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Climate change and the macro economy

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Abstract

This Occasional Paper reviews how climate change and policies to address it may affect the macro economy in ways that are relevant for central banks' monetary policy assessment of the inflation outlook. To this end, the paper focuses on the potential channels through which climate change and the policy and technological responses to climate change could have an impact on the real economy. Overall, the existing literature suggests a likelihood that climate change will have demand-side implications, but will also cause a negative supply shock in the decades to come and may even have the potential to lead to widespread disruption to the economic and financial system. We may already be observing a rise in the costs resulting from an increased incidence of extreme weather conditions. The direct effects stemming from climate change are likely to increase gradually over time as global temperatures increase. Nevertheless, it is extremely difficult to obtain reliable estimates of the overall macroeconomic impact of climate change, which will also depend on the extent to which it can be brought under control through mitigation policies requiring major structural changes to the economy. In order to implement such policies political economy obstacles will need to be overcome and measures will need to be put in place that address underlying market failures. They could involve significant fiscal implications, with an increased price of carbon contributing to higher overall prices. At the same time, these measures could also foster innovation, generate fiscal revenues and dampen inflationary pressures as energy efficiency increases and the price of renewable energy falls.

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Executive summary

This Occasional Paper reviews how climate change and the policies to address it may affect the macro economy in ways that are relevant for central banks' monetary policy assessment of the inflation outlook. To this end, it reviews the evidence regarding the potential channels of transmission and economic impacts of climate change, as well as climate mitigation policies with potential significance for macroeconomic policymakers. The literature focuses almost exclusively on the implications for economic analysis, whereas other issues of potential relevance for a central bank, for instance relating to monetary policy, financial stability and banking supervision, are not covered to a significant extent.

The potential direct economic impacts of climate change are wide-ranging and potentially substantial. Direct impacts can be expected in agriculture and fisheries, as well as in other sectors, such as energy, tourism, construction and insurance. According to the Organisation for Economic Co-operation and Development (OECD), with no further mitigation actions, global temperature rises of 1.5-4°C may lower global real GDP by 1.0-3.3% by 2060 and by 2-10% by 2100. However, model-based estimates are very uncertain and can be challenged in relation to their underlying assumptions and because they may ignore important (possibly non-linear) impacts and understate key risks. While the near-term trend impacts of climate change may remain muted, as the rise in global temperatures is a gradual process, its effects may be felt earlier in the form of rising costs associated with extreme weather events. Moreover, early policy efforts to address climate change may imply large up-front costs, but are likely to reduce long-term costs.

Major structural change is required to combat global climate change. This means that government policy intervention is needed to overcome market failures and political economy challenges. Focusing on Europe, the European Union (EU) aims to become a net zero greenhouse gas emissions economy by 2050. A key policy in support of this aim was the creation of a market-based carbon-price through an emissions trading system (EU-ETS). However, the EU-ETS does not (yet) appear to be sending a consistent signal to investors, as the price of carbon fell significantly after 2008, although it has recently recovered. Governments have also chosen to subsidise renewable and nuclear energy, usually in the form of fixed payments for a set period of time, with rates differing according to the technology supported.

Major investment in climate mitigation is already underway to decarbonise electricity generation and increase energy efficiency, but a lot more needs to be done to decarbonise the economy. New climate abatement measures will also be needed to prepare for sea level rise and more extreme weather patterns. Further innovation is also required if decarbonisation is to be achieved at a manageable cost. While innovation has already led to sharply falling renewable energy costs, energy storage could be improved and the use of electricity in transport extended.

The positive macro impact of mitigation measures could be held back by risk aversion but boosted by innovation spillovers. Renewable energy has a very different cost structure to conventional fossil fuels and needs substantial up-front capital expenditure. Investors may be wary about lending to renewable energy projects if they perceive them as risky – for instance owing to uncertainties regarding government policy – or if they lack knowledge about this relatively new sector. However, there may be scope for innovation in new clean technologies to spill over to the rest of the economy and support growth. While R&D spending on energy appears low, the rapid deployment of renewable energy may be stimulating innovation through "learning by doing". The deployment of such technologies continues to exceed expectations.

Climate change policies require a larger role for state intervention, partly through fiscal measures. However, the net impact on public finances is unclear. The process of internalising the negative environmental externality of CO_2 emissions could raise additional revenues, particularly if implemented through new carbon taxes. At the same time, abatement and mitigation measures may imply a need for either additional government expenditure or the crowding out of other public investment spending.

Inflation may be pushed up by measures to raise the price of carbon, although this may be offset by falling prices for renewable energy and as a result of increased energy efficiency. Market-based emissions trading or new taxes on high-carbon (particularly fossil fuel-based) activities may cause prices to rise. However, this could be offset by further innovation in renewable energy (which would lower electricity prices) and higher energy efficiency, both of which could reduce the weight of energy in the consumption basket.

There is also a risk that climate change may lead to widespread disruption to the economic and financial system. An unexpectedly abrupt change in government policy or further disruption from technological progress in renewable technologies could cause a very rapid move away from fossil fuels, with diverging impacts across sectors. In turn, this could cause a (possibly sharp) fall in physical capital values and a drop in asset prices, which could potentially have broader macroeconomic impacts.

1 Introduction

Global greenhouse gas emissions and temperatures are continuing to rise.[1] Compared with pre-industrial times, global CO_2 levels have risen by around 120 parts per million (ppm) and now exceed 400 ppm, and human activities[2] are estimated to have led to around 1°C of global warming.[3] Limiting global warming to 2°C would require a sharp change in the pattern of rising global CO_2 emissions.[4] Immediate action to restrict the rise in CO_2 concentrations to 450 ppm may limit global warming to around 2°C – which is often seen as a threshold beyond which the costs and risks of climate change increase significantly.[5] However, currently human emissions of CO_2 and other greenhouse gases (GHGs) are increasing rather than decreasing rapidly.

If global emissions continue to rise on their current trajectory, global warming may exceed 4°C later this century. In most of the future scenarios developed by the Intergovernmental Panel on Climate Change (IPCC), without additional efforts to reduce GHG emissions, global warming is "…more likely than not to exceed 4°C above pre-industrial levels by 2100". Scenarios which involve a continuation of the current accelerating pace of CO_2 emissions, and which only flatten off at the end of this century could see CO_2 concentrations exceed 1000 ppm and median estimates of global warming of 4.1-4.8°C, with the full range of estimates ranging from 2.8°C to 7.8°C.[6]

Although the basic science of global warming is well established, there is substantial uncertainty regarding the precise impacts, both in the near term and at longer horizons. Impacts could be wide-ranging, covering physical systems (such as glaciers, rivers and sea levels), biological systems (such as terrestrial and marine ecosystems) and human systems (such as food production, health and production systems).[7] The complexity of the interactions between rising temperatures and these systems means that there is considerable uncertainty about the timing and magnitude of impacts, particularly where there is a risk of tipping points or system collapse.

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1 Anthropogenic emissions include greenhouse gases, aerosols and their precursors.

2 See, for example, Stock (2019).

3 According to the US National Oceanic and Atmospheric Association, the CO_2 concentration breached 400 ppm early in 2015. Temperature rises are in a "likely" range of between 0.8°C and 1.2°C according to IPCC (2018), p. 6.

4 Some researchers have voiced doubts as to whether limiting change to 2°C is feasible even with ambitious policies (see Nordhaus, 2017).

5 Given the inherent uncertainties involved in such calculations, it should also be seen as a range (480-530 ppm) rather than a point estimate – see IPCC (2014a), p. 13. In addition, a recent report by the IPCC (2018) shows that many of the adverse impacts of climate change expected as a result of an increase to 2°C would already start to be felt at the 1.5°C mark. For instance, by 2100 the global rise in sea level would be 10 cm lower with global warming of 1.5°C compared with 2°C. Global warming of 1.5°C would lead to the likelihood of an Arctic Ocean free of sea ice in summer once per century, compared with at least once per decade with global warming of 2°C. Coral reefs would decline by 70-90% with global warming of 1.5°C, whereas virtually all coral reefs (> 99%) would be lost with2ºC of global warming.

6 IPCC (2014b), pp. 18-19.

7 IPCC (2014b). For a European focus, see the analysis by the European Commission.

Climate change is an example of market failure involving externalities and public goods. The market failure derives from the costs associated with the burning of fossil fuels that go beyond the private costs for the users as a result of externalities with repercussions for wider society (local air pollution and GHG emissions). These costs lead to a "social cost of carbon" which will not be internalised by the market without government action. The broad range of actions required to reduce CO_2 emissions have significant "public good" characteristics, suggesting that they will be underprovided by the market without government intervention. At the same time, many aspects of climate change and the associated impacts will continue for centuries, as the stock of CO_2 in the atmosphere will be maintained, even if emissions of GHGs are significantly reduced. This raises issues of intergenerational equity.

Actions to tackle climate change may be hampered by a wide range of political economy considerations. The externalities that apply to economic agents are also relevant for countries. This is because the market failure aspects of climate change may lead some countries to "free-ride" on the actions of others and avoid the adjustment costs associated with climate mitigation policies. This implies a need for cross-country cooperation aimed at "burden-sharing", although it may be more difficult to achieve in the current international climate. Policymakers in Europe and other advanced economies may take comfort in expectations that the direct costs for richer nations at higher latitudes are likely to be lower than for other parts of the world.[8] Taking action against climate change may also seem less urgent and more politically contentious in the light of the weakness of many euro area economies in the aftermath of the economic crisis.[9]

This Occasional Paper reviews the main issues regarding the economic impact of climate change and climate policies.[10] The focus is almost exclusively on macroeconomic impacts, such that other issues of potential relevance for a central bank, for instance relating to monetary policy, financial stability and banking supervision, are not covered to a significant extent.[11] Section 2 briefly reviews the possible environmental impacts of climate change in Europe, outlines the current policy framework and develops a stylised framework for economic and climate interactions. Section 3 focuses on the macroeconomic impacts of climate change, reviewing which sectors may be affected, the potential aggregate size of the impact and the possible timing of the effects. Section 4 gives an overview of the economic impacts of policies to reduce CO_2 emissions and to adapt to ongoing climate change, and a summary follows in Section 5.

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8 For instance, in Canada, Russia and Scandinavia; see Bowen (2013) and Stern (2007).

9 See Kahn and Kotchen (2010).

10 These two distinct channels are often referred to as "physical" and "transition" risks respectively, particularly in the discussion of financial stability risks (see, for example, Batten et al., 2016). However, as the impacts of climate change policy on the wider economy can be positive as well as negative, we prefer to label these as potential policy "impacts" rather than "risks".

11 For monetary policy aspects, see De Santis et al. (2018) on the purchases of green bonds under the Eurosystem's asset purchase programme, and in relation to financial stability and banking, see the special feature in the ECB's Financial Stability Review (Giuzio et al., 2019) and ESRB (2016).

2 Environmental impacts of climate change and the current policy framework

2.1 Climate change in the European Union

While the Earth's climate has varied throughout its history, there is growing evidence that the period of relative stability in which humans evolved may be coming to an end as a result of our emissions of greenhouse gases.[12] Changes in the Earth's climate can be a natural phenomenon, for instance related to the frequency of sunspots or changes in the Earth's orbit. However, since the industrial revolution, humankind has been emitting ever increasing quantities of GHGs, such as CO_2, which have the potential to increase the average global temperature. Such emissions have had a marked impact on the composition of the Earth's atmosphere: compared with pre-industrial times, global CO_2 levels have risen by around 120 ppm and now exceed 400 ppm. It has been estimated that human activities have led to around 1°C of global warming compared with pre-industrial times.[13]

While there is great uncertainty, the predicted impacts of rising carbon concentrations on the climate are complex and heterogeneous across regions, even within Europe (see Figure 1). Most of the European continent is expected to experience higher temperatures, but with asymmetric changes in precipitation. It is likely that rainfall will be higher in central and northern Europe, while southern Europe may face more droughts and dryness.

