3 percent of assets for banks, 10 percent of assets for pension funds and 11 percent of assets for insurers. Finally, Weyzig et al. (2014) estimates that in a quick transition to a carbon-neutral economy, losses for all EU banks, insurers and pension funds combined would amount to €350 – 400bn. These losses would

be higher, however, if the transition to a carbon-neutral economy is initially slow and highly uncertain.

### 3.3.3. Distribution of impacts

3.3.3.1. Sector impacts

To date, there exists limited research on the distribution of transition risk impacts across sectors. A study by Carbon Trust (2008) investigates both the value-at-risk and the opportunities for value creation that come with the transition to a carbon-neutral economy, for a select number of sectors. They estimate a potential value-at-risk of 65% for the aluminium and automotive sector, 35% for the oil and gas sector, 22% for the building insulation sector, 15% for the beer sector and 5% for the consumer electronics sector. Companies that are well prepared to take advantage of opportunities may, however, also see a significant upside, up to an 80% value gain for the building insulation sector, 60% for the automotive sector, 35% for the consumer electronics sector and 30% for the aluminium sector. Opportunities are modest for the oil and gas sector (5%) and non-existent for the beer sector.

Chart 1 **Capital re-allocation in the energy sector consistent with the IEA's 2°C pathway**
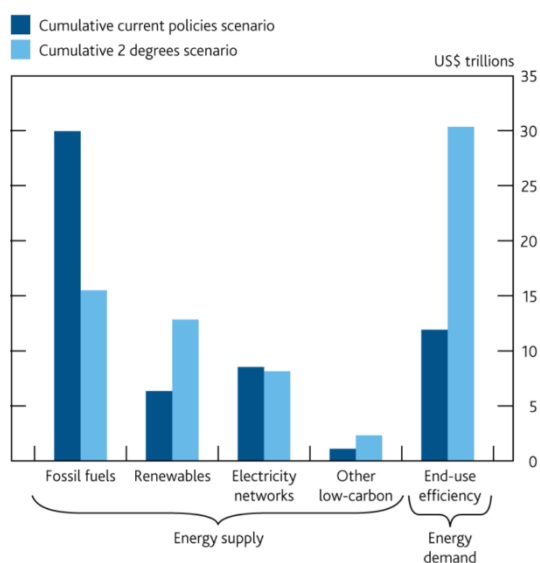
Source: International Energy Agency World Energy Outlook (2017) and Bank of England calculations.

Chart 2 **Equity valuation losses in high-carbon technology exposures in the case of a climate Minsky moment, including fossil fuel price shock, in 2030**
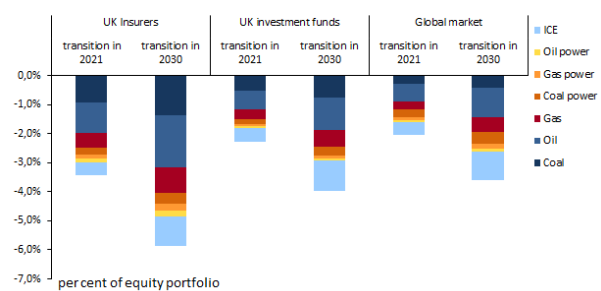
Source: Bank of England (2019).

HSBC (2013) assesses transition risks for listed European oil and gas companies by calculating the impact on firm value if oil and gas prices were to decline to levels that are consistent with a low-carbon world. They estimate that the value at risk for European oil and gas companies is 40-60% of their market capitalisation.

Hebbink et al. (2018) conducted a detailed study of the impact of a carbon tax of €50/tonne on industrial sectors in the Netherlands. They found that the tax would increase production costs mostly in the mining and quarrying (4.4%) and manufacturing of base metals (3.9%) sectors. Taking into account demand elasticities, they estimate that the cost increases would lead to a decline in sales of 7.5% in the mining and quarrying sector, 4.3% for the chemicals sector and between 1.5-3% in the transport, base metals and agriculture sectors. If the tax were to be implemented at the European level, cost increases would be higher (due to higher costs of imports), but the impact on sales would be smaller as exports would be less affected.

In Vermeulen et al. (2018), the relative vulnerability of a sector to transition risk is determined on the basis of its *embodied carbon emissions*, i.e. all the carbon emitted in the value chain for that sector's final goods and services. The relative vulnerability is calculated by weighing the embodied CO_2 emissions in their final goods and services with the share of those goods and services in the economy's GDP. Using this approach, they find high vulnerability in the manufacturing, mining, transport and utilities sectors. By contrast, Battiston et al. (2017) consider a sector's *direct* GHG emissions to identify which ones are likely to be affected by climate policies. Taking into account the European carbon leakage risk classification, they identify the fossil, utilities, transport, energy-intensive and housing sectors as most likely to be affected.

4. Key assumptions

Most of the models for both macroeconomic and financial stability are heavily dependent on some common assumptions and share many of the same uncertainties as outlined in Table 6 below. These assumptions usually refer to factors such as the

future path of climate policies, the rate of progress in carbon-neutral technologies, the feedback loops effects, the level of adaptation and adaptive capacity and nonlinearities or uncertainties related to the nature of climate risks.

Of these assumptions, climate policy and technological progress are particularly important for understanding possible future pathways: the balance between the two will determine the levels of physical and transition risk, and how and when they could materialise.

The future of climate policy is highly uncertain, and compounded by time horizons and political economy: the policies must be initiated far in advance, with the benefits being diffuse and felt further into the future, while the costs of climate policies are potentially felt more immediately. Including the timing and nature of climate policy shifts in modelling is a further step to improve the impact evaluation of these policies on financial stability: a well-managed and orderly transition leaves enough time for financial markets to adjust, while an abrupt change may cause more concern about a rapid repricing and then more volatility.

Key technologies (for example carbon capture and storage) will be particularly important for some sectors, and result in less disruption to existing business models. Depending on the type of technological progress – for example, disruptive or incremental – it could reduce costs or even result in an increase in GDP.

While many of these assumptions and uncertainties are shared across macroeconomic and financial stability, there are also some specific assumptions that are relatively important for particular purposes but less relevant for others. For example, the choice of discount rate (in IAM models for instance) is critical to explain the macroeconomic impacts of physical damages: over a long time horizon (up to 2100), small differences in discount rate can significantly change the present value of the climate damages.

Table 6 **Impacts of key modelling assumptions on physical and transition risk scenarios**

Key assumptions and uncertainties	Macroeconomic physical	Macroeconomic transition	Financial stability physical	Financial stability transition
Future of climate policy	Determines the extent of warming.	Determines the speed and timing of transition.	Determines the extent of warming.	Determines the speed and timing of transition, and also may have diffuse impacts on different sectors (for example, a widespread carbon tax).
Rate of progress in carbon-neutral technology	Determines the extent of warming.	Could reduce costs or actually result in an increase in GDP.	Determines the extent of warming.	Key technologies (for example carbon capture and storage) will be particularly important for some sectors, and result in less disruption to existing business models.
Feedback loops within the model	Key assumptions (e.g. about GDP) are often taken as external to the model.	Economy may be affected indirectly through second-round effects	Financial stability risk could be exacerbated by second-round impacts.	Financial stability risk could be exacerbated by second-round impacts.
Level of adaptation and adaptive capacity	Higher levels of adaptation could lower the long-term physical damages but might entail higher adaptation costs in the short-term.	More diversified economies, adaptive firms, and resilient financial systems could reduce transition costs.	Higher levels of adaptation could lower the long-term physical damages but could entail higher adaptation costs in the short-term.	More diversified economies, adaptive firms, and resilient financial systems could reduce transition costs.
Non-linear impacts / uncertainties in climate modelling	Damages may be higher than expected, either through direct losses to particular sectors or through general macroeconomic channels.	Higher-than-expected damages could impact the speed and timing of climate policy.	Damages may be higher than expected, either through direct losses to particular sectors or through general macroeconomic channels.	Higher-than-expected damages could impact the speed and timing of climate policy.

