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The climate and the economy

Discussion Papers

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Discussion papers

Discussion papers are research-based papers on policy relevant topics. They are singled out from standard Working Papers in that they offer a broader and more balanced perspective. While being partly based on original research, they place the analysis in the wider context of the literature on the topic. They also consider explicitly the policy perspective, with a view to develop a number of key policy messages. Their format offers the advantage that alternative analyses and perspectives can be combined, including theoretical and empirical work.
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Abstract

Climate change and the public policies to arrest it are and will continue reshaping the global economy. This Discussion Paper draws on economic research to identify some key medium- and long-run economic implications of these developments. It explores implications for growth, innovation, inflation, financial markets, fiscal policy, and several socio-economic outcomes. The main message that emerges is that climate change will cause income divergence across individuals, sectors, and regions, adjustment in energy markets, increased inflation variability, financial markets stress, intensified innovation, increased migration, and rising public debt. These challenges appear manageable for EU member states, especially under an early and orderly transition scenario. At the same time, the direction, scope, and speed of economic transformation is subject to large uncertainty due to two separate factors: the wide range of climate scenarios for a given trajectory of greenhouse gas emissions and the exact policy path governments choose, especially in the context of the ongoing Russian aggression in Ukraine.

JEL classification: D6, E3, F2, G2, O1, Q5

Keywords: Climate change, growth, inflation, financial markets, socio-economic implications

Non-technical summary

Climate change and the public policies to arrest it are and will continue reshaping the global economy. In this Discussion Paper, we draw on economic research to identify some key medium- and long-run economic implications of these developments. Climate change presents not just a threat to life as we know it, but also an opportunity to reinvent the global economy. We provide an educated speculation about how the world will likely change, based on our reading of the academic literature and on reasonable assumptions regarding the evolution of the climate and of public policy.

We argue that in the near future, climate change will cause income divergence across individuals, sectors, and regions, adjustment in energy markets, increased inflation variability, financial markets stress, intensified innovation, increased migration, and rising public debt. While serious, these challenges appear manageable for EU member states that on average stand to gain from rising temperatures. This is especially true under a scenario of early and orderly climate transition.

At the same time, the direction, scope, and speed of economic transformation is subject to two types of uncertainty. First, the effect of increasing emissions on the climate is intrinsically uncertain. This means that for a given increase in the concentration of greenhouse gases in the atmosphere, there is a wide range of climate – and from there, economic – outcomes, ranging from the benign to the catastrophic. Second, the path of the economy depends on the type, scope, and speed of implementation of climate policies by governments. The cost to both the real and the financial sector is lowest when climate policies are introduced in a foreseeable and gradual way. In contrast, the ongoing aggression by the Russian Federation in Ukraine may precipitate abrupt changes in world energy markets, as well as in climate policy. Both will plausibly accelerate the transition to green energy, but also increase the risk of a disorderly transition.

An effective and smooth transition towards a net-zero economy requires a large-scale, coordinated response between fiscal authorities, central banks, regulators, and supervisors. The dual objective should be to transition to a green economy while mitigating as much as possible the adverse economic effects. The ECB's optimal monetary policy in response to the challenges posed by climate change and the policy response thereto is one of inflation forecast targeting. Beyond that, the ECB is expected to take actions, within its mandate, to support the green transition, but the nature of the challenge significantly exceeds the competencies and policy tools of the central bank.

"A change in the weather is sufficient to recreate the world and ourselves."

Marcel Proust

1. Introduction

Climate change and the public policies to arrest it are and will continue reshaping the global economy. This note draws on economic research to identify some key medium- and long-run economic implications of these developments. As the opening quote suggests, climate change presents not just a threat to life as we know it, but also an opportunity to reinvent ourselves and our system of economic interactions. We provide an educated speculation about how the world will likely change, based on our reading of the academic literature and on reasonable assumptions regarding the evolution of the climate and of public policy.

The main message is: climate change will cause income divergence across individuals, sectors, and regions, adjustment in energy markets, increased inflation variability, financial markets stress, intensified innovation, increased migration, and rising public debt. While serious, these challenges appear manageable for EU member states that on average stand to gain from rising temperatures (Burke et al., 2015b). This is especially true under a scenario of early and orderly climate transition.

At the same time, the direction, scope, and speed of economic transformation is subject to two types of uncertainty. First, the effect of increasing emissions on the climate is intrinsically uncertain. This means that for a given increase in the concentration of greenhouse gases in the atmosphere, there is a wide range of climate – and from there, economic – outcomes, ranging from the benign to the catastrophic. Second, the path of the economy depends on the type, scope, and speed of implementation of climate policies by governments. The cost to both the real and the financial sector is lowest when climate policies are introduced in a foreseeable and gradual way. In contrast, the ongoing Russian aggression in Ukraine may precipitate abrupt changes in world energy markets, as well as in climate policy. Both will plausibly accelerate the transition to green energy, but also increase the risk of a disorderly transition.

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The note is structured by thematic areas. Section 2 discusses the role of uncertainty in predicting the effect of climate change on the economy. Section 3 focuses on how climate change and the green transition will affect economic growth. Section 4 explores the outlook for inflation. Section 5 looks at

[2] See "The ECB pledge on climate change action," https://www.ecb.europa.eu/pub/pdf/other/ecb.pledge_climate_change_action211103~6af74636d8.en.pdf

how financial markets will be affected by climate change and climate policies. Section 6 analyses the outlook in terms of fiscal costs, inequality, migration, and conflict.

2. Climate change and uncertainty

2.1. What do we know about global warming?

The nature of climate change, the extent to which it is affected by humans, and its potential effects on our economy constitute complex questions. This complexity stems from a mixture of elements and technical details coming from the natural and the economic science. As a result, it can be difficult for commentators to sort between opposing views, as well as for the interested citizens to reach their own conclusions.

The global surface temperature has increased by about 1 ^{O}C relative to the pre-industrial period. In addition, each of the four last decades has been successively warmer than any decade that preceded it since 1850.[3]

A relevant question is to what extent this increase is caused by humans. It is well known that Earth's temperature varies naturally for many reasons that do not depend on human behaviour. One factor comes from the fact that Earth's orbit around the sun varies according to a fixed pattern, which in turn affects the average temperature. Another factor has to do with variations in the tilt of the Earth's axis.

Humans can also affect the climate, for instance, by emitting greenhouse gases into the atmosphere. The dominant greenhouse gas emitted by humans is carbon dioxide. It accounts for about 75 percent of total emissions of greenhouse gases. Carbon dioxide is primarily emitted as a by-product when fossil fuels – i.e., coal, oil, and natural gas – are burnt.

It is well accepted that the recent increase in global temperatures is largely driven by human activity. For example, the latest report from the UN Intergovernmental Panel on Climate Change (IPCC), IPCC AR6 (IPCC, 2022), establishes that it is "unequivocal that human influence has warmed the atmosphere, oceans and land." What is less clear is the extent of the anthropogenic contribution. According to the previous report (IPCC, 2014) it "is extremely likely that more than half of the observed increase in global average surface temperature from 1951 to 2010 was caused by the anthropogenic increase in greenhouse gas concentrations and other anthropogenic forces together."

2.2. Two effects from increasing the amount of carbon dioxide in the atmosphere

It has been known for more than 100 years now that the amount of carbon dioxide (and other greenhouse gases) in the atmosphere can influence the climate and the temperature. The resulting greenhouse effect is not entirely a bad thing: without greenhouse gases in the atmosphere, the average temperature of the Earth would be about -20 ^{O}C instead of the approximately 15 ^{O}C that we have right now. The presence of carbon dioxide in the atmosphere only becomes a problem when its concentration increases beyond the long-term equilibrium value.

[3] IPCC AR6.

The *total* effect of emitting an additional unit of carbon dioxide can be divided into two sub-effects: the *direct* effect and the *feedback* effects.[4] The two can differ in their size and direction.

The direct effect comes from the fact that carbon dioxide in the atmosphere does not affect the inflow of energy, but it does affect the outflow. Specifically, solar radiation passes right through the carbon dioxide, but carbon dioxide makes it more difficult for heat to radiate back into outer space. Hence, if the climate system is initially in balance (steady state), an increase in the amount of carbon dioxide in the atmosphere will cause the temperature to rise until the system reaches balance again.[5] The effect is not particularly large but it is also uncontroversial. In fact, it can easily be replicated and shown to exist in a simple laboratory experiment.

While the direct effect is known with relative certainty, the feedback effect is not, and this makes the total effect of increasing the amount of carbon dioxide in the atmosphere highly uncertain. Examples of feedback effects when the earth warms up include effects on cloud formation, wind and water flows, and the melting of ice sheets. These effects can either strengthen or weaken the direct effect and their respective effects are much harder to quantify. Current estimates, however, suggest that the feedback effects will strengthen the direct effect (IPCC, 2022).

2.3. The climate sensitivity, tipping points, and threshold effects

There is substantial uncertainty about how much the Earth will warm when the concentration of carbon dioxide in the atmosphere increases. Reflecting this uncertainty, the IPCC provides an interval for the so-called *equilibrium climate sensitivity*. The climate sensitivity tells us by how much the global temperature will increase if we were to double the amount of carbon dioxide in the atmosphere. In the latest report (AR6), the climate sensitivity is reported to *likely* be in the range between 2.5 ^{O}C to 4 ^{O}C, with a best estimate of 3 ^{O}C. The climate sensitivity is *very likely* between 2 ^{O}C and 5 ^{O}C.[6] See Figure 1. These intervals are slightly narrower than in the previous IPCC report (AR5), but they are still (very) wide.

[4] See Olovsson (2018) for a more elaborate discussion.
[5] This direct effect was first shown by the Swedish chemist and physicist Svante Arrhenius in 1896.
[6] The likely range implies a probability of more 0.66. The very likely range implies a probability of more than 0.90.

