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NationalBank
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Eurosystem

Productivity in the Face of Climate Change

Results from the European System of Central Banks (ESCB) Expert Group on Productivity, Innovation and Technological Change

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Summary

Both climate change and the policies implemented to mitigate and avert it will inevitably affect labour productivity. Climate and meteorological changes, including both long-run changes in temperatures and sea levels and more frequent extreme weather events, are commonly referred to as physical risks. Meanwhile, the impacts resulting from the shift to a net-zero economy are referred to as transition risks and include those associated with the implementation of climate policies, such as carbon taxes, new regulations, subsidies and other developments induced by changing consumer preferences and demand. Physical and transition risks will affect all three components of the traditional production function framework, i.e. capital, labour and total factor productivity, with the latter being influenced by changes in production technology.

Physical risks are expected to have an overall negative effect on productivity. A sustained rise in temperatures is likely to weaken productivity growth, especially in Southern Europe, thus leading to larger growth differentials within the euro area. The productive capital stock may be partially destroyed by natural disasters or longer-term weather patterns or by increased allocation to non-productive adaptation strategies. Climate-related migration may also occur, although historically most displacement takes place within countries rather than across borders, and Europe could stand to benefit overall from immigration from other, more affected regions. Total factor productivity growth is also likely to be affected by more hostile climatic conditions, disruptions to firms and supply chains, and the increasing allocation of resources to adaptation rather than innovation.

While a disorderly transition might not affect productivity in the short term, in the medium and long term an orderly transition path seems preferable. Orderly transition scenarios assume that climate policies are introduced relatively early and become gradually more stringent over time. Conversely, disorderly scenarios feature higher transition risks due to policies being delayed or diverging across countries and sectors. Based on an analysis of these scenario assumptions from the Network of Central Banks and Supervisors for Greening the Financial System (NGFS), an orderly transition scenario would lead to relatively higher immediate emission costs, due to a comparatively stronger increase in the price of carbon. This would suppress aggregate output and imply a decline in labour productivity. However, in the disorderly scenario the carbon price would have to be raised sharply at a later stage in order to limit global warming, thus ultimately exceeding the emission costs of an orderly transition. Accordingly, we find that the labour productivity associated with an orderly transition is notably higher than in the case of a disorderly transition in the medium to long run. An orderly transition also reduces the risk of stranded assets.

It remains to be seen whether innovation will succeed in creating green technologies that can compete with carbon‑intensive technologies in terms of efficiency. It has even been suggested that environmental regulations, by creating incentives for innovation, can improve productivity enough to offset the costs of regulation, in a process known as the Porter hypothesis. We find some, qualified, support for this hypothesis. Better environmental protection is associated with a short-term increase in productivity growth at the industry level in countries that are at the technological frontier. Analysis at the firm level similarly finds that the most productive firms can achieve productivity gains, as they are able to access advanced technology and resources for R&D and knowledge-based capital. However, less advanced firms may require higher investments to comply with the new regulation, leading to a temporary decline in productivity growth. The impact also differs depending on the type of regulation, with market-based policies (such as carbon taxes) having a less distortionary effect and R&D subsidies being the most effective in spurring green innovation.

The green transition will entail a significant reallocation of capital and labour within and across sectors, with mixed effects on productivity. At given levels of sectoral productivity, reallocation away from carbon-intensive sectors towards those that benefit from the green transition may mechanically lower productivity. When emission costs are increasingly accounted for, emission-intensive sectors are likely to contract due to higher relative prices. These sectors currently tend to have higher productivity than those likely to be driven by the green transition (notably construction). However, stricter regulation and higher carbon prices are likely to induce sector-level clean-up effects as the least productive firms are pushed out of the market, although this positive cleansing effect at sector level will likely be dampened at the aggregate level as the sectors likely to benefit from the transition tend to be less productive. Market entry may decline in the most affected sectors driven by carbon taxes, given the higher productivity threshold needed to enter the market. Within a given firm, the reallocation of production factors away from energy towards capital and labour is likely to have a negative impact on productivity due to diminishing marginal returns. The reallocation of economic activity goes hand in hand with that of labour. While the overall negative effects of the reallocation of labour to green activities should remain manageable, the impact will be heterogeneous across geographical areas and types of workers, possibly leading to the human equivalent of stranded assets.

1. Introduction

Climate change will cause large, permanent economic losses in Europe in the long run, unless timely and sufficient adaptation and mitigating actions take place. It takes time for the full warming impact of atmospheric greenhouse gasses (GHGs) to materialise. So even if the transition to a net-zero carbon economy were to accelerate, the global average temperature would continue rising, potentially bringing with it an increased frequency and magnitude of natural hazards such as windstorms, floods and droughts.[1] The speed of the transition to net zero will determine by how much the atmospheric stock of man-made greenhouse gases will grow, and consequently the ultimate degree of warming. Hastening the transition would therefore reduce the ultimate economic impact of physical risks, but could also negatively affect short- and long-term growth.

This report discusses the channels of medium-term impact of physical risks and the green transition on (labour) productivity. For that purpose, a group of experts from the European System of Central Banks (ESCB) have been pooling their expertise and sharing macro, sector and firm-level data as part of an Expert Group on Productivity, Innovation and Technological Change. In what follows, physical risks that are the result of long-run changes in average temperatures and sea levels are referred to as chronic risks, while the impact of natural hazards such as droughts, wildfires and storms are referred to as acute risks. In addition, the path to carbon neutrality and its enabling policies and regulations might also disrupt economic performance, in what is

1 There is mounting evidence of a link between climate change and the frequency, intensity and concurrence of weather extremes (see Intergovernmental Panel on Climate Change, 2021).

referred to as transition risk. This report attempts to distinguish their impact on the three factors contributing to labour productivity: capital stock, labour supply (including the influence of worker health, skills and education on output) and total factor productivity (TFP), which is driven by innovation, technology and an efficient allocation of resources. Given that available studies do not distinguish cleanly between these factors, the channels set out below also involve a degree of blurring among them.

The economics of climate change and the green transition are subject to extensive uncertainty and substantial knowledge gaps. There is a wide range of potential transition paths and uncertainty surrounding estimates of how higher greenhouse gas (GHG) concentrations translate into climatic changes, and how those climatic changes themselves translate into economic impacts. Moreover, impacts of physical risks are known to be non-linear in nature, and are affected by feedback loops and so-called "tipping points", meaning the sudden acceleration of feedback effects or points of no return to lower temperatures.[2] As temperatures and the magnitude of physical events exceed the past experiences for which we have economic data, the calibration of models based on such historical data becomes increasingly suspect, assuming in the first place that the models incorporate relevant channels: many integrated assessment models, for example, do not incorporate the impact of acute physical risks or non-market channels such as migration flows or health costs in their damage functions.

2 Examples include the change in ocean streams or the melting of the Greenland ice sheet. The likelihood of such catastrophic events increases at higher temperatures.

Table 1

Channels of impact of climate-related risks on labour productivity

Risk type	Capital stock	Labour supply	TFP and innovation
Chronic physical risk	Loss of agricultural land due to temperature, salinification of soil due to rising sea levels, and water stress	Higher rates of mortality and sickness	Capital invested in adaptation less productive in aggregate and diverts resources away from innovation
	Shifts in tourism flows	Climate-induced migration	Agglomeration effects from migration might be positive for productivity
	Disruption of economic activity in coastal areas as sea levels rise	Reduced labour efficiency due to higher temperatures, including fewer hours worked	
Acute physical risk	Destruction of capital stock due to disasters	Higher rates of mortality and sickness	Disaster-caused bankruptcies and localised reductions in access to finance causes reallocation between firms, for better or worse
	Opportunity to replace old, destroyed capital with newer, more technologically advanced capital	Disaster-induced migration	Rebuilding process distracts management, reducing overall productivity
	Greater uncertainty and volatility reduces willingness to invest over the long run	Loss of education and skills	
Transition risk	Increase in stranded assets	Skill mismatches increasing structural unemployment	Reallocation of output between firms within sectors may prove more or less efficient
	Higher energy costs from carbon taxes in the short term could reduce funds for investment	Economic migration	Environmental regulations reduce productivity, perhaps offset by innovation

Source: Eurostat.

Actions taken to mitigate the impact of climate change, by reducing future physical risks, are projected to result in higher potential output in the long run relative to counterfactual of unmitigated climate change. By contrast, during the transition period there may be declines in potential output, particularly if assessed relative to a counterfactual of no climate action, arising from the reallocation of both capital and labour from carbon-intensive activities to green ones and from the time needed by firms to adjust to new regulations, technologies and relative prices.

This report uses a combination of modelling and empirical work to qualitatively discuss and, where possible, quantify the various channels that affect labour productivity and its three determinants: capital stock, labour supply, and TFP growth driven by innovation. These channels are discussed in more detail further below and are summarised in Table 1, which distinguishes between chronic risks (discussed in Section 2), acute physical risks (discussed in Section 3) and transition risks (discussed in Section 4).

2. Chronic physical risk

2.1 Introduction

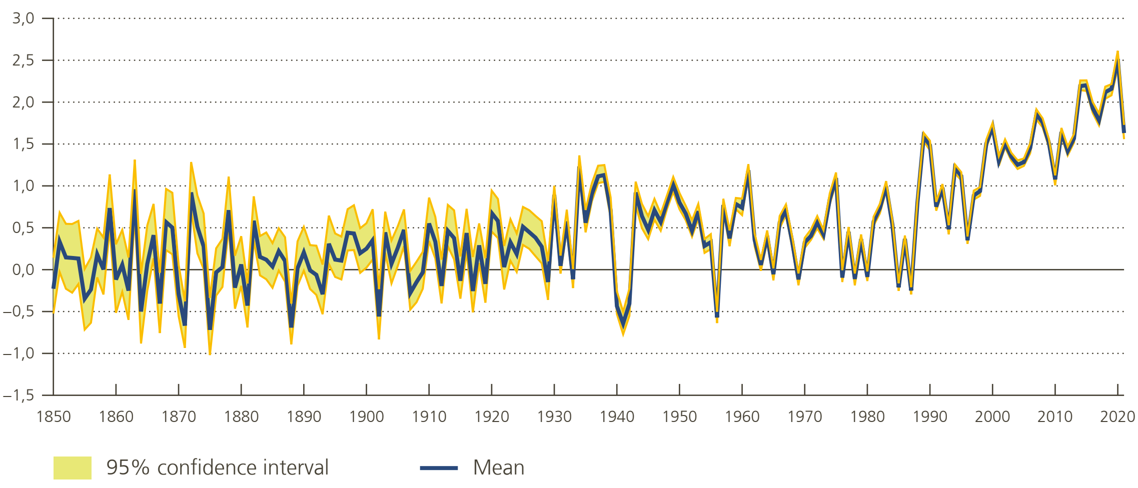
Physical risk covers the direct effect of climate change on resources and on their productivity. Physical risk is chronic if related to a more gradual effect of global warming, caused by longer-term shifts in climate patterns, such as rising sea levels or higher temperatures. It is to be distinguished from acute physical risk, which is caused by extreme weather events and hazards such as floods, landslides, extreme temperatures, storms and hurricanes, droughts or wildfires. Acute physical risk is covered in the next section.

Temperatures in Europe have risen markedly over the last few decades. The average temperature in Europe has risen by approximately 2 °C over the past century and by approximately 1.5 °C since the 1980s (Figure 1).

Figure 1

Temperature anomaly in Europe

(in degrees Celsius)



Sources: European Environment Agency, Met Office Hadley Centre and Climatic Research Unit.
Note: Anomaly defined as a deviation of the annual average near-surface air temperature in Europe from the mean for the years 1850-1900. Europe is defined as the land area between 34° and 72° northern latitude as well as –25° and 45° eastern longitude.

The long-run economic implications of climate change are subject to considerable uncertainty. This includes the uncertainty surrounding the exact climatic impact, including the existence of trigger thresholds for highly non-linear tipping points and compound climate events, and also how climate affects the economy. Estimates are usually based on integrated assessment models (IAMs), which incorporate feedback between economic activity, emissions and changes in climate. Yet the estimates made using IAMs depend substantially on the structure of the underlying model and embedded assumptions. Earlier IAMs suffer from limited inclusion of the impact of acute physical catastrophes on capital, damage functions that do not fully account for non-linearities, and the absence of a link between capital destruction and productivity growth. Adjusting IAMs to include these channels results in damage estimates that are much higher and correspondingly higher optimal paths for carbon prices.[3]

Long-run changes in average temperatures and precipitation patterns are likely to have varying impacts on certain sectors, regions and parts of the population across Europe; the impact is predominantly negative, although some regions may stand to gain. For example, climate change is expected to reduce snow availability for skiing in winter and make parts of Southern Europe less attractive as summer holiday destinations, as they may become too hot, with further issues surrounding the availability of freshwater during the high tourist season.[4] By contrast, parts of Northern Europe, including Finland, are expected to become more attractive as holiday destinations. The overall impact for Southern Europe will depend on choices over when to go on holiday: while the height of summer may be too hot, the spring and autumn months might become more enticing holiday periods. The consequences of higher temperatures for other heat-exposed industries such as construction, mining, transportation, utilities and agriculture will likely also differ considerably across countries, depending on their geographical location.[5]

The impact on agriculture is also expected to be mixed, with Northern Europe potentially on course for somewhat higher crop yields on average, but Southern Europe facing lower yields. While the opportunity exists to switch crop species to adapt to higher temperatures, water supply is expected to constrain options, most notably in the south.[6] There is also a risk of increased salinification from rising sea levels reducing available agricultural land.[7] Yet while adaptation might be made to changes in mean temperature and precipitation, their distribution around the mean will widen also, resulting in lower productivity, as noted below in the section on acute physical risks. Since other food-producing regions in the world may suffer greater climate-related impacts, the value of European production may actually increase.