Evidence suggests that the impacts may be particularly marked in the Mediterranean region, including southern Europe, northern Africa and the Near East.[14] The growth in human emissions may already have increased dryness in the area and "…this tendency will continue to increase under higher levels of global warming" (Hoegh-Guldberg et al., 2018). Drying results from both lower precipitation and rising evaporation, as well as increased plant transpiration, from the ground and ocean surface to the atmosphere.

There may be risks to food security in central and southern Europe, which could be disproportionately larger at 2°C than at 1.5°C of global warming. Risks to freshwater in central and southern Europe in the 2°C scenario are significant, with changes expected in major river basins.[15] While higher and more volatile rainfall may lead to increased run-off in some rivers, increasing the occurrence of flooding, lower rainfall may become a concern for river navigation. In Europe, sea level rise seems

12 This paper does not enter into the scientific debate on global warming. It assumes that climate change is happening and that it is largely man-made and then explores the economic implications. This assumption would seem to be supported by the vast majority of climate scientists (see, for example, the analysis of Cook et al. (2016) and the discussion on this issue by NASA).

13 According to the US National Oceanic and Atmospheric Association, the CO_2 concentration breached 400 ppm early in 2015. Temperature rises are in a "likely" range of between 0.8°C and 1.2°C according to IPCC (2018), p. 6.

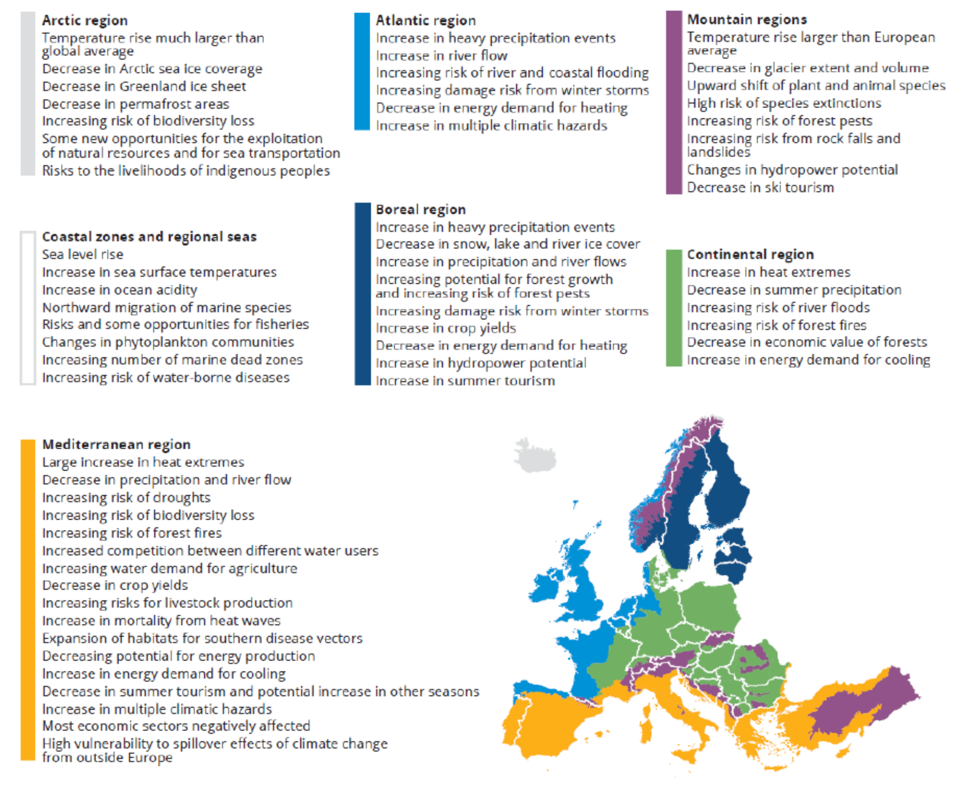
14 According to IPCC (2018) and Hoegh-Guldberg et al. (2018).

15 See Hoegh-Guldberg et al. (2018).

more acute along the Atlantic coasts than in the Baltic Sea, where landmasses that rise after the ice age are mitigating such effects.[16]

Figure 1

Potential impact of climate change in the European Union



Source: European Commission (2018a), p. 3.

2.2 The EU policy framework, the Paris Agreement and central bank initiatives

Reflecting the need for coordinated government action, the EU has set itself a long-term goal of achieving an 80-95% decrease in greenhouse gas emissions between 1990 and 2050, with intermediate targets in 2020 and 2030. The European Commission has developed its strategic long-term vision for a prosperous, modern, competitive and climate-neutral economy by 2050.[17] As this is a long-term goal, it was also necessary to set intermediate targets for GHG emissions, renewable energy use and energy efficiency improvements for 2020 and 2030, as shown in Table 1 below. EU Member States have also committed to reaching their own national renewables targets ranging from 10% in Malta to 49% in Sweden in 2020.[18]

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16 See European Environment Agency (2019).

17 See European Commission, 2050 long-term strategy.

18 There are other more specific targets, such as those related to the use of transport fuels and energy efficiency improvements. In addition, the OECD has also taken stock of the coverage of adaptation in national communications (2015c), see Table 3.

Table 1

EU targets for renewable energy and greenhouse gas emissions

(percentages)

EU target	Renewable share of energy consumption	Energy efficiency improvement	Reduction in greenhouse gas emissions since 1990
Latest data (2017)	17.0%	17%	22%
2020	20%	20%	20%
2030	32%	32.5%	40%
2050	-	-	80-95%

Sources: Eurostat and European Commission (2019).

At present the EU seems on course to meet the targets for renewable energy, energy efficiency and reductions in greenhouse gas emissions by 2020, although most emissions now originate from outside Europe. In 2017 in the EU the share of renewable energy in gross final energy consumption had risen to 17% from 8.3% in 2004, greenhouse gas emissions had fallen by 22% compared with 1990 and the EU's total carbon footprint was equal to 7.2 tonnes of CO_2 per person. However, carbon emissions associated with the production of the EU's imports also need to be considered. Once the carbon embodied in goods imported into Europe is included, European CO_2 emissions are significantly higher. For the EU-28, consumption-based estimates of CO_2 emissions were around 15% higher than production-based estimates in 2015. At the global level, greenhouse gas emissions are increasing.

At the global level, during the Paris Climate Conference (COP 21) in December 2015, 195 countries adopted the world's first comprehensive climate agreement. Although it was no more restrictive than the existing EU framework for Europe, the Paris Agreement nevertheless increases global peer pressure to meet the global warming target. The Agreement sets out a global action plan aiming to avoid dangerous climate change by limiting global warming to well below 2°C and pursuing efforts to limit it to 1.5°C. The signatories to this agreement committed to the aim of rapidly reducing CO_2 emissions in order to achieve net zero emissions in the second half of the 21st century.[19] While the Agreement does not bind countries to certain emission levels, it requires them to publish their nationally determined contributions every five years and establishes a formal review process. As it increases the credibility of national policy initiatives, this may help send clearer signals to investors and developers of new technologies relevant for the transition to a low-carbon economy.[20]

The Network of Central Banks and Supervisors for Greening the Financial System (NGFS) was established in December 2017 to assess the extent of climate change on financial stability.[21] Initiated by the Banque de France, the NGFS currently has 48 members and 10 observers from central banks and supervisors around the world. The ECB joined in April 2018. The purpose of the NGFS is to enhance the role of central banks and supervisors in understanding and

[19] Notably the United States has withdrawn from the Agreement.

[20] The EU formally ratified the Paris Agreement, thus enabling its entry into force on 4 November 2016.

[21] Network for Greening the Financial System (2019).

subsequently managing climate risks and strengthening the global response required to meet the goals of the Paris Agreement. One of its most beneficial impacts has been the sharing of conceptual frameworks to address the various typologies of risks and shocks stemming from unabated climate change. The first NGFS report of April 2019 gave six recommendations, namely to integrate climate-related risks into financial stability monitoring and micro-supervision; integrate sustainability factors into own-portfolio management; bridge data gaps; build awareness and intellectual capacity; achieve robust and internationally consistent climate disclosure; and support the development of a taxonomy.

From a systemic risk perspective, a joint Project Team on climate risk monitoring was set up in 2019 by the Advisory Technical Committee and the Financial Stability Committee of the European Systemic Risk Board (ESRB). The Project Team has two aims. First, it will implement a pilot monitoring framework for climate-related systemic risks in the EU financial sector, including risk indicators and an exposure analysis. Second, the team aims to build a conceptual framework to identify forward-looking scenarios to assess climate risks and transmission channels, and quantify the scenario impact through appropriate metrics based on a stress-test exercise.

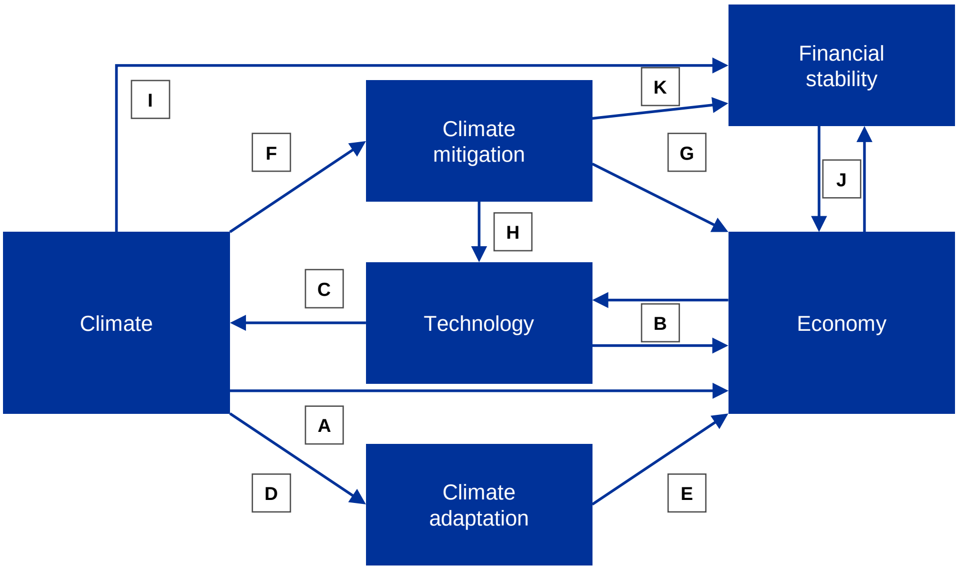
2.3 A stylised representation of the evolving linkages between the climate and the economy

The linkages between the climate and the economy are complex and evolving (see Figure 2). Before the industrial revolution, the economy was primarily agricultural and while the climate could affect the economy – for instance through the impact of changes in sunlight and rainfall on harvests (arrow A in Figure 2), economic activity had no significant impact on the climate. Indeed, for most of the pre-industrial period, the pace of economic growth was thought to be extremely slow by modern standards.[22]

With the onset of the industrial revolution, technological developments enabling the large-scale use of fossil fuels to support automation began to change these patterns. The technological breakthroughs enabled more rapid and persistent economic growth (B). However, a by-product of these new technologies was the increasing release of GHGs from the burning of fossil fuels. When the industrial revolution was confined to the north-west corner of Europe this had little impact on the composition of the atmosphere. However, as these technologies were adopted around the world, the impacts became globally significant, leading to a phenomenon of anthropogenic global warming. With these new technologies, the economy began to affect the climate (C). As the climate changes, the feedback from the climate to the economy (A) will likely strengthen these linkages (see Section 3 for more detail).

[22] According to Crafts and Mills (2017), UK trend real GDP growth per capita was close to zero before the 1660s. It picked up in the run-up to the industrial revolution and then underwent a major acceleration thereafter.

Figure 2
Linkages between the climate and the economy



One response to climate change is to try to adjust to it through climate adaptation (D).[23] For instance, this could involve building stronger sea defences to hold back rising sea levels, designing buildings that can better survive more violent storms and keep the heat out, or creating new crop varieties that can survive more extreme conditions. While many doubt that this strategy alone will be sufficient to deal with climate change, it is likely to be required to address what is widely believed to be inevitable global warming that is "in the pipeline" as a result of past greenhouse gas emissions. As such activities have a cost and involve significant investment, it is likely that they will have an impact on the economy (E).