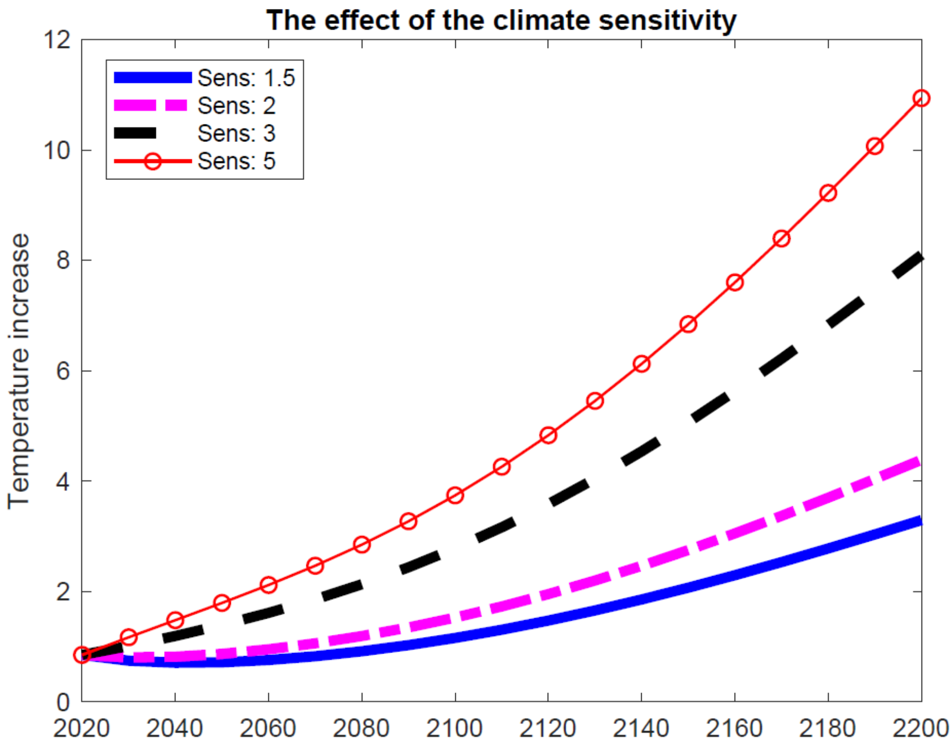

Figure 1: The increase in average atmospheric temperatures for different climate sensitivities.

The principal implication of the unknown climate sensitivity is that the total magnitude of the greenhouse effect is highly uncertain. It is clear that an increasing concentration of carbon dioxide in the atmosphere will raise atmospheric temperatures and change the climate. However, we cannot rule out either relatively modest effects or very severe effects from doubling the concentration of carbon dioxide in the atmosphere.

Similar uncertainty applies to our ability to predict threshold effects and tipping points. The argument is often made that, if a specific amount of carbon dioxide in the atmosphere were to be exceeded, the climate could respond in a non-linear and irreversible fashion**.** Even though such a scenario cannot be ruled out, empirical support for such view is lacking on the global scale. As argued in IPCC AR6, "[F]or global climate indicators, evidence for abrupt climate change is limited". Even though the climate system is complex and there are many non-linear effects, findings suggest that many nonlinearities tend to cancel each other and to produce an approximately linear relation between the amount of accumulated emissions and the global mean temperature (Matthews et al., 2009).

3. The real economy

3.1. Climate change, climate policy, and global growth: Cooling or heating?

Changes in the climate have affected people and their economic conditions throughout history and they will continue to do so also in the future. These costs result from a combination of factors, such as more extreme weather, rising sea levels and flooding, damaged eco systems, and financial instability.

Due to the intrinsic uncertainty of how the climate will change, it is hard to assess the costs to be expected from climate change with any precision. This is mainly because it requires assumptions about developments that have not yet happened. The costs will also depend crucially on how well our economies are able to mitigate the effects from global warming, on how we can adapt to it, on what policy we choose to arrest it, and on how successful these policies are.

With this uncertainty in mind, it is nevertheless possible to predict that the cost of climate change will be sizeable and unequally distributed. William Nordhaus – who pioneered the analysis of the economic effects of climate change[7] – and Andrew Moffat carry out a Meta study and report that on a global scale, the impact of climate damages would amount to a permanent reduction of global GDP by two percent.[8] The IPCC reports that it is reasonable to expect losses of 1 to 5 per cent of global GDP with an increase of global average temperatures of 4 ^{O}C (IPCC, 2007). It is important to note that the estimates from both these studies are highly uncertain. These numbers can, at first sight, be perceived as relatively small, but that conclusion is incorrect. First, 2% of current global GDP is $1.62 trillion, which is a large number. Second, the costs will not be distributed evenly but they will hit certain regions particularly hard. For example, Burke et al. (2015b) show that in year 2100 with unmitigated climate change GDP per capita in Sub-Saharan Africa will be 80% lower, while it will be 70% higher in Europe.[9]

Similarly, the effect of climate change on the growth rate of GDP appears to be non-negligible and concentrated in poorer regions of the world. Dell et al. (2009) use historical fluctuations in temperature within countries to identify their effects on aggregate outcomes. They find that there are large negative effects of higher temperatures on growth but only in poor countries. Specifically, they find that a 1 ^{O}C rise in the temperature reduces the economic growth rate in that year by 1.3 percentage points. In rich countries, however, changes in temperature are not found to have a robust discernible effect on growth. Finally, Colacito et al. (2019) find a contrasting result in that they also find a negative effect on the growth rate from higher temperatures for the United States.

The evidence suggests that the effect of carbon policy on the real economy in the EU has been ambiguous. Some studies have found a substantial contractionary effect from climate policy. For example, Känzig (2021) finds that the EU carbon policy has had sizable and persistent contractionary effects. According to this study, euro area GDP, aggregate investment, aggregate consumption, and unemployment follow hump-shaped paths relative to a baseline after an increase in the ETS carbon price caused by EU carbon policy. In response to a climate policy intervention normalised to increase the HICP energy price index by 1%, aggregate consumption declines by 0.5% by the second year and begins to return to zero only in the fourth year. The unemployment rate effect reaches a peak of about 0.2-0.4pp in the second year and remains at least 0.1pp higher than the baseline four years after the shock. Other studies however have found a moderate-to-nil or even positive real effects of climate

[7] For his work on climate economics, Nordhaus received the Sveriges Riksbank Prize in Economic Sciences in Memory of Alfred Nobel in 2018.

[8] Nordhaus and Moffat (2017). See also the study in OECD (2015) that arrive at a similar number: about two percent. The study argues further that if the temperature increase would reach 4^{O} C, then the costs could amount to up to 10 percent of GDP. Weizman (2009) argues that the costs of climate change are considerably larger when low-probability high-impact catastrophes are taken into account.

[9] Note that the costs are typically expressed in terms of percentages of GDP. This is just to make the numbers easier to relate to, but the costs could, of course, instead be expressed in dollars.

policy. For example, McKibbin et al. (2021) document a negative effect of national carbon policies in the euro area on GDP, but this effect disappears once the authors control for country and time fixed effects. Metcalf and Stock (2020) even find a zero to modest positive impact of European national carbon policies on GDP and total employment growth rates. Along the same vein, Estrada and Santabarbara (2021) argue that a well-designed carbon policy may boost economic activity in the medium run, as long as the revenues are used to reduce other, more distortionary taxes.[10]

The real effect of climate policy crucially depends on the response of the technology. The faster climate-friendly technologies emerge as a result of more stringent climate policy, the more positive the medium-term effect on output and productivity.

As a general conclusion, it is fair to say that while the total economic growth costs of climate change are uncertain, the downside is potentially very large.

3.2. Energy markets and growth

The evolution of energy markets is central to the future path of climate change. The reason is obvious: fossil fuels (coal, oil, and natural gas) are the link between the economy and the climate. As mentioned above, the burning of fossil fuels accounts for the majority of the greenhouse gas emissions. Fossil fuel is a non-renewable energy source and these resources are depleted over time. The problem with respect to the climate is that the stock of fossil fuels is way too large: if everything gets used up, we can expect very large increases in the global mean temperature. For instance, global coal reserves are so large that they would allow us to extract coal at the current rate for another 500 years and that would by all means lead to too much global warming.[11]

Hence, if we want to make sure that the temperature increase stays below a certain target, we are going to have to drastically reduce the usage of fossil fuels on a global scale. This is not an easy task. Fossil fuels have some very appealing properties: they are highly effective, and they work irrespective of whether the sun shines or the wind blows. In addition, they have fuelled our economies since the Industrial Revolution. It seems uncontroversial to say that our current economies are heavily dependent on these fuels.

Given this dependence, it is natural to ask if it is possible to reduce fossil fuel use without sacrificing too much economic growth. Will reducing fossil-fuel use require us to go back to the zero-growth regime that was present from the beginning of human history to the Industrial Revolution?

Our ability to substitute away from fossil fuel is much higher in the long-run than in the short-run. Hassler et al. (2021) assess quantitatively the questions: (i) what will our future look like given our dependence on natural resources in finite supply? and (ii) how will consumption growth be affected by lower fossil-fuel use? The findings show that, in the short run, it is basically impossible to substitute fossil fuel for other inputs. In the short run, higher GDP leads to higher energy consumption and vice versa. Over the longer run, however, the relationship is different and more flexible. The reason is that signals of fossil fuel scarcity (i.e., price shocks) triggers R&D and innovation that improves energy

[10] While a number of papers have studied the interaction between climate policy and the real economy, the main challenge in this literature is identifying the climate policy shock. In this respect, the paper by Kanzig (2021) goes one step farther than the rest of the field by 1) identifying a carbon policy shock from regulatory updates, and 2) by doing so for more than one country.

[11] See Rogner (1997).

efficiency. As a result, more energy-efficient techniques and products are developed as fossil fuel become scarcer. In the long run, it is therefore possible to use less fossil fuel without a drop in GDP because energy efficiency is higher. Similarly, it is likely that carefully designed policies could stimulate R&D and innovation and improve the energy efficiency.