Properties and economic activity in coastal regions are at risk from rising sea levels. Estimates from the European Union on the global mean sea level point to a likely (66 % confidence) rise this century (2100 relative to 1995-2014) by 0.28-0.55 m for a very low emissions scenario, 0.44-0.76 m for an intermediate emissions scenario and 0.63-1.02 m for a very high emissions scenario.[8] Rising sea levels are likely to lead to capital destruction (potentially more accurately described as submerged rather than stranded assets) or divert productive assets into adaptation usage.

International studies show that human health and performance tend to suffer from high temperatures.[9] Productivity declines beyond the comfort range of 19-22 °C, with estimates of about a 2 % decline in productivity per degree Celsius above the comfort zone of 25 °C. Physical exertion becomes severely limited above a humidity-inclusive temperature of 35 °C.[10] When certain temperature thresholds are exceeded, not

3 See, for example, Weitzman (2012), Dietz and Stern (2015).
4 See Amelung and Moreno (2009).
5 For a definition of heat-exposed industries see Graff Zivin and Neidell (2014).
6 See, for example, Jacobs et al. (2019) and Ceglar et al. (2019).
7 See, for example, Hassani et al. (2021).
8 European Environmental Agency, indicator on the Global and European sea level rise, published 16 December 2022.
9 Temperature-related productivity losses are identified in panel analyses (see Hsiang 2010 for Central and South America and Colacito et al. 2018 and Deryugina and Hsiang 2014 for the United States) and in experimental studies (see Seppänen et al., 2005). Regarding the health consequences of rising temperatures, see, inter alia, Vicedo-Cabrera et al. (2021).
10 See Heal and Park (2016).

only productivity but also labour input may fall.[11] Workers in industries highly exposed to climatic conditions, including agriculture, construction and manufacturing, may see their working time decline by as much as an hour on days when temperatures exceed 29 °C. The impact is not confined to physical activities, as for instance the mathematical ability (although not reading) of students is significantly affected when temperatures exceed 26 °C.[12] However, where initial temperatures are low, a temperature increase can have a positive impact on labour input and productivity, as shown in the next sub-section.[13]

2.2 The impact of changing temperatures on European productivity growth: an empirical analysis

We examine the macroeconomic impact of changing temperatures via panel regressions.[14] Specifically, a regression analysis is used to estimate the effect of average annual temperature $T_{i,t}$ in year t and country i on hourly labour productivity growth ($\Delta Y_{i,t-1}$). It is assumed that annual temperature changes are exogenous.[15] The model controls for precipitation ($R_{i,t}$) and includes lagged values of productivity growth ($\Delta Y_{i,t-1}$), country-fixed (a_i) and year-fixed effects (τ_t) as well as a residual ($\varepsilon_{i,t}$).[16]

$$\Delta Y_{i,t} = a_i + \tau_{\mathrm{t}} + \rho \Delta Y_{i,t-1} + \beta_1 T_{i,t} + \beta_2 T_{i,t}^2 + \gamma_1 R_{i,t} + \gamma_2 R_{i,t}^2 + \varepsilon_{i,t}$$

The model allows for nonlinearities, which are captured by the quadratic term in the regression. This implies that the overall effect of a temperature increase on productivity growth may depend on the (average) temperature level of a country. The data set covers 31 European countries (all 27 EU countries plus Iceland, Norway, Switzerland and the United Kingdom) for the period from 1963 to 2019.[17]

For this panel of European countries, we find a significant nonlinear relationship between the annual average temperature and the growth in hourly labour productivity. We also find a positive linear term (<F>) and a negative quadratic term (<F>).[18] This implies that starting from a low temperature, a rise in temperature is beneficial, while starting from a high temperature, it has adverse effects (see Figure 2).[19] Hence, given an average annual temperature of 4 °C – as measured for example in Sweden or Finland in 2020 – the point estimates suggest that a 1 °C increase in the annual average temperature would increase annual labour productivity growth by about 0.4 pp.[20] The point estimate becomes negative for average temperatures above 14 °C. The average annual temperature in 2020 for a considerable number of the western and central European countries included in the sample is close to this threshold, around which the macroeconomic impact of a rise in temperature is not distinguishable from zero. The greater the gap between the initial temperature and

11 See Graff Zivin and Neidell (2014) and Hsiang et al. (2017) for the United States, Hsiang (2010) for Central and South America, Somanathan et al. (2021) for India and Burke et al. (2015) for a global panel.

12 See Graff Zivin et al. (2018).

13 See also Tol (2018).

14 This exercise draws heavily on an analysis presented in Deutsche Bundesbank (2022), which focuses on the impact of changing temperatures on economic growth in Europe. The model is based on earlier studies of the global impact of rising temperatures; see Burke et al. (2015) and Dell et al. (2012).

15 This assumption is quite typical for such studies. See Auffhammer et al. (2013).

16 In view of the strong correlation between precipitation and temperature data, it seems appropriate to include both variables (see Auffhammer et al., 2013). Country fixed effects control for time- invariant differences between the growth rates, while year fixed effects capture joint trend movements and year-specific one-off effects. The estimated temperature effect is thus derived from country- specific deviations in the labour productivity growth rate and in the average annual temperature from the European average (see Burke et al., 2015).

17 Temperature and precipitation data are taken from the Climatic Research Unit of the University of East Anglia, which aggregates the data from individual weather stations at the country level using geographical distance weighting. The time series can be downloaded from the World Bank's Climate Change Knowledge Portal. For the analyses, the monthly temperatures were consolidated as an annual or quarterly average. The labour productivity growth rates are taken from the Penn World Tables. The model is estimated based on an unbalanced panel dataset.

18 The linear effect and the quadratic effect) of the average temperature both show a statistically significant difference from zero at the 95 % confidence level.

19 Comparable results are also found for the impact of changing temperatures on GDP growth. Here, the relationship turns out to be more significant (see Deutsche Bundesbank 2022).

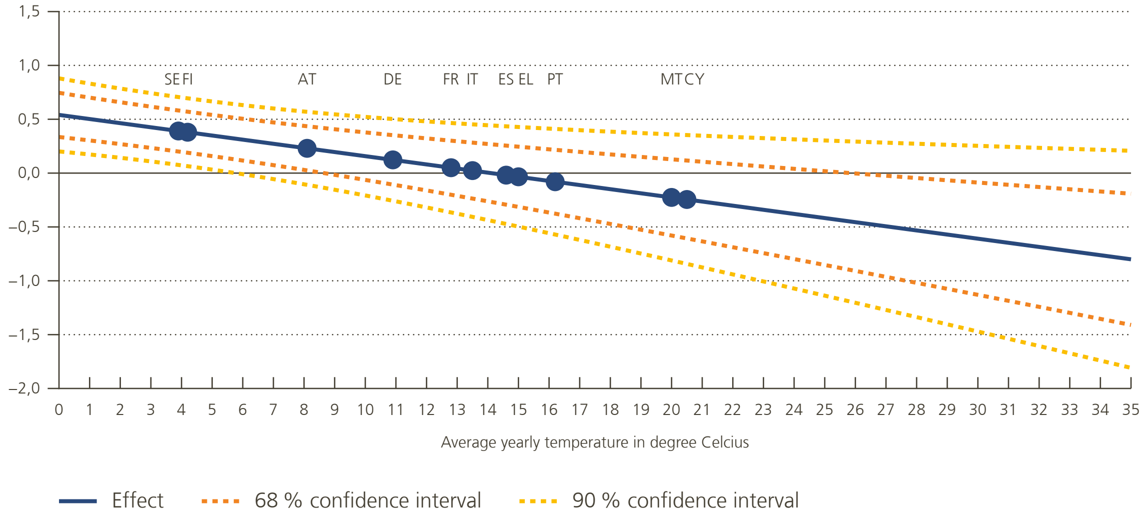
20 While referring to the implications of the point estimates for illustrative purposes, it should be noted that there is a substantial degree of estimation uncertainty with respect to country-specific implications, as indicated by the confidence bands.

this threshold value, the stronger the estimated impact. Given an average annual temperature of over 25 °C, the point estimates imply that a 1 °C increase in the annual average temperature would dampen annual labour productivity growth by more than –0.4 pp.[21]

Figure 2

Change in hourly productivity growth due to a 1 °C increase in the average yearly temperature

(in percentage points)



Sources: CRU TS climate dataset, Penn World Tables, and Deutsche Bundesbank calculations.
Notes: Estimated impact of an increase in the average yearly temperature by 1 °C on annual hourly productivity growth (in percentage points, vertical axis). The effects are estimated using a panel approach with historical data from 1963 to 2019, including both year and country fixed effects. The panel encompasses data for all Member States of the European Union plus Iceland, Norway, Switzerland and the United Kingdom. Dashed lines show 68 % and 90 % confidence intervals.

The estimation results indicate that the temperature increase has had a heterogeneous impact on labour productivity growth in the individual European countries to date. Between 1960 and 2020, the average rise in mean temperature in the European countries was between 0.01 °C and 0.06 °C per year.[22] The estimated coefficients can be used to assess the overall impact of the historical temperature changes on the labour productivity growth rate in 2020 in each country. These projections imply that labour productivity growth in some northern European countries might have been favoured by the rise in temperature. In the absence of any temperature changes, the projections suggest lower productivity growth of about 1 percentage point (pp) in Sweden and Finland in 2020.[23] For southern countries, the overall effect for this period is negative though not (yet) statistically significant.[24] Moreover, it follows from the estimations that a progressive temperature increase would adversely affect macroeconomic developments in Europe in the long term, with considerable growth differentials sometimes emerging, even among euro area economies.

21 The estimates are robust in specifications that include region-specific time fixed effects (west, east Europe), quadratic or linear time trends instead of year fixed effects that exclude the lagged dependent variable or abstract from countries with time series below 30 years.

22 With the exception of Iceland, where average temperatures in 1960 were extraordinarily high, yearly mean temperatures in 2020 exceeded their 1960 level in all countries considered by between 0.5 °C (Ireland) and 3.3 °C (Estonia).

23 Macroeconomic climate models also identify varying effects across EU countries (see European Commission 2018). Given the long time span, however, these numbers underlie considerable estimation uncertainty.

24 Nevertheless, with temperatures rising further, negative effects on productivity in Southern European countries are likely in the future.

When interpreting these results, it should be borne in mind that estimates of this kind are fraught with uncertainty. First, estimation uncertainty is high, partly due to sharply fluctuating average annual temperatures over time. Furthermore, not all economic effects of climate change are captured by the empirical approach chosen. This is the case, for instance, with the impact of extreme weather events [25] or the spillover effects of climate change in other regions of the world. Moreover, it should be noted that the estimations reflect historical developments and so the impact of further temperature increases may differ. For instance, it is conceivable that the overall economic costs will increase considerably if climate-related tipping points are transgressed. [26] Conversely, adaptation to climate change can limit the impact on economic growth.

Estimations based on historical data suggest that a sustained rise in temperature will likely lead to larger growth differentials in the future. In addition to the reservations stated above, the long-run impact may be more muted if economies are able to adapt to higher temperatures. For example, mortality rates for hot days in the United States have declined since the 1960s, which has been attributed to greater use of air conditioning. [27] However, capital invested in adaptation measures, such as air conditioning or sea walls, is non-productive and therefore reduces effective capital stock and potentially diverts resources away from innovation and therefore productivity growth. Although most of the literature has hardly seen any successful adaptation over in recent decades, [28] adaptation measures might be effective in reducing the damage caused by climate change, alleviating the impact on both output and productivity.