The other response to climate change is to try to stop it happening through climate mitigation policies (F). In principle, there are two ways of doing this. The first is to focus on economic growth as constituting the problem and try to restrict economic activity so that its impact on the climate is lowered (G).The second is to implement policies which change the technology that both enable economic growth but also lead to the GHG emissions (H).[24] New technologies, for instance based on forms of renewable energy, could replace those based on fossil fuels. The aim would be to cut or significantly reduce the adverse link between economic activity and the climate, enabling growth to continue without leading to climate change. The rollout of new technologies would involve significant expenditure, investment, innovation and

[23] Adaptation refers to the ability of a system to adjust to climate change to moderate potential damage or to cope with the consequences. The IPCC defines adaptation as the "… adjustment in natural or human systems to a new or changing environment, including anticipatory and reactive adaptation, private and public adaptation, and autonomous and planned adaptation." Mitigation involves permanently eliminating or reducing the long-term risks of climate change. The IPCC defines mitigation as "An anthropogenic intervention to reduce the sources or enhance the sinks of greenhouse gases." A list of mitigation and adaptation activities has been put forward by the EU Technical Expert Group on Sustainable Finance (2019).

[24] Acemoglu et al. (2012) suggest that the need for policies to redirect technical change from dirty to clean industries may only be transitory. Once such policies have been in place for a sufficient period, innovation in these new technologies could become self-sustaining.

changes in relative prices, which would have wide-ranging economic impacts (B). The impact of climate policies on the economy is discussed in Section 4 of this paper.

Another dimension is the potential interaction with the financial system. In recent years there has been a growing recognition that climate change may be relevant for financial stability. Related risks can stem directly from the damage caused by climate change, "physical risks", which may affect the insurance and banking sectors (I). There are also potential indirect effects, such as abrupt changes in government policies on climate mitigation, "transition risks", which lead to some business activities – for instance those based on fossil fuels – becoming unviable and the associated assets becoming "stranded" (K). There may also be feedback loops between the impacts of climate change and climate change policies on the wider economy and the financial sector (J). The "climate – real economy – financial" linkages are discussed briefly in Section 4.

3 Macroeconomic impacts of climate change

3.1 Potential supply and demand shocks

Climate change can be seen as an adverse shock to the supply potential of the economy. Rather than being purely temporary in nature like the weather, climate change appears to be a trend change that is expected to be accompanied by greater volatility. As an adverse supply shock it would likely put downward pressure on output, upward pressure on prices and lower future potential growth.[25] Moreover, the uncertainty about the pace and extent of climate change, and humankind's ability to adapt to it, is likely to translate into increased uncertainty surrounding future potential growth. This is likely to imply some volatility, as economic agents' expectations of potential growth are revised in the light of changing weather patterns and emerging scientific evidence thereof. Finally, changes in agents' preferences might influence demand for products and change behaviours, with implications for production and supply.

At the same time, climate change may lead to changes in demand conditions. While in the short run damages to infrastructure may boost investment, expectations of weaker economic growth and income prospects, as well as heightened uncertainty, may lead to firms investing less and households saving more and consuming less in the medium term. Trade may also be affected by disruptions to transportation and infrastructure following rising global temperatures.

3.2 Impacts on output

Attempts have been made to estimate the expected economic impacts of climate change, but these are subject to considerable uncertainties. A number of organisations and academic researchers have developed estimates of the potential impact of climate change on the global economy and particular regions. Given the uncertainties about the pace of climate change and its impact and the long horizons over which such estimates apply, this is an inherently heroic exercise.

Integrated Assessment Models are often used to estimate the costs of climate change and the social cost of carbon.[26] The difficulties in predicting mitigation efforts and future GHG emissions aside, it is very hard to calculate predicted damages from the current "Integrated Assessment Models".[27] For example, there is uncertainty about "climate sensitivity", i.e. the response of temperature increases to atmospheric

[25] See Economides and Xepapadeas (2018).

[26] See, for instance, DICE models (Nordhaus and Sztorc, 2013, FUND (Anthoff and Tol, 2013) and PAGE (Hope, 2006).

[27] See Network for Greening the Financial System (2019a) for an overview of modelling approaches.

GHG concentrations. There is also uncertainty about the distribution of damages that societies may face at any given temperature.

According to modelling work conducted by the OECD, if no mitigation actions are taken beyond those that have already been adopted, global temperatures are expected to rise by 1.5-4°C, resulting in an adverse impact on the level of global real GDP that rises over time to reach somewhere in the range of 1.0-3.3% by 2060 and 2-10% by the end of the century.[28] Changes in crop yields and productivity are expected to have the largest adverse impact on global GDP growth, causing a cumulative loss of 0.9% and 0.8% respectively by 2060. While all regions are negatively affected by climate change, poorer countries are likely to be affected to a larger extent than Europe.[29] Climate change may also slow the rate at which emerging market countries catch up with the developed world. Meanwhile, mainly at higher latitudes, there is a possibility that the benefits of climate change may exceed the damages over the next few decades.

These aggregate estimates are associated with large uncertainty bands and the impact is not expected to be felt before several decades have passed by. The wide range of outcomes may partly reflect non-linearities stemming from increasing difficulty in capturing cross-sectorial and regional adjustments that become larger as changes in factor supply and productivity become more extensive.[30] There are additional uncertainties regarding the potential size, type and timing of the impacts of climate change.

Other estimates suggest small or positive economic impacts from global warming up to 1°C and the potential for significantly rising costs and greater uncertainty regarding the impacts at higher temperatures. One study analyses a range of 27 estimates of the impact of global warming on GDP at different levels of temperature increase. This suggests wide uncertainty bands, with losses ranging between 0% and 12.5% of GDP within the 95% confidence interval for a temperature increase of 3.5°C.[31]

Estimates of the macroeconomic impact of climate change are often disputed as they depend on key assumptions, such as the discount rate and highly

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[28] In the estimates referred to above, the OECD assumes a baseline with no climate policies, a continuation of current policies and plausible socioeconomic developments, such as demographic trends. No unexpected climate change-related shocks are included. A so-called ENV-Linkages model with 35 economic sectors and 25 regions (OECD, 2015b, p. 27) is used, linking each climate impact to labour, capital and intermediate inputs and resources in the production function of a particular region. The model does not cover non-market dimensions of well-being, which cannot be linked to a production function, such as (i) flood damages, (ii) premature deaths from heat stress aggravated by increasingly vulnerable ageing societies alongside reduced winter mortality from extreme cold, (iv) losses of ecosystem services, (v) the higher likelihood and the expected permanent impact of high-impact, large-scale singular events (irreversible tipping points), such as the effects of weather-related disruption of infrastructure, and (vi) negative effects on stressors related to human security associated with migration and conflict.

[29] Burke and Tanutama (2019) find that, while the impacts of a given temperature exposure do not vary considerably between rich and poor regions, additional warming will exacerbate inequality and economic development alone will not reduce damages.

[30] In addition, OECD (2015a) discusses a number of key uncertainties, such as those related to projecting socioeconomic drivers of economic growth; the mix of energy carriers used to produce energy; the emission intensity of other emission sources; the climate system that links emissions to temperature change; regional patterns of climate change, the impacts of climate change on specific impact categories and the economic consequences of these impacts, including the valuation of non-market impacts.

[31] See Tol (2018).

uncertain estimates of the social cost of carbon. Although in project appraisal it is common to discount future costs, it is controversial in the assessment of climate policy, as large costs far in the future may appear small in discounted terms, in turn raising issues of intergenerational equity.[32] The social cost of carbon, which includes the wider societal impacts of emitting CO_2, is the key parameter in most assessments of the costs of climate change. Estimates typically range between USD 10 and USD 200 per tonne, with some others reaching much higher.[33]

In addition, model-based estimates often ignore many other potentially important factors that are difficult to model. The costs associated with low-probability events with possibly enormous economic consequences are typically excluded from such models (e.g. methane emissions from the thawing of the permafrost or the seabed, the potential collapse of land-based polar ice sheets, the Himalayan icecap glaciers or important ecosystems and biodiversity).[34] Some models may also assume exogenous drivers of trend economic growth,[35] thereby automatically limiting the impact of climate change, and may ignore the convexity of the rising costs of climate change at higher temperatures.[36] In contrast, they may also not account well for the possibility of very significant changes in technology.[37]

There are signs that the damage from extreme weather events has increased in recent years.[38] Global weather-related disasters caused a record €283 billion in economic damages in 2017. The share of weather-related catastrophes has increased steadily to account for over 80% of insured losses in 2018 (see Chart 1).[39] While it is difficult to link any specific event to climate change, extreme weather events such as forest fires, flash floods, typhoons and hurricanes appear to be having larger impacts. For instance, it is estimated that the rise in the sea level of 20cm that has occurred since the 1950s raised the surge losses associated with the 2012 superstorm Sandy in New York by 30%.[40] Among other things, that storm had a severely impact on air and land transport in the area, lowering demand for energy and is reported to have destroyed more than half a million homes.[41] In Europe, storm Ophelia in 2017 was the first strong East Atlantic hurricane to reach Ireland and in 2018 storm Leslie caused damages in Portugal and Spain.[42] Looking ahead, the European Commission

32 For instance, while the social cost of carbon estimates used in US Federal Rulemakings, ranging from USD 10 per tonne to USD 100 per tonne, was based on discount rates of 3%, the United States is currently referring to social costs of carbon that only consider domestic damages and discount rates of 3-7%, giving rise to estimates of much lower social costs, see Auffhammer (2018).

33 Some estimates reach over USD 1,000 per tonne, see Grubb (2014), others range between USD 177 per tonne and USD 805 per tonne, see Ricke et al. (2018).

34 Stern (2013); Dow et al. (2013); and Auffhammer (2018).

35 Roos (2018) estimates a model with endogenous growth including changing societal values.

36 See Dietz and Stern (2015).

37 See Auffhammer (2018).

38 The possible impact of severe weather events was discussed in a speech given by President Robert S. Kaplan of the Federal Reserve Bank of Dallas on 24 June 2019 entitled “Economic Conditions and the Stance of Monetary Policy”. See also Batten (2018), pp. 24-26.

39 See Giuzio et al. (2019).

40 See Lloyds (2014).

41 See Huffington Post 20 October 2013.

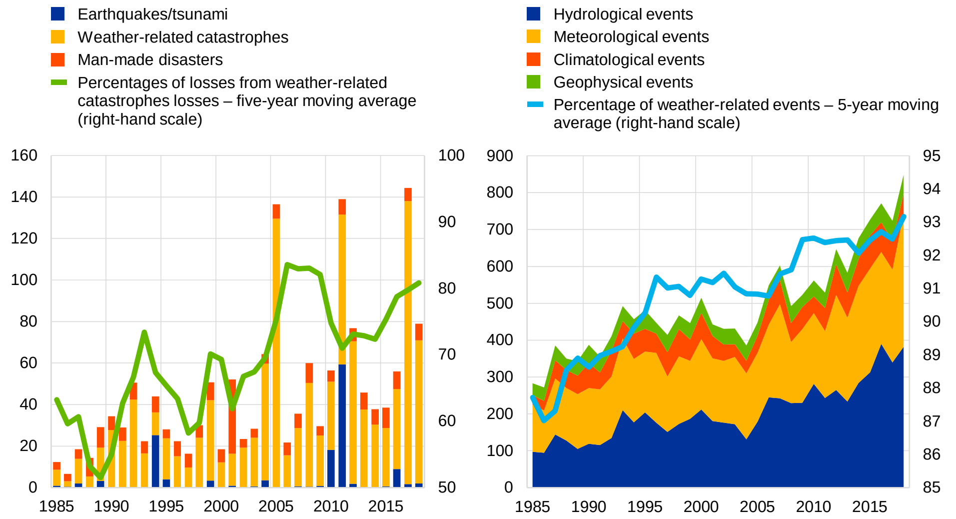
42 European Commission (2018a).

estimates that weather-related disasters could affect about two-thirds of the European population by 2100, compared with 5% today.[43]

Chart 1

Global insured catastrophe losses and number of relevant natural loss events worldwide

(1985-2018; left panel: left-hand scale: USD billions; right-hand scale: percentages; right panel: left-hand scale: number of events; right-hand scale: percentages)



Source: Giuzio et al. (2019).