5. Knowledge and methodology gaps

5.1. Alternative modelling approaches

5.1.1.1. Macroeconomic forecasting models

Models of the type used for forecasting output and inflation within the time horizon of monetary policy (2-3 years) can be augmented with climate-related natural disasters. This would apply both to DSGE models as well as semi-structural macro-modelling approaches. For example, in Keen and Pakko (2011) a natural disaster destroys a significant share of the economy's productive capital stock, as well as temporarily disrupting production, which is modelled as a transitory negative technology shock.

There are however only a few examples of these types of models, and there is scope for improving the modelling channels to include, e.g. labour supply effects or the impact of natural disasters in partner countries on international trade and on the exchange rate. A description of different macroeconomic modelling approaches is included in Box 4.

More work also has to be done to understand the link between climate change and the likelihood and severity of extreme weather events. In this respect macroeconomic modellers could borrow well-advanced methodologies used by insurance firms to quantify physical risks for events such as hurricanes, droughts, extreme precipitation and flooding Longer term modelling of potential output is also relevant for monetary policy. These models are based on production function relationships, which are well developed in the sustainable/green growth

BOX 4

Macroeconomic modelling approaches

Many macroeconomic modelling frameworks have been developed to analyse the impacts of climate change and assist policy design. These models can be categorised in different classes and assessed across several dimensions. There are various approaches to classify models in the literature and some hybrid or multi-module models do not fall in any clear category (Hourcade et al., 1996; Herbst et al., 2012). Building on this literature, Table 7 presents nine broad groups of models.

These models differ on some key characteristics, some of which can be particularly important to consider when analysing the long-term transformation process to a carbon-neutral economy. First, an important element of climate change analysis is to account for feedbacks between human and nature systems, and trade-offs and synergies. In this regard, IAMs allow integrating various systems into one modelling framework.

Differences between models arise also from their treatment of technological change. Energy systems undergo fundamental changes, driven by disruptions in technologies. Models which allow for radical changes or the emergence of new technologies are well suited for climate change analysis.

Dynamic analyses are needed to assess transformation pathways and provide a long-term perspective. Modelling assumptions as to perfect or imperfect foresight contribute however to very different estimates of the costs of climate change. Some modelling approaches, such as DSGE models, can incorporate directly uncertainty and imperfect foresight. However they have other

limitations such as requiring other restrictive assumptions and accounting for non-linearities.

Models differ also dramatically in terms of details and sectoral disaggregation. This reflects the trade-off between the level of detail in terms of climate systems versus the applicability of economic scenario analyses. On one hand, the modeller would like to incorporate sufficient detailed and available data to account for the complexity of climate change. On the other hand, the modeller would ideally like to have information that can readily be used in scenario analyses.

These dimensions are not exclusive of other key characteristics, such as the choice of the modelling technique (analytical/numerical), the analytical approach (top-down/bottom-up), the geographical coverage and uncertainty (deterministic/ stochastic). Various methods may be used for different purposes. Therefore, a methodology is chosen depending on the type of work and analysis to be carried out. For instance, network models are useful to study interconnections across financial institutions but not to study macro impacts.

Many economic models can be called upon to conduct such analysis but none of them fully captures the specificities of climate-related risks. The best methodology will strongly depend on the question at hand but more importantly, on the availability of forward-looking scenarios of transition paths which can relate different climate scenarios and their possible impacts on the financial system.

…/…

Table 7   Strengths and weaknesses of economic models of climate change

Name	Description	Strengths	Weaknesses
Integrated Assessment Models	IAMs describe and assess the interactions between human activities and environmental processes. They include descriptions of socio-economic systems as well as environmental systems, and the interactions between the two.	• Feedbacks between human and nature systems • Analyse trade-offs/synergies	• High level of aggregation • Damage functions calibrated on limited information
Computable General Equilibrium Models	CGE models depict the economy as a system of monetary flows across sectors and agents, solving numerically combination of supply and demand quantities, as well as relative prices to clear the commodity and labour market simultaneously.	• Information on price and market adjustment mechanisms • Comprehensive cover of economic sectors and regions, accounting for interlinkages	• Simplified representation of agents' choices • Lack of information on quantities for biophysical flows
Input-Output Models	IOs represent interdependencies between the different sectors of an economy, distributing a sector's output throughout the other sectors. Environmentally extended input-output analysis track flows of embodied impacts in products and services between many sectors of the economy simultaneously.	• Information at industry level • Detailed accounts of environmental impacts of demand for goods and services	• Extrapolation of past trends • Decisive role of relative prices, constraining policy options to price instruments
Dynamic Stochastic General Equilibrium Models	DSGE models use a set of equations with dynamic and stochastic characteristics based on applied general equilibrium theory and microeconomic principles, such as nominal rigidities, short-run non-neutrality of money and monopolistic competition.	• Microfounded • Accounts for uncertainty	• Computationally intensive • Restrictive assumptions related to market clearing and agents' decision processes
Macro-econometric Models	ME models are systems of dynamic equations to represent demand and supply functions, estimated using past observations.	• Account for market imperfections • Represent non-equilibrium dynamic processes and transitional paths	• Parameters estimated using past observations • No policy simulations at micro level
Agent-based Models	ABMs are computer models that describe complex systems and their emergent properties building around a set of agents, clusters of beliefs and actions rules. In an ABM, heterogeneous decision-makers (agents) dynamically interact with each other and their common environment.	• Micro-level representation of climate/economic interactions • Reflect emergent behaviours	• Substantial data requirements to specify behavioural rules • Less applicable to stress tests.
Stock-flow Consistent Models	SFC models are based on a flow-of-funds representation of an economy, i.e. balance sheets positions and flows between economic sectors ensuring that every flow of payments is tracked and every financial stocks is recorded as a liability for someone and an asset for someone.	• Explicit representation of the financial system • Interrelatedness of agents' balance sheet	• No explicit micro-behavioural modelling • Little flexibility due to accounting approach
Network Models	Network models are extensions of hierarchical structures, representing items and their relationships. It allows many-to-many relationships to be managed in a tree-like structure that allows multiple parents.	• Interconnectedness between financial actors • Account for reinforcing feedback loops and cascade to the real economy	• Non-traditional methods of analysis
Overlapping Generation Models	OLG models recognise that decisions taken today affect not only the future utility flows of people currently alive, but also the utility flows of future generations (unlike the infinitely lived representative agent models).	• Inter-generational redistribution and long-term perspective • Model explicitly life-cycle investment decisions	• Closed economy • No endogenous systemic risks stemming from climate change or transition

literature. The long term impact of climate change can be incorporated in production functions by modelling the impact of global warming on the physical, natural and human capital stock and on labour supply. Further work has to be devoted to the modelling of climate-related migration and the impact of global warming on total factor productivity (TFP) through the diversion of resources to the adaptation and rebuilding of physical capital.

Regarding transition risks, changes in climate policy are included in the broader fiscal policy variables and are therefore implicitly included in current models. Energy supply risks can also be modelled as technology shocks in DSGE-type models. However, more work is needed to consider more explicitly such risks in macroeconomic forecasting models, by including for instance climate-related taxes and subsidies as well as the effects of environmental regulations on firms and households.

There could also be economic effects from the materialisation of transition risks into large and permanent financial losses in asset values, namely through wealth effects which might reduce household consumption and companies' business investment plans. This kind of interactions between macroeconomic and financial impact of climate change are discussed further below.

5.1.1.2. Agent based models

The conventional approach in macroeconomic modelling is based on the "representative" consumer or firm, and is built on the assumption that agents are independent decision makers, and that individual decisions can be scaled up to the aggregate economy level. The complexity intrinsic in economic systems is difficult to model within this approach. Agent based modelling (ABM) represents a different approach to studying the emergent properties of such complex systems. ABM can identify different types of interactions across agents, and the global system properties that result from these interactions (Patt and Siebenhüner, 2005).