3. Acute physical risk

Acute physical risks can affect future productivity by triggering shocks that propagate through firm-to-firm linkages, amplifying their impact. These shocks arise from unpredictable events, disrupting business operations. Research shows that such shocks can have widespread, yet generally underestimated, consequences due to interdependencies in the economy. [29] If certain firms or regions are disproportionately large suppliers of inputs to the rest of the economy, shocks that severely impair firm-level or region-level productivity can propagate and be amplified by input-output linkages, causing aggregate fluctuations. [30]

Acute physical risks already affect Europe and are projected to become more frequent and more severe. For Northern and Central Europe, the natural hazard most likely to increase is flooding, whereas for Southern Europe, the largest increase is likely to be in the form of heatwaves, droughts and accompanying wildfires. Less than 10 % of firms in Northern and Central Europe are exposed to high physical risk, though this percentage increases in Southern Europe (Figure 3). [31]

In the near term, disasters are almost exclusively negative for GDP growth, though the distribution of the impact is highly skewed. A disaster in the 75th percentile of the underlying natural hazard (such as degree of extreme precipitation or wind speed) has a contemporaneous impact of around 0.1 % of annual national GDP. A disaster in the 95th percentile reduces GDP by 0.46 %, while one in the 99th percentile reduces annual GDP by 6.9 %. [32] So while the economic impact of natural hazards has so far been limited in Europe, increased

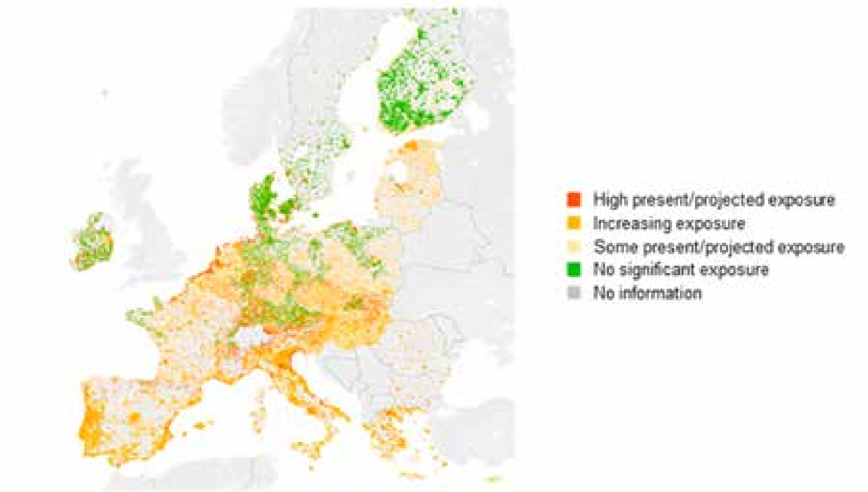
25 For more information on the impact of extreme weather events, see, inter alia, Hsiang and Narita (2012), Lesk et al. (2016) and Deutsche Bundesbank (2017b).
26 Tipping points refer to critical thresholds in a system that, when exceeded, can lead to a significant change in the state of the system, often on the understanding that the change is irreversible; see Intergovernmental Panel on Climate Change (2018).
27 Barreca et al. (2016).
28 Burke et al. (2015).
29 Acemoglu et al. (2012), Dhyne et al. (2022).
30 Grassi (2017).
31 Alogoskoufis et al. (2021).
32 Felbermayr and Gröschl (2014).

magnitude is likely to bring with it more visible impacts. In particular, the literature points to a threshold of resilience, below which the impact is limited, but where the impact rapidly accelerates once breached. Factors that help to raise the threshold of resilience include higher GDP per capita, improved literacy, better institutional quality, better insurance coverage and greater availability of credit.[33]

Figure 3

Corporate exposure to physical risk drivers

(maximum risk level of each firm)



Sources: Alogoskoufis et al. (2021); Four Twenty Seven, AnaCredit, and ECB calculations.

Notes: Based on a sample of 1.5 million firms in Europe, 1.1 million of which are located in the euro area; information refers to head office location and subsidiaries of the largest listed firms, showing the maximum risk level across the following hazards: floods, heat stress, hurricanes, sea level rise, water stress and wildfires. The risk levels defined by Four Twenty Seven are "high present/projected exposure", "increasing exposure", "some present/projected exposure" and "no significant exposure". If a given firm has "no significant exposure" to floods but "increasing exposure" to heat stress, it is marked with "increasing exposure" on the map. The indicators and risk levels are based on data showing the current and projected (until 2040) extent of the various physical hazards. The indicators and risk levels are taken directly from Four Twenty Seven. Any potential economic impact is not taken into account.

There are important feedback loops between chronic and acute physical risks, as a change in average climatic conditions can increase the probability of crossing thresholds and reaching tipping points. For example, an increase in average temperatures substantially increases the likelihood of a particular day exceeding the temperature thresholds noted above. This is particularly the case for summer periods, where the increase in hot temperature extremes is expected to be up to 3 °C for 1.5 °C global warming in mid-latitudes. Central and Southern Europe and the Mediterranean are expected to witness some of the strongest increases in hot extremes globally.[34]

There is also an important interaction between rising sea levels and storm surges causing flooding. At present, five million Europeans are at risk from a one-in-100 years flooding event. Under an intermediate warming scenario, that frequency increases to every 11 years by 2050 and every three years by 2100.[35] For the eastern and western Mediterranean, the likelihood of such events, even in an intermediate warming scenario, is projected to be twice per year. Meanwhile, the eastern Mediterranean is projected to witness current

33 Noy (2009).
34 Intergovernmental Panel on Climate Change (2018).
35 Vousdoukas et al. (2017).

one-in-1 000 years events every three years on average by the end of this century.[36] These events are likely to affect tourism beyond the gradual impacts noted above and contribute to capital losses in the affected areas.

The overall impact on potential output can be proxied by estimates of the long-run impact of disasters at national level. Several definitions of recovery are used in the literature. Some authors treat a return to the previous level of GDP as a recovery, while others define it as the attainment of the previous GDP, inclusive of its trend. There is much less evidence of a full recovery under the latter definition. There is some evidence of creative destruction, whereby countries take the opportunity to upgrade capital and achieve higher growth rates,[37] although there appears to be a fairly restrictive set of conditions that must be met for this improvement to occur. Relatively richer developing economies closely interconnected with advanced economies appear able to import new capital and advance closer to the technological frontier, whereas poorer economies seem unable to benefit from the "opportunity". Hence, post-event GDP dynamics depend crucially on factors such as the level of development of the country, institutional quality, access to finance, insurance coverage and fiscal space to support and invest in the most affected areas, as discussed in more detail below.

The potential positive impact on GDP of an event disappears entirely for large disasters, which at best have no effect in the long run and often have a negative impact.[38] Indeed, examples of countries to have successfully restructured their economies and substantially boosted production in the wake of a severe disaster are so vanishingly rare that the 1 755 Lisbon earthquake remains pretty much the only one.[39]

At a more disaggregated level, while there are some success stories, the balance of the literature points to much more permanent scarring in regions more heavily affected by disasters.[40] In particular, there is substantial evidence of sustained outward migration from affected regions, which can exacerbate the relative economic decline.[41] Often the younger and more educated leave, since they are able to find employment elsewhere, leaving behind a population that is older and less skilled. The population of New Orleans had been falling since 1960 and the city was already in long-term decline when Hurricane Katrina struck in 2005. A year later, there were fewer children in proportion to the population, the average education level had fallen, and the median age had increased by six years.[42]

The impact of these migratory flows can persist for decades. Cities that were more affected by the 1906 San Francisco earthquake and fire experienced slower population growth even by the end of the century.[43] Heavily eroded counties in the Dust Bowl era of the 1930s witnessed significant outward migration. The price of farmland fell by around 30 % relative to less eroded counties, reducing collateral and overall access to finance. The economic effects lasted for more than half a century, even though soil quality recovered much faster.[44] Similar trends were also witnessed in the 20th century, with Nagasaki and Hiroshima eventually returning to their previous population trend by 1960 and 1975 respectively.

Yet negative effects are not universal: some regions are able to remain competitive post-disaster and others benefit from inward migration. The Black Death killed around 40 % of Western Europe's population between 1347 and 1352. While most cities recovered their population within one or two centuries, the recovery was

36 There are two reasons why northern Europe is projected to be less affected than the Mediterranean. First, the land is still undergoing uplift in recovery from the previous ice age, with sea levels in the northern Baltic actually projected to fall. Second, tidal range is important, as storm surges can be masked if they occur towards low tide. The tidal range at Le Havre between low and high springs is 7.3 m, at Larnaca it is 0.4 m. A storm surge of 1.4 m at Le Havre at low springs is still 6 m below the naturally occurring sea level six hours later, while in Larnaca it would be 1 m above it.

37 Skidmore and Toya (2002).

38 Hallegatte and Dumas (2009).

39 See Pereira (2009). While the economic growth experienced by both Germany and Japan following WWII perhaps provides two more examples, both were already economically powerful nations prior to the war.

40 Noy and duPont (2016).

41 Bier (2017).

42 Vigdor (2008).

43 Vigdor (2008), Ager et al. (2019).

44 Hornbeck (2012).

uneven, and it did not necessarily result in the collapse of those cities with higher mortality rates. Those cities with natural advantages, such as being on important trade routes, recovered faster, mostly through inward migration.[45]

Estimates of the potential future impact of climate on labour migration vary substantially. While the population at risk of catastrophic events rises substantially, not all those affected will move, and a substantial share of migration is likely to be internal displacement to other parts of the same country rather than external migration.[46] One estimate puts the number of climate-related asylum seekers to the European Union at 100,000 per year in 2050.[47] Compared to the 1 million or so people that sought asylum in the European Union in 2022,[48] this number is still relatively modest.

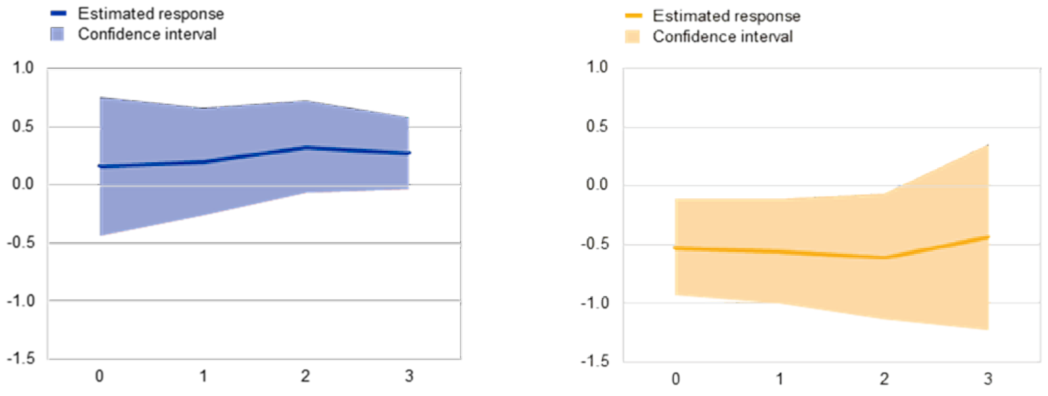
At the level of individual firms and households, the initial impact of direct damage and indirect impacts through disruption can lead to substantial declines in income, which can have long-term consequences. Where households and firms have access to external forms of support to smooth temporary income fluctuations, the impact of a disaster on aggregate consumption and investment is more muted. Examples of such external support reducing disaster impacts include foreign aid, deeper capital markets and fiscal transfers.[49]

There is an important role for insurance in mitigating the long-run impact of disasters. Insurance payouts can provide liquid funds to accelerate the rebuilding of destroyed capital, thereby reducing disruption and long-term scarring. Indeed, highly insured large disasters do not have a significant impact in developed economies, whereas large disasters with low insurance rates have a negative impact on growth.[50] Yet only around a quarter of the damage caused by disasters is currently insured in Europe, a share that could well decline if increased risk and premiums lead to insurance retreat. Moreover, coverage rates fall to below 5 % for some countries and are also typically lower for hazards such as droughts and wildfires.[51]

Figure 4

Impact of insured vs uninsured losses from a large-scale disaster on annual GDP growth rate

a) High share of insured losses (percent) — b) Low share of insured losses (percent)



Source: Fache Rousová et al. (2021).
Note: Projections for quarter of impact of large-scale disaster (quarter 0) and three subsequent quarters.

45 Jedwab et al. (2019).
46 Burzynski et al. (2022).
47 Missirian and Schlenker (2017).
48 Eurostat, Annual Asylum Statistics.
49 McDermott et al. (2014).
50 Fache Rousová et al. (2021).
51 ECB EIOPA (2023).

The importance of insurance and access to finance is also confirmed at the micro level. Businesses that held business interruption insurance during the 2010/2011 Canterbury earthquakes in New Zealand exhibited better productivity and profitability two to three years later than those that did not. However, prompt payment was crucial: those businesses where the payout was delayed fared no better than those without insurance.[52] More generally, firms that can maintain access to finance appear to weather the shock better. This can lead to sub-optimal outcomes if access is not directly correlated to productive potential, such as if only larger firms had access to finance.[53] Accelerated bankruptcy of firms that would otherwise have been productive can have negative aggregate productivity consequences and trigger externalities through network effects which further depress the regions affected by the disaster.

The structure of balance sheets also matters for firm-level impacts. Firms in regions affected by disasters can exhibit higher rates of employment growth and capital investment post disaster, but slower rates of total factor productivity growth, suggesting that the process of rebuilding diverts resources and can cause disruptions to firm-level efficiency. Those firms with higher rates of intangible assets, which presumably suffer less in the way of capital destruction, appear to fare better post disaster, likely by increasing their market share at the expense of more affected firms.[54] The impact on productivity can be durable: there is some evidence that destructive events can reduce innovation rates for decades in the areas affected.[55]

Access to finance and insurance is crucial for households too, in order to maintain and grow (human) capital. Faced with a reduction in income, poorer households may struggle to maintain essential expenditure and be forced to liquidate assets, likely at fire sale prices. This can prevent them building up capital, including human capital, and trap them in poverty.[56] Babies born to mothers who were pregnant at the time of the 1918 influenza pandemic had lower socioeconomic status in adulthood and lower probability of graduating from high school, including relative to siblings in the same household.[57] This effect can be quite pernicious and last for more than one generation, given the importance of parental educational attainment on child education outcomes.[58]

Lastly, it is important to consider the potential impact of acute physical risks in the context of increased frequency of shocks, rather than treating each event separately. Several studies point to an ex ante impact of more frequent disasters, with the exact mechanisms dependent on the specification of the general equilibrium model employed.[59] In some, the increased uncertainty results in more precautionary savings, which lowers consumption and investment in aggregate. Alternatively, households might prefer to invest in government bonds rather than increase their exposure to physical capital embodied in firms. As a result, the spread over the risk-free rate paid by firms increases, reducing desired investment and capital stock. Other studies also highlight a decline in labour supply, since lower capital stock reduces the marginal product of labour, and hence wages and willingness to work.