3.3 Broader impact on the real economy

A significant share of the potentially adverse macroeconomic impacts stems from the effects of climate change on productivity. As discussed above, a part of the modelled output losses in the OECD results stem from lower productivity. Climate change could have an adverse effect through a number of channels. Higher heat and humidity levels could also have an impact on productivity through a reduced capacity to work and losses in output.[44] Productivity may be adversely affected by both higher average temperatures and more frequent extreme weather events.

There is also potential for adverse effects on the capital stock and capital formation through lower investment. The capital stock could be reduced as a result of damage to physical capital (infrastructure, buildings and equipment), potentially affecting the government, businesses and the household sector. While such damage may stimulate replacement investment in the short term, at the aggregate economy level, it is likely to lower net wealth. If firms become more pessimistic about the future impact of climate change on growth, they may decide to reduce investment, leading to a lower capital stock and potential output growth.

[43] European Commission (2018a).

[44] Deryugina and Hsiang (2014) look at daily temperature changes in US counties over a 40-year period. The researchers estimate that productivity per individual workday declines 1.7% for each 1°C (1.8°F) rise in temperature above 15°C (59°F). A weekday above 30°C (86°F) costs a county an average of USD 20 per person in lost income. See also the wider discussion on this issue in Batten (2018), pp. 17-18.

The labour market and household sector may also be adversely affected by global warming. Rising temperatures may have an impact on health and the ability of people to work, leading to lower labour input (see Box 1).[45] With reduced labour input and lower productivity, households may anticipate diminished future income prospects, which could lead them to reduce their spending. Lower net wealth from damage to the capital stock may also potentially weigh on consumer spending. As climate change affects patterns of migration (see Box 2), some regions may experience a decline in the labour supply, while others may see an increase.

Trade and the pattern of production may be affected in response to the impact of climate change on transport. While some transport links may improve in colder regions of the world, more violent storms, changes in precipitation patterns and extremely high temperatures may have adverse effects elsewhere (see Box 1). If firms choose to relocate from areas that are particularly adversely affected by climate change, there may be reallocations of the capital stock, employment and hence output across countries.

Climate change is also expected to have broader welfare impacts that may be poorly tracked by GDP losses alone. By design, GDP does not account for important welfare determinants, from the health risks associated with a changing climate to the disruption caused by communities forced to relocate. Estimates of environmental externalities and the depletion of natural resources (or damage to natural capital) do not directly enter standard national accounting, while activities that are intended to address them, such as healthcare and pollution abatement expenditure, generally make a positive contribution to GDP. This measurement issue has led to efforts to complement GDP with satellite accounts that gauge environmental and societal variables affecting welfare.[46]

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45 For a discussion on possible human capital impacts, see Batten (2018), p. 11 and p. 18.

46 For an example of environmental-economic accounting, see the System of Environmental-Economic Accounting (SEEA) developed by the United Nations in collaboration with statistical agencies such as Eurostat.

Box 1
Potential sectoral impacts of climate change[47]

Prepared by Malin Andersson and Julian Morgan

Many sectors are likely to be adversely affected by climate change, while agriculture at higher latitudes may initially benefit to some extent.[48] Climate change is likely to have an impact on both the European production system and its physical infrastructure. Global population movements may increase as a result of extreme events and the rise in sea levels.

Agriculture, fisheries, forestry and bioenergy production are expected to be directly affected.[49] The agricultural sector will probably see changes in crop yields. There are likely to be increased cereal yields in northern Europe, but decreased yields in southern Europe, as pests and plant diseases increase. Climate change will also have an impact on the productivity of specific areas of land and water. Changes in rainfall patterns are likely to cause an increase in irrigation needs. However, irrigation may not be sufficient to prevent damage to crops from heat waves in some sub-regions. Water availability from river abstraction and from groundwater resources may be reduced significantly in the context of increased demand from agriculture, energy, industry and households. A warming climate may increase forest productivity in Northern Europe, although damage caused by pests and diseases might also increase in all sub-regions and there may be a higher risk of wildfire and storm damage.

The energy, energy-intensive and construction sectors are likely to be affected as the demand for cooling and heating changes. There may be a decrease in demand for heating and an increase in the need for cooling. The supply of more energy-efficient buildings and cooling systems, as well as demand-side management should reduce future energy demand. However, the supply of hydropower may decrease in parts of Europe owing to water shortages. Thermal power production may also decrease during summer and overheating in buildings may become a more frequent problem.

In the transport sector, while climate change may reduce winter road accidents at higher latitudes, it may adversely affect inland water transport on some rivers. For instance, there are reports that the low water levels of the Rhine River have already had an impact on river transport in the area.[50] Rail infrastructure may also sustain more damage from high temperatures. Weather extremes – for instance on transport – may lead to economic damage amounting to 0.5%-1% of global GDP by mid-century,[51] as well as bring some benefits, such as a reduction in winter maintenance costs.[52]

The health sector may be adversely affected, and social welfare costs may increase owing to increased risks to health and mortality from extreme events. Heat and cold exposure, as well as infectious, cardiovascular and respiratory diseases, especially in southern Europe, may increase. According to an assessment by the World Health Organisation (WHO) in 2018, across the world between 2030 and 2050 "… climate change is expected to cause approximately 250,000 additional deaths per year, from malnutrition, malaria, diarrhoea and heat stress." Healthcare costs may also

[47] This box draws heavily on IPCC (2014c).

[48] For example, Canada, Russia and Scandinavia; see Bowen et al. (2013) and Stern (2007).

[49] A United Nations (IPBES) report (2019) finds that up to a million species are threatened by extinction, and that direct and indirect human impacts have severely damaged 75% of the terrestrial environment and 40% of the marine environment upon which these animals depend.

[50] See "Market Insight", Central Commission for the Navigation of the Rhine, April 2019.

[51] See Stern (2007).

[52] See IPCC (2014c).

increase owing to high levels of local air pollution – for example in the form of particulates and nitrogen dioxide – as a result of burning fossil fuels. Air pollution-related lung diseases and premature deaths are already an issue in many large cities around the world. It is estimated that air pollution primarily caused by the burning of fossil fuels results in 3.7 million premature deaths a year globally.[53]

The insurance and banking sectors could be faced with issues such as the accurate pricing of risks, the availability of capital after large loss events and an increasing burden of losses potentially affecting risk premia and insurability, both within and outside Europe. Certain risks may become very expensive to insure, even uninsurable, for instance properties in areas vulnerable to floods, fires or hurricanes.[54] Higher insurance costs and a larger exposure to non-insurable risks could induce the household and corporate sectors to increase their precautionary savings.[55] Governments may face pressure to cover losses that are not covered by insurance. Legal liability risks may also be a possibility, if parties who feel that they have suffered loss and damage from climate change turn to litigation. If such claims were successful, it could have implications for liability insurance providers.[56]

Tourism may also be affected, as activity could decrease in southern Europe and increase in northern and continental Europe.

3.4 Impacts on inflation

Inflation may be affected by the impact of climate change in the agricultural and energy sectors. As climate change affects agricultural yields, there is a potential for lasting impacts on the prices of agricultural commodities (see Box 1). However, as yields may rise in some regions of the world (at least initially) and fall in others, the overall impact is likely to depend on the location of a country and the sources of its agricultural imports. Commodity prices may also be affected by reduced land availability from sea level rise and desertification.

Extreme weather events also have the potential to affect inflation. A recent study found that storms and floods have the potential to cause an increase in inflation in developing countries in the short term (i.e. in the subsequent one to two quarters), whereas droughts can have a more persistent upward impact on inflation lasting a number of years.[57] The results suggest that more severe natural disasters can also have an impact on inflation in developed countries.

There are also likely to be indirect impacts on inflation stemming from the wide-ranging impacts of climate change on demand and supply discussed above. In particular, upward price pressures may emerge from a decline in the supply potential of the economy.

53 See WHO (2018).
54 See Giuzio et al. (2019).
55 See Lane (2019).
56 See Carney (2015) and Batten et al. (2016).
57 See Parker (2018).

Box 2
Climate change and migration

Prepared by Claudio Baccianti

While the direct impact of climate change on Europe and North America is predicted to be less severe than on other regions globally, there may be significant spillover effects as a result of migration. An analysis of data on asylum applications in Europe and on weather variations in 103 countries of origin in the period 2000-14[58] estimated that by the end of the century global warming could lead to an increase in asylum applications by 28% and 188% under two different IPCC scenarios.[59]

Other studies support the notion that weather shocks can induce emigration from developing countries. Cattaneo and Peri (2016) and IMF (2017) find that a rise in temperature and in the incidence of weather-related disasters trigger higher migration in developing countries, with the exception of those with the lowest incomes. Households in very poor areas cannot afford to relocate and are therefore less likely to migrate, while remaining vulnerable to climate change.

Climate change and related natural disasters may exacerbate societal conflicts. One study links the unusually severe drought that occurred in Syria in 2007-10 to a long-term drying trend in the region, which may have been the result of anthropogenic climate change.[60] The drought was seen as adding a stressor to an already fragile situation, which went on a few months later to break out into a civil war. A growing literature has recently provided evidence on the potentially significant contribution of climate change to the outbreak of armed conflicts in vulnerable areas. Armed conflicts may potentially trigger extensive migration from the affected countries.

Rising sea levels may become an additional driver of migration. Projections for the increase in the global mean sea level are for 0.2-0.8m in the 1.5°C warming scenario and 0.3-1.00m in the 2°C scenario relative to the average in the period 1986-2005. Hundreds of millions of people live in vulnerable coastal areas from where they might be forced to migrate. It is estimated that more than four million people in the United States could be affected.[61]

58 See Missirian and Schlenker (2017).

59 The IPCC's representative concentration pathway (RCP) scenario 4.5 results in 98,000 additional asylum applications per year and the RCP scenario 8.5 results in 660,000 additional asylum applications per year, see COACCH (2018). RCP4.5 is a medium-low emission scenario in which forcing is stabilised by 2100. The RCP8.5 scenario represents a non-climate policy scenario, in which GHGs carry on increasing over the century, leading to very high concentrations by 2100.

60 Kelley et al. (2015).

61 See Hauer et al.(2016).

4 Macroeconomic impacts of policies to mitigate or adapt to climate change

4.1 Overview

Substantial changes in the structure of the economy are needed to mitigate and adapt to climate change. If undertaken, such changes can be expected to have an impact on the European economy much more quickly than rising temperatures. The changes required are wide-ranging but mainly affect energy use, transport, industry, buildings, waste management, agriculture and forestry. Given the potentially very broad range of policy initiatives that may be implemented in these areas, we focus largely on some of the major issues for energy generation, energy efficiency and transport that illustrate the wider challenge of decarbonising the economy.[62] If current policy intentions are implemented, the pace of change will accelerate significantly in the coming years.[63]

These changes will imply significant government policy interventions to overcome pervasive market failures.[64] A number of market failure-based arguments favour government intervention to support decarbonisation. First, as discussed in Section 2, there are negative externality arguments relating to reducing GHG emissions, but there are also potential positive externalities stemming from knowledge spillovers from innovation in new technologies. Second, investment in renewables is also likely to show significant returns to scale, as can be seen in the rapid fall in the costs of production for renewable energy. Third, as a new industry, there are likely to be information failures that hamper the availability of finance for renewables.[65] Finally, given that information uncertainty, there may be a risk of misdirected investments in assets or activities that are ultimately not beneficial for the environment, for example as a result of "greenwashing".