The increase in energy efficiency comes at a cost. When more R&D resources are allocated to improve the energy efficiency, less resources are used for improving the capital/labor productivity with lower capital/labor technical progress as a result. This cost is not particularly large however: the long-term growth rate is estimated by Hassler et al. (2021) to be 1.7% per year, i.e., only slightly lower than during the post-war era. Along the same vein, Greenstone and Nath (2021) find that mandating renewable resources to be a specified share of electricity generation raises electricity prices by 11% and reduces carbon emission by as much as 25% in the short-to-medium run.

A related question is to what extent climate change will affect the demand for energy. For instance, there might be increased demand for air conditioning as the temperature increases. This is a question that has not yet been well researched.

Similarly, the ongoing Russian aggression in Ukraine can affect energy markets, thereby accelerating the green transition but increasing the risk of disorderly transition. Energy prices have already increased substantially relative to their pre-war levels. In addition, as part of the sanctions imposed on Russia by the US and the EU, the import of coal has already been banned,[12] and the import of oil and gas will be phased out faster than previously planned. This should stimulate the switch to green energy. At the same time, to not make the transition away from coal and oil too costly, relatively cheaper natural gas can be used as a transitional source of energy for longer than originally envisaged. This would slow down the green energy transition, both directly and via depressing innovation in renewable technologies.

The overall conclusion is that it should be possible to phase out fossil fuels, but the transition needs to be somewhat gradual and take place over a few decades. Else, the economic cost to the current generation is prohibitive.

3.3. Climate policies and innovation

The costs to society of addressing climate change crucially depend on *how* we choose to address it. Fulfilling the goal of the Paris Accord requires a reduction in greenhouse gas emissions of almost 8% per year, each year until 2030.[13] There are two options for how to achieve such substantial reductions. The first one is to dramatically reduce the consumption of goods whose production, processing, and delivery are associated with emissions of greenhouse gases in the atmosphere. The necessary reduction in annual economic activity exceeds that recorded during the covid-19 pandemic.[14] The second is to continue consuming those same goods, but to make sure that they are produced and delivered using low-carbon technologies, a process known as the “green transition".

[12] At the same time, the environmental benefits of this decision are being undone in many EU countries which have lifted restrictions on domestic coal power generation (https://www.businessinsider.com/europe-energy-emergency-plans-coal-power-russia-cuts-gas-supply-2022-6).

[13] See (UNEP, 2019).

[14] Estimates put the decline in greenhouse gas emissions during 2020 between 5.4% and 6.4% (Liu et al., 2020; Global Carbon Project, 2021).

Achieving the ”green transition” quickly enough requires nothing short of a climate-technology revolution. Much of the reduction in carbon emissions since the 1970s has been achieved thanks to the development and adoption of energy-saving technologies. However, continued progress is hampered by missing technologies in energy generation, manufacturing, transportation, and agriculture (Aghion et al., 2022). The question therefore becomes whether – and to what extent – climate policies can stimulate green innovation. The importance of the answer is underscored by the fact that the optimal path of carbon emissions is rather different in models with static versus models with endogenous technology.

The literature has studied the relationship between energy-saving innovation and two broad factors: market forces and public policies. Market forces are exemplified by changes in energy prices. Public policies are typically proxied by changes in the price of carbon, such as the imposition of carbon taxes or excise taxes on fuel.

Studies using various methods and samples have reached the same conclusion: higher energy prices speed up innovation in energy-saving technologies. The first such force to study are oil and/or energy prices. Newell et al. (1999) show that the energy efficiency of home appliances was strongly correlated with energy prices. Using a time series of US patent data, Popp (2002) finds that a 10% increase in energy prices leads to 3.5% more patents in energy-saving technologies. Hassler et al. (2021) use aggregate data on GDP, energy, capital, and labor to compute a measure of the energy efficiency, and they show that energy efficiency has increased steadily since the oil shocks of the 1970s. Aghion et al. (2016) investigate how gas prices shape innovation in the car industry. They find that a 10% increase in fuel prices leads to 8.5% more innovation that develops alternatives to fossil fuel engines, and a 8.3% decline in innovation within the class of fossil fuel engines. In other words, the literature has broadly concluded that the direction of energy-saving innovation is endogenous and can be changed by market forces.

Pricing carbon has been shown to have a similar positive effect on innovation in energy saving and low-carbon technologies. Aghion et al. (2016) find a similar increase in innovation in climate-friendly technologies when studying changes in fuel taxes instead of changes in fuel prices. The advantage of this method is that taxes are a policy instrument, therefore more exogenous to firm conditions. At the same time, the elasticity of innovation turns out to be lower than in the case of fuel prices. This is to be expected as demand is driven by the final price that consumers pay rather than the tax itself. Calel and Dechezlepretre (2016) compare firms that are regulated by the EU’s ETS to firms that are not and find that ETS-regulated firms increase low-carbon innovation (as measured by patent filings) by 10%, relative to non-regulated firms.

The reaction of innovation to market forces and public policies is crucially shaped by path dependency, i.e., by the type of knowledge that firms have accumulated so far. Aghion et al. (2016) compare firms that have accumulated knowledge in fossil fuel engine technologies to firms that have accumulated knowledge in alternative engine technologies. They show that absent changes in gas prices, dirty technologies dominate clean ones, and the gap widens over time. In an alternative scenario where gas prices go up by 40% permanently, the stock of clean knowledge overcomes the stock of dirty knowledge within 15 years. Therefore, path dependency makes it easier for clean technologies to catch up to dirty ones in the presence of significant policy changes. Furthermore, Acemoglu et al. (2012) show that if carbon-intensive technologies are more advanced initially, the carbon-intensive sector earns higher revenues, and consequently, entrepreneurs will favour innovation and hire more scientists in the "dirty" sector.

The reaction of innovation to market forces and public policies is also shaped by market size. Joelle and Smeets (2015) show that an increase in renewable market size increases renewable innovation, while a larger fossil fuel market leads to more fossil fuel intensive innovation.

It has also been suggested that carbon taxes should not be imposed in isolation, but in combination with R&D subsidies. To achieve a given overall reduction in emissions, carbon taxes should be higher if not accompanied by R&D subsidies, whereby innovation is stimulated solely by the adjustment in the relative price of clean versus dirty products. In contrast, R&D subsidies in the green sector increase the likelihood of innovation in green technologies. As green technological alternatives are invented earlier, carbon taxes can be lower. Acemoglu et al. (2012) provide a unified framework for the analysis of these two policies. They show that relying solely on a carbon tax, instead of a combination of taxes and subsidies, generates welfare losses equivalent to 1.9% of consumption every year. They also show that absent policy, the gap between dirty and clean technologies will widen, leading to a more prolonged catch-up later on with reduced growth.

This analysis provides strong support for the notion that climate policy needs to be frontloaded. This contrasts with models where technological progress is exogenous. Such models recommend that carbon tax is progressive. At the same time, it is consistent with the argument in Hassler et al. (2018) that the welfare loss associated with climate policy that is too strict is significantly lower than the welfare loss associated with climate policy that is too lenient.

The literature has provided caution against overinvesting in bridge technologies, i.e., technologies that are at intermediary levels of climate friendliness. Acemoglu et al. (2021) show that to a large extent, the decline in green innovation since 2011 is due to the shale gas revolution in the US. Fracking has allowed natural gas to be extracted at low cost from the shale. As a result, natural gas has largely substituted coal in energy generation. Because natural gas is 60% cleaner than coal, this has contributed to a substantial reduction in overall carbon emissions in the US, to the tune of 500 million tons annually (Fell and Kaffine, 2018). At the same time, green innovation in electricity has collapsed. This is explained by the fact that the now cheaper natural gas has reduced the incentives to invest in renewables. The conclusion is that bridge technologies may divert innovation away from clean technologies and reduce emissions today at the expense of increasing emissions tomorrow. Thus, policy (in the form of subsidies for green innovation) needs to accompany the adoption of bridge technologies. This has implications for the EU, too, where natural gas has recently been classified as "green" for the duration of the energy transition.

Analysis has also suggested that while subsidizing green technologies is important for innovation, it is even more important to make fossil energy more expensive. Policy can help stimulating green innovation, for example by subsidizing investments in green technologies. At the same time, it is important to be aware that this policy should not be considered an alternative to a carbon tax (or a quantity restriction), but rather a complement. Hassler et al. (2022) show that relying exclusively on subsidies to the green sector is a highly risky climate policy that is unlikely to be able to slow down sufficiently global warming. In the first case, consumers and firms might just consume more energy, including both green and fossil. Meng (2021) shows that if a policy relies exclusively on green subsidies, it would have to be very large and be in place for at least 50 years for it to have even a 50 percent chance of being successful. Hence, subsidies to green energy production should be used as a complement to a carbon tax or a quantity restriction if we want to be on the safe side when it comes to mitigate global warming.

Finally, current policies that try to address the fallout from the Ukraine war by lowering energy prices are costly in terms of dealing with climate change via innovation. This is because as the evidence suggests, market forces are superior to climate policies in stimulating innovation. More climate-friendly are those policies that compensate households and firms for the higher cost of energy, without distorting prices.