Physical risks are therefore likely to affect all three determinants of potential output, with the impacts likely to be almost exclusively negative. The productive capital stock may be depleted through destruction by catastrophes or longer-running climate trends, or by increased use of non-productive adaptation. Meanwhile, labour supply can be reduced by increased mortality and sickness rates. There is likely to be some climate-related migration, although much of it is likely to be internal, and Europe as a whole may benefit from inward migration from other regions that are worse affected. Total factor productivity growth is also likely to be impaired, through more hostile climatic conditions, firm-level and supply chain dislocations, an increasingly

52 Poontirakul et al. (2017).
53 Basker and Miranda (2018), Uchida et al. (2015).
54 Leiter et al. (2009).
55 Noy and Strobl (2022).
56 Carter et al. (2007), Nazrul and Winkel (2017).
57 Almond (2006), Beach et al. (2018).
58 Caruso and Miller (2015).
59 For example, Isoré and Szczerbowicz (2017), Cantelmo (2022), Dietrich et al. (2021).

large share of resources devoted to adaptation rather than to innovation, and a productivity‑dampening change to business dynamism.[60] Furthermore, extreme weather events could lead to inefficient levels of firm exits and distortions of allocative efficiency.

4. Transition risk

Transition risk refers to the risk resulting from mitigation policies as economies move towards a greener, less polluting society. Such policies, which are used to implement carbon reduction objectives from deals like the Paris Agreement or the Fit for 55 package (see Box 1), lead to changes in the energy and industrial system and cause impacts throughout the economy. For example, firms involved in fossil fuel production and those with a high emission intensity could face higher costs of doing business and/or high investment costs in carbon‑mitigating technologies. Further, although direct costs for firms in other sectors will be lower, higher prices of intermediate inputs could result in a notable rise in indirect costs. Overall, relative prices are likely to change and the entire economy will have to adjust. Climate policies are the main driver of the related risks, as they formalise the need to adjust and prescribe the speed of the transition.

60 Basker and Miranda (2018) found that Hurricane Katrina led to inefficient levels of firm exits and distortions of allocative efficiency.

BOX 1

Overview and international comparison of climate policies in the EU

To help mitigate climate change, EU countries have set ambitious targets in recent years and have introduced a wide range of policy measures. In particular, the EU aims to become climate‑neutral by 2050.[1] Key climate policy measures and packages to reach these targets include the long‑established European Emissions Trading System (EU‑ETS)[2] and the EU Green Deal agreed in 2019,[3] which includes the "*Fit for 55*" package,[4] consisting of a broad set of climate‑, energy‑ and

1 This means that, by 2050, EU countries will have to drastically reduce their greenhouse gas emissions and find ways of compensating for the remaining emissions to reach a net‑zero emissions balance. As an intermediate step towards that goal, EU states agreed to reduce their greenhouse gas emissions by 2030 by at least 55 percent compared to 1990 levels. See Climate change: what the EU is doing – Consilium (europa.eu).

2 Set up in 2005, the EU ETS is the world's first international emissions trading system. It is a "cap and trade" scheme where a limit is placed on the right to emit specified pollutants over a geographic area and companies can trade emission rights within that area (see. e.g. EU Emissions Trading System (EU ETS) (europa.eu)). The cap is reduced over time so that total emissions fall. It operates in all EU countries plus Iceland, Liechtenstein and Norway and limits greenhouse gas emissions from more than 11 000 installations, such as power stations and larger industrial plants (for example, factories that produce cement, lime and chemicals). It covers around 45 % of EU's greenhouse gas emissions (EU Emissions Trading System | Environmental Protection Agency (epa.ie)).

3 It is a package of policy initiatives, which aims to set the EU on the path to reaching climate neutrality by 2050 (see European Green Deal – Consilium (europa.eu)).

4 See https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55-the-eu-plan-for-a-green-transition/.

transport-related policy measures, such as a revision of the EU-ETS, a carbon border adjustment mechanism (CBAM)[5] and stricter CO_2 emission standards for cars.

Climate measures take the form of market-based mechanisms, non-market-based mechanisms and subsidies. Governments can use market mechanisms to reduce emissions among economic agents, perhaps by imposing a carbon price (direct price signal). Explicit carbon taxes, such as those levied in Sweden, Switzerland, Finland or France, and the EU-ETS are examples of this approach. Governments can also rely on non-market mechanisms, in the form of regulation policies to enforce limits and standards. This might include minimum insulation requirements for housing, or the gradual phase-out of cars that run on fossil fuels. A third way through which authorities can stimulate climate change mitigation is by supporting green innovation and investment in clean technologies. This might be achieved by subsidising research and development on low-carbon energy technologies, though also by supporting the price for green technologies in order to guarantee their economic viability.

The country-specific use of these types of instruments can be illustrated and quantified by using the OECD Environmental Policy Stringency index (EPS). In its 2021 version, this index evaluates and aggregates the stringency of 13 environmental policy measures across 40 countries over the 1990-2020 period.

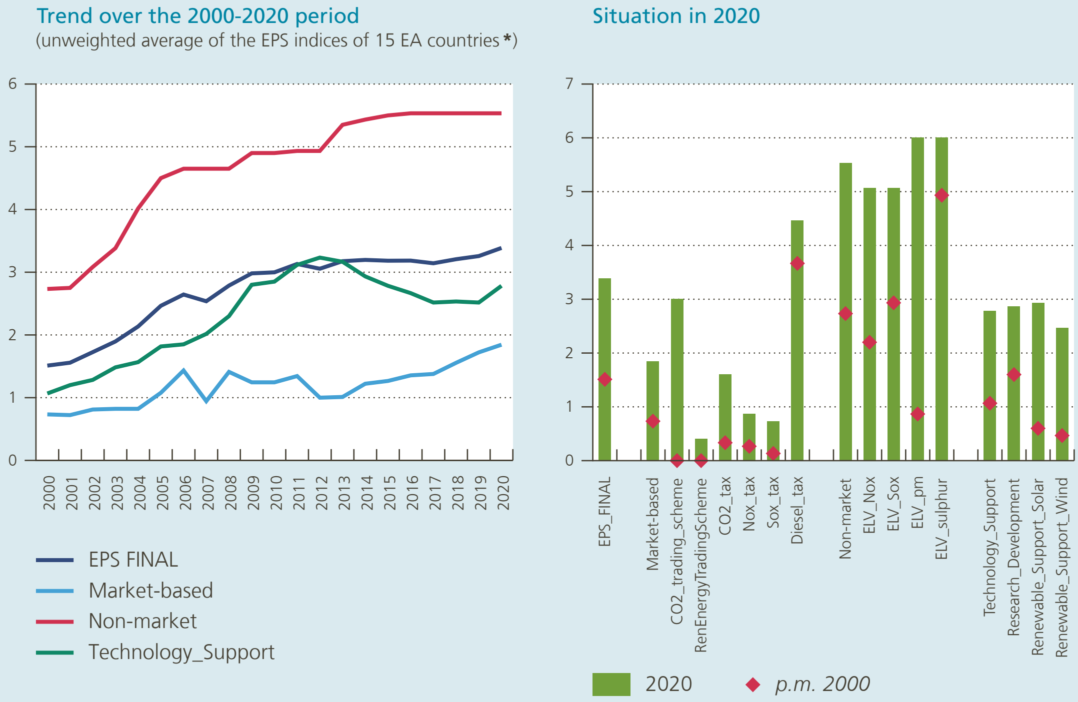
According to this indicator, climate policy in the euro area (EA) has steadily become much more stringent over the last two decades. All three types of measures (market, non-market and technology support) have gained importance in the EA. According to the OECD indicator, regulation (non-market) was the most frequently used mechanism in 2020, followed by technology support, while market-based measures were less frequent.

Non-market measures were by far the most important environmental policy measures used in the EA in 2020. The three technology support sub-indicators are not yet fully developed. By contrast, large differences appear for the market-based measures. Two indicators, a diesel tax and the CO_2_trading_scheme indicator (the latter referring to the EU-ETS system in which all EA countries are participating), are quite widely used, while the other four sub-indicators experience low use.

5 The objective of the carbon border adjustment mechanism is to prevent that the emissions reduction efforts of the EU are offset by increasing emissions outside its borders through relocation of production to non-EU countries or increased imports of carbon-intensive products. See Fit for 55 – The EU’s plan for a green transition – Consilium (europa.eu) or Carbon Border Adjustment Mechanism (europa.eu).

Figure A

Climate policy in the euro area



Source: OECD, own calculations.

1 Austria, Belgium, Estonia, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, The Netherlands, Portugal, Slovakia, Slovenia and Spain.

Notes: The Environmental Policy Stringency index (EPS) and all of its sub-indices range from zero (no policy) to six (most stringent). The following sub-indicators are used:

– For the market-based measures: the average annual permit price of CO_2 trading schemes (CO_2_trading_scheme), the mandated percentage of electricity from green sources (RenEnergyTradingScheme), the tax rate for carbon dioxide emissions (CO_2_tax), the tax rate for nitrogen oxide emissions (Nox_tax), the tax rate for sulphur oxide emissions (Sox_tax) and the tax rate for a litre of diesel fuel used in transport for industry (Diesel_tax).

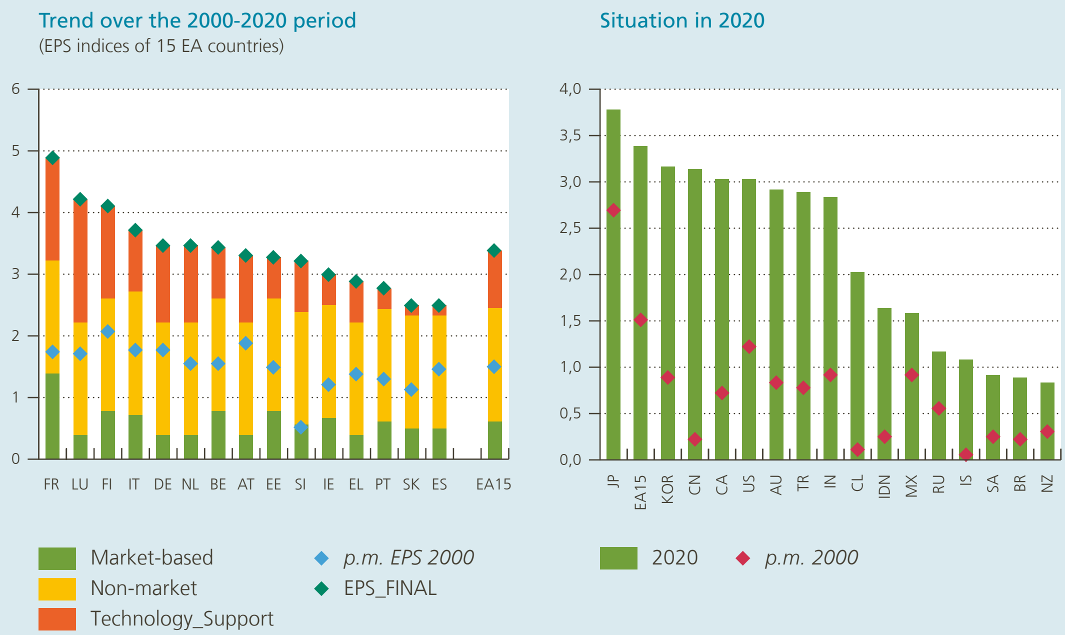
– For the non-market based measures: the maximum concentration of emissions of nitrogen oxides, sulphur oxides and particulate matter permitted for a large, newly-built coal-fired power plant (ELV_Nox, ELV_Sox and ELV_pm, respectively) and the maximum concentration of sulphur permitted in diesel for automobiles (ELV_sulphur).

– For the technology support measures: the amount spent by the government for R&D on low-carbon energy technologies relative to the size of the country's nominal GDP (Research_Development) and the level of price support for solar and wind energy technologies from feed-in tariffs and renewable energy auctions (Renewable_Support_Solar and Renewable_Support_Wind).

The indicators hide diverging situations between countries. As the EA indicators are calculated as (unweighted) averages of the indicators of the individual Member States, these figures hide diversity between countries. Climate policy appears to be most stringent in France, Luxembourg and Finland, while it is least stringent in Slovakia and Spain. While the latter countries are comparable to the EA average for market-based and non-market measures, the latter countries fall behind with respect to technology support. In France, which tops the ranking, more market-based measures and technology support are provided than on average in the EA.