In order to achieve the EU targets, the cornerstone of European policy was intended to be the establishment of a carbon price via emission trading schemes (EU-ETS).[66] The EU-ETS was set up in 2005 and involves a "cap and trade" system of tradable permits to release CO_2 applicable to large emitters. By trading, it was thought that carbon reductions could take place in an economically

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62 For illustration, see CCC (2019) for an assessment of how the United Kingdom could achieve a net zero emissions target by 2050.

63 Some estimates suggest that, in order to meet targets, full or close to full decarbonisation will be required in electricity generation, road transport and buildings (European Climate Foundation, 2010). New forms of renewable energy will also require substantial changes in the distribution and transmission of electricity, as renewable sources tend to be more dispersed than traditional large power stations.

64 Climate policy is sometimes said to suffer from two tragedies. The first is the well-known "tragedy of the commons". This refers to the capacity of the atmosphere to absorb greenhouse gases as the "commons" which is being over-exploited by nations and individuals. The second is the "tragedy of the horizons" (see Carney, 2015), whereby the benefits of releasing greenhouse gases are experienced by today's population, but the costs are incurred by future generations.

65 The pervasive market failures affecting green finance are discussed extensively in the Green Finance Synthesis Report, G20, (2016).

66 The third trading period runs until 2020 and the fourth trading period is set for the years 2021-2030. See EU Emissions Trading System (EU ETS).

efficient manner, as falls in carbon emissions should take place where the marginal costs of doing so were lowest. By restricting and gradually reducing the availability of permits, it was hoped that an increasing market price of carbon would be established – and would send the correct signal to investors – without the need for governments to judge where to set the carbon price through taxation. There is now some evidence that the EU-ETS may have helped to increase innovation in low carbon technologies.[67]

However, the EU-ETS does not appear to have provided a consistent signal to investors, as the price of carbon has shown large swings. The price of a tonne of CO_2 fell from close to €30 in 2008 to well under €10 in 2012, remaining very low until recently. According to the European Commission, the first phase of the scheme suffered from an excessive allocation of allowances in some areas, mainly owing to errors in emission projections. When verified emissions data were published, the market price of allowances fell. Subsequently there was a prolonged period of economic weakness as a result of the financial and sovereign debt crises, which are thought to have had an adversely impact on the demand for permits. However, the EU-ETS price increased rapidly in 2018 to reach pre-crisis levels at above €20.

The most important factor behind the price surge appears to be the agreement to reform the EU carbon trading system. The European Commission has set up the Market Stability Reserve (MSR), a price stabilisation mechanism that started operating in January 2019. The MSR intervenes in the market to control the surplus of allowances according to predefined rules. The EU-ETS reform also increased the speed of reduction of the annual emissions cap from Phase 4 (covering the period 2021-2030). These measures appear to have been sufficient to lift market expectations on the carbon price.[68]

An alternative way of shifting the associated social costs of climate change onto polluters is through carbon taxes.[69] Government attempts to influence economic agents' expectations in the direction of rising carbon prices through ex ante commitments to raise carbon taxes in a progressive manner may appear to be an economically efficient signalling device. For this to work, it is essential that government intentions are perceived as credible, with a low probability that a future government will renege on such commitments.[70] However, raising carbon prices through taxation can be vulnerable to political pressures. Examples of instability in government climate policies (for example affecting both carbon pricing and subsidy support) point to doubts about the credibility of new initiatives.[71] Hence carbon pricing alone may not (yet) be providing sufficient incentive for the necessary investments in low carbon forms of energy such as renewables and nuclear.

Individual EU Member States have also chosen to use subsidies to help achieve their targets for renewable energy. These are usually in the form of fixed payments

67 See Calel and Dechezleprêtre (2016).

68 Model-based estimates of the optimal carbon price presented by Nordhaus (2017) suggest that it would need to rise over time from around USD 35 per tonne in 2015 to over USD 80 per tonne in 2050.

69 See Gillingham and Stock (2018) for the cost of reducing GHG emissions.

70 Bassi et al. (2017) develop metrics to assess the current credibility of European policy commitments.

71 OECD (2015b) emphasises the importance of policy credibility and cites a number of examples of government policy instability affecting carbon pricing, p. 73.

for a set period of time, with the rates differing depending on the renewable technology. Such subsidies provide a degree of certainty to project developers and investors where carbon pricing is not yet an option. To avoid distorting energy prices and the market, however, these schemes should be time-limited and carefully designed.[72] Otherwise, they can leave the government exposed to risks of misjudging the pace of innovation for specific technologies and hence providing excessive support.

Changes in regulations may also help reduce GHG emissions. The Clean Power Plan developed in the United States is one such example.[73] In Europe, for instance, stricter emission limits for cars and vans were decided upon in April 2019 to ensure that from 2030 onwards new cars will emit on average 37.5% less CO_2 and new vans will emit on average 31% less CO_2 compared to 2021 levels. Between 2025 and 2029, both cars and vans will be required to emit on average 15% less CO_2.[74] Limits for trucks and other heavy-duty vehicles were also adopted in June 2019. Although regulation can be efficient in some cases, it may be costly per reduced tonne of emitted GHG. Regulatory approaches might also be limited in scope and can be amended by political successors.

4.2 Required investment

Significant investment in mitigating climate change is already taking place to decarbonise electricity generation in Europe and this seems likely to continue. Although the share of renewable energy in gross final energy consumption is only rising gradually, new capacity in electricity generation is increasingly being provided by renewables rather than by traditional coal-fired power stations. The International Energy Agency (IEA) is drawing up different scenarios reflecting how the world energy market might develop up to 2040. Under its "New Policies Scenario", which includes policies and targets announced by governments, the IEA expects a significant expansion in the contribution of renewables to primary energy demand and a correspondingly large drop in the contribution of fossil fuels in advanced economies.[75]

The need for new infrastructure is not limited to electricity generation. Substantial investment will also be needed in energy efficiency in domestic and commercial premises. According to figures from Eurostat, primary energy consumption has been falling in the EU since the mid-2000s and in 2014 was 12.6% lower than in 2006 despite a significant increase in GDP over the same period.[76] This reflects a number of factors in addition to increased energy efficiency, including the secular shift from more energy intensive industries to services.

72 The EU has issued guidance on support schemes to help governments when they design or revise support schemes.

73 See Stock (2019).

74 See Climate change: what the EU is doing.

75 International Energy Agency (2015).

76 Since 2014 energy consumption has recovered slightly, but remains around 10% below its 2006 level.

Climate adaptation will entail investment in infrastructure to prepare for sea level rise and changes in weather patterns, with some areas experiencing more precipitation and violent storms, while others face droughts. These are likely to affect different parts of Europe in different ways, but improvements to water management (for example, improved flood defences, water supply, distribution and water efficiency), wildfire management in drought areas and strengthening of buildings against storms in some areas will all be required.[77] This will entail major infrastructure investment in a wide variety of areas. This is likely to accelerate significantly in the coming years.[78]

Such investment may provide a temporary demand stimulus, although not all of the new investment will be additional, as part of it will simply involve renewal of ageing capital stock.[79] At the European level, the European Commission has estimated that €180 billion of additional annual investment will be needed between 2021 and 2030.[80] According to a large international study, around USD 90 trillion of global infrastructure investment is likely to be needed between 2015 and 2030, even in a "business as usual" scenario without decarbonisation. The study calculated that an additional USD 9 trillion will be required for energy efficiency and USD 5 trillion for low carbon power generation, but that USD 9.3 trillion could be saved from reduced capital expenditure on fossil fuels, electricity transmission and distribution and in the design of more compact cities. On balance, therefore, the net infrastructure cost would be around USD 4 trillion (about 5% of gross world product). Moreover, the lower operating expenditure for the low-carbon infrastructure could ultimately save USD 5 trillion, leading to potential net savings of USD 1 trillion.[81] The potential net additional infrastructure expenditure in the order of USD 4 trillion – as discussed above – over 15 years equates to around a little over 0.3% of gross world product per annum. Using different figures for net investment from the IPCC, the OECD estimates that there could be a need for a rise of around 5% in the annual level of total fixed investment in OECD countries.[82]

Renewable energy has a very different cost structure from conventional fossil fuels and needs substantial up-front capital expenditure. It tends to be very capital intensive, but to have very low marginal costs, as its underlying energy source is available at zero cost. By contrast, fossil fuel use tends to require less capital investment, but has an ongoing need for a fossil fuel feedstock to provide energy. This makes the deployment of renewables more dependent on the cost and availability of finance to support the initial high investment.

Investors may be more wary about lending to renewable energy projects if they perceive them to be risky – for instance owing to uncertainties regarding

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77 See, for example, IPCC (2014d), p. 77.

78 The United Kingdom's Committee on Climate Change – an official technocratic body set up to monitor progress in climate mitigation and adaptation – estimates that there has been a substantial shortfall in capital expenditure on flood defences which leaves the United Kingdom vulnerable to elevated flood risk damage. See CCC (2014).

79 In the context of proposals for a "Green New Deal" in the United States, Diaz (2018) et al. find that frontier renewables (wind, solar, wave and geothermic) not only reduce CO_2 emissions but also spur growth.

80 European Commission (2016) and European Commission (2018b).

81 New Climate Economy (2015) and New Climate Economy (2016).

82 OECD (2015b).

government policy – or if there is a lack of knowledge about this relatively new sector. Recognising the difficulties in raising finance for a new sector, governments have also provided support through state investment banks. Notably, the European Investment Bank (EIB), the largest multilateral provider of climate finance in the world, provided €16.2 billion to climate change mitigation and adaptation in 2018 (29% of its financing).[83] The EIB has an explicit climate strategy to provide finance aimed at keeping global warming below 2°C by financing projects for climate change adaptation, R&D in development, efficiency, renewable energy and lower carbon transport.[84]

4.3 Innovation

Substantial innovation in areas such as renewable energy generation, energy storage and electric vehicles will be needed for decarbonisation and there are signs that this is already taking place.[85] The cost of solar photovoltaic electricity generation fell from around USD 1200 MWh in 1990 to less than USD 100 MWh for the best utility scale projects in 2014.[86] Indeed the cost of most forms of renewable electricity generation in many locations is now reported to be competitive with electricity generated by burning fossil fuels (see Table 2). Renewable energy overall could be a consistently cheaper source of electricity generation than traditional fossil fuels by 2020.87 Innovation in renewable energy has progressed rapidly in the last years (see Chart 2) and the deployment of alternative energy technologies has repeatedly exceeded expectations.[88]

Nevertheless given the inherent variability in renewable electricity generation, there is an ongoing need to improve energy storage and for electricity to replace fossil fuels in a wider range of transport modes. A number of potential innovation "game changers" have been identified which could be transformative in terms of reducing CO_2 emissions and also offer wider economic benefits. In addition to energy storage and electric vehicles, technologies to capture and store CO_2 emissions from power stations and advanced forms of bioenergy exist.[89]

Although a major challenge, the innovation required to develop new clean technologies could have significant benefits in terms of knowledge spillovers to the rest of the economy. According to an analysis of patent citations, new technologies – such as clean energy or electric cars – generate substantially more

[83] For instance to Germany's Kreditanstalt für Wiederaufbau (KfW).

[84] The EIB also provides financial support to sustainable projects in over 160 developed and developing countries and helps mobilise private funding to promote environmental goals. It financed projects worth €15.15 billion in 2018, including biodiversity, clean air, clean water, sustainable transport, renewable energy and energy efficiency. See EIB - Climate and environment.

[85] An overview of the wide range of areas where innovation is needed and the state of play is provided by Eis et al. (2016).

[86] New Climate Economy (2014), p. 39.

[87] IRENA (2018).

[88] For instance, this can be seen in the IEA projections on electrical capacity of renewable energy, excluding hydropower, published in the World Energy Outlook (WEO) series.