4. Implications for inflation and monetary policy

4.1. Are climate change and climate policy inflationary or deflationary?

In economic models, climate change and carbon policy shocks act like adverse productivity shocks. Climate change "damages" factor productivity: a smaller quantity of output can be produced from a given amount of labour, capital, and land – possibly a much smaller quantity after a tipping point has been reached. Extreme weather events may act like very large adverse productivity shocks. A steady rise in global temperature amounts to more modest productivity shocks. Extreme weather events may also destroy capital and farmland directly and reduce labour supply, and the consequences of a decrease in input supply of this kind for the economy resemble the effects of an adverse productivity shock. A carbon tax (or an equivalent climate-change-mitigation policy) acts like an adverse productivity shock that is temporary, with the overall productive capacity of the economy reduced for some time while firms and households adjust away from fossil to non-fossil energy sources.[15]

Adverse productivity shocks raise the marginal cost of production, and this effect is inflationary. Since climate change and carbon policies act like negative productivity shocks, they raise the marginal cost of production and therefore can be expected to cause some inflationary pressure in the economy. Similarly, extreme weather events which reduce the availability of inputs are inflationary "supply shocks". As global temperature continues to rise, very large climate-related inflationary shocks ("tail events") may occur more frequently. The inflationary effects of climate change may be referred to as "climateflation". The direct inflationary effects of a higher price of carbon energy constitute "fossilflation". The process of adjustment by firms away from carbon energy into non-carbon energy, or green investment, may trigger "greenflation".[16]

Climate change and carbon policy shocks are bound to affect economic sectors differentially, inducing through relative price changes. For example, climate change may have a disproportionate impact on agriculture while carbon taxation on sectors that rely heavily on carbon energy as an input. Since climate change and carbon pricing affect sectors differentially, they can be expected to induce relative price changes in the economy. Such relative price changes may be very persistent or permanent, and they will take place over time independent of the aggregate inflation rate, whether inflation runs at, above, or below the central bank's target.

There is an argument for the central bank that faces relative price changes to tolerate a rise in headline inflation so long as sticky-price inflation remains on target. The overall effect of climate

[15] Nakov and Pescatori (2010) show that, under standard assumptions in an economic model, the macroeconomic effects of an energy price shock are the same as those of an aggregate total factor productivity shock.
[16] See Schnabel (2022).

change or carbon policy shocks on inflation depends on monetary policy. If monetary policy targets a constant aggregate inflation rate, inflation in some sectors will run above that rate while inflation in other sectors will run below it. The reason is that relative prices of goods must adjust. Economic models suggest that, when facing shocks that necessitate relative price changes, it is optimal for monetary policy to attach more weight to inflation in sectors where prices are relatively sticky. The intuition is that distortions in the economy arise when prices are sticky, and it is these distortions that optimal monetary policy seeks to minimise. Therefore, the best monetary policy stabilizes the rate of change of sticky prices in the economy (an object not necessarily equal to the typically reported core inflation rate), even if the rate of change of all prices (headline inflation) turns out to be higher or lower.[17]

Climate change and carbon policy shocks are not simply "supply shocks", however, because they affect aggregate expenditure which in turn affects aggregate output. Productivity damage from climate change lowers society's resources. Disposable income of households and cash-flows of firms decline. Since not all households and firms can borrow an optimal amount to smooth their consumption and investment spending, and not all have accumulated sufficient savings, aggregate expenditure falls. This effect exerts further contractionary pressure on aggregate output, over and above the direct effect of climate change on productivity. To think in terms of an introductory economics textbook, *both* the aggregate demand and aggregate supply curves shift. Similarly, a carbon tax is likely to lower disposable income and cash-flows, even if budgetary revenues from it are fully rebated to taxpayers, because the economy's output can be expected to fall for some time as resources move between sectors. If tax revenues are not rebated, then taxpayers' wealth decreases and their disposable income and cash-flows are likely to fall even further.[18]

In contrast to the direct effect via productivity, the aggregate expenditure effect is *de*flationary. As households and firms curtail their spending, production and marginal costs decline, giving rise to some deflationary pressure in the economy. This effect is likely to be more persistent than the direct inflationary impact, because one can expect consumption and investment expenditure to decline gradually and to recover slowly. Overall, the economy may experience some up-front inflationary pressure from "the supply side", followed by some more protracted deflationary pressure from the "demand side". The projected inflation rate may increase considerably more in the short run than in the medium run. Inflation may even be forecast to return to the central bank's target in the medium term in the absence of a change in the central bank's policy rates.

In the past, carbon policy changes have caused some inflation in the euro area, but the inflationary effects, at least so far, have been modest. Economists can use the historical data on the market price of CO2 emission permits in the EU Emissions Trading System to assess the effects of the EU carbon policy on inflation and other macroeconomic variables in the euro area. One needs to tackle an identification problem that arises because the ETS carbon price tends to rise with the level of economic activity. Isolating the component of the ETS carbon price driven by climate policy gives rise to the following conclusions. In response to a climate policy intervention normalised to increase the HICP energy price index by 1%, the HICP price level jumps by about 0.15% in the same month; depending on the model specification, it may continue to rise for 6 months or so, to about 0.3%, and then drifts

[17] Aoki (2001), Woodford (2003), and Benigno (2004). The argument is symmetric, so that it is also optimal to tolerate a fall in headline inflation so long as sticky-price inflation remains on target.

[18] A large, recent literature on macroeconomic models with heterogenous agents and incomplete risk sharing emphasises the role of the indirect expenditure effect in the transmission of aggregate disturbances. See, for example, Kaplan et al. (2018) and Guerrieri et al. (2020).

down. The core HICP price level jumps by less and returns to zero after about 2 years (Känzig, 2021). Thus, the EU climate policy has caused some inflation in the euro area, but the inflationary effects, at least so far, have been modest. At the same, the policy has led to a persistent rise in the headline HICP relative to core HICP price level (Känzig, 2021). McKibbin et al. (2021) obtain broadly similar findings in a study of the consequences of *national* carbon policies in the Member States. These authors find positive effects of carbon pricing on headline CPI, HICP and PPI but no statistically significant effect on core CPI.[19] Konradt and Weder di Mauro (2021) study the carbon tax in British Columbia. They find that the carbon tax *lowered* the CPI relative to the rest of Canada, an effect driven by prices of non-traded goods.

In the historical data, the ECB responded little to carbon policy shocks. Känzig (2021) finds that the ECB policy rate changes little following an EU carbon policy shock, with a maximum change (decrease) of about 10bps. The historical carbon policy shocks in the euro area have not been large, and future, larger policy changes – or policy changes that take place with different initial conditions than in the past, when inflation was largely below the ECB's target – may have different effects from what the available data shows.

This empirical evidence can be rationalized in a model with a strong aggregate expenditure effect. In the model, there is a sector with flexible prices which produces carbon energy and a sector with sticky prices which uses carbon energy as an input and produces the aggregate consumption good. Some households cannot borrow and live hand-to-mouth. In this environment, a carbon tax depresses aggregate expenditure, in particular because disposable income of hand-to-mouth households declines. The aggregate expenditure effect, as opposed to the direct effect on productivity, is the main reason why economic activity falls and no persistent inflationary pressure arises in the model (Känzig, 2021).[20] This result from recent research is consistent with the older, more tentative conclusion of Kilian's (2008) review of how energy prices affect the aggregate economy with a focus on the oil price shocks of the 1970s. Kilian writes (p. 904): "The traditional view of oil price shocks has been that they act as aggregate supply [or] technology shocks (…). An increasingly popular alternative view (…) is that oil price shocks affect the economy primarily through their effect on consumer expenditures and firm expenditures instead."

The ETS carbon price can be compared with model-based estimates of the socially optimal carbon price. The ETS carbon price exceeded €90 per ton of CO2 emissions before the Russian invasion of Ukraine in February 2022. See Figure 2. The "Fit for 55" proposal by the European Commission features a significant reduction of emission rights, which may drive the ETS price up to about €130. The Network for Greening the Financial System considers several scenarios and argues that a price of €160 could be needed for net zero emissions by 2050. Integrated assessment models, which combine the neoclassical economic growth model with climate change analysis, can be used to calculate the level of the carbon price that would be socially optimal, that is, that would correctly reflect the negative externality from carbon energy use. A typical model-based estimate of the optimal carbon price is in the range of €50-100.[21] In comparing this range of numbers with the ETS price, it is important to keep in mind that a

[19] See the estimates with country and time fixed effects in Table 3 in McKibbin et al. (2021).

[20] Guerrieri et al. (2020) study how an adverse sectoral supply shock can trigger "a fall in aggregate demand larger than the shock itself," implying downward pressure on the aggregate price level. The mechanism is essentially the same as in Känzig's model.

[21] In a representative agent model, the optimal carbon tax depends crucially on the discount rate: the optimal carbon tax is about €50-100 per ton of CO2 emissions with a low discount rate, which attaches a fairly large weight to welfare of future generations, and €10-25 with a more standard discount rate used in economics (Golosov et al., 2014, and Stern and Stiglitz,

model-based optimal carbon price is typically assumed to be comprehensive (to apply to any use of carbon energy) whereas currently the ETS carbon permits cover only about 45% of carbon energy use in the EU. In fact, one way the EU climate policy is expected to evolve is by making carbon pricing more comprehensive (as opposed to increasing the carbon price).

Source: Datastream and ECB calculations
Notes: Monthly price average ETS spot price as calculated by authors. Measured as € per ton of CO_2 emissions. Observation period running from April 2005 until March 2022.

Figure 2: The ETS carbon price.

Model simulations suggest that the expected future, gradual tightening of the EU carbon policy is likely to produce moderate inflationary effects. The integrated assessment model of Hassler et al. (2021) is used to compare two scenarios for the future EU climate policy: an *up-front* increase of a comprehensive EU carbon tax from €30 to €100, and a more realistic *linear* increase of the carbon tax from €30 to €100 over three decades, both relative to the baseline with a €30 carbon tax forever. A carbon tax increase gives rise to multiple incentives in the model, including to invest in green energy and to extract oil. The top row in Figure 3 shows the gradual change scenario. The bottom row in the same figure displays the up-front change scenario. One period in the model equals one decade. Both scenarios have essentially identical end outcomes, in year 2100. In the gradual change scenario, the energy price rises in steps, with each step smaller than the previous one, even though the tax schedule is linear.[22] Thus, most inflationary pressure occurs up-front, in the first decade, and it is moderate: a rise by 15% over 10 years in the energy price, with a multiplier of 0.3 based on Känzig (2021), would imply an average annual increase in headline HICP of 0.45pp.[23] In the less realistic, up-front change scenario, the energy price rises strongly in the first decade and *falls* afterwards. GDP rises in both scenarios relative to the baseline, due to lower productivity damages from climate change (the possible short-run contractionary effects of carbon taxation on the real economy are not captured here, because one period in the model equals one decade).