Figure B

Climate policy in euro area countries: situation in 2020



Source: OECD, own calculations.
Note: The Environmental Policy Stringency index (EPS) and all its sub-indices range from zero (no policy) to six (most stringent).

European climate policy is strict. In an international comparison, European climate policy proves to be very stringent. Of the non-European countries for which the EPS index was calculated, only Japan had a higher EPS index value than the EA in 2020. The United States and China, as well as certain other countries (such as Korea, Canada, Australia, Türkiye and India) have implemented somewhat less stringent measures. In contrast, many emerging countries (like Indonesia, Mexico and Brazil) as well as some developed countries (such as Israel and New Zealand) have significantly lower EPS levels. As in the EA, in the rest of the world non-market-based climate policies are most widely used.

4.1 The productivity benefits of an orderly transition

The green transition requires us to replace carbon-intensive capital with "green" capital that incorporates carbon-free technology. The relative speed of that replacement will affect the total amount of capital available in the economy. If sharp increases in the price of carbon, regulations or shifts in consumer preferences force the early obsolescence of carbon-intensive capital ("stranded assets"), then the overall stock of productive capital will likely decline. Green capital requires technological development and investment, which is itself a gradual process subject to possible resource constraints. The pace of the transition therefore matters. If carbon prices increase in a gradual and predictable manner ("orderly transition"), obsolete capital can be replaced once depreciated with new green capital. If, however, carbon prices rise too sharply and/or erratically ("disorderly transition"), this can result in substantial losses of capital.

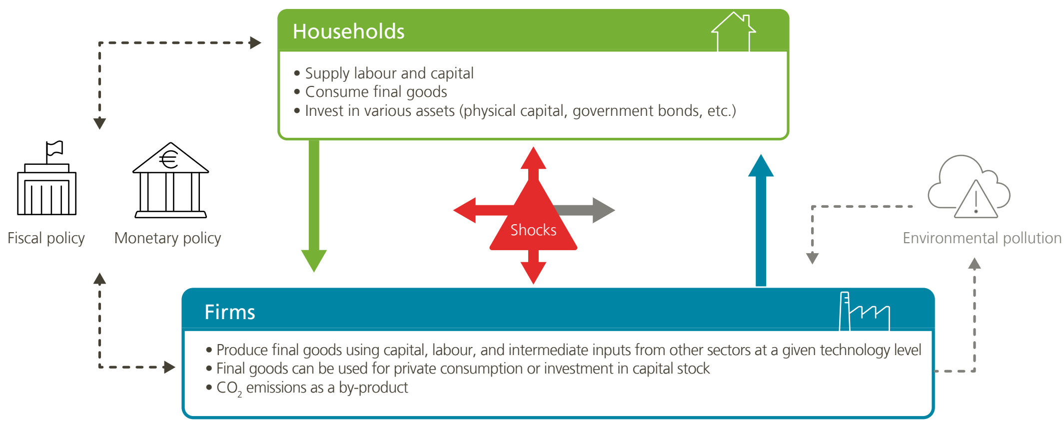
Climate policies, such as those significantly raising the cost of carbon, are intended to trigger this transition. The impact of climate policy measures is, however, likely to vary substantially across economic sectors. This, in turn, may contribute to the build-up of systemic risks in the financial system, potentially jeopardising financial stability and the fulfilment of the monetary policy mandate. The degree of heterogeneity across sectors depends, inter alia, on sector-specific characteristics such as emissions intensity. The design of climate policy may also play a pivotal role.

Hence, models with sufficient sectoral disaggregation are needed in order to adequately gauge the macroeconomic implications of climate risks. However, traditional multi-sector models are typically static in nature and focus on long-run equilibria, making them less suitable for analysing key adjustment processes. Dynamic stochastic general equilibrium (DSGE) models can be modified to investigate the adjustment processes triggered by climate policies, but typically feature a high level of aggregation.

We use the environmental multi-sector DSGE model known as EMuSe (Environmental Multi-Sector) to analyse climate policy-induced transition dynamics while taking into account sectorial adjustments.[61] A central feature of the EMuSe model is the assumption that firms do not use only capital and labour but also intermediate inputs for production (see Figure 5),[62] which they may obtain from various sectors. The composition of intermediate goods bundles varies by economic sector, and the intermediate inputs can be substituted only to a limited extent.[63] Emissions, too, differ by sector, and are a by-product of production. The immediate influence of environmental policy is represented in the model via two channels: a carbon price path and the trend in sector-specific emissions intensity. The carbon price constitutes an additional cost component, which firms take into account when deciding on optimal quantities and prices. Changes in emissions intensity over time, by contrast, can be understood as a reduced-form representation of exogenous environmentally-friendly technological progress. The total emissions costs of a firm are the product of the carbon price, its emissions intensity and output – with the former two affecting the firm's marginal production costs. The income generated by the carbon pricing is redistributed to households in a lump sum manner.

Figure 5

EMuSe, the environmental multi-sector DSGE model



Source: Deutsche Bundesbank.

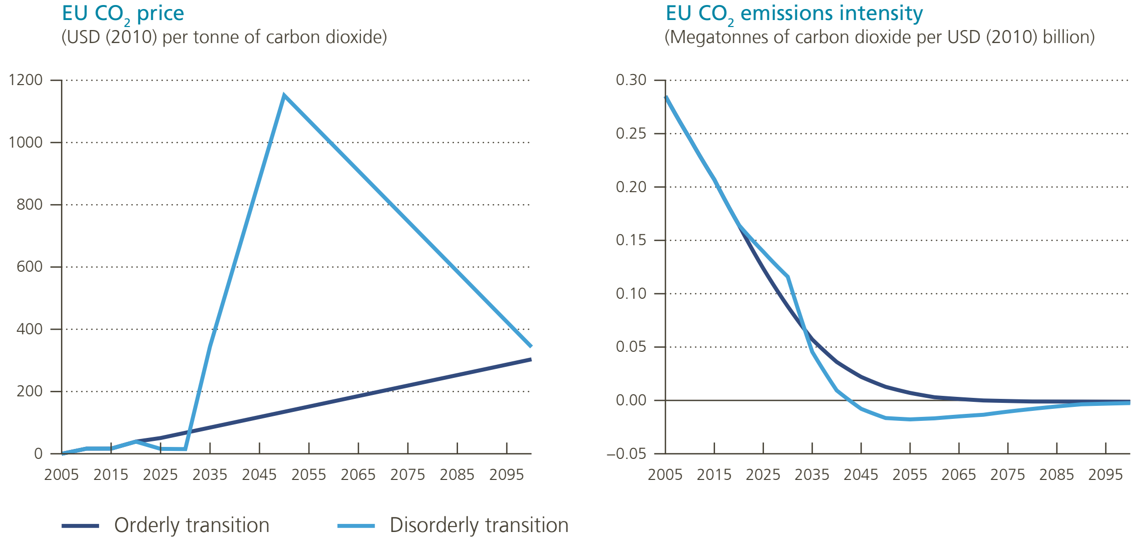
61 See Deutsche Bundesbank (2022).
62 For a detailed description of the EMuSe model, see Hinterlang et al. (2022).
63 Production linkages are calibrated using data from the World input-output database.

In order to reflect various climate policy designs, we consider several climate transition scenarios provided by the NGFS. The scenarios are grouped into three broad categories: orderly transition scenarios, disorderly transition scenarios and "hot house world" scenarios.[64] While orderly transition scenarios assume that climate policies are introduced relatively early and become gradually more stringent over time, disorderly scenarios feature higher transition risks due to policies being delayed or diverging across countries and sectors. Hot house world scenarios assume that climate policies are implemented in only a few jurisdictions, and that global efforts are insufficient to halt global warming. The various scenarios deliver, inter alia, region- and country-specific trajectories for the carbon price as well as paths for emissions intensities, i.e. the emissions-to-output ratio.[65]

We feed the NGFS pathways for emissions prices and emissions intensities[66] – for both an orderly transition scenario and a disorderly transition scenario[67] – into a closed-economy, ten-sector version of the EMuSe model (Figure 6). The model is parameterised to depict the EU along with the United Kingdom.[68] In the case of the orderly transition scenario, climate policy level of intervention is assumed to increase steadily, giving a 67 % chance of limiting global warming to below 2 °C compared to pre-industrial levels. For the disorderly transition scenario, it is postulated that far-reaching climate action with a view to limiting global warming to less than 2 °C compared to pre-industrial levels is not implemented until 2030. In order to compensate for this prolonged period of relative inaction, climate action increases drastically from 2030 onwards.

Figure 6

Projections for selected transition scenarios



Source: Network of Central Banks and Supervisors for Greening the Financial System (NGFS).

64 NGFS transition pathways are modelled using well-established Integrated Assessment Models (IAMs), which combine economic, energy, land-use and climate modules to provide coherent scenarios. Specifically, the orderly and disorderly scenarios used in this analysis are represented by the NGFS-projections "Below 2 °C", and "Delayed Transition", respectively. For details, see Network of Central Banks and Supervisors for Greening the Financial System (2021).

65 The transition path for the emissions intensity might be interpreted as the evolution of „green technological progress", since it characterizes the scenario-specific development of the emissions-to-output ratio.

66 It is assumed, for simplicity, that the emissions intensity will change to the same extent across all sectors, which is justified by the fact, that the NGFS scenarios do not provide data allowing to derive sector specific paths for the emissions intensity.

67 The analysis assumes that the trajectory of the emissions price and the sectoral emissions intensity given for the simulation period from 2005 to 2100 is known to all agents in the model.

68 The ten sectors are specified according to the industry standard classification system of the EU (NACE Rev. 2) and encompass Agriculture, forestry and fishing (NACE section A), Mining and quarrying (NACE section B), Manufacturing (NACE section C), Electricity, gas, steam and air conditioning supply (NACE section D), Water supply, sewerage, waste management and remediation activities (NACE section E), Construction (NACE section F), Wholesale and retail trade, Transportation and storage, Accommodation and food service activities (NACE sections G-I), Professional, scientific, technical activities, and Administrative and support service activities (NACE sections M-N), and Arts, entertainment and recreation and Other service activities (NACE sections R-S). For more information on the NACE classification, see Eurostat (2008).

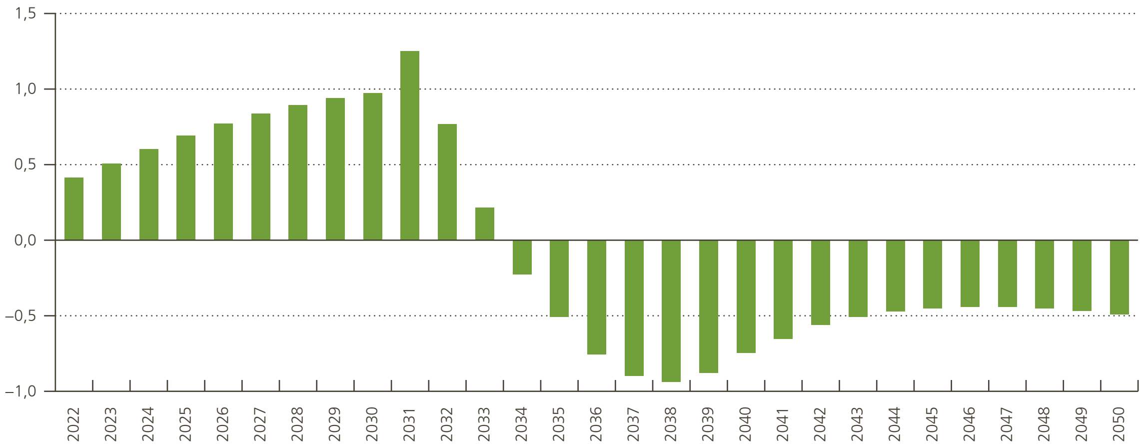
We find that the design of climate policy can have a substantial impact on labour productivity (Figure 7). Specifically, in the orderly transition scenario, emission costs are markedly higher at the outset than in a disorderly transition. This difference is mainly driven by the earlier carbon price increase in the orderly transition scenario, which depresses aggregate output. From the year 2030 onwards, however, the situation reverses. In the disorderly transition scenario, a massive increase in the carbon price is needed in order to curb global warming to less than 2 °C. As a result, emissions costs from that point onwards are significantly higher than they would have been under an orderly transition and labour productivity is considerably lower.

The EMuSe model shows that the burden resulting from climate policy measures varies across the sectors of the economy (Figure 8). This can be seen, for example, when looking at the policy-induced transition path in 2050. In this case, the energy sector, which has a comparatively high emissions intensity, is heavily affected by the sharp increase in the carbon price under the disorderly scenario. The extent to which this development also affects other sectors largely depends on production linkages.

Figure 7

Difference in projected labour productivity between a disorderly and an orderly transition from 2020 until 2050 in the EU

(in percentage)



Sources: Deutsche Bundesbank calculations based on the DSGE model EMuSe and NGFS projections.
Note: The Figure shows the difference in (hourly) labour productivity between a disorderly and an orderly transition. Both scenarios are modelled in comparison to the steady-state baseline case and subsequently the difference between the scenarios is calculated. The model is calibrated for the EU together with the United Kingdom.