ABMs are commonly applied in climate change modelling, for example in areas such as climate change adaptation (Patt and Siebenhüner, 2005), consumer energy choices (Rai and Henry, 2016) and climate-related migration (Thober, Schwarz and Hermans, 2018).

ABMs have also found widespread use in macroeconomics and finance, as well as including both real and financial interactions (Assenza et al., 2015). Macroeconomic models of particular interest for central bank policymakers and regulators include those addressing business cycles (Gualdi et al., 2015) and especially monetary policy (Gatti and Desiderio, 2015).[15] Example ABMs applied to financial markets include credit frictions (Fischer and Riedler, 2014), asset pricing (Franke and Westerhoff, 2012), leverage cycles (Aymanns and Farmer, 2015),

Table 8 **Evidence gaps in macroeconomic impacts of climate change**

Type of risk		Economic outcome	Timing of effects	Evidence gaps
Physical risks from:	**Extreme climate events**	Unanticipated shocks to components of demand and supply	Short to medium run	Theoretical models that include the different transmission channels. Quantitative evidence on the impact on GDP components (e.g. physical capital)
	Global warming	Impact on potential productive capacity and economic growth	Medium to long run	Quantitative evidence on migration and TFP impacts
Transition risks		Demand/supply shocks or economic growth effects	Short to medium run	Further quantitative evidence on the impact of climate policy on investment, jobs and productivity. Quantitative evidence on the impact of low carbon transition on GDP growth.

[15] See Turrell (2016) for a further discussion of ABMs' application to macroeconomics.

systemic risk (Thurner et al., 2016) and corporate bond trading (Braun-Munzinger et al., 2016).

The limitation of standard modelling approaches for studying climate change impacts is particularly evident in the works based on IAMs (both first and second generation). Assuming that a set of representative agents exists, IAMs are in most cases poorly suited to analyse the distributional consequences of climate change. Different sectors, workers and consumers might be affected and respond differently to physical and transition risks. On the contrary, Krussel and Smith (2009) provide the first climate-economy DSGE model that introduces income risk and agent/consumer heterogeneity and ABMs seem particularly suited to account for heterogeneity and different behaviour assumptions. Gerst et al. (2013) and Wolf et al. (2013) are two examples of ABMs that incorporate climate factors into an economy with heterogeneous consumers and/or firms.

More recent studies use a bottom-up micro founded approach to estimating economic climate damages (Hsiang et al., 2017; Houser et al., 2015) instead of top-down macro-level approaches (first generation IAMs). Hsiang et al. (2017), consider for instance the effects of temperature, rainfall and carbon emissions on a number of sectors. Sectoral impacts are then aggregated into a multidimensional probabilistic damage function linking global mean surface temperature to market and non-market costs in the US built up from empirical analysis using micro level data. While important differences remain, comparisons between the two approaches suggest that top-down and bottom-up empirical estimates are beginning to converge, and future investigation should reconcile these differences.

5.2. Financial stability assessments

The literature currently shows some of the theoretical channels through which physical and transition risks could affect financial stability, but there is room for additional research in more precisely identifying and quantifying the possible risks, particularly in the relatively shorter-term.

The evolving scientific understanding of climate change risk suggests that physical impacts are manifesting more quickly than previously expected (IPCC, 2018), and emerging understanding of "climatic tipping points" (non-linearities) suggest that physical impacts could accelerate even further under certain conditions (melting of Greenland and Antarctic ice sheets, for example). Notably, decision-makers and business leaders consider extreme weather, natural disasters, and failure of climate change mitigation and adaptation to be three of the top five most *likely* and *impactful* risks of the next ten years.[16]

As a first step, it would be useful to understand which risks are most pressing, to have research more concretely focused on specific short-term impacts for particular sectors and geographies, and the macroeconomic and financial stability implications. For example, the Prudential Regulation Authority (PRA, 2018) highlighted some specific examples of credit, market, and operational risk for the UK banking sector, including increasing flood risk to mortgage portfolios, declining agricultural output, severe weather events leading to repricing of sovereign debt, and severe weather events impacting the business community. Real estate and agriculture are two sectors that are both particularly important and more immediately exposed to physical impacts of climate change. Banks and insurers exposed to these sectors could be affected by climate-related events on both the assets (e.g. increased probability of default and loss given default on real estate) and liabilities side (insurance claims) of the balance sheet. This could also create macroeconomic impacts (through *inter alia* output losses, negative wealth effects, higher prices and unemployment) which would amplify the initial impacts (see Section 5.3).

Given the level of global interconnectedness, it could also be particularly helpful to identify how extreme weather events and gradual warming are impacting countries with low adaptive capacity, and how that could have spillover effects for other countries and the global economy (e.g. through

increased sovereign credit risk, political instability, global supply chains and migration).

In the longer-term, the physical impacts of climate change could affect the profitability and business models of certain sectors (notably insurance/reinsurance, real estate, agriculture, electricity production), as noted in Section 3.2. There is some theoretical discussion of these impacts (for example, Scott et al. (2017) on the impact of increasing incidence of extreme weather events on insurers), but the long-run implications for financial stability are relatively unexplored.

On the transition risk side, there is some consideration of how the transition, particularly to carbon-neutral energy generation, could create stranded assets, and the possible implications of a sudden shock (Vermeulen et al., 2018). The potential size of the impacts is dependent on assumptions about when and how the transition happens, and which sectors it affects. Combining the existing and emerging research on credit, market, insurance, and sovereign default risk with more sophisticated scenario analysis could better quantify the potential risks. In Vermeulen et al. (2018), for example, four severe but plausible transition risk scenarios are considered which, using various models, are linked to market, interest rate and credit risk to gauge the potential losses for financial institutions. Such analyses could become further refined when more sophisticated analyses of the impact of transition risks on sectors and firms become available. In addition, a better picture of the possible transition risks for households would enable an analysis of how transition risks may impact the mortgage and consumer credit portfolios of financial institutions.

Table 9 **Financial stability impact of climate change**

Type of risk		Financial outcome	Timing of effects	Evidence	Evidence gaps
Physical risks from:	**Extreme climate events**	Unanticipated shocks to physical assets, insurance distress, bank distress, possible systemic disruption	Short to medium run	Lamond (2009) Garmaise and Moskowitz (2009) Klomp (2014) Battiston et al. (2017) Lambert, Noth and Schuwer (2014) Landon-Lane, Rockoff and Steckel (2009) Cortes and Strahan (2017) von Peter, von Dahlen and Saxena (2012) Economist Intelligence Unit (2015)	Physical impacts of accelerated climate change (tipping points) Shorter-term (up to 2030) physical impacts and channels for financial stability risk (e.g. via particular sectors or geographies)
	Gradual warming	Anticipated shocks to physical and financial assets	Medium to long run	German Federal Ministry of Finance (2016) Scott et al. (2017)	Shorter-term (up to 2030) physical impacts
		Anticipated changes to financial- and non-financial sectors (e.g. long-term impacts on profitability of agriculture, insurance)	Medium to long run		Medium-to-long term implications for particular sectors (agriculture, real estate, insurance/reinsurance)
Transition risks		Unanticipated shocks to financial assets (stranded assets)	Short to medium run	IEA (2017) IRENA (2017) Mercure et al. (2018) DNB (2016) Weyzig et al. (2014) Battiston (2017) Vermeulen et al. (2018)	Stranded assets under 1.5°C scenario Granular definition of plausible, disruptive transition scenarios and the financial implications (firm-level, sectoral, economy-wide) Transmission channels, feedback loops that could create systemic risk

Another plausible transition scenario for the EU could convert a range of EU emissions trading system (EU ETS) carbon prices into implications for profitability for high-emissions firms (taking into account the level of pass through to consumers), convert that into financial implications (equity prices, likelihood of credit default) and the larger economy (with larger pass through having less of an impact for firms but more on households' balance sheets and consumption). There is some initial discussion of how transition risks could affect the fiscal positions of certain countries (particularly fossil fuel exporting) but additional research on the implications for sovereign debt, default risk, and financial stability could also be useful.