2021). In an overlapping generations model, one can compute a climate policy that makes each generation from today at least weakly better off (in practice, the welfare of people alive today may be unaffected whereas future generations will be strictly better off). This alternative approach yields an optimal carbon tax of about €70 (that is, also in the €50-100 range), rising annually at 1.5% (Kotlikoff et al., 2020).

[22] The energy price in the model is a constant-elasticity-of-substitution aggregate of oil (and fracking), coal, and green energy prices.

[23] This is a conservative estimate in the sense that the simulation produces a rise in the energy price in the first decade that is somewhat smaller than 15% and 0.3 is a somewhat larger multiplier than the most likely value based on Känzig (2021).

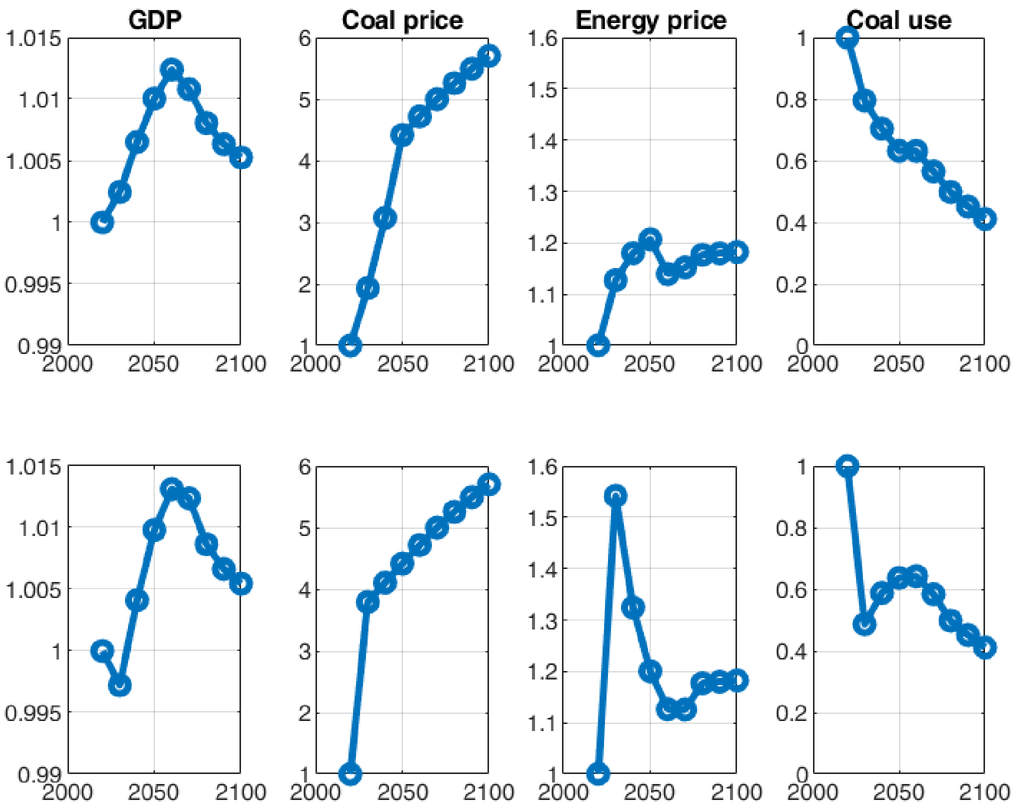

Figure 3: Implications for GDP, prices, and coal use under different policy scenarios. Top row: a gradual implementation of the carbon tax (the carbon tax is gradually increased and reaches its final level of €100 after 3 decades). Bottom row: an immediate implementation of the full carbon tax €100. The initial tax in 2020 is €30.

Climate change poses a much more significant risk to price stability than climate-change-mitigation policy. The realistic tightening of the EU climate policy simulated in Hassler et al. (2021) implies, under conservative assumptions, an average annual increase in headline HICP of 0.45pp for a decade, and smaller effects afterwards. This is a non-trivial impact. For comparison, however, in 2021 the HICP energy price level increased by more than 20%, *in one year*. Future possible climate-related supply disruptions or extreme weather events can produce relative price changes of size comparable to or greater than the COVID-19 pandemic or a war.

When the relative price of energy, food or other goods rises sharply because of a supply disruption or an extreme weather event, the society is worse off *even if* the aggregate price level remains perfectly stable. A supply disruption, global temperature rise, or an extreme weather event make the society worse off by reducing resources available for consumption. A carbon tax is also likely to make people living today worse off for some time, because aggregate output is likely to fall temporarily as factors of productions reallocate between sectors. If inflation does run above the central bank's target for a period of time in the aftermath of the shock and if people are worse off, it does not follow that they would have been better off with inflation continuously equal to the central bank's target. The key question for social welfare is "what path would real incomes (real consumption spending) have followed with a different short-to-medium-run path of inflation?"

4.2. Implications for monetary policy

Climate change and carbon policy shocks may increase medium-to-long-term inflation expectations and may create a risk of very persistent inflation. When households and firms are uncertain about the medium-to-long-run inflation rate, they update their beliefs using observations of actual inflation outcomes. In this process, individuals may rely relatively more on regular or salient purchases such as energy and food. Therefore, an inflationary shock may increase medium-to-long-run inflation expectations and may create a risk of inflation persistently above levels consistent with price stability. The likelihood of de-anchoring increases if the direct inflationary impact of the shock is large (e.g., a severe climate disaster, a substantial hike in a carbon tax), if a series of sizable shocks occur one after another, if inflation is running above the central bank's objective to begin with, or if the deflationary expenditure effect is dampened by fiscal policy (e.g., a transfer policy to support lower-income households; a green investment policy for the public or private sector or both). The risk of persistent inflation constitutes a reason for monetary policy to tighten in response to a disturbance to climate or carbon policy.

Monetary policy affects inflation with a delay, and therefore the optimal response of a central bank to shocks involves inflation-forecast targeting rather than current-inflation targeting. In the aftermath of a shock, it takes time to assess its precise consequences for the aggregate economy. Furthermore, if the central bank decides to alter its policy in response to the shock, this policy change will affect aggregate expenditure, production, and inflation only with a delay. Therefore, the optimal monetary policy response involves *inflation-forecast* targeting rather than *current-inflation* targeting. The central bank constructs conditional projections of inflation, and other relevant variables, *at medium-term* given alternative monetary policy choices and selects the preferred projection. This is a general argument that applies also to shocks due to climate or climate policy. After a climate change or carbon policy shock, the projection conditional on an unchanged monetary policy is likely to show inflation running above target for some time. The same projection may also indicate a substantial risk of inflation remaining above target in the medium-to-long run. On the other hand, projections conditional on a monetary policy tightening are likely to show even greater damage to the real economy than from the shock alone. Importantly, the projections will depend on the expected fiscal policy measures in response to a climate shock or to accompany a carbon pricing shock, such as budgetary transfers to support lower-income households and subsidies for or direct spending on green investment. Such measures may be expected to reduce the contractionary aggregate expenditure effect.[24]

Choosing monetary policy in the aftermath of an adverse "supply shock", whether climate-related or not, involves trading-off the risk of more inflation for longer against greater short-to-medium-term damage to real activity. Adverse "supply shocks" produce upward pressure on inflation and downward pressure on real activity. If a "supply shock" causes an increase in inflation, multiple paths of future inflation will generally be consistent with medium-term price stability, with each such path associated with a different future path of real activity. Choosing a monetary policy then involves trading-off the risk of more inflation for longer against greater short-to-medium-term damage to real activity. The trade-off depends on the nature and size of the shock (e.g., an extreme supply disruption vs. a modest rise in the carbon tax), on initial conditions (e.g., inflation expectations and inflation at the time when the shock occurs), any fiscal policy response to the same shock, and on projections of

[24] The "inflation-forecast targeting" approach to monetary policy is presented by Svensson (1999) and Woodford (2007). See Jaumotte et al. (2021) on the macroeconomic effects of a comprehensive policy package, which complements carbon pricing with a green fiscal stimulus, consisting of green public investment and subsidies to renewables production.

the state of the economy (e.g., wage developments) at medium-term. If risks to medium-term price stability are seen to be significant, the optimal policy mix is likely to involve some degree of monetary tightening *together with* a fiscal policy intervention, for example a transfer policy, to reduce the contractionary pressure on the real economy.[25]

5. The financial sector

Climate change poses a potential threat to the financial system via the materialization of physical risks, transition risks, or liability risks.[26] These risks are distinct from each other, and they affect different financial institutions in different ways.

Physical risk stems from the uncertain economic and financial costs due to the gradual rise in temperatures and more frequent and severe weather disasters, such as floods, droughts, and wildfires. These events disrupt local economic activity and erode asset values, potentially resulting in economic and financial losses for businesses and households. Physical risk thus mainly affects investors and financial institutions via their exposure to businesses and households that are vulnerable to these risks.[27]

Transition risk arises from the uncertain speed and scope with which climate policies, green innovation and changes in public sentiment take place. Transition risk affects financial institutions both indirectly, i.e. via their exposure to businesses and households that are vulnerable to these risks, and in a direct way, for example due to increased attention by investors to environmental criteria when investing in financial institutions.

Liability risk arises when households or firms that suffered losses from the effects of climate change seek compensation from those they hold responsible. Such claims could for example hit carbon extractors and emitters – and, if they have liability cover, their insurers. Legal action, or the credible threat thereof, can act as a driver of adaptation to the physical risks associated with climate change (UNEPFI, 2021). These risks, however, are arguably the most difficult to model and to predict. What is clear is that the likelihood of legal action relating to physical risks will depend on the magnitude of the underlying physical risks, and thus indirectly on the success and pace of the green transition to contain these physical risks.

The materialization of all the above risks is uncertain and crucially depends on the future evolution of greenhouse gas emissions, which are the main driver of climate change. The exact future path of these emissions is surrounded by uncertainty and depends on whether further action will be taken to reduce emissions, when these actions will be put in place, and how effective they ultimately will be. This complicates any attempt to make predictions about the impact of climate change on financial markets and institutions.