Figure 8

Difference in projected labour productivity between a disorderly and an orderly transition in 2050

(in percentage)

Sources: Deutsche Bundesbank calculations based on the DSGE model EMuSe and projections by the NGFS.
Note: Business services are defined as NACE sections M to N: Professional, scientific and technical activities and Administrative and support service activities.

4.2 Environmental policy and innovation

Governments across Europe are taking action to stimulate the adoption of carbon-free technology. As stated earlier, a successful transition needs new and green capital and many governments have put regulation in place to foment the adoption of less carbon-intensive technologies (see Box 1 above). As we mentioned earlier, these environmental or transition policies cover a broad range of tools, including carbon taxes, performance standards and research and development (R&D) subsidies for environmentally-friendly technologies.

While these policies are aimed at emission reduction, they can also have a negative impact on productivity by making firms less operationally flexible and pushing up costs due to the necessary adjustments. In addition, new green technology might be less efficient than existing carbon-intensive technology and carbon-related investment might well crowd out other forms of productivity-increasing investment.

In part, this reduction in efficiency may be a measurement issue. Current carbon-intensive technology embodies an underpriced negative externality in the form of climate change. Since environmental degradation is not included in GDP, the overall aggregate impact of physical risks on productivity is not incorporated into its measurement, so green technology that avoids this externality may only appear less productive. Similarly, capital put in place solely to abate carbon emissions does not have a measured output. If carbon abatement is achieved by adding a further step (e.g. carbon capture) to the existing production process, there is, by definition, more capital and inputs to reach the same (measured) output. Thus, measured productivity in terms of GDP per worker or per hour worked will not fully incorporate the benefits of implementing green technology, particularly against the true counterfactual of increased physical risks.

Environmental regulation might also trigger investments in green innovations, thus producing productivity gains that could compensate for possible short-term costs. This is known as the Porter hypothesis.[69] The “strong” version of the Porter hypothesis states that increases in environmental regulation

69 Porter and van der Linde (1995).

stringency raise overall productivity, while the "weak" version holds that optimally designed environmental regulation spurs innovation. A third, "narrow", version predicts market-based tools to be more effective in boosting innovation than command-and-control policies. Although there are many empirical analyses testing the validity of one or various of the versions of the Porter hypothesis, the results remain inconclusive. Moreover, most relevant studies are focused on single countries or industries and suffer from limited external validity, while potential endogeneity issues are rarely addressed in a robust manner. These issues hinder reliable policy recommendations.

Productivity effects at the sector level of environmental regulation could be positive in countries that are at the technology frontier. A recent OECD study[70] considered the effects of environmental policy stringency at the industry level and found that the impact was strongest among technologically advanced countries. In these countries, the implementation of tighter environmental policies led to a short-term yet temporary increase in TFP growth. This impact becomes weaker as a country-industry pair moves further away from the global productivity frontier. There is some evidence of technology diffusion from leading industries to lagging ones and of catch-up for other country-industry pairs (technology diffusion is discussed in Box 2 below). This means that industries that have adopted advanced technologies can have a positive impact on the productivity growth of lagging industries.

70 OECD (2021).

BOX 2

The diffusion of climate change technologies and policies, and the role of institutions and governance

This box assesses the diffusion of technologies and policies aimed at climate change adaptation and mitigation.[1] It also addresses potential cross-country heterogeneity in this regard, and the role played in that heterogeneity by the institutions and governance of the countries concerned. The motivation for studying this issue is that institutions and governance have, for some time, been essential in achieving superior economic outcomes. Using an approach applied in previous work on the diffusion of digital technologies, this box explains the extent to which institutions and governance support the introduction and use of climate change technologies/policies (CCTPs).[2]

1 Climate change is one of the major structural changes transforming the functioning of the euro area and the global economy, together with (de)globalisation, digitalisation and demographic trends. On the latter, see for example Lodge and Pérez (eds., 2021), Anderton, R. and Cette, R. (eds., 2021), and Anderton et al. (2020).

2 Climate mitigation notably includes renewable energy/energy efficiency, while climate adaptation includes, among other mechanisms, climate assessment and monitoring, resource planning, and health and safety. For more concrete examples, see the taxonomy of the UN Climate Technology Centre and Network (CTCN). A further distinction of interest can be drawn between policies based on market mechanisms (taxes and subsidies) and policies based on non-market mechanisms (regulation), as discussed elsewhere in this report, though this is left for future efforts. For the approach used, see Baccianti et al. (2022). An alternative approach for estimating the seminal diffusion model is presented by Hoffreumon and Labhard (2022). The implications for growth are examined by Labhard and Lehtimäki (2022).

The evidence provided in this box suggests that for EU countries, a greater diffusion of change technologies/policies tends to be associated with higher quality of institutions. This is especially the case for technologies, more than for policies. In specifications allowing institutions to affect the diffusion of technologies and policies both on their own as well as in conjunction with CCTPs, these effects are significant in all the cases examined. This is on top of the effects produced by control variables included in the specifications, such as per capita real GDP growth as a control for the evolution of economic activity, as well as income and material wealth of a society, and human capital as a proxy for education and social wealth.

However, from a pure cross-country perspective, this is not immediately evident. The upper panels in Figure A show diffusion (vertical axis) and institutions and governance (horizontal axis) for 2020 (the most recent year for which all the data series are available), and the associated linear trend line, for euro area countries (in blue) and for the other EU countries (in yellow), using three series for CCTPs and the WGI (Worldwide Governance Indicators), as explained in the notes to the Figure. The trend lines show essentially a horizontal line for climate change adaptation and mitigation technologies (CCATs and CCMTs), and a downward-sloping line for climate change policies (CCPs), both for the euro area and the other EU countries. The slope for the euro area is steeper, largely owing to the greater variation in the level of CCTPs on one hand and institutions and governance on the other within that group.

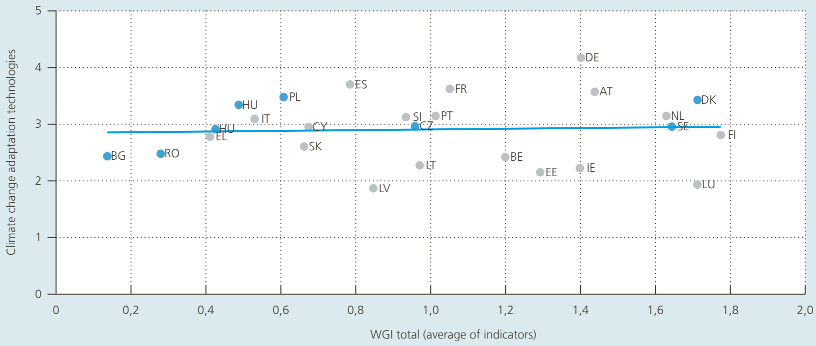
The assumption underlying this analysis is that diffusion is characterised by an acceleration in its early stages and a deceleration later. Such a pattern is consistent with the presence of heterogeneous agents and the underlying models of social influence and learning. The lower panels in Figure A illustrate that in the case of climate change technologies (CCTs), in the short sample available, diffusion appears to be petering out, with the diffusion curve flattening and appearing to converge to what may be the maximum rate of adoption. In the case of CCPs, the diffusion curve even displays a downward slope, which could be signalling a decline in the use of those policies. [3]

3 An important caveat is that the variables used in this box are expressed in logs and as a percentage of a total in the case of policies. Therefore, they may fall in response to an increase in the remaining percentage accounted for by other technologies. Further, it should be noted that a decline in one technology and/or policy may be accompanied by a rise in another, and so is not necessarily akin to bad news for climate change technologies or policies. A further caveat is that the level of technologies does not account for quality and the convergence could imply that while less new technologies are introduced, their effect on mitigation or adaptation could actually be higher. The downward slope could also be due to some aspects of (previously) national taxation moving to EU-level, such as the emission trading system, although such matters fall outside the scope of this this box.

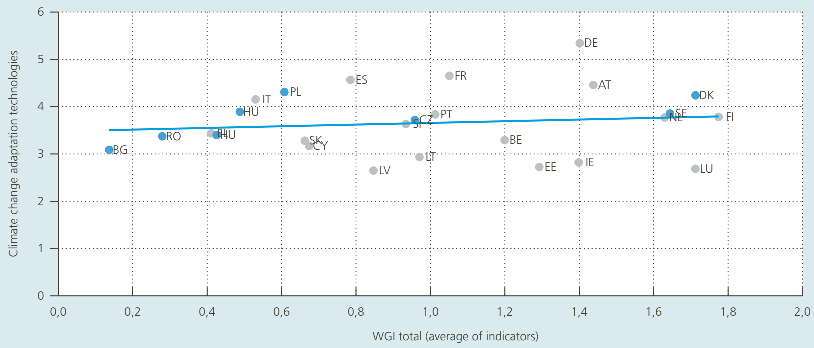
Figure A

Diffusion of climate change technologies/policies and quality of institutions and governance

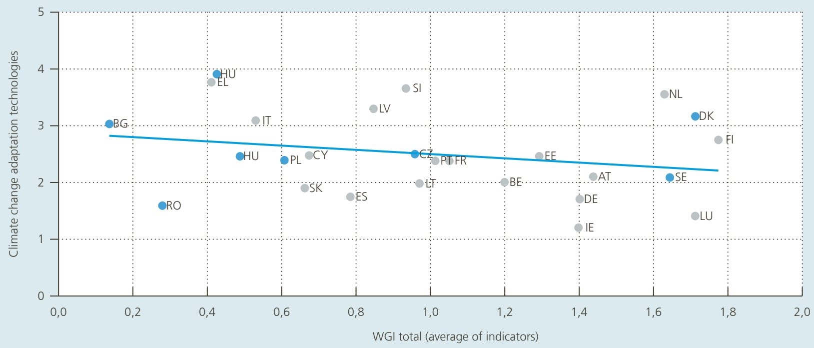
Diffusion of CCATs, and institutions and governance, 2020



Diffusion of CCMTs, and institutions and governance, 2020



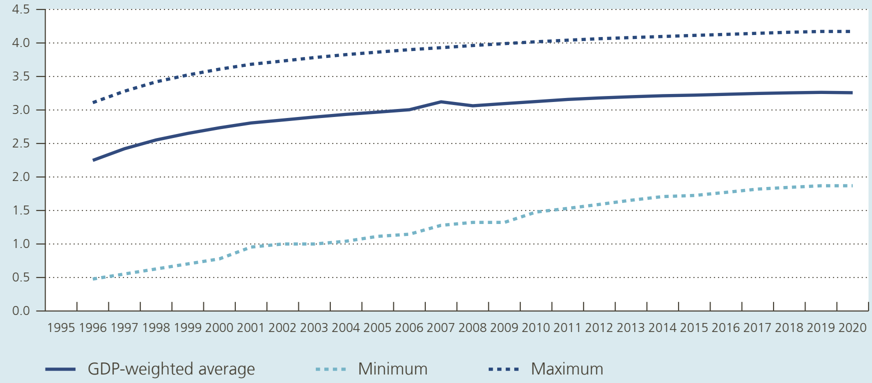
Diffusion of CCPs, and institutions and governance, 2020



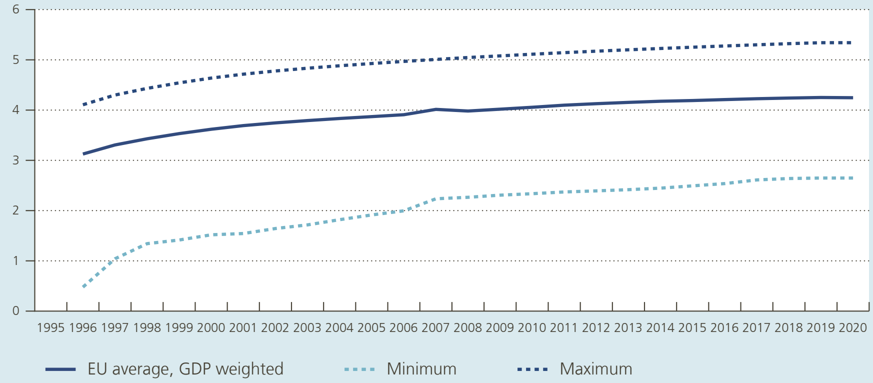
Sources: ECB staff calculations based on data from OECD (data set on innovation in environment-related technologies), World Bank (World Development Indicators – WDI; and Worldwide Governance Indicators – WGI).

Notes: Panels (i) to (iii) show the observations and the fitted line for 2020. Black diamonds/lines refer to euro area countries and grey dots to non-euro area EU countries. Malta is omitted from the graphs due to unavailability of data for the climate technologies and policy variables. WGI indicators are normalised, with higher values indicating higher quality. Panels (iv) to (vi) show the sequence of observations for 1996-2020 for the GDP-weighted average, minimum and maximum values. The climate change-related variables are climate change adaptation as a percentage of the total for CCATs, environment-related technologies for CCMTs and environmental taxes as a percentage of the total for CCPs.