Then, to connect the sectoral and geographically-specific transition scenarios with implications for financial stability would require further research into transmission channels and feedback loops, perhaps combining with new research in financial risk and network analysis.

5.3. Interactions between macroeconomic and financial climate shocks

It is widely recognised that macroeconomic and financial shocks can interact and amplify: in the past, price instability has been shown to contribute to financial crises (Schwartz, 1995; Bordo, Dueker and Wheelock, 2001). Conversely, financial crises can generate large falls in output.

The interaction between macroeconomic shocks from climate change and financial stability shocks – and vice-versa – has not, however, been explored and this is a particularly important gap in the current literature. One example – discussed above – is the potential realisation of transition risks as stranded assets and their impact on the real economy. Some of these linkages are shown in Figure 1 below.

Another example is the possibility of natural disasters reducing collateral values of the housing stock and weakening households' balance sheets, in turn reducing household consumption. Insured losses from natural disasters can lead to financial losses for both insurers and banks, reducing the latter's' ability to lend to households and corporates, and thus reducing the financing available for reconstruction of physical capital in affected areas. Increased uncertainty from more frequent climate-related weather events could also increase uncertainty for investors, causing decreases in asset prices, losses for banks and reduced availability of lending for productive investment to corporates (Batten et al., 2016). Some of these linkages are shown in Figure 2 below.

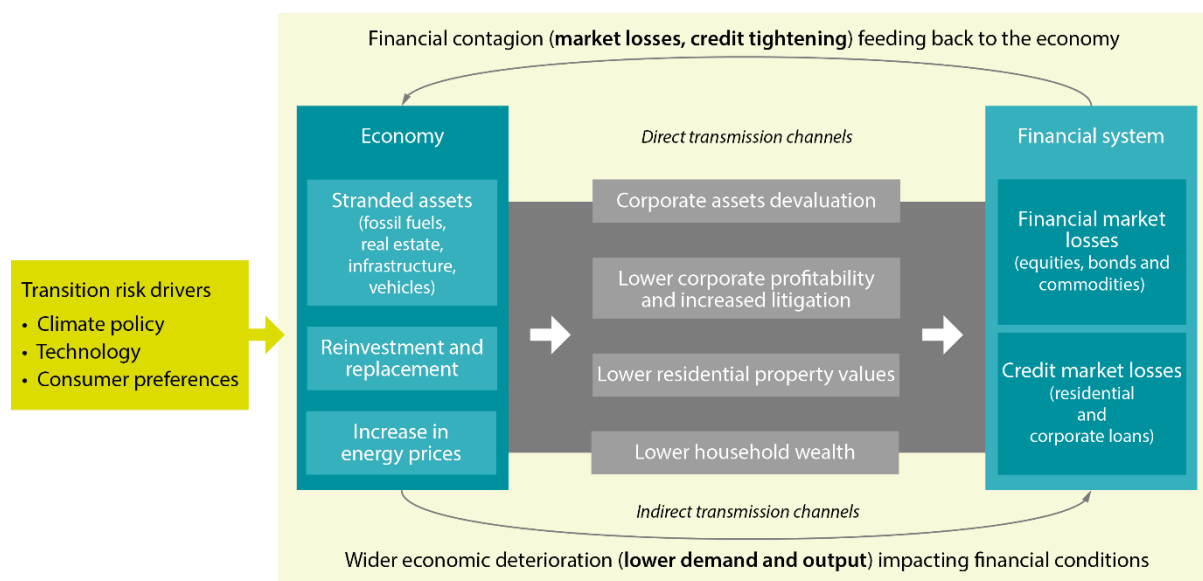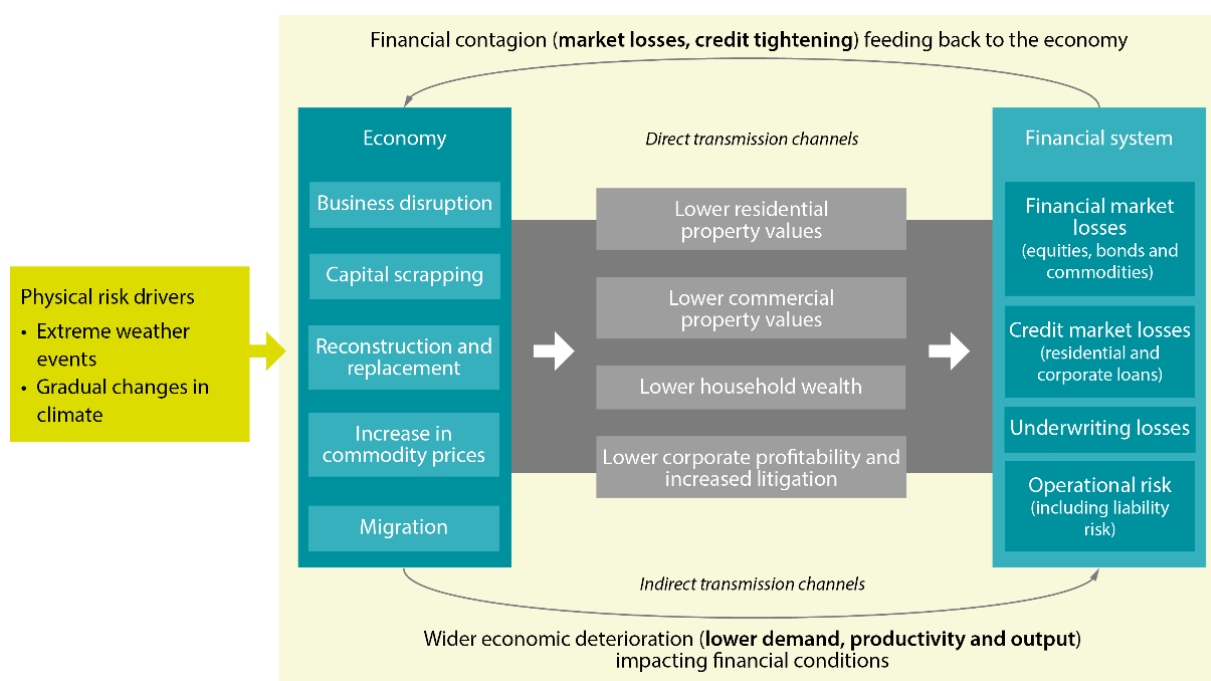Figure 1 **Relationships between transition risk, the economy and financial system**

Figure 2 **Relationships between physical risk, the economy and financial system**

5.4. Combinations of physical and transition risks in scenario analysis

As mentioned before, physical and transition risks are interlinked: the absence of sufficiently forceful policy measures aggravates physical risks (DNB, 2017), while an ambitious climate policy may intensify transition risks; nevertheless, a belated policy response to climate change would probably require even more drastic measures (ESRB, 2016; Finansinspektionen, 2016).

Though much of the existing literature focuses on one element or the other, it will be important to consider both in conjunction. This requires the use of scenario analysis and careful consideration of how to combine meaningfully the different approaches used for physical and transition risk in order to create more multi-dimensional approaches. For example, in an adverse scenario, the negative effects of reduced energy supply and increased energy costs combined with the exposure of financial institutions to carbon-intensive assets could generate contagion in the wider financial system by interacting with other financial frictions. Moreover, they might interact with the impact of climate-related physical shocks, e.g. natural catastrophes (ESRB, 2016).

Another limitation is that they tend to be focused on the long-term costs of climate change and linear economic transformations. Less work has been done to develop scenarios where the transition occurs in a disorderly way and over shorter time horizons. These scenarios would be of particular relevance to the financial system. The work on scenarios carried about by the NGFS is at an early stage, but set out briefly in Section 6. 2.