5.1. Physical risk

[25] See Drudi et al. (2021) for a broad discussion of the implications of climate for monetary policy in the euro area.
[26] See, e.g., Carney (2015).
[27] Additionally, there's some operational risk for financial institutions stemming from physical risk, such as the potential destruction of branches in disaster areas, which could affect financial institutions in a direct way.

While natural disasters have become more frequent and destructive, existing research indicates that, for the time being, banks have largely managed their impact. Natural disasters have lead to higher non-performing loans and reduce bank solvency, but only to a limited extent (Klomp, 2014; Noth and Schuwer, 2018). This resilience is partly driven by additional profits coming from the increase in loan demand following natural disasters (see, e.g., Blicke et al., 2021; Cortes and Strahan, 2017; Duqi et al., 2021; Schuwer et al., 2019). Locally entrenched banks are more likely to provide this recovery lending (Berg and Schrader, 2012; Cortes, 2014; Chavaz, 2016; Koetter et al., 2020), as private information obtained through close relationships with borrowers becomes more important due to the reduction of available collateral.

An asset class that is particularly vulnerable to physical risk is real estate. A quickly growing literature on US real estate prices shows that real estate located in areas with higher flooding risk sells at a discount. Key determinants for this pricing-in of flooding risk are either local experiences with flooding (Artreya and Ferreira, 2015), how strong buyers' beliefs in climate change are (Baldauf et al., 2020; Bernstein et al., 2019), and the extent to which home buyers pay attention to climate risks (Giglio et al., 2021).

The vulnerability of real estate to physical risks also has repercussions for the provision of homeowner insurance. After catastrophic events such as hurricanes and floods, homeowner insurers raise insurance rates, lower insurance coverage and in some cases exit from affected areas, reducing the affordability and availability of insurance for homeowners (Born and Viscusi, 2006; Klein, 2007; Lamond and Penning-Rowsell, 2014; McAneney et al., 2016; Schwarze and Wagner, 2007).[28] A reduction in available insurance could lead to larger losses for households and firms when physical risks materialize, thus hurting consumption and investments (ECB, 2021a).

Limiting the materialization of physical risks in the future requires a reduction in global emissions. According to the United Nations, global emissions would need to fall by 7.6% each year between 2020 and 2030 to limit the rise in global temperatures to 1.5°C above pre-industrial levels, as targeted under the 2015 Paris Agreement. Future physical risks depend on the rate, peak and duration of global warming. They are estimated to be larger if global warming exceeds 1.5°C than if global warming gradually stabilizes at 1.5°C, especially if the peak temperature is high, e.g., about 2°C (IPCC, 2018).

5.2. Transition risk

The introduction of policies aimed at reducing carbon emissions, such as a carbon tax or an emissions trading system, brings along transition risk to financial institutions. Such policies could have a negative impact on the value of carbon-intensive assets, on firms owning these assets, and ultimately on investors and financial intermediaries providing credit to these firms. Similarly, very disruptive (but ecologically beneficial) technological changes could suddenly cause a shift in relative prices of carbon-intensive and low-carbon technologies, and in the value of the firms that depend on these technologies. Financial intermediaries that have large exposures to firms holding these assets – either via loans granted to these firms or by holding bonds or equity stakes in these firms – could face losses on these exposures.

[28] Related, industry analysts confirm that homeowners in areas hit by the floods in Germany and Belgium in summer 2021 are facing higher insurance premiums, see https://www.reuters.com/article/us-europe-weather-germany-insurance-trfn-idUSKBN2ET218.

Whether carbon-reducing policies and technological changes lead to large financial losses for financial intermediaries will depend on whether they are introduced in a foreseeable and orderly way. If climate policies are introduced early-on and with a clear long-term timeline, then financial intermediaries and investors will be able to gradually adjust their investment allocations, price-in the transition risk, and build-up buffers that can absorb potential future losses (see, e.g., Batten, Sowerbutts and Tanaka, 2016). If on the other hand new policies are introduced abruptly, this could lead to severe corporate distress in carbon-intensive sectors and corresponding losses in investor portfolios.

The limited availability of information on company exposures to transition risks and the lack of a universally accepted standard for emission disclosures hinder financial markets and institutions to perfectly price-in these risks. Attempts have been made to classify firms according to their climate disclosures, often as part of a broader environmental, social, and corporate governance (ESG) rating. The correlation between these measures, however, is typically low, bringing into question their robustness (Berg et al., 2019; Berg et al., 2021; Boffo and Patalano, 2020; Carbone et al., 2019). Additionally, ESG ratings often lack transparency regarding their exact methodology and data they draw on (OECD, 2021). It is thus unsurprising that investors value an individual firm's transparency: voluntary disclosure of emissions mitigates the negative valuation effect that stems from higher emissions (Jouvenot and Krueger, 2020; Matsumura et al., 2014). More transparent, comparable, and widely available environmental scores would allow investors to use ESG ratings as a more effective tool for pricing-in climate risk and for rebalancing their portfolios in light of increased climate risks.

The EU taxonomy for sustainable activities aims to provide appropriate definitions for which economic activities can be considered as environmentally sustainable. The European Commission sees the establishment of a unified classification system as a crucial step to reorient capital flows towards sustainable investments.[29] In a nutshell, recent EU regulation[30] requires issuers of financial products to report whether the economic activity underlying the product is environmentally sustainable under the framework of the EU taxonomy. Additionally, large "Public Interest Entities" [31] such as credit institutions and insurance companies now must provide information on how and to what extent their balance sheets reflect economic activities that qualify as environmentally sustainable. This effort should lead to more transparency regarding the sustainability of financial products and of the activities of financial institutions.

Banks appear to be pricing in at least part of the evolution to a low-carbon world. Notwithstanding the limited available information on firm-specific transition risks, a rapidly growing literature has shown that carbon-intensive firms face a higher cost of bank credit in recent years. This increase in funding cost typically takes off after events that signal regime shifts in climate policies. Ehlers et al.

[29] See EU commission communication on the action plan on financing sustainable growth: https://ec.europa.eu/info/publications/sustainable-finance-renewed-strategy_en

[30] Regulation (EU) 2020/852 of the EU Parliament and of the Council of 18 June 2020 on the establishment of a framework to facilitate sustainable investment

[31] So-called "large Public Interest Entities" (i.e. public interest entities that either have a balance sheet total that exceeds €20,000,000 or a turnover that exceeds €40,000,000) with more than 500 employees. Public Interest Entities are defined as (i) Credit institutions, other than those referred to in Article 2 of the Credit Institutions Directive; or (ii) Insurance companies; or (iii) Companies governed by the law of a Member State and whose transferable securities are admitted to trading on a regulated market of any Member State; or (iv) Designated by Member States as public interest entities, e.g., companies that are of significant public relevance because of the nature of their business, their size or the number of their employees. See Non-Financial Reporting Directive (Directive 2014/95/EU, October 22, 2014). Note that there is currently a proposal to expand this reporting requirement to a wider set of companies, see the Commission's proposal for a Corporate Sustainability Reporting Directive (CSRD).

(2021) for example find a loan risk premium related to carbon emission intensity in syndicated loan markets after the Paris Agreement in 2015. They argue that this agreement increased the awareness of banks to carbon risk. This awareness is also apparent from a survey conducted by Krueger, Sautner and Starks (2020) among a set of institutional investors. Degryse et al. (2020) and Kleimeier and Viehs (2018) demonstrate that firms that voluntarily disclose their emissions borrow at lower rates, again particularly after the introduction of the Paris Agreement. Ivanov et al. (2021) show that high-emission firms face higher interest rates and shorter loan maturities after the introduction of cap-and-trade emission schemes in California. The flip side of this is that in the absence of global climate policy, banks adjust to policy shocks also by reallocating fossil lending towards countries with weaker supervision and lower environmental standards (Laeven and Popov, 2021). Overall, banks' increased awareness of transition risk found in the literature is in line with the SSM's recent report on the state of climate-related risk management in the banking sector (ECB, 2021b). This report indicates that euro-area banks have made considerable progress in integrating climate considerations in their risk management practices over the past years. This integration is, however, still work in progress, as many institutions still don't have practices in place that are fully aligned with the expectations of the SSM.

Similar findings hold for equity markets, while evidence on corporate bond markets is more ambiguous. Over the past decade, equity markets have typically valued firms with high carbon emissions at a discount (e.g., Bolton and Kacperczyk, 2021; Pastor et al., 2022). This especially holds during times when investors' attention to climate risks is likely to be high, such as periods with abnormally warm weather (Choi et al., 2020; Engle et al., 2020). Evidence on corporate bond markets is more mixed. On the one hand, bonds of firms with low environmental scores tend to have higher risk premia (Seltzer et al., 2020; Alessi et al., 2019). In contrast, corporate bonds labelled as green bonds do not necessarily differ in pricing from 'normal' bonds (Larcker and Watts, 2020; Flammer, 2021). Part of the contradiction in these studies might arise from the fact that there is no perfect overlap between environmental scores and methodologies used to label a bond as a green bond. This again emphasizes the importance of having more transparent and unified data regarding the sustainability of financial products and of firms' activities more in general.

5.3. How resilient is the financial sector?

Climate stress tests can help in understanding the potential reaction to large climate shocks. While the pricing-in of transition risk indicates increased awareness of these risks, it tells us little about the potential impact of large, unforeseen changes in climate policy. It also carries limited information about whether loss-absorbing capital buffers at financial institutions are sufficient to cope with the losses that could materialize. Similarly, existing evidence that the impact of physical risk on banks has been limited (see section 5.1 above) doesn't necessarily imply that this will be so in the future. For one, future weather disasters might be a lot more severe than what we have experienced thus far. Climate stress tests are thus useful to assess how bank capital would be affected under a number of hypothetical climate scenarios (e.g., NGFS, 2020). These scenarios typically depend on the extent to which climate policies are adopted in a timely and effective manner. Based on that, the transition will be orderly or disorderly.