[89] New Climate Economy (2014), Chapter 7 Innovation.

knowledge spillovers than conventional electricity or cars.[90] This is because such technologies are at an earlier stage of the innovation process and therefore appear to have experienced more radical innovations with more general applications. There is also evidence that innovation in clean technologies responds positively to increases in the cost of fossil fuels.[91]

Table 2
Global electricity costs in 2018

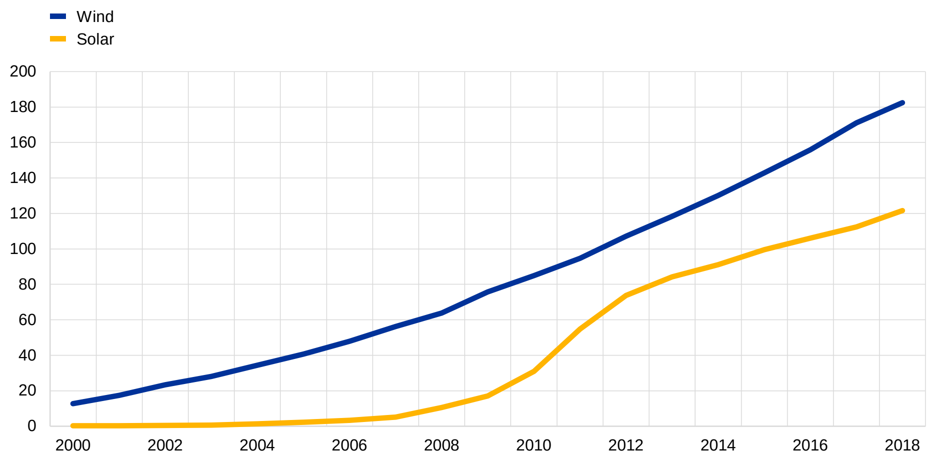
(USD/kWh, percentages)

	Global weighted average (USD/KWh)	5-95th percentile range (USD/KWh)	Change 2017-18 (percentages)
Fossil fuels	-	0.049-0.174	-
Photovoltaic solar panels	0.085	0.058–0.219	−13%
Concentrated solar thermal systems	0.185	0.109–0.272	−26%
Offshore wind	0.127	0.102–0.198	-1%
Offshore wind	0.056	0.044–0.100	−13%

Sources: IRENA © (2019), Renewable Power Generation Costs in 2018, International Renewable Energy Agency, Abu Dhabi.
Notes: Concentrated solar thermal systems concentrate radiation from the sun to heat a liquid substance which is then used to drive a heat engine and drive an electric generator. This indirect method generates alternating current (AC) that can be easily distributed on the power network. Photovoltaic solar panels differ from solar thermal systems in that they do not use the sun's heat to generate power. Instead, they use sunlight through the "photovoltaic effect" to generate direct electric current (DC) in a direct electricity production process. The DC is then converted to AC, usually with the use of inverters, for distribution on the power network.

Chart 2
Electrical capacity of renewable energy deployment in Europe

(GW)



Sources: © IRENA (2019), Renewable capacity statistics 2019; and IRENA (2018), Renewable Energy Statistics 2018, The International Renewable Energy Agency, Abu Dhabi.

It has been suggested that the new technologies needed to decarbonise the world economy and increase the efficiency with which natural resources are used could constitute a part of the next industrial revolution, also supporting potential growth. Increased resource efficiency may be essential in order to satisfy the consumption requirements of a burgeoning global middle class. In this context, the

[90] Dechezleprêtre et al. (2013).

[91] Aghion et al. (2012).

emerging "cleantech" sector could provide substantial scope for innovation-driven economic growth in the coming years.[92]

Despite these potential opportunities, current levels of R&D in energy appear to be very low. Private R&D expenditure in large energy companies represents a far smaller share of sales than R&D spending by firms in other industries such as pharmaceuticals, IT and manufacturing.[93] While public R&D spending on energy technologies in the EU approximately doubled in real terms between 2000 and 2013, it remains significantly below the levels spent in the early 1980s. It also ranks lower than spending on other categories, such as industry, health, space exploration and defence. There is also substantial variation in spending across countries – ranging from 0.001% of GDP (Portugal in 2013) to 0.167% of GDP (Luxembourg in 2012) with an OECD average of 0.045% of GDP.[94]

European public spending on energy R&D is minimal compared with current spending on the deployment of renewable energy, although the latter can stimulate private innovation indirectly. A study has shown that, in 2010 the six largest European countries spent €315 million to support R&D compared with €48.3 billion to support deployment of renewables.[95] However, as subsidies for deployment encourage "learning by doing", they can also stimulate private innovation, which leads to cost reductions for renewables. For instance, it has been estimated that a doubling of installed capacity can lead to cost reductions in the order of 15-30% for solar power and 5-18% for wind energy.[96]

4.4 Industrial structure and competitiveness

It is often feared that more polluting industries may gravitate towards countries with less stringent environmental protection, known as the "pollution haven hypothesis". There has been some concern in Europe, particularly among countries that have taken the lead in deploying low carbon technologies, that increasing the use of renewable energy may drive energy intensive industries elsewhere in search of lower energy costs. Output and emissions would then rise in these so-called pollution havens, neutralising partly or in full the effort to lower global emissions. Such concerns have heightened since the availability of lower (direct) cost shale gas has emerged in the United States.

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92 Perez (2002) has identified five successful technological revolutions, from the original industrial revolution starting in the United Kingdom in the 1770s to the IT and telecommunications revolution starting two hundred years later in the United States. Each involved an installation period normally associated with some form of financial mania, a turning point recession followed by a deployment period of strong growth ("golden ages"). Perez (2014) sees green growth supported by the IT and telecommunications revolution as providing the conditions for a new "golden age" of strong growth. Others such as Stern (2015) build on the Perez framework and argue that cleantech and biotech could constitute a sixth industrial revolution by themselves. Acemoglu et al. (2012) also find that by redirecting technical change from dirty to clean industries, there may not need to be a significant shock to long-term growth.

93 Grubb (2014), p. 321, Figure 9.3.

94 OECD (2015b).

95 Zachmann et al. (2014).

96 Grubb (2014), p. 323.

Empirical studies suggest that the unilateral implementation of environmental regulation and carbon pricing appears to have limited effects on competitiveness.[97] This work shows that worsening trade balances in pollution-intensive industries are likely to be offset by higher exports in sectors with low-carbon intensity. Moreover, pollution-related expenditure is limited compared to other costs, such as wages. International production specialisation is therefore mostly determined by other factors and policies, such as the quality of the local workforce and the absence of trade barriers.

It has also been argued that, contrary to the pollution haven hypothesis, stricter environmental policies may lead to efficiency gains as firms react by innovating to improve business performance, which is known as the "porter hypothesis".[98] The theory behind this is that firms, faced with the requirement to meet higher standards, are forced to invest in innovation with benefits for themselves and potential positive spillovers for the economy as a whole, more than offsetting any adverse effects on polluting industries. In this case, industries in the innovating countries may gain a competitive advantage over foreign competitors.

According to the empirical literature, climate change mitigation can affect productivity through different channels and has a small impact in most sectors. The direct impact of carbon pricing is likely to increase production costs and lower profits, which may discourage firm-level investment and therefore productivity. Switching to low-carbon technologies does not necessarily improve firms' performance, because only some energy and pollution abatement technologies are able to deliver cost-saving gains.[99] Furthermore, low-carbon production systems may be less productive than fossil-based ones in the early stages of the decarbonisation process and their adoption may dampen productivity growth, at least initially. Emission-related costs nevertheless account for a small fraction of total costs in most sectors and, within industries, environmental policy is found to increase productivity of frontier firms, while negatively affecting producers at the bottom of the productivity distribution.[100] As a result, the aggregate policy effects on productivity are expected to be small but heterogeneous across industries and firms.

While aggregate impacts may be small, as clean industries and frontier firms expand output and employment, the prospective negative effects on the emission-intensive, trade-exposed and least productive producers are a cause for concern during the transition. Production of fossil fuels, ferrous and non-ferrous metals and chemicals are vulnerable to carbon leakage and competitiveness issues, especially if the policy action is not coordinated at the global level. Potentially negative effects on profitability and employment in those sectors are not only due to the high pollution and energy intensity, but also to technological constraints in switching to cleaner processes and to international competition that prevents firms from fully

97 Recent studies include Kozluk and Timiliotis (2016) and Naegele and Zaklan (2019). Dechezleprêtre and Sato (2017) is a comprehensive literature review of ex post evaluation studies. See Carbone and Rivers (2017) for a review of ex ante studies.

98 Porter (1991) and Porter and van der Linde (1995).

99 Rexhäuser and Rammer (2014) show that, among different environmental innovations, only technologies targeting resource efficiency have a positive effect on firm profits.

100 See Albrizio et al. (2017).

passing on emission-related costs to consumers. Ex ante policy simulation studies find that a 20% emissions cut in advanced economies reduces output in those industries by around 5% on average.[101]

Carbon border taxes have been proposed as a way to address such competitiveness concerns.[102] In essence, such taxes envisage imposing duties on imported goods to account for the fact that they have been produced under looser environmental standards. The taxes aim to achieve a more level playing field so that countries cannot gain a competitive advantage by adopting weaker standards. Moreover, countries wishing to tighten regulations can do so without adversely affecting their own competitive position. To some extent, this approach reduces the need for close international cooperation. However, such taxes are extremely difficult to calibrate precisely for each imported good (they require detailed knowledge of production processes and the supply chain) and run the risk of being (mis)used as a form of protectionism.[103] Moreover, it does not address the fairness argument put forward by developing countries that the majority of the signatories to the Paris Agreement are the main polluters in cumulative terms and that carbon emissions contributed to these countries' development.[104]

4.5 Stranded asses and a disorderly transition

Achieving a 2°C limit on global warming requires not burning most of the known reserves of fossil fuels. If the world is to have a 50% chance of keeping to the 2°C limit for global warming, it was estimated in 2014 that 1.1 trillion tonnes of CO_2 emissions was left for all human activities – the "carbon budget". However, proven reserves of coal, oil and gas could provide between 3-5.4 trillion tonnes of CO_2 – or around three to five times the carbon budget.[105] This implies that unless feasible ways are found to store CO_2, the vast majority of these fossil fuel reserves cannot be burnt if the climate targets are to be met.

It is sometimes argued that the need to leave a large proportion of fossil fuel reserves in the ground will lead to "stranded assets".[106] It has been suggested that there is a risk of a "carbon bubble" developing, whereby the valuations of large fossil fuel companies are based on an assumption that policymakers will not act decisively to decarbonise.[107] Irrespective of whether this is a reasonable assumption, there may be a significant risk that the international community will change course,

[101] See Carbone and Rivers (2017).

[102] See Helm and Hepburn (2017).

[103] Output-based rebating is a possible alternative that may address competitiveness concerns while being easier to implement (see Fischer and Fox, 2012). This approach is an output subsidy that alleviates the increase in prices caused by carbon pricing in domestic production, especially in the most energy-intensive and trade-exposed industries, therefore limiting carbon leakage, while preserving the incentive to switch to low-carbon technologies.

[104] Europe and the United States represented more than 50% of global emissions until close to 1995, see Annual total CO_2 emissions, by world region.

[105] New Climate Economy (2014a), Chapter 4, Energy, Figure 2, p. 7.

[106] There might be regulatory stranding – owing to a change in policy or legislation; economic stranding – owing to a change in relative costs or prices; or physical stranding – owing to distance, flood or drought, see Carbon Tracker's stranded assets.

[107] See Wolf (2014).

and may do so suddenly, for instance following a catastrophe which is widely believed to be related to climate change.[108] Alternatively, the technological change currently driving down the costs of some forms of renewable energy may ultimately largely remove the need for fossil fuels.