6. Menu of options for central banks and supervisors

This section sets out options for how central banks and supervisors can respond to climate-related risks including through macroeconomic modelling, scenario analysis, stress testing, key risk indicators and financial stability assessments.

6.1. Macroeconomic modelling

The effects of climate change on aggregate macroeconomic variables are difficult to measure, especially the impact caused by gradual changes in climate conditions. At the same time, it is key for central banks to identify more clearly climate risks as

both physical and transition risks impact macroeconomic variables that are central in the monetary frameworks.

Physical risks imply increases in the frequency and severity of negative supply shocks. This makes it more difficult for central banks to forecast output gaps (the gap between actual GDP and its potential level), and, by extension, inflation – which is key for calibrating monetary policy. Thus, central banks need to evaluate climate-related supply shocks in the calibration of the long-run growth rate used in their forecasting models, because this could have an important impact on short-term forecasts of output gaps and inflationary pressures.

Physical risks might also lead to volatility as well as shifts in food and energy prices, triggered by changes in weather conditions, and the transition to a carbon-neutral economy might increase reliance on renewables, including bioenergy. Monetary policy has to take into account such changes in food and energy prices as they can have second-round effects on core inflation. As it is the case with other factors driving food and energy prices, climate-related factors need to be included in central banks' long-term inflation outlook analysis. At this point, a key question is how the policy space of central banks will be affected by an increasing likelihood of extreme weather events, and whether this increased likelihood widens the uncertainty bands surrounding the longer-term inflation outlook. Climate policy needs also to be factored in order to gauge underlying inflationary pressures. The design of climate policy can significantly affect how central bankers can respond to their direct and indirect effects. For instance, fluctuating allowance prices under a cap and trade policy would make inflation forecasting more difficult for central banks than a policy such as a carbon tax or a hybrid approach in which carbon prices are more stable and predictable.

Currently, the degree to which climate considerations are integrated in monetary policy and financial stability operations is related to the mandate of central banks, which can differ quite significantly (Campiglio et al., 2018). Central banks in developed economies often have relatively narrow mandates primarily focusing on price stability and sometimes financial stability. Due to their independence, these central banks generally try to avoid interfering with market dynamics and government policies, unless this is necessary to achieve their primary objective. Central banks in emerging countries generally have broader mandates that give them more tools to promote green investments. The People's Bank of China has integrated green finance considerations into its macro-prudential assessment framework. Banks with a higher proportion of green loans and banks that have issued green bonds would get higher scores. Moreover, higher tiers allow local banks to use eligible green loans and green bonds as collaterals to borrow from the central bank at costs lower than the market.

Although central banks and supervisors have not developed macroeconomic models that are yet suitable for analysing climate-related risks, some use their existing models for scenarios that go beyond the usual three-year horizon. The time horizon generally goes over ten-years, and the effects are taken into consideration in the central baseline scenarios in order to better understand the possible transmission channels to the macroeconomy and the impact of climate change, and transition risks, on key macroeconomic variables (including investment, trade, government revenue and employment). Some work has also been performed to model the long- and short-run impact of energy price on TFP and on GDP based on different scenarios of energy price developments over a long time horizon (up to 2100) (Henriet et al., 2014). However, the permanent effects of climate change on the potential growth rate have, as far as we know, not yet been included in central banks' forecasting process.

Although climate change risks do not generally feature in macroeconomic forecasts in the short and medium term, some institutions account for the macroeconomic impacts of climate-related events. For instance, in Mexico, the effects on growth of climate-related events like hurricanes or particularly acute cold fronts or heat waves are assessed on an *ad hoc* and *ex post* basis by Banco de Mexico (i.e. given that a climate event occurred, what is its short and medium term impact on GDP growth, including that from the possible use of public insurance funds, should they be available). While accounting ex post for losses due to specific weather-related disasters is

important for forecasting purposes, monetary policymakers should better measure and include in forecasting models the cumulative effects of more frequent events in the future (Batten, 2018). In Singapore, demand or supply conditions associated with climate change risks (e.g. agricultural import price changes, fall in manufacturing output of trading partners due to environmental policy changes, etc.) are incorporated holistically in the assessment of baseline macroeconomic conditions, which in turn feeds into the macroeconomic forecast. Growth and inflation forecasts also broadly consider developments in weather-sensitive sectors such as utilities and retail sales.

6.2. Scenario development

Assessing the impacts of climate change can be challenging because of the uncertainties around the course of climate change itself, the breadth and complexity of transmission channels, the primary and secondary impacts and the need to consider, in aggregate, some combination of both physical and transition risks. Even if all these challenges were addressed, over long time horizons, estimates will be highly dependent on the assumptions made about how climate policy and technology will evolve.

Given the sensitivity of results to these underlying assumptions, hypothetical scenarios can be used to explore the direction and broad scale of outcomes. These scenarios should have a clear, plausible, qualitative narrative but also be data-driven and provide quantitative parameters to help anchor assessments of economic costs and financial risks. They can help identify sectors or geographies which are particularly vulnerable either to physical or transition risks or a combination thereof.

Physical risk scenarios are used to model different climate outcomes, usually specified as a temperature range, given a certain level emissions. The most widely used physical scenarios are the Representative Concentration Pathways that feed into IPCC assessments but a number of others have been developed (see summary in IPCC, 2014). These scenarios can be used to estimate the physical damages of climate change in comparison to a scenario without climate change (see Section 2.2.2 of this report, including Burke et al. (2015), OECD (2015), Economist Intelligence Unit (2015)).

Transition scenarios are used to explore different mitigation options to reach a certain climate outcome. These scenarios are developed by academics and have been summarised by the IPCC Working Group III within IPCC reports (see a

Figure 3   **Projections of population (KC and Lutz, 2016), economic growth (Dellink et al., 2016) and urbanisation (Jiang and O'Neill, 2016) across shared socioeconomic pathways**
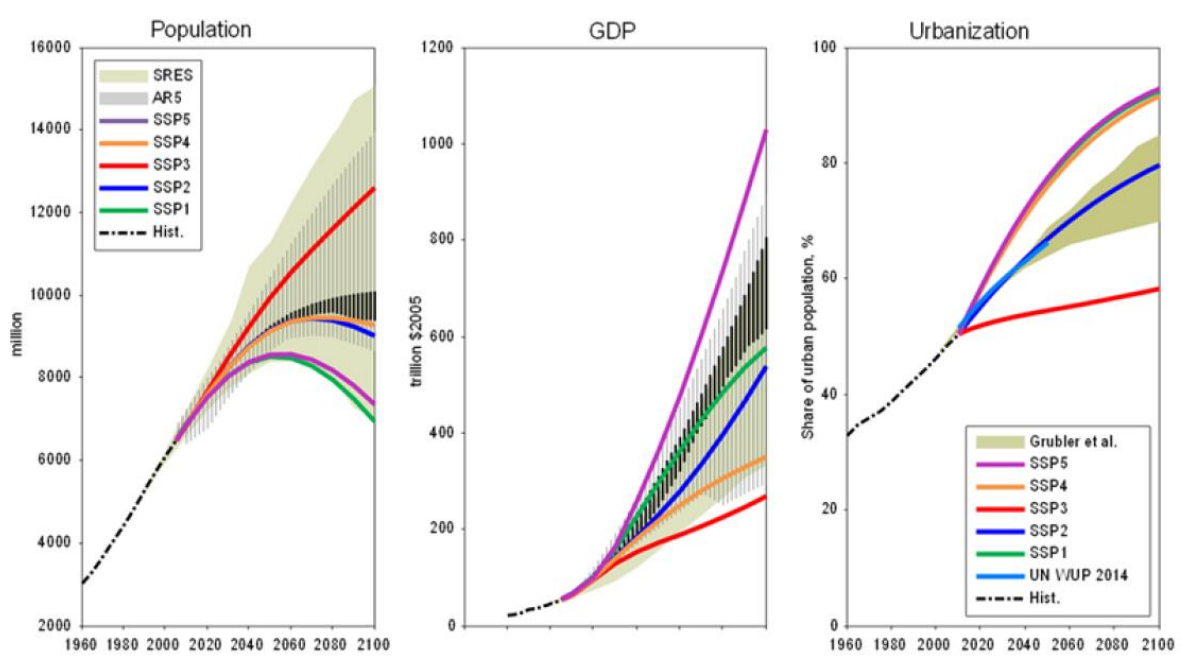
summary of 1.5°C scenarios in Section 2.3.3.1). They have also been developed by a number of energy agencies (IEA and IRENA) and energy firms (Shell, BP, Total, Equinor).