As long as the implementation of climate policies is gradual and communicated to stakeholders in a forward-looking manner, the impact of climate policies on financial stability can be contained.[32]

[32] See ECB (2021a).

Stress tests typically show that the financial losses from a disorderly transition are large, but manageable, and that a gradual and clear carbon policy implementation limits such losses. For example, solely focussing on the cost of transition, a DNB climate stress test suggests that financial institutions in the Netherlands would face sizeable, but manageable, losses in the event of a disruptive energy transition, while timely implementation of climate policies would help to avoid unnecessary losses.[33] Extending the DNB climate stress test to the euro area, the ESRB (2020) shows that sudden policy and technological shocks are estimated to have a limited impact on bank capital, with losses up to 0.8% of capital over a 5-year horizon, compared to a baseline scenario that consists of inherently non-disruptive policies. Jung et al. (2021) on the other hand show that climate change could lead to substantial capital shortfalls for US banks when transition risks rise sharply.[34] The ECB's 2021 top-down climate risk stress test (Alogoskoufis et al., 2021) emphasizes that there are clear benefits to acting early. The short-term costs of transition are relatively small in comparison with the costs of unfettered climate change in the medium to long term. Compared to an orderly transition scenario, they estimate a 3.5% expected loss on euro area banks' credit portfolios in case of disorderly transition over a 30-year horizon, while losses in a no-transition scenario would lead to expected losses of up to 8.5%. Finally, projections made by banks in the recent Climate Biennial Exploratory Scenario published by the Bank of England also indicate that financial costs will be lowest with early, well-managed action to reduce emissions (Bank of England, 2022).

At the same time, the impact of climate shocks will likely be heterogeneous across banks, and not all banks are at the moment well-equipped to deal with climate-related risks. The ECB's 2021 top-down climate risk stress test (Alogoskoufis et al., 2021) shows that banks domiciled in some countries could experience more higher expected losses under a hot-house-world scenario as compared to the average bank in the euro area, mainly due to higher expected damages to physical collateral. Combined with the observation of the SSM that the climate-related risk management practices of many euro-area banks currently don't meet supervisory expectations (ECB, 2021b), this could lead to problems at individual banks. Most affected will be the banks that are exposed to climate risk but do not manage to properly integrate climate risk in their risk management practices.

Within the European financial sector, investment funds are considered to have the largest exposure to transition-sensitive sectors such as utilities, transport and fossil fuel extraction.[35] Amzallag (2021) analyses the potential impact of an abrupt policy or technological shock on European investments funds, and finds that fund loss in his climate risk scenario might be as high as 443 billion EUR, which corresponds with 9% of fund portfolio assets included in the exercise. Exposures of euro area banks to high-emitting firms appear limited on average but are concentrated in a few large exposures for some banks (Alogoskoufis et al., 2021; ESRB, 2020): the top 10% of most polluting portfolios finance 65% of total emissions.

[33] Depending on the scenario, losses for banks lead to a maximum drop in CET1-ratios of 4.3 percentage points over a 5-year horizon, from 16 to below 12%, while losses for insurers could decrease their solvency ratio with 16 percent points, from around 180% to 164 percent. Pension funds could face a reduction of 5.5 percentage points in their coverage ratio, dropping from around 110% to below 105%. See De Nederlandsche Bank (2018). All numbers come from a comparison with a baseline scenario that consists of inherently non-disruptive policies. The economic losses are brought about by (sudden) policy changes, technological breakthroughs, or a (sudden) drop in consumer and investor confidence due to uncertainty about the policy path.

[34] To do so, they develop a CRISK measure that capture the expected capital shortfall for US financial institutions in a climate stress scenario.

[35] See, e.g., Amzallag (2021), Battiston et al. (2017), ESRB (2020).

Overall, climate risks to the financial system appear to be contained, and future losses are manageable, especially under orderly transition. The impact of physical risks on the financial sector are currently manageable, while the materialization of future physical risks depends on the evolution of global warming. Climate policies can help in minimizing temperature increases, and as long as the implementation of these policies is gradual and communicated to stakeholders in a forward-looking manner, their impact on financial stability should be limited.

5.4. Financing the green transition

Apart from being exposed to climate risks, financial markets and institutions can also actively contribute to the green transition by facilitating climate-friendly investments. The climate risk–mitigating role played by the financial sector ranges from financial innovation in green bonds and portfolio allocation by large institutional investors increasingly guided by ESG sustainability objectives to changes in bank credit allocation based on bank preferences for green versus carbon-intensive assets (Giglio et al., 2021).

The banking sector is of special importance in the green transition in the euro area, given its importance as a key source of firm funding. Banks can enforce emission reduction by actively cutting credit to carbon-intensive firms, by channelling credit towards green firms, and/or by providing credit to carbon-intensive firms for investment to reduce carbon emission. In recent years, banks have been taking part in various climate actions (e.g., the Net-Zero Banking Alliance) and making a variety of green pledges. Recent empirical evidence indicates that green pledges of banks affect carbon emissions via credit reallocation from carbon-intensive to green firms but not via providing loans to carbon-intensive firms for the investment necessary to reduce carbon emissions (Degryse et al., 2022; Kacperczyk and Peydro, 2021).[36] In addition, green regulatory initiatives such as the Paris Agreement lead banks to reallocate credit away from polluting firms (Reghezza et al., 2021). Similarly, in case the economy is hit by a climate shock (e.g., floods and wildfires), banks can be of vital importance to smooth out the consequences of the shock. Strahan and Cortes (2017) and Koetter et al. (2020) for example emphasize the important role that (multi-market) banks can play in addressing demand shocks that arise from natural disasters.

The importance of non-banks in the firm funding mix has been on the rise, and so has their role in mitigating climate change risks. Large institutional investors manage an enormous (and growing) amount of investments. Their holdings can result in large stakes in their portfolio firms, which makes them likely pivotal voters who can engage with portfolio companies and pressure them to curb their greenhouse gas emissions (Azar et al., 2021). Beyond possible altruistic reasons, asset managers can be incentivized to facilitate green transition by aiming to attract or retain investors sensitive toward environmental concerns. There is evidence that mutual funds categorized as low sustainability face investor outflows (Hartzmark and Sussman, 2019) and that funds actively compete for investors with ESG preferences, by shifting their holdings towards more climate-conscious firms (Ceccarelli et al., 2020) and actively engaging with polluting firms to reduce their carbon emissions (Krueger et al., 2020; Hoepner et al., 2022).[37]

[36] Related et al. (2019) and Nguyen and Phan (2020) show that greater exposure to climate risk is associated with a reduction in corporate financial leverage.

[37] A recent Economist article reports that carbon-intensive assets are increasingly bought by private equity funds who care less about investor ESG activism (The Economist, Feb 12, 2022).

Having well-developed equity markets also helps in spurring green innovation and reducing carbon emissions. Using a large panel of countries and industries over the period 1990-2015, De Haas and Popov (2022) show that a financial structure tilted towards equity financing reduces carbon emissions at the country, sector, and firm level. This happens because stock markets facilitate the adoption of cleaner technologies in polluting industries and help reallocate investments towards energy-efficient sectors. The latter is in line with the evidence in Bolton and Kacperczyk (2021), who show that investors in US equity markets increasingly avoid the most carbon-intensive sectors.

6. Fiscal and socio-economic implications

6.1. Fiscal implications

Climate policies are inextricably linked to fiscal policy. Climate change is happening because producers emit too much greenhouse gases. In turn, they do so because they do not pay the costs associated with carbon emissions. This problem can be solved by charging producers for their emissions. There are two largely equivalent ways to do this: a tax on carbon and emission permits. Both make emissions more costly for producers and both raise revenue for the government. As the theory goes, there is an optimal carbon tax (or price of the emission permit) and it is equal to the social cost of carbon, the damage to welfare done by a unit of carbon over its lifetime in the atmosphere. An influential literature has attempted to quantify the social cost of carbon. The central findings range from the $26 per tonne of CO2-equivalent emissions found by the US Interagency Working Group (Greenstone et al., 2013) to the $250 found in Stern (2007).

A carbon tax interacts with the rest of fiscal policy in three separate ways. First, it discourages economic activity and thus reduces the tax base for other taxes. This way, it exacerbates economic distortions caused by other taxes. Second, it raises revenue, which can be used to reduce other taxes. Should a broad-based carbon tax be introduced in the European Union based on the estimates of the social cost of carbon given above, it would raise between 0.5% and 5% of GDP in tax revenue every year.[38] Third, it softens the impact of climate change and thereby reduces the amount of government spending necessary for adaptation. At the same time, it creates more fiscal scope for governments to increase spending on public R&D, with a view of speeding up the development of breakthrough green technologies. Interactions of a carbon tax with fiscal policy are studied in Barrage (2020a). She recommends setting the carbon tax 8-24% below the social cost of carbon, since the adverse effect on other taxes' base is large.

Taking fiscal policy into account magnifies the costs of climate-policy inaction. Adaptation to climate change implies sharp increases in public spending. Thus, it also implies a greater need to raise revenue. Against this backdrop, a carbon tax is a valuable addition to the fiscal policy toolkit. Quantitatively, Barrage (2020b) finds that a carbon tax optimally set at $62 reduces the necessary government spending on climate adaptation by 0.3% of GDP on average over the rest of the 21st century, relative to a scenario without a carbon tax. Correspondingly, the average labour-income tax rate is 0.7% lower in the scenario with optimal carbon taxation. In this model, the introduction of a carbon tax increases welfare roughly as much as an additional $23 trillion of GDP over the rest of the century. This is the

[38] This calculation uses the 2019 value of CO2-equivalent emissions in the EU, which the European Environment Agency reports as 3.5 billion tonnes.

value of instituting a carbon tax and, to put it into context, it is approximately equal to the United States' GDP. As the paper shows, 7% of the value of climate policy comes from the beneficial effect on fiscal policy.