If the risk of stranded assets were to materialise, it could affect a significant share of the economy, possibly affecting fossil fuels, aviation, energy and automobiles. There are notable examples where new environmental policies or changes in energy prices have disproportionately affected some parts of the economy. For instance, the introduction of new emissions test procedures (Worldwide Harmonised Light Vehicle Test Procedure or WLTP) in September 2018 was seen as causing considerable reductions in German car production in the subsequent months. Rising oil prices in the early part of this century also had a disproportionate impact on US motor vehicle manufacturers, which had specialised in producing larger and less fuel-efficient vehicles, contributing to a crisis in this sector.

There is growing interest in whether such stranded assets may pose financial stability risks.[109] For instance, following a sudden change in energy policy, such as an unexpectedly sharp rise in carbon prices or the introduction of regulatory measures to ban certain technologies, there may be a very rapid move away from fossil fuels with diverging impacts across economic sectors. This may lead to a sharp spike in energy costs and/or a restriction in the availability of energy with significant macroeconomic effects. Such effects may also happen without policy actions, for instance if there is further dramatic technological progress in renewable energy or if households and investors revise their beliefs about the economic significance of climate change, perhaps following specific news or events.[110]

A sudden revaluation of carbon-intensive assets may have the potential to affect financial institutions. The combined effect of a sharp fall in physical capital values and a drop in asset prices could potentially even be disruptive enough to trigger an economy-wide recession.[111] Although this may ultimately lead to some creative destruction of high-carbon sectors and a reallocation of resources to the sectors that are robust to climate change, there may be risks to financial stability which would not be present in a more gradual or ordered transition.

4.6 Fiscal implications

Climate change policies imply a larger role for state intervention through fiscal measures, although the net impact on public finances is unclear. The process of internalising the negative environmental externality of CO_2 emissions, as reflected in

[108] An example of a sudden change in policy following an event was the decision of the German government to close all nuclear power stations after the Fukushima disaster in 2011.

[109] See ERSB (2016); Giuzio et al. (2019); Coeuré, B. (2018); Mersch, Y. (2018); and Lautenschläger, S. (2019).

[110] This point is mentioned in Lane (2019); other research suggests that short-term shifts in market sentiment induced by awareness of future climate risks could lead to economic shocks and substantial losses for some investors; see CISL (2015).

[111] The ESRB investigated the so-called carbon bubble and its potential implications for systemic risk in 2016, see ESRB (2016) and Lane (2019).

the social cost of carbon, could potentially raise additional revenues,[112] but new policy measures would seem to imply a need for additional government expenditure or the crowding out of other public investment and public spending, as well as coverage of losses not covered by private insurance.

Carbon-related taxes clearly offer scope for increasing revenues, but increasing the price of carbon through trading systems such as the EU-ETS may yield much more limited fiscal benefits. As much as 96% of emission allowances were allocated for free in the 2008-12 period, while around half were free between 2013 and 2020.[113] As the aim is to reduce emissions, the optimal carbon tax from the perspective of incentivising behavioural change will not necessarily be consistent with high levels of revenue. Finally, green tax revenues may be "recycled" for other purposes – such as to support energy efficiency – in order to make carbon taxes more politically acceptable.

There is also a need to find ways to fund subsidies for the deployment of renewable energy and climate adaptation measures, either through taxation or levies on users of energy. In most cases, the cost of decarbonising electricity generation will fall on energy users, either through emissions trading, carbon taxes or levies to pay for subsidies for renewables. In 2014 the UK Department for Energy and Climate Change estimated that the costs of the range of energy subsidies and levies will account for an increasing share of UK domestic energy bills. This is set to reach GBP 191 per household in 2030. Significant increases are also occurring in the energy costs of the business sector, particularly energy-intensive ones.[114]

4.7 Impacts on households and inflation

The abovementioned costs can be substantially offset by the potential savings resulting from increased energy efficiency, also supported by government policies. The UK Department for Energy and Climate Change estimated that domestic energy consumers will save on average GBP 251 per year in 2030 as a result of government measures promoting energy efficiency, yielding a net average saving of around GBP 60 per year per household from government climate change policies.

Potential efficiency savings can also come from users of products, such as automobiles. The US Department of Transportation and the Environmental Protection Agency estimate that – as a result of rising vehicle standards – by 2025 car owners will be saving between USD 2,400-5,000 in lower fuel costs over the life of their vehicle.[115]

Inflation may be pushed up by measures to increase the price of carbon. Market-based emissions trading or new taxes on high-carbon activities may raise

[112] See Ligthart (1997).

[113] See OECD (2015b).

[114] See UK Department of Energy and Climate Change (2014).

[115] See Bianco et al. (2014).

prices, particularly fossil fuel-based energy. Given the volatility seen in the EU-ETS price of carbon, emissions trading schemes may have the potential to lead to greater volatility in inflation than would be the case for carbon taxes.[116] However, the impact of carbon taxes may also be unpredictable if there are unexpected changes in tax rates, reflecting changing political priorities.

Upward inflation impacts may be offset by continued falls in the price of renewable energy and increased energy efficiency. Higher inflation stemming from carbon pricing may be offset by further innovation in renewable energy. This should lead to lower electricity prices and increased energy efficiency, which may in turn reduce the weight of energy in the consumption basket. Box 3 shows that the effects appear to differ between domestic energy use and transportation.

Box 3
Energy efficiency and the contribution of energy to inflation

Prepared by Claudio Baccianti

Energy is an important component of the consumer price index. In the HICP, the overall weight of energy for the euro area was 10.1% in 2018. The contribution of energy inflation was 0.6 percentage points in 2018, approximately one-third of the total.[117] This measure only captures inflation in final-use energy products such as electricity and gasoline, while energy price shocks also have an impact on the price of non-energy goods indirectly through demand substitution and input-output linkages in production.

One of the main pillars of climate policy is the diffusion of energy-saving technologies, which would potentially reduce the expenditure share and the role of energy in the inflation process. From 1996 the weight of energy in the HICP has remained almost unchanged, while real energy prices have risen steadily in the euro area. This fact suggests that increasing energy efficiency has contributed to keeping the expenditure shares of energy products in check.

This box presents some evidence regarding country-level efficiency trends in household energy consumption for the European Union during the period 1996-2018. Aggregate trends in energy conservation are estimated as the variation in expenditure shares – the item weights from the HICP – that is not explained by changes in relative prices and income. This is an imperfect measure of technical efficiency improvements, because it also captures behavioural changes and other unobserved factors. Further details on the calculation are provided in the Annex. The energy demand model is estimated separately for two items, namely (i) *Electricity, gas and other fuels*, and (ii) *Fuels and lubricants for personal transport equipment*, with rather diverging results.

There is poor substitutability in energy consumption, and energy weights tend to expand when prices rise. The estimated elasticity of substitution between energy products and the rest of the goods and services in the basket is 0.32 for electricity and gas and 0.11 for transport fuels. This result is in line with the literature.[118] On average income has a negative impact on the weight of electricity, gas and other fuels, suggesting that energy for heating, lighting and cooking is a necessary good with an income elasticity lower than one. The coefficient of income for transport fuels is instead

[116] See McKibbin et al. (2017).

[117] See ECB (2019).

[118] See Labandeira et al. (2017).

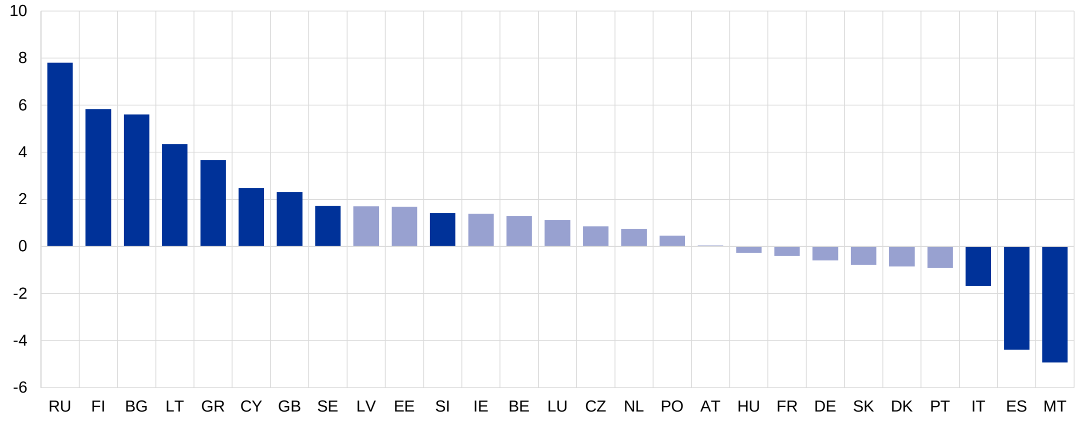
not statistically different from zero, as the use of private transportation more closely follows the level of GDP per capita.

In most countries, there is evidence of significant trends towards energy conservation.[119] According to our measure, efficiency gains have lowered the expenditure share of electricity and gas consumption each year by 7.8% in Romania and 5.8% in Finland, although this effect has been weaker in other countries (see Chart A). In private transportation, the model identifies broad-based downward trends in energy consumption that are unexplained by changes in income and fuel prices, reflecting significant improvements in the fuel economy of light-duty vehicles (see Chart B).

Looking ahead falling prices and higher investment in energy-saving technologies could put downward pressure on the energy share in the HICP, assuming that these effects are not offset by increases in demand. The expansion of and innovation in the field of renewables could put downward pressure on electricity and gasoline prices, leading to a decline in energy expenditure. In addition, countries can only reach their emission reduction targets through a significant increase in energy efficiency, suggesting further scope for energy demand reductions.[120] However, this may be partially offset by a "rebound effect", if the wealth gains stemming from lower energy bills lead households to increase their demand for energy.

Chart A

Energy efficiency, estimated average growth rates – electricity, gas and other fuels



Source: Authors' calculations based on Eurostat data.

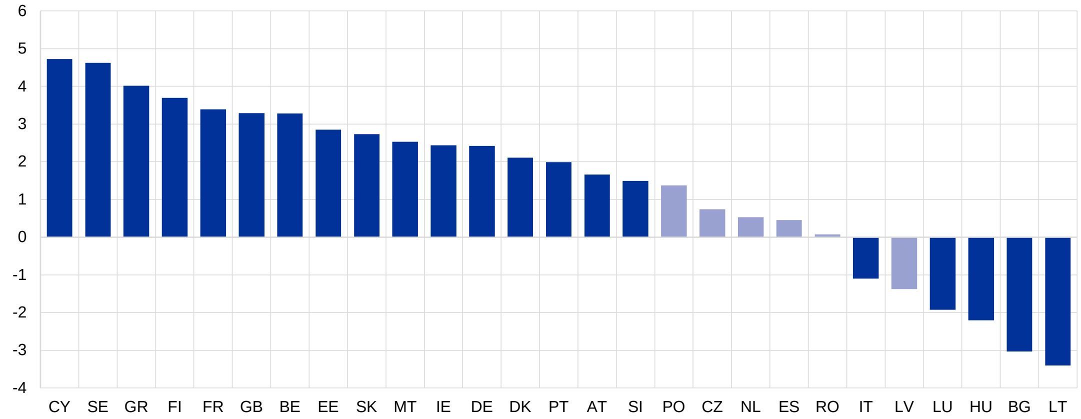
[119] These results are in line with the literature; see Spencer et al. (2017).

[120] See IEA (2017).

Chart B

Energy efficiency, estimated average growth rates – fuels and lubricants for personal transport equipment

(percentage points; bars are shaded dark when the rate is statistically significant at 5%)



Source: Authors' calculations based on Eurostat data.