These scenarios use different economic assumptions as inputs and work is underway to help standardise them along different narratives of socioeconomic development. See for example the shared socioeconomic pathways (SSPs) which model a range of different climate outcomes along economic narratives with differing levels of mitigation and adaption. These are shown in Figure 3.

Although in reality there is a continuum of physical and transition risk outcomes, there are two main factors from these scenarios that determine the potential impact on the economy and financial system:

- the total level of mitigation or, in other words, how much action is taken to reduce GHG emissions (leading to a particular climate outcome);
- whether the transition occurs in an orderly or disorderly way, i.e. how smoothly and foreseeable the actions are taken.

An orderly transition includes scenarios where the transition to a carbon-neutral economic occurs in a gradual, anticipated, continuous and efficient way. Other 'disorderly transitions' may involve sudden, unanticipated, unpredictable and/or discontinuous changes. These scenarios are less common. Figure 4 below shows four representative high-level scenario narratives that take both physical and transition dimensions into consideration.

The bottom right scenario can be used to consider the long-term physical risks to the economy and financial system on the current level of emissions. The bottom left orderly scenario can be used to understand how climate policy (such as a carbon price) and other shifts in technology and sentiment to reduce emissions would affect the economy and the financial system.

The two scenarios at the top can be used to consider how physical and transition risks could crystallise in the economy and the financial system over a short time period (for example, in response to extreme weather events or a shift in climate policy leading to a sudden reassessment of future developments).

6.3. Stress testing exercises

The objective of these exercises is to assess the resilience of the financial system to hypothetical, extreme, but plausible scenarios. This is done by defining, using climate scenarios as an input, stresses to the economy and financial markets and then quantifying the impact to the balance sheet of individual institutions. A key difficulty is defining plausible scenarios for how climate-related risks may impact on the financial system in much shorter time horizons than those used for macroeconomic modelling.

Exercises that assess the resilience of the general insurance sector to catastrophes are the most developed in several jurisdictions and some also tested the simultaneous default of reinsurers and decreasing equity and corporate bond prices. These exercises have generally concluded that general insurers are reasonably well capitalised to manage the physical risks.

Whilst only one central bank, the DNB, has already completed a stress testing exercise to date which assessed the resilience of the Dutch banking system to differing levels of policy and technology change

Figure 4   **High-level framework for scenario analysis for central banks and supervisors**
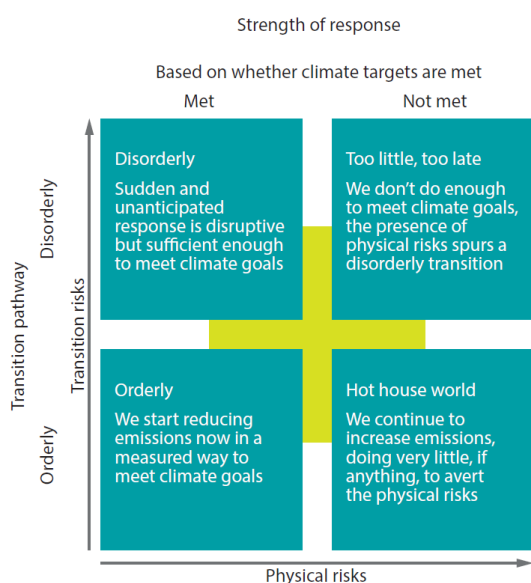
(Vermuelen et al., 2018), a number of others are currently in the process of designing a model. These predominantly focus on estimating the impact of transition risks on banks' balance sheets. However, some are also looking at the exposures of lenders to physical risk events such as drought.

These stress testing exercises must include forward-looking scenarios. Risk assessment that relies on historical data might systemically underestimate potential risks, taking into account the increasing likelihood of climate-related damages and the uncertainties and long time horizon of climate change and the transition period.

6.4. Key risk indicators

As central banks and supervisors learn more about the links between climate change and the financial system, they are discussing key risk indicators (KRIs) to monitor the potential risks. Examples of KRIs include insured and non-insured losses due to catastrophe events, residential loans in areas exposed to frequent natural disasters, financial indicators such as equity prices and profitability of companies in "non-green" sectors, credit exposure to sectors with high GHG intensity and the global carbon price. A preliminary draft list of key risk indicators has been developed by the NGFS and is included in Annex 1.

6.5. Financial system exposure analysis

The objective of exposure analysis is to identify the transmission channels of climate related risks to the financial system and size the potential exposure. For example, multiple central banks and supervisors have compared the geographic distribution of insurance coverage and retail lending activity to the potential physical risks, e.g. hurricanes and floods.

Others have looked to quantify the exposure of financial portfolios to transition risks by identifying the proportion of assets, such as equities and corporate bonds, held in sectors most at risk from the transition to a low carbon economy. While this captures first round effects, it may not fully incorporate the wider risks of financial contagion from an unanticipated economic transition.

Some central banks and supervisors have as well published reports assessing the prudential risks to individual institutions. The other holds dialogue with financial entities, such as non-life insurance companies, to identify the effects, including the size of net losses, of natural-disaster to the whole industry. In order to mitigate these risks, they are developing frameworks to ensure that climate risks are assessed as part of their prudential risk assessments.

One of the key barriers to assessing climate-related exposures is the availability of data to support granular, bottom up, quantitative analysis. Central banks and supervisors must combine standard macroeconomic, financial markets and supervisory reporting data with new climate-related databases. Some of the providers include government meteorology and environment agencies, TruCost, Exiobase, World Input Output Database (WIOD), International Energy Agency, Global Data (for energy and fossil fuel), WardsAuto (for automobiles) and the Emergency Events Database (EM-DAT).

7. Key findings

The review of the literature suggests that the physical and transitions risks posed by climate change can have substantial macroeconomic and financial stability implications. They are therefore important for central banks and supervisors to monitor, but there are challenges in accurately quantifying the size of the impacts and the transmission channels.

Assessing the macroeconomic consequences relies mostly on IAMs which, even for the second generation, present some drawbacks especially to analyse the non-linearity and non-uniformity consequences of climate change. But new initiatives have been undertaken which are better suited to account for heterogeneity (climate-economy DSGE model, Gerst et al., Wolf et al.). Estimating the impacts of climate-related risks on the financial stability is mostly based on partial approaches ((i) balance sheet analysis; (ii) scenario based approaches and (iii) case studies (mainly in physical risk space) which do not usually take into account second-round and other feedback effects. Because

of the wide-ranging challenges (global analysis, focus on long-term consequences, appropriately accounting for historically unprecedented risk and uncertainty and examining the possibility of major, irreversible changes) sizing precisely the impacts of climate-related risks is currently not an easy task and analytical gaps must be filled in. A list of these research questions is included in Annex 2.

Quantitatively measuring the impact of climate-related risks on the macro-economy is also highly dependent on the initial assumptions taken (time horizon, discount rate, climate change scenario, accounting for uncertainty, timing of reaction, policy action, deployment of new technologies, integration of feedback effects) and the results, positive or negative, vary deeply across regions and sectors. Although transmission channels affecting both supply and demand are already well identified, one important consequence of climate change mitigation remains not agreed upon: will the net impact on growth be positive or negative?