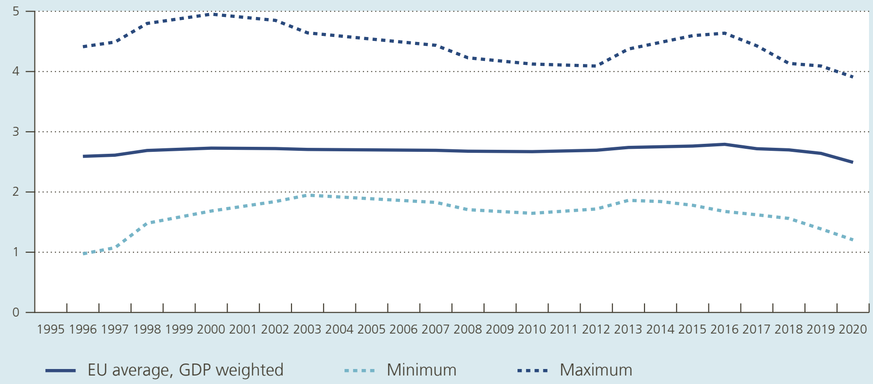
Diffusion of CCATs, 1996-2020



Diffusion of CCMTs, 1996-2020



Diffusion of CCPs, 1996-2020



Sources: ECB staff calculations based on data from OECD (data set on innovation in environment-related technologies), World Bank (World Development Indicators – WDI; and Worldwide Governance Indicators – WGI).

Notes: Panels (i) to (iii) show the observations and the fitted line for 2020. Black diamonds/lines refer to euro area countries and grey dots to non-euro area EU countries. Malta is omitted from the graphs due to unavailability of data for the climate technologies and policy variables. WGI indicators are normalised, with higher values indicating higher quality. Panels (iv) to (vi) show the sequence of observations for 1996-2020 for the GDP-weighted average, minimum and maximum values. The climate change-related variables are climate change adaptation as a percentage of the total for CCATs, environment-related technologies for CCMTs and environmental taxes as a percentage of the total for CCPs.

Overall, these findings suggest that high-quality institutions may entail superior outcomes in the fight against climate change. It is worth noting a few caveats. First, as mentioned above, data availability remains poor for the climate technology and policy variables and there is no established or benchmark data set. Moreover, CCTPs are multi-faceted, so the specific series used here are representative to a certain extent only and further work on the process is needed. Lastly, and perhaps most importantly, climate change itself is multi-dimensional and dynamic in nature, so an all-encompassing conclusion on what the level and adoption of technologies and policies implies for climate change is extremely elusive.

Table A

Diffusion of CCTPs and quality of institutions and governance

	Euro area		EU	
	(1)	(2)	(3)	(4)
CCAPs				
effect on spread	0.002	–0.221**	–0.037*	–0.215***
effect on speed	–	0.034***	–	0.029***
R2 (adjusted)	0.80	0.79	0.82	0.79
CCMTs				
effect on spread	–0.032	–0.267***	–0.057***	–0.281***
effect on speed	–	0.028***	–	0.027***
R2 (adjusted)	0.81	0.80	0.80	0.80
CCPs				
effect on spread	0.042	–1.047***	0.021	–0.853***
effect on speed	–	0.400***	–	0.334***
R2 (adjusted)	0.15	0.58	0.18	0.54

Source: ECB staff calculations.

1 Notes: The table shows the estimates of the effect of institutions on the spread of digitalisation (in the long run) and, for specifications (2) and (4), also on the speed of coefficients (in the transition), for the euro area and the EU. The estimated equations, derived from the so-called epidemiological model of diffusion and including control variables, are described in Baccianti *et al.* (2022). Asterisks ***/**/* denote the levels of significance at 1 % / 5 % / 10 %, respectively. The climate change-related variables are alternative/renewable energy as a percentage of the total for CCATs, climate change/environment-related technologies for CCMTs and environmental taxes as a percentage of the total for CCPs.

At the firm level, these positive impacts on productivity are less pronounced. The OECD study shows that only 10 % of firms benefit from the change in regulation, while one third of the sample experiences a negative impact. The largest and most productive firms are better equipped to profit from the changes, due to their access to advanced technology and resources for R&D and knowledge-based capital. However, they may also outsource and relocate production. Smaller, less advanced firms may require higher investments to comply with the new regulation, leading to a temporary decline in productivity growth. Significant negative effects found at the firm level are not necessarily incompatible with less negative industry-level results since industry-level analysis also accounts for entry and exit.

We empirically test the Porter hypothesis and the impact of transition policies on TFP growth among firms in the euro area. We use firm-level data to test the strong, weak and narrow versions of the Porter hypothesis.[71] We use estimated firm-level CO_2-equivalent emissions to identify which firms are most exposed to environmental policy changes, and thereby identify causal impacts. Changes in environmental policy are measured by means of the OECD Environmental Policy Stringency (EPS) index, recently updated to include information from 1990 to 2020. As explained above, the EPS indicator is a summary indicator for three different types of environmental policies, which can be analysed separately: market-based policies, such as CO_2 taxes, non-market-based policies, such as standards and regulations, and innovation support policies.[72] We use a unique dataset covering more than three million individual firms (22 million observations) from six euro area countries (Germany, France, Italy, Spain, Belgium and Portugal) between 2003 and 2019. The dataset combines two types of firm-level information: (i) financial accounts from Orbis and iBACH,[73, 74] used to estimate TFP at the firm-level;[75] and (ii) estimated firm-level CO_2-equivalent emissions (from the merged data of Urgentem and Orbis).[76] This procedure allows us to flag those firms most exposed to changes in regulation. The estimation of impacts on those more exposed firms ultimately facilitates the identification of causal effects in this analysis. Local projections[77] are used to estimate non-linear impulse responses of firm TFP growth to a shock in environmental regulation, defined as a tightening of the EPS indicator.[78] We also use the three sub-indicators of the EPS to capture the TFP impacts of different types of environmental policies, distinguishing between market-based measures, non-market-based policies and support for green R&D. We control for unobserved heterogeneity (firm, sector, country and time fixed effects) and rely on a broad set of controls (TFP frontier growth, distance to frontier, output gap, firm characteristics) to minimise the risk of omitted variable bias. We also use lagged controls and emission indicators to avoid endogeneity problems with TFP growth.

Our analysis shows that the TFP of high-polluting firms declines significantly more than that of their low-polluting peers when environmental policy becomes more stringent, thus prompting us to reject the strong Porter hypothesis for the overall population of firms. TFP growth among high polluters decreases with tightening environmental policy. However, it is important to distinguish between different policy types, as they affect TFP growth differently. In the case of high-polluting firms, technology support policies (green

71 The section draws from the results of two recently published ECB Working Papers (Groiss et al., 2023 and Groiss et al., forthcoming) that use firm-level balance sheet data from six euro area countries to estimate firm performance, together with patent application data to measure firm innovation.

72 Environmental policies are discussed in Box 1.

73 European Committee of Central Balance Sheet Data Offices' BACH (Bank for the Accounts of Companies Harmonized).

74 For the construction of the data set, we closely follow Kalemli-Ozcan et al. (2015) and Gopinath et al. (2017) to pursue a standard cleaning procedure. In particular, we retain only unconsolidated accounts and remove sole proprietorships. We restrict our analysis to non-financial and non-governmental sectors, and remove firms operating in the mining, energy and real estate sectors (NACE Rev. 2 codes C to N, except K and L) to obtain reliable TFP values. In addition, we remove firm-year observations with less than one employee, negative value added and inconsistent balance sheet or income statement relations, including those with negative asset holdings. Furthermore, we retain only firms with at least two consecutive years of reporting so as to be able to create growth rates. Lastly, all balance sheet variables are winsorised at the 1st and 99th percentiles to limit the influence of outliers.

75 Following Ackenberg et al. (2015).

76 The CO_2-equivalent emissions for all firms in the sample are estimated using a machine learning algorithm. The model selects the regressors (via lasso algorithm) and finds the best non-linear patterns (tree) to estimate the dependent variable, CO_2 emissions. The estimated coefficients are then used to predict the CO_2-equivalent emissions of all firms in the sample.

77 See Jorda (2005).

78 To define a shock, we use a binary variable flagging year-on-year positive (tightening) changes in the EPS indicator (or sub-indicators). Alternatively, we define a shock as a large reform by flagging year-on-year changes in the EPS indicator belonging to the top 25 % of the cross-country and cross-year distribution.

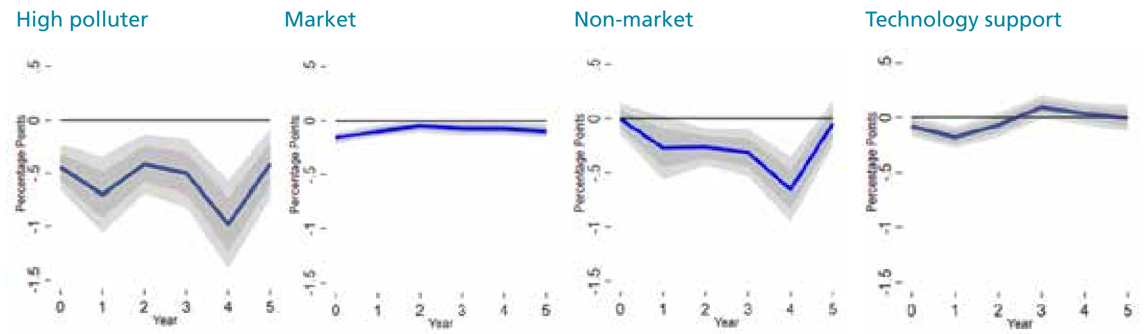
R&D subsidies) have only short-term negative effects over a transition period before boosting TFP growth.[79] In contrast, market policies (taxes, ETS) have persistent, albeit quantitatively small, negative effects, while non-market tools (emission limits) reduce TFP growth the most over the period of five years following the policy change considered in the analysis (Figure 9). This significant negative TFP impact of non-market policies, relative to market-based mechanisms, could be the result of their more discretionary nature, thus making them prone to lobbying and additional red tape.[80] Quantitatively, the impact of more stringent regulation on TFP growth is quite significant: a one standard deviation (SD) EPS shock reduces firm TFP growth among high polluters by four percentage points (pp) on average after five years. Given the median annual TFP growth of 2.6 % among high-polluting firms, this means that a one SD EPS shock reduces cumulative TFP growth by one third over five years.

Our results confirm that market-based policies have less of a distorting impact. This is the "narrow" version of the Porter hypothesis. In contrast to the overall and the non-market policy indicator, the sub-indicator for market-based policies shows smaller negative effects on polluting firms. After five years the TFP growth declines by 2.6 pp after a one SD market EPS shock. Market-based policies have fewer distorting impacts (and therefore more limited negative TFP growth effects) than non-market policies.

Figure 9

Firm-level impulse response function of positive environmental policy stringency (EPS) changes on TFP growth among polluting firms

(in percentage points)



Source: ECB calculations.

Note: Impulse responses of polluting firms' TFP growth to 1 pp EPS shocks (positive changes) over five years. Blue line represents mean responses, dark grey area 68 % confidence bands, and light grey area 90 % confidence bands. Polluting firms defined as those in the top six bins of the pollution distribution.of the total for CCATs, environment-related technologies for CCMTs and environmental taxes as a percentage of the total for CCPs.

Not all high-polluting firms are equally affected. To explore heterogeneous impacts across firms, we introduce an interaction term with the firm's size, the firm's equity ratio, our proxy for access to capital, as well as an interaction with the number of patent applications filed by the firm in the past. The latter is intended to capture the innovativeness of the firm, or whether the firm has the infrastructure needed to innovate in place. The results of the exercise are shown in Figure 10, where the bars capture the impacts for the top 10 % of firms in terms of size, equity ratio and innovativeness, and the dots for the bottom 10 %. The figure shows cumulative TFP growth after three years of the change in each type of environmental policy.

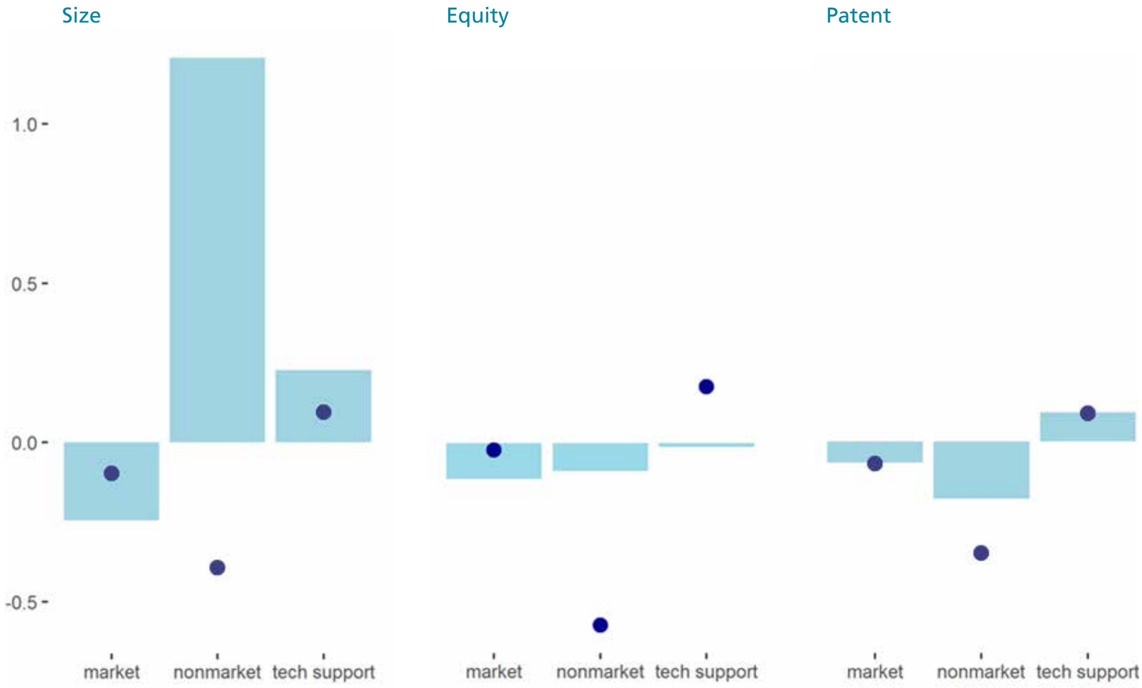
79 The initial negative TFP impact of investment in technology and innovation is also found in the context of investment in digital technologies (see the report of the expert group on digitalisation and productivity, Anghel et al., forthcoming).