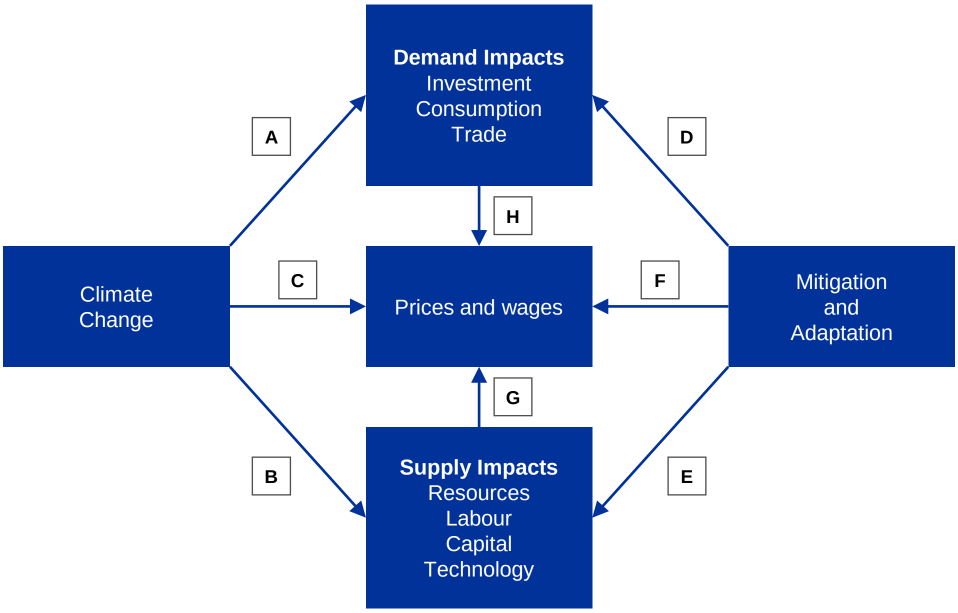
5 Summary

This paper has reviewed the possible channels through which climate change and climate change policies may have an impact on the macro economy. The potentially wide-ranging economic impacts identified in this paper are summarised in Figure 3.

A changing climate can have direct demand-side impacts (A). For instance, if businesses anticipate slower economic growth, they may scale back investment. Also, if households become more pessimistic about their future incomes, they may decide to save more and consume less. Trade may be affected as the warming planet has an impact on transport. While some transport links may improve in colder regions of the world, more violent storms, changes in precipitation patterns and extremely high temperatures may have adverse effects elsewhere.

Potential effects can be expected on the supply-side of the economy (B). In particular, there may be significant impacts on the availability of some natural resources (agriculture, fisheries and forestry), and the capital stock may be adversely affected by climate-related damage and reduced investment. Rising temperatures may also have an impact on health and the ability of people to work at higher temperatures, leading to lower labour input.

Figure 3
Broad linkages between the climate, policies and the economy



At the same time, climate change policies may also have a potential impact on the wider economy. Mitigation and adaptation policies will require substantial amounts of investment, which can be expected to have an impact on the demand side of the economy (D). Paying for this type of investment may imply a rise in the costs of energy (e.g. through taxation, levies or carbon pricing), which may lead to lower real incomes and thereby adversely affect consumption. If mitigation measures are not applied consistently across countries, there may be changes in the patterns of trade as countries with more stringent policies may end up specialising in less polluting industries.

Mitigation policies may in particular have an impact on the supply side of the economy (E). As already discussed, mitigation essentially involves the replacement of an old fossil fuel-based technology with a new technology based on renewable forms of energy. This transition will likely have major implications for the capital stock and the nature of innovation. Changes in the structure of the economy are also likely to imply a reallocation of employment from declining high-carbon industries to expanding low-carbon sectors.

From a central bank perspective, both climate change and climate change policies are likely to have direct and indirect impacts on inflation, also increasing its volatility. If climate change affects agricultural yields and more volatile weather patterns affect harvests, then there may be significant impacts on prices and inflation (C). Climate policies that involve raising the price of carbon through taxation or market-based mechanisms are also likely to have a direct impact on inflation and its volatility (F). Finally, there are likely to be indirect impacts via both demand (H) and supply (G) impacts from climate change and policies.

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Annex: Methodology for the decomposition of energy inflation

This Annex describes the econometric model used in Box 3 to estimate the contribution of energy-saving technological progress to inflation as a result of changes in energy expenditure.

Households in country c derive utility U from a basket of consumption goods B which includes both energy and non-energy goods. Household preferences are specified as follows:

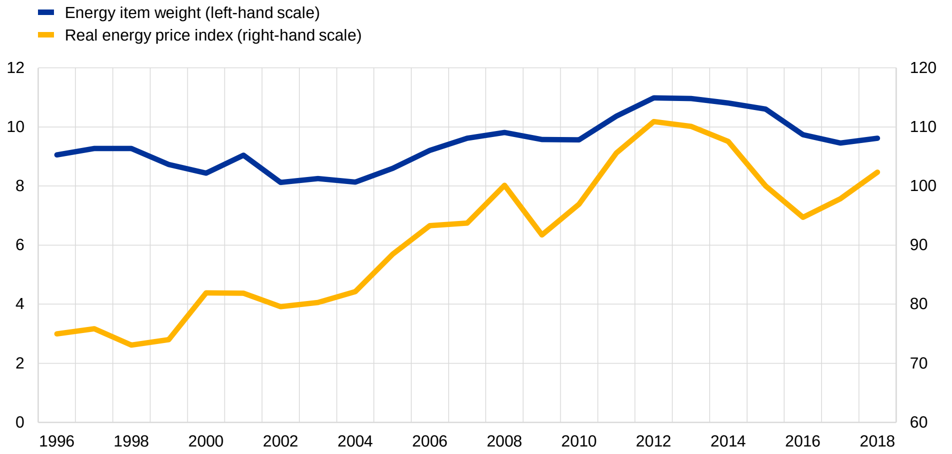
$$U_{ct} = \left[\sum_{i \in B} \pi_{ci} E_{i,ct}^{\frac{\varepsilon-1}{\varepsilon}} (x_{i,ct} + \bar{x}_i)^{\frac{\varepsilon-1}{\varepsilon}}\right]^{\frac{\varepsilon}{\varepsilon-1}},$$

where the parameter ε measures the degree of complementarity between goods, π_{ci} is a share parameter, $\bar{x}_i$ is a parameter that introduces non-homotheticity and that affects the elasticity of substitution between goods. Finally, $E_{i,ct}$ is an index measuring the efficiency in the use of good i.

Chart A.1

Euro area index and weight for energy

(percentages; index: 2015=100)



Source: Eurostat.
Note: The real energy price index is the energy price index divided by the all-items HICP.

Using the demand functions obtained from the utility maximisation and the overall price index P_{ct}, the optimal expenditure share of good i is:

$$S_{i,ct} = \pi_{ci}^{\varepsilon} E_{i,ct}^{\varepsilon-1} \left(\frac{P_{ct}}{p_{i,ct}}\right)^{\varepsilon-1} \left(\frac{x_{i,ct}}{x_{i,ct} + \bar{x}_i}\right) \qquad (1)$$

The efficiency variable is an exponential function of time, $E_{i,ct} = e^{\gamma_{ic}t}$. Technological progress makes the use of energy more efficient if $\gamma_{ic} > 0$, with $i = E$. On the contrary, if $\gamma_{ic} < 0$, technology becomes overall less efficient in terms of energy requirements.

Applying the natural logarithm to equation (1), expenditure shares are decomposed into four components: one term capturing time-invariant and country-specific factors (i.e. climatic conditions), energy efficiency trends, changes in relative prices and income:

$$\ln \mathrm{s}_{\mathrm{i,ct}} = \varepsilon \ln \pi_{ci} + (\varepsilon - 1)\gamma_{ci} t + (\varepsilon - 1) \ln \frac{P_{ct}}{p_{i,ct}} + \ln \left(\frac{x_{i,ct}}{x_{i,ct} + \bar{x}_i} \right) \quad (2)$$

If goods are complements, i.e. $\varepsilon < 1$, and energy efficiency rises over time, $\gamma_{cE} > 0$, then the expenditure share of energy declines. The third term on the right is the effect of non-homotheticity. The expenditure share of good i in the level of income decreases if $\bar{x}_i < 0$, while it increases if $\bar{x}_i > 0$ or it is independent of income if $\bar{x}_i = 0$.

The econometric model for demand of good i includes country-fixed effects, time trends with heterogeneous slopes, the relative price of good i and the logarithm of the GDP per capita Y_{ct}:

$$\ln \mathrm{s}_{\mathrm{ct}} = \alpha_c + \delta_{\mathrm{c}} t + \beta_1 \ln \frac{P_{ct}}{p_{i,ct}} + \beta_2 \ln \mathrm{Y}_{\mathrm{ct}} + \eta_{ct} \quad (3)$$

The estimated values for δ_{c} and β_1 are then used to retrieve the value of the elasticity of substitution and the average growth rate of the energy efficiency index, γ_{ci}. Note that the contribution of technological progress is estimated as a residual, capturing persistent trends in energy expenditures that are unexplained by changes in relative prices and in income.

Table A.1

Trend in HICP weights and price changes

(percentage points; average percentage change)

Country	Item weights in 2018, percentage points		Average percentage changes, 1996-2018			
	ELE-	FTRA	Rel. price ELE	weight ELE	Rel. price FTRA	weight FTRA
AT	4.49	3.25	0.72	-0.34	1.34	-0.72
BE	6.61	3.34	1.99	-0.01	1.89	-0.89
BG	6.70	6.67	3.07	-1.45	0.29	1.51
CY	3.15	5.25	3.91	1.01	3.52	0.14
CZ	9.34	3.46	2.36	-0.44	-0.93	-1.46
DE	6.50	3.91	1.95	0.09	1.59	-0.06
DK	6.46	3.00	1.17	-0.16	1.62	-0.35
ES	5.39	5.78	0.69	2.37	1.58	1.30
EE	6.70	5.08	3.37	-2.43	3.88	4.15
FI	3.38	3.90	2.71	-2.54	1.43	-1.45
FR	5.12	3.90	1.43	0.42	1.89	-0.81
GB	3.40	3.00	2.82	-1.27	2.03	-1.31
GR	4.03	4.81	2.52	-1.37	2.26	0.90
HU	6.94	7.68	0.99	-0.46	0.06	2.15
IE	4.00	4.49	2.25	-1.95	1.95	0.12
IT	5.09	4.33	0.63	1.05	1.03	2.05
LT	6.00	6.58	3.11	-2.70	2.30	9.54
LU	2.98	8.58	1.10	-1.77	1.55	4.45
LV	8.24	5.62	2.36	-0.79	3.02	5.38
MT	2.21	4.08	2.14	2.69	2.25	1.02
NL	4.40	3.76	2.58	-0.79	1.40	0.35
PO	9.13	4.37	1.88	-1.04	2.61	2.18
PT	4.06	3.95	0.96	0.35	1.87	1.10
RU	6.25	5.87	3.89	-4.20	1.66	2.67
SK	11.33	3.52	5.29	3.14	-0.41	1.24
SI	6.27	5.54	2.07	-0.47	1.83	0.66
SE	5.90	3.02	2.24	-0.74	1.79	-2.68

Source: own calculations based on Eurostat data.
Notes: ELE: Electricity, gas and other fuels, FTRA: Fuels and lubricants for personal transport equipment. Rel. price is the relative price defined as the difference between the percentage change in the price of the specific good and in the overall HICP.

Table A.2
Trend in HICP weights and price changes

(parameters)

	$i = ELE$	$i = FTRA$
Log relative price of energy, $P_{ct}/p_{i,ct}$	-0.678***	-0.890***
	(0.06)	(0.09)
Log real GDP per capita	-0.410*	0.228
	(0.19)	(0.17)
Observations	573	575
Elasticity of substitution parameter, ε	0.32	0.11
F-test, hp: $\varepsilon = 0$ ***p-value***	30.27 0.00	1.47 0.24

Sources: Own calculations based on Eurostat data.
Notes: Real GDP per capita is expressed in purchasing power standards relative to the EU28 average. The dependent variable is the weight of the product in the HICP index. The model also includes fixed effects and country-specific time trends. Standard errors are clustered by country. The panel series for product weights are stationary according to the Im-Pesaran-Shin (2003) test. Abbreviations: ELE: Electricity, gas and other fuels, FTRA: Fuels and lubricants for personal transport equipment.

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