Assessing the impacts of climate-related risks on financial stability faces the same issues: transmission channels are broadly identified (direct vs. indirect consequences, credit/market/insurance risks, consequences on sovereign risk) but diversified assumptions (sectors taken into account, climate policy, feedback loops, transition pathways, availability of new technologies, protection gaps) generate a wide range of results.

The range of estimations calls for an important work of mapping and rationalising the assumptions which can be done by developing some plausible high level scenarios to consider how different combinations of physical and transition risk may impact the economy while being flexible enough to account for differences between regions, sectors, industries and firms. Moreover, financial stability assessment using modelling approaches necessitates more bottom-up quantitative estimates of risk for individual issuers and borrowers which is currently lacking. There is also a need to better understand how physical and transition risks are interrelated, and the potential for climate-related feedback loops between the economy and financial system.

It is key for central banks and supervisors to identify more clearly climate-related risks as both physical and transition risks: i) impact macroeconomic variables that are central in the monetary frameworks and ii) may generate the potential for financial instability. As a consequence, the NGFS has started this work to better understand climate-related risks and develop tools to identify and address the build-up of risk, potentially including climate-related economic forecasting, the development of macroeconomic scenarios, scenario-based stress testing, key risk indicators and financial exposure analysis.

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Acknowledgments

Annex 1 Preliminary list of key risk indicators

1. A monitor to track significant climate change issues

Risk monitoring need to answer the broad questions of "what state of the world we are currently in?" and "what may happen tomorrow?". This can be divided into two topics: (i) tracking the state of the system ('diagnostic monitoring') and (ii) helping to identify emerging trends ('prognostic monitoring'). Conventionally, monitoring is based on observations (or a combination of observations and model assessments) and comes before scenario analysis or stress testing.

For the purpose of financial stability surveillance, an effective climate risk-monitoring framework should provide an assessment of the potential risks of current and future climate change. Monitoring should cover climate-related risks (physical and transitional), its causes (climate indicators) and its consequences for the financial system (evolution of financial institutions' risk profile, changes in macro financial key variables), with a potential differentiation across counterparties/financial instruments. A subcategory of transition risks, relevant also for a better understanding of how climate change is incorporated in investment decision-making, relates to monitoring the development of green finance products and markets and the risks/opportunities associated to them.

2. Defining a set of accurate metrics and listing sources

a. Overall objective

Global climate change mitigation target(s)

GHG emissions target(s)

b. Physical risk indicators

> **Key questions:**
> ⇨ What is the current state of climate (evolution of long-term average temperature and precipitation)?
> ⇨ What are the trends identified in terms of impacts of climate change: what scenario are we currently in? Which scenarios appear plausible in a specific time horizon (e.g. average duration of a given credit portfolio)?
> ⇨ What are the impacts of climate change: human casualties and cost perspective of physical risk by sectors?

Indicator	Data availability	Horizon of the risk	Potential source
Primary indicators for central banks and supervisors monitoring			
GHG concentration in the atmosphere	Quantitative / Easy to obtain	Present	IPCC
Current GHG emissions	Quantitative / Easy to obtain	Present	IPCC
Predicted GHG emissions	Quantitative / Modeling needed	Future	IPCC
Global and regional long-term temperature increase	Quantitative / Easy to obtain	Present	IPCC
Global output evolution by sectors	Quantitative / Easy to obtain	Present	IPCC
Losses incurred by types of events (adjusted by the increase in value of affected assets and taking into account differences in terms of development)	Quantitative / Easy to obtain	Present	Munich Re
Losses incurred by sectors (adjusted by the increase in value of affected assets and taking into account differences in terms of development)	Quantitative / Hard to get	Present	
Secondary indicators for increased analysis			
Ocean acidification	Quantitative / Easy to obtain	Present	IPCC
Long-term changes in precipitation	Quantitative / Easy to obtain	Present	IPCC
Long-term reduction of the cryosphere ex cyclical variations	Quantitative / Easy to obtain	Present	IPCC
Long-term sea level rise	Quantitative / Easy to obtain	Present	IPCC
Number, intensity and extension of windstorms, e.g. tropical cyclones and tornados	Quantitative / Easy to obtain	Present	CatNat.net
Number and duration of droughts	Quantitative / Easy to obtain	Present	CatNat.net
Number and landmass affected by floods	Quantitative / Easy to obtain	Present	CatNat.net
Number, intensity of and areas affected by hail, blizzards and other weather anomalies	Quantitative / Easy to obtain	Present	CatNat.net
Evolution of insurance premiums (adjusted by non-climate factors and the increase in value of insured assets)	Quantitative / Easy to obtain	Present	
Adaptation measures taken, and cost of adaptation (e.g. flood protection measures, hurricane proof building codes)	Qualitative and quantitative / Hard to get	Present	

c. Transition risk indicators

Key questions:

⇨ What is the trend in terms of transition risk across different sectors, mitigation and adaptation?

Indicator	Data availability	Horizon of the risk	Potential source
Primary indicators for central banks and supervisors monitoring			
Current state of sectors directly exposed to transition risks (coal/oil/gas production and refinement industry, fossil energy production, cement production, transportation, buildings (heating, warm water and electricity), manufacturing industry…, by NACE codes): evolution of global output, net income, value of shares, carbon intensity/energy efficiency…	Quantitative Easy to obtain for economic data Hard to get for climate exposure pending improvement of disclosures	Present	Disclosures
Progress in mitigation and adaptation processes (production capacity and costs): technological advances, engagement with investee companies/debtors	Qualitative and quantitative Hard to get	Present	
Evolution of commodities prices	Quantitative Easy to obtain	Present	Bloomberg
EU Emission Allowances price	Quantitative Easy to obtain	Present	www.eex.com
Secondary indicators for increased analysis			
Announced and implemented climate policies at global, regional and local levels, including global carbon price, national, regional and local environmental/carbon taxes	Qualitative Easy to obtain	Present and future	

d. Green finance: scaling-up, pricing and risks

> **Key question:**
> ⇨ How is the financial system keeping up pace with the transition?
> ⇨ What are the changes in risk premia, maturities, use of green bond proceeds, % share of capital markets?

Indicator	Data availability	Horizon of the risk	Potential source
Primary indicators for central banks and supervisors monitoring			
Green financial markets development by products (outstanding amount) and regions. Comparison with total market value.	Quantitative Easy to obtain (bonds) Hard to get (data on investment in funds, green versus non-green)	Present	CBI, Eikon
Evolution of risk premia	Quantitative Easy to obtain	Present	Bloomberg
Maturities	Quantitative Easy to obtain	Present	Bloomberg
Uses of green bonds proceeds	Qualitative Easy to obtain	Present	CBI
Consistency of products with green classifications/labels	Qualitative Easy to obtain	Present	CBI
Alignment with 2°C target or respective binding national target	Quantitative Modelling needed	Present Forward looking	
Secondary indicators for increased analysis			
Development of financial innovation	Qualitative Easy to obtain		

e. Impacts on the real economy and on the financial system

> **Key question:**
>
> ⇨ What are the observed impacts of climate change and the transition to a carbon-neutral economy on the macroeconomy and on the financial system?
> ⇨ What are the short and long-run impacts on the supply-side and on the demand-side?
> ⇨ For physical risks: what is the exposure of lending and investment portfolios to these sectors and regions? What is the impact of these events on macroeconomic variables?
> ⇨ For transition risks: What impact is this having on macroeconomic variables? What is the trend in terms of transition risk on financial markets (eg. carbon prices, commodities, equities, bonds etc.) and credit ratings? What are different policies which are being announced and what is their impact?