Lax fiscal policy, resulting in higher public debt, could solve the intergenerational problem posed by the introduction of climate policies. Climate change is a long-term problem and current generations do not stand to gain from solving it as much as the generations of the future. Kotlikoff et al. (2019) find that a generational win-win is nonetheless possible. To achieve this, they find that the introduction of a carbon tax should be accompanied by a reduction in other taxes that more than compensates for the increase in government revenue. This increases the welfare of current generations despite the carbon tax. Future generations benefit greatly from the preservation of the climate and, even though they are saddled with somewhat higher public debt, their welfare is improved. This argument becomes stronger in an economic environment with low interest rates.

A changing climate may pose a threat to debt sustainability. This is because more government spending will be needed for climate adaptation and since climate-related disruptions to production may become more frequent. As one extreme example, Marto et al. (2018) calibrate a model to the economy of Vanuatu and study cyclone Pam, which in 2015 did damages amounting to 60% of the archipelago's yearly GDP. They find that in the aftermath of natural disasters fiscal resources become tight and inflows of funds from international donors are key for resilient new infrastructure to be built. Additionally, Melecky and Raddatz (2011) find that after a climatic disaster shock, public deficits increase less in countries with higher insurance penetration, as they can quickly allocate private resources to recover productive capacity rather than using public resources.

While advanced economies, such as EU member states, are less vulnerable on average to weather shocks and can borrow more easily to cushion the shock, this is not the case for all members. The five member states with the greatest burden in terms of public debt as a share of GDP are also the only member states, together with Malta, whose GDP growth over the rest of the century is projected to be reduced by climate change, according to Burke et al. (2015b).

6.2. Inequality

Climate change is likely to adversely impact people's well-being through multiple socio-economic channels. These include (but are not limited to) labor productivity, working and living conditions, food security, access to water and natural resources, consumption of electricity, health outcomes, destruction of assets, crime, political tensions, and instability. Crucially, these consequences are expected to have a spatial variation. First, the economic effects of temperature changes will differ across sectors, as the relationship between temperature and productivity is sector-specific. Research has pointed to reallocation between agricultural and non-agricultural production in response to climate change (Conte et al., 2020; Costinot et al. 2016; Desmet and Rossi-Hansberg, 2015; Nath, 2021), with the estimated adaptation gains ranging from modest to large. Second, the economic effects of temperature changes will differ across latitudes. Low-latitude countries in general, and their rural regions in particular, will be the most adversely affected. Third, coastal areas are heterogeneously exposed to rising sea levels, which depends not only on the projected ocean levels, but also on the population distribution by elevation in the regions at risk. Fourth, responses to global warming are likely to vary with local topographical, hydrological, and ecological characteristics, thus exogenously predetermining how a given area will be affected by climate change. Finally, countries differ in their ability to provide efficient mitigation strategies, such as insurance against flooding.

By affecting countries, regions, sectors, and people differently, climate change can have a material effect on inequality. The first thing to notice is that the long-run increase in temperatures will hurt some countries, but benefit others. Burke et al. (2015b) find that there is an optimal temperature of around 13 ^{o}C where economic performance peaks.[39] Warming above this temperature causes economic productivity to decline – with a rate that accelerates the hotter a country gets – but warming below this temperature causes economic productivity to increase. Accordingly, Scandinavian countries are set to benefit substantially from global warming, Mediterranean countries are set to experience a substantial reduction in GDP growth, while most other European countries will experience a small boost. Burzynski et al. (2022) also find that climate change will exacerbate pre-existing income differences across countries. According to their estimates, climate change will nearly double the world's population subsisting below the relative threshold of extreme poverty (from 4% to 7.5%).

There is a well-established link between weather shocks and poverty in developing economies,[40] but the same relationship is unlikely to hold in the same way in developed economies. In developed economies, an interesting question, which protests such as those by the so-called yellow vests in France since 2018 have focused attention on, is the impact of climate policy on inequality, especially within countries. This topic is understudied. Owen and Barrett (2020) show that the 13% flat surcharge on households' energy bills, established to fund low-carbon policies, is regressive. This is because energy bills represent a larger share of the expenditure of poorer households. The poorest quarter of the population spend around 0.8% of their income on the tax, roughly four times as much as the richest quarter. Känzig (2021) finds that in response to a carbon price policy shocks, consumption expenditure falls somewhat more strongly and much more persistently among low-income households than among high-income households.

6.3. Migration

Population displacement is simultaneously a consequence of rising temperatures, an adaptation mechanism to climate change, and one channel whereby climate change affects GDP. Using a dynamic model, Burzynski et al. (2022) estimate that there will be between 45 and 97 million working-age migrants of all education levels over the course of the 21st century, depending on the future trajectory of the concentration of greenhouse gases in the atmosphere. Of these, the middle-of-the-road scenario predicts 24 million climate migrants to Europe, compared with 17 million to North America.

When the dynamic effect of migration is taken into account, the predicted decline in GDP as a result of climate change is typically smaller than in models where migration is absent. For example, Desmet et al. (2021) find that predicted GDP losses due to coastal flooding associated with climate change are one order of magnitude smaller than in static models (losses of 0.11% of GDP in year 2200 vs 4.5%). After accounting for migration, Burzynski et al. (2022) find that global GDP shrinks by 9% in 2070 and by 12% in 2100. Africa, Asia, and South America are most affected by these losses, where GDP plunges by 40%, 25%, and 34%, respectively; however, there are substantial differences across different

[39] To put this number into perspective, 13 ^{o}C is the average annual temperature in Milan, Lyon, and San Francisco.
[40] See Hallegatte et al. (2018).

scenarios, with GDP losses differing by a factor of 2 between the most benign and the most severe. In comparison, European GDP *increases* by 7% partly thanks to inflows of climate migrants. These general trends are confirmed by Missirian and Schlenker (2017) who study the effects of source-country climate shocks on asylum applications to the EU. They find that the effects are large and significant. They predict climate change to increase asylum applications to the EU by 100,000 per year by 2100, which corresponds to a roughly 30% increase.

In addition, climate change accelerates urbanization, especially in developing countries, and raises the world's stock of human capital. Burzynski et al. (2022) show that this is because people tend to move from poorer regions to richer regions, where access to education is quasi-universal.

6.4. Conflict and violence

Climate change can increase the frequency and severity of human conflict. This is true both for interpersonal conflict (i.e., crime against property and other human beings) and for intergroup conflict (i.e., riots, coups, and wars). A number of theoretical channels have been proposed. For example, changes in the climate may alter the supply of natural resources and lead to disagreement over their allocation, or they may increase the relative appeal of using violence to achieve an objective. Burke et al. (2015a) conduct a meta-analysis of 55 such studies. They find that deviations from moderate temperatures and precipitations patterns systematically increase the risk of conflict. Numerically, a 1 standard deviation increase in temperatures leads to a 2.4-percent increase in interpersonal conflict and to a 11.3-percent increase in intergroup conflict.[41]

The detrimental effect of climate change on conflict is not restricted to developing economies. For example, Ranson (2014) studies the effect of temperature on crime in the US with a 30-year panel of county-level data. He finds a positive and significant effect of temperature on crime. The effect is remarkably stable over time and space. Extrapolating from the estimates in the analysis, the author argues that climate change will cause an additional 22,000 murders in the US between 2010 and 2099, corresponding to a 2.2-percent increase relative to the baseline with no climate change.

The most widely accepted explanation for why climate change increases interpersonal and intergroup conflict is its negative effect on personal income. Since weather shocks reduce income, they also reduce the opportunity cost of engaging in conflict. Kim (2014) studies a panel of 148 countries and finds that weather shocks that depress GDP per capita significantly increase the probability of a coup attempt. An increase in temperature by one standard deviation increases the probability of a coup by around 20%, a very large effect. However, it is difficult to draw conclusions for developed economies from the literature about the effect of climate change on the likelihood of intergroup conflict. This is especially true since developed economies tend to be less exposed to the changing climate.

Alternatively, climate change may have a direct psychological impact on humans that increases the propensity for violence. Baysan et al. (2019) use a panel of data from Mexico. They find that temperature has a significant effect on violent crime but none on non-violent economically motivated crime such as car thefts. This is evidence that non-economic factors also drive the relationship between weather shocks and conflict. With support from the medical literature (e.g., Seo et al., 2008), they

[41] Arguably, this literature is mostly focused on developing economies.

propose a physiological connection between body temperature regulation and the propensity for violent behavior. These insights have important implications for the effect of rising temperatures and more frequent extreme weather events on conflict in the future.

7. Conclusion

We review the rapidly growing academic literature on the consequences of climate change and climate policies for the real economy. The conclusion we reach is that climate change will lead to permanent changes in the organization of economic interaction. Chief among these are income and growth divergence across individuals, sectors, and countries, major shifts in energy markets, increased inflation variability, stress in various financial market segments, a climate technology revolution, intensified migration flows, higher public debt, and higher likelihood of interpersonal and interstate conflict.

These challenges should not be underestimated, yet they appear manageable for EU member states. However, this conclusion is subject to two sources of uncertainty. First, the effect of increasing emissions on the climate in the future resides within a wide interval of outcomes, ranging from the benign to the catastrophic. the most benign a scenario of early and orderly climate transition. Second, the exact nature of economic transformation depends on what climate policies governments choose and on how they choose to implement them. The cost to both the real and the financial sector is lowest under an orderly transition scenario. In contrast, exogenous shocks like the ongoing Russian aggression in Ukraine may precipitate abrupt changes in climate policy, accelerating the transition to net-zero, but increase the risk of a disorderly and costly transition.

An effective and smooth transition towards a net-zero economy requires a large-scale, coordinated response between fiscal authorities, central banks, regulators, and supervisors. The ECB will face a number of unique challenges and will need to pay attention for a long time. To name just a few, climate change and the green transition will make it more challenging to achieve its primary mandate, and as the fiscal outlook of some member states deteriorates, there will be renewed pressure on the ECB to intervene in sovereign markets.

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