Indicator	Data availability	Horizon of the risk	Potential source
Primary indicators for central banks and supervisors monitoring			
Overall and insured losses in USD for relevant loss events, adjusted by the increase in value of insured assets	Quantitative Easy to obtain	Present	The Geneva Association
Insurance undertakings for the liabilities side: sum insured in buildings, movable property and business interruption, also compared to overall insurance portfolio, particularly in disaster-prone regions	Quantitative Easy to obtain	Present	Disclosures
Financial institutions: average carbon intensity of exposures/assets/portfolios, type of exposures (direct finance, structured finance), share of income of exposed sectors to these risks (for ex. stranded assets), duration of exposures (equity vs. debt instruments), indirect exposure via other financial institutions, loans contraction from banks, loss of confidence from investors, higher credit risk and counterparty risk, lower ratings, permanent lower prices of exposed assets, liquidity risk on these assets	Quantitative Hard to get	Present	Disclosures
Residential loans and (un)insurability in areas facing natural disasters, financial indicators such as assets/equity prices (loss in value of assets, lower stock prices, higher CDS and lower profitability of companies in "non-green" sectors …)	Quantitative Hard to get worldwide consolidated data	Present	
Evolution of credit ratings	Quantitative Easy to obtain	Present Forward looking	Bloomberg
ESG ratings	Quantitative Easy to obtain	Present	Bloomberg, Sustainalytics
Performance indicators of exposures/assets	Quantitative Easy to obtain	Present	MSCI
Climate VaR ("Carbon Beta", "ClimateXcellence" tool,…)	Quantitative Methodology issue	Present	Carbon Delta CARIMA project CO Firm
Secondary indicators for increased analysis			
Macroeconomic variable evolution: GDP growth, inflation, unemployment, sovereign risk, population growth	Quantitative Easy to obtain	Present	
Evolution of insurance premiums (adjusted by non-climate factors and the increase in value of insured assets)	Quantitative Easy to obtain	Present	

Annex 2   Research questions

This annex outlines some key research areas identified in this note.

Macroeconomic forecasting

- Improved, short-term DSGE-type models for output and inflation that include climate impacts, including e.g. labour supply effects, natural disasters, international trade, balance of payments:
  - Research using insurance/physical modelling of increased likelihood of severe weather to inform model inputs;
- Modelling longer-term impacts including migration, impact of natural disasters and adaptation on TFP;
- For all of the above, models that include endogenous and non-linear climate impacts;
- Impacts on emerging markets.

Financial stability assessments

- Analysis of potential financial stability impacts and transmission channels:
  - From both physical and transition risk,
  - on a reasonable timeframe (2020-2035),
  - using sector- and country-specific scenarios based on current national policy to create realistic gradual and abrupt transition scenarios (many current scenarios either apply an abrupt shock in the form of a high global carbon price, or assume a shift from one pathway to another, which is not realistically how the transition is likely to happen);
  - Impacts on multiple levels: individual firms, real economy, financial institutions, and larger financial system (profitability, credit default, asset prices, etc.),
  - including feedback loops and spillover effects,
  - with sensitivity analysis regarding the underlying assumptions, and a confidence interval if possible,
- Impacts of potential tipping points (i.e. rapid and irreversible acceleration of warming);
- Impacts of a 1.5°C transition scenario;
- Longer-term implications for profitability/viability of particular sectors (e.g. insurance and reinsurance);
- Feedback loops between macroeconomic impacts and financial stability risk;
- Case studies on past historical examples of transition risk;
- Pricing risk to inform possible policy changes (e.g. possible prudential policy adjustments);
- KRIs: identifying relevant indicators for monitoring climate-related risks;
- Impacts on emerging markets.

Scenarios

- Defining plausible, granular, abrupt transition scenarios that take into account political economy considerations (i.e. what would a sudden ratcheting up of ambition look like on a national level, taking into account current country policies, NDCs, country-specific factors like economic production and energy mix, etc.);
- Scenarios with combined physical and transition impacts;
- Research/analysis/framework for how to take into account volatility around climate trends when presenting and making decisions around climate extrapolations – how best to evaluate risk, which is rising on an erratic trend, trend changes vs shocks, anticipated vs unexpected risks.

New tools and data:

- Spatial finance: https://sa.catapult.org.uk/spatial-finance-initiative/
- Data science and AI: https://www.turing.ac.uk/research/interest-groups/sustainable-finance;
- Widely- available, comparable, verifiable, and granular data on climate risks and opportunities (e.g. on measuring the impact of investment, risks to individual firms).

Annex 3 Further examples of physical risk impacts on financial risks

- **Insurance sector**: Currently modelled insurance losses could be undervalued by 50% if recent extreme weather trends became normal and morbidity as well as mortality could rise as climatic conditions deteriorate (Carney, 2015). DNB estimates that the climate-related claims burden may rise between 25% and 131% by 2085 compared to 2016 (DNB, 2017). In addition, insurers may also bear costs from liability claims against e.g. insured carbon-intensive energy firms for their contribution to the physical effects of climate change (ESRB, 2016; Carney, 2015). Investment decisions not taking into account reasonably foreseeable impacts of climate change may also incur liability in negligence (Stenek et al., 2011). Insurers may lose customers due to rising premiums or deal with uninsurability due to excessive uncertainty, volatility and severity of certain risks (Stenek et al., 2011).

- **Energy**: KeySpan Energy Delivery's (now National Grid) natural gas sales dropped by 19% in Massachusetts and New Hampshire in the winter of 2006, compared to its forecasts. This led to a reduction in net gas revenues of $51.8 million compared to 2005.

- **Agriculture**: OECD noted that droughts in Australia were a factor in the sharp agricultural commodity price spikes between 2006 and 2008 and drought months over most of the country will likely increase by 20% until 2030 (Stenek et al., 2011).

- **Sovereigns**: Tanzania's president explained that $4.8 million out of the government's development budget had to be reallocated to repair damages to the central railway line and roads caused by heavy rainfall in December 2009 and January 2010. The country's development plans would have to be postponed or abandoned (Stenek et al., 2011).

- **Asia**: The risk level of China is aggravated by migration from rural areas into the coastal. This migration pathway has increased the concentration of risk exposure in urban areas towards extreme weather phenomena. Particularly endangered areas are the upper regions of the Yangtze and Yellow rivers for soil degradation and dams, the northern and north-western parts for desertification and droughts and the south-eastern coastal regions for increasing typhoons and flooding (Asian Development Bank, 2017). The heaviest snowstorms in China for 50 years occurred in the winter of 2007/8 and disrupted operations at 24,000 telecommunications base stations resulting in missed revenue of at least $152.8bn for telecommunication providers (Stenek et al., 2011). Thailand's stock exchange index temporarily dropped by as much as 28 per cent as a reaction to the monsoon-made floods in 2011. The economic costs were estimated at $45bn and the Bank of Thailand had to cut policy rates to support the economy's recovery (Scott et al., 2017). In the future, the annual precipitation is expected to increase by up to 50 per cent over most land areas in Asia. Sea level is estimated to rise between 0.65 and 1.4 meters by the end of the century and continue to rise thereafter (Asian Development Bank, 2017).

- **Developed countries**: The insurance coverage against natural hazards in German industry currently stands at nearly 100%, but could sharply decline if premiums or uninsurability were to rise due to climate change (Lewis et al., 2017). Regions where climatic conditions are currently deemed too cold for optimal economic activities, like Sweden, may to some extent benefit from rising temperatures (German Federal Ministry of Finance, 2016; Finansinspektionen,2016; Finansinspektionen, 2016). However, even in presumably safe havens like Germany or Sweden here insurance companies and other financial firms might still be hit through their international engagements (Finansinspektionen, 2016). Further, assets in developed countries may be affected by increased capital depreciation, which could increase by 10-20% in Alaska by 2030 regarding transport, water, and sewage infrastructure (Stenek et al., 2011).

- **Water dependency**: As semiconductor production relies heavily on clean water supply, a factory shutdown or construction delay at Intel or Texas Instruments due to water shortages could lower revenue by $100-$200 million during a quarter which corresponds to reduced earnings of $0.02-$0.04 per share.