80 Blanchard et al. (2023).

Figure 10

Environmental policy stringency (EPS) shock on TFP after three years, showing heterogeneity of impacts across firms

(in percentage points)



Source: ECB calculations.
Note: Cumulative TFP growth after three years of a policy change. Bars represent the top 10 % of firms and dots the bottom 10 % of firms in terms of size, equity, and patents.

While the TFP impact of market and green technology support is similar across different types of firms, the impact of non-market policies is significantly different, especially across firms in different size classes (Figure 10). We find that small firms, defined as those at the bottom 10 % of the size distribution, suffer a cumulative loss of about 0.5 pp in TFP growth after three years of tightening regulation and standards, while large firms gain more than 1 pp in TFP growth. This stark difference in the effects of non-market policies is due to the fact that large firms have easier access to the finance needed to adapt their production process to the new regulations, as proxied by the different impact on TFP growth of firms lying at different extremes of the equity ratio distribution. It could also be the result of different patenting experiences, given that large firms are better equipped to adapt and invest in new technologies. Some stylised facts on green investment at larger firms are given in Box 3 below, while the importance of green finance is discussed in Box 4 further below.

BOX 3

Green investment in large euro area firms

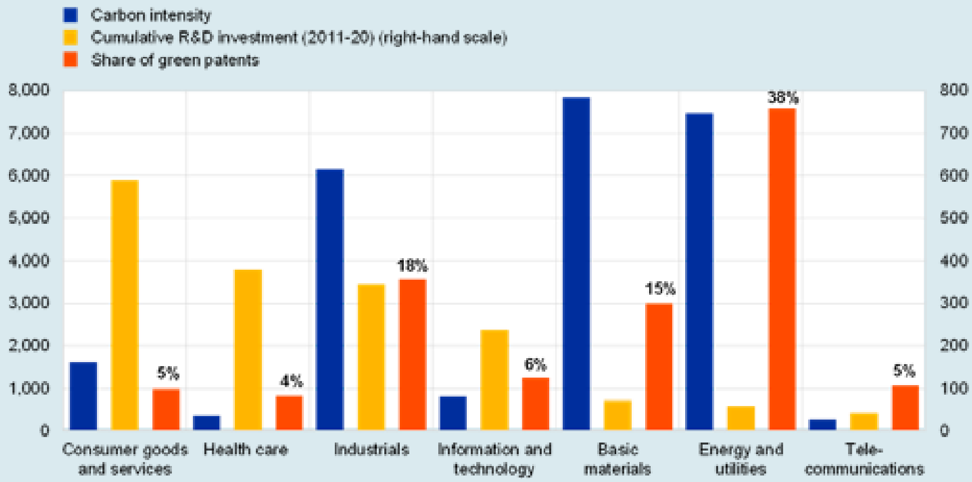
This box describes the progress made in developing green technologies and looks at the possible impact on productivity of their roll-out across the economy. In contrast to other parts of this section, we do not look at the impact of climate change or climate policies, and nor do we assess the level of green investment against policy targets. Instead, we merely compile a few stylised facts from available data to obtain an overview of green innovation and show how it may affect productivity in the years ahead.

Green patents account for a substantial share of all patents registered in the most polluting sectors, indicating that a significant proportion of their R&D spending over the last decade was devoted to green technologies. The sectors with the highest decarbonisation needs include those producing basic materials (among others for the construction sector), energy and other industrial goods (which includes transport equipment). As shown in Figure A, for these sectors the share of patents related to climate change mitigation and adaptation registered by the largest R&D investors in the EU is the highest, ranging from 15 % to 38 %. Moreover, these sectors are also among the ones with the highest propensity to innovate, accounting for 59 % of all patents and 84 % of all green patents. In contrast, the share of green patents in less polluting sectors was between 4 % and 6 % only, which is consistent with the previous firm-level analysis, which found that environmental policies have an insignificant impact on the patenting behaviour of non-polluting firms.

Figure A

EU cumulative private sector R&D investment and green innovation by sector

(left-hand scale : tonnes of CO_2 equivalent / USD millions, right-hand scale : EUR billions)



Sources : European Commission EU Industrial R&D Investment Scoreboard for R&D investment, EC-JRC/OECD COR&DIP© database v.3 for patents, Urgentem for emissions, ECB staff calculations.

Notes : Carbon intensity refers to the ratio of CO_2 emissions to revenues ; the figure shows 2020 sectoral averages. Cumulative R&D investment is computed as the sum of R&D investment (in nominal terms) of the 500 companies that invested the largest sums in R&D across the 27 EU countries plus the United Kingdom over the period 2011-2020. The starting year 2011 is due to a change in sector definitions in the Industry Classification Benchmark managed by FTSE Russell. The sector of main business is based on the Industry Classification Benchmark. Green patents are defined as those related to climate change mitigation and adaptation. Green innovation refers to the share of green patents registered by the top 462 R&D investors in the years from 2016 to 2018.

The roll-out of green technologies supported gross fixed capital formation before and, particularly, during the COVID-19 pandemic. Investment in energy transition in the euro area is estimated to have more than doubled between 2016 and 2021, reaching some € 110 billion, equivalent to 9 % of GDP, in 2021.[1] The level of investment increased across all technologies, though especially so in electrified transport (including charging infrastructure) as well as electrified heat, mainly installation of residential heat pumps, and renewable energy such as solar and wind. Meanwhile, the deployment of green technologies may also have shortened the usage period of capital and hence contributed to the increase in the consumption of fixed capital seen in recent years.[2] While the pace of green investment has accelerated, large additional investments will be needed to reach the EU target of zero net emissions by 2050. Those investment needs will also depend on the policy mix, including carbon pricing, bans and other forms of regulation, and green subsidies.

The green transition affects labour productivity on several dimensions. The first concerns the impact of reallocating from “brown” activities towards “green” activities, as discussed in section 5.3. While the impact of this on aggregate employment is estimated to be fairly limited, there may be an impact on aggregate productivity if the level of productivity is different across sectors. Another dimension would be the impact on productivity of replacing brown with green technology within industries. In the following paragraphs, we look at two examples which have made the largest contributions to the green investment in recent years.

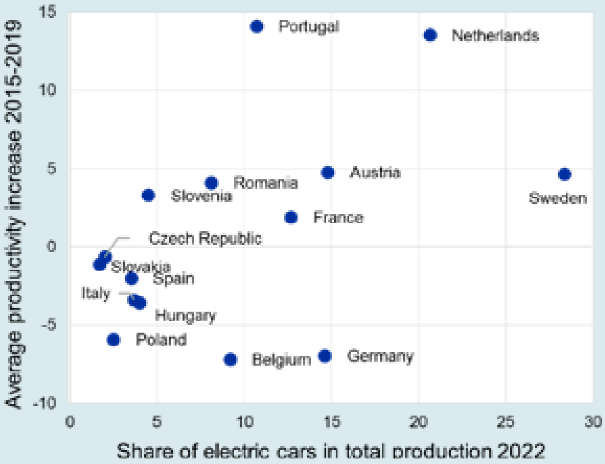
In transportation equipment manufacturing, the shift to battery-powered vehicles could boost productivity. Figure B below shows the annual change in real output per person employed in the manufacturing of motor vehicles and trailers industry over the period 2015-2019, plotted against the share of electric vehicles in terms of units in total production, adjusted for shifts in the share of passenger cars and the different sizes of commercial vehicles. This adjustment does not account for the change in composition of production within each category, such as where production switches to another model, or where new plants are opened, which distorts productivity developments across countries. However, there remains a loose positive relationship between labour productivity growth and the share of electric vehicles produced, which ranges from below 5 % of the vehicle float in Eastern European countries to 28 % in Sweden. This positive relationship can be explained by the reduced complexity of electric cars compared to combustion engine vehicles.[3] Furthermore, technology upgrades may also include productivity gains from tapping improved organisational know-how.

1 Andersson et al. (2022).
2 Vandeplas et al. (2022).
3 https://www.fticonsulting.com/emea/insights/articles/impact-electrically-chargeable-vehicles-jobs-growth-eu

Figure B

Share of electric vehicles and productivity growth in manufacturing of motor vehicles across EU countries

(percentages / percentage change)



Sources: ACEA, ECB calculations.
Notes: 2022 refers to the first three quarters. The current share of electric cars in total production is also indicative of the growth over recent years, as this was close to zero in 2015. Green innovation refers to the share of green patents registered by the top 462 R&D investors in the years 2016 to 2018.

With respect to energy supply, the impact on productivity of increased deployment of renewable energy generation is less clear-cut. Notably, electricity generated from renewable sources has increased strongly over the last 20 years, now accounting for nearly 40 % of final electricity consumption in the euro area. This increased electricity generation from renewables could boost productivity in the energy generating sector as additional capital is deployed and capital deepening becomes productivity-enhancing. However, the impact on total factor productivity and the structure of labour in this sector is undetermined, given the numerous steps involved in generating energy.

Ultimately, the impact of the green transition on aggregate productivity will depend on the re-skilling of labour currently employed in the activities in need of decarbonisation. One of the largest contributions to this will have to come from the residential sector. The transition towards renewable construction materials, achieving improvements in heating efficiency and so forth is an ongoing process. How it will affect labour productivity is a complex matter and therefore hard to foresee at this juncture.

BOX 4

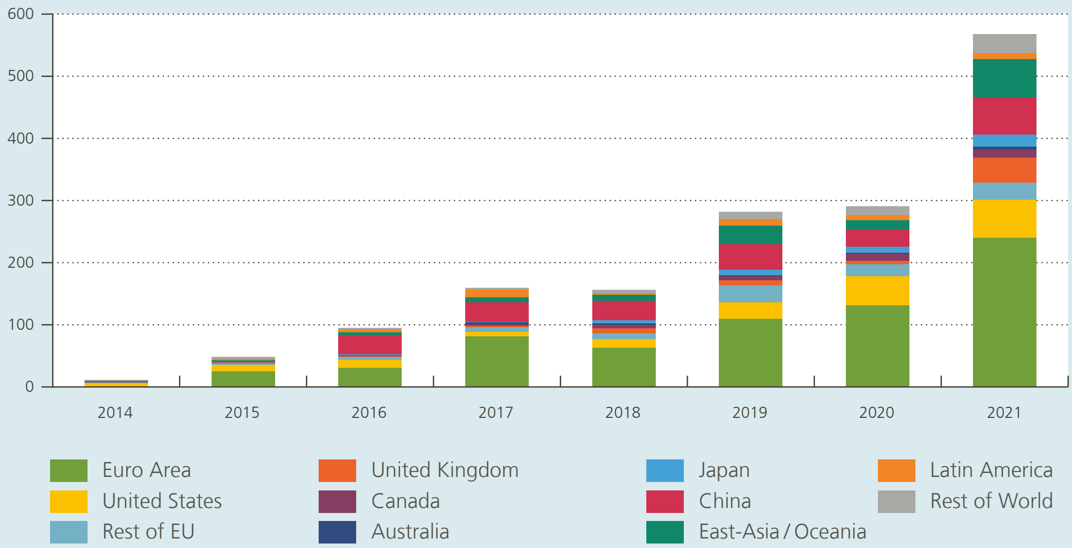
Green finance in Europe

This box considers the role of financial markets in the process of mitigating GHG emissions and promoting adaptation to climate change. Well-functioning and integrated capital markets would complement banks as an effective source of financing for sustainable growth and would thus improve the allocation of capital within the economy, facilitating entrepreneurial, risk-taking activities and investment, notably in green technologies and other long-term projects. Green bonds can play a significant role when it comes to financing a more sustainable European economy. The EU green capital markets are dynamic and rapidly growing, which may foreshadow heavier levels of investment in sustainable projects and an increase in green bond issuance in the future.

Figure A

Issuance activity in the global green bond markets

(USD billion)



Source: Refinitiv.

Notes: The bars present the amounts (in USD billion) issued in bonds classified as green, according to Refinitiv, each year from 2014 to 2021 per country of residence of the bond issuer and per year of bond issuance. Specific countries are then grouped according to geoeconomic criteria (e.g. bonds issued by euro area issuers are grouped in the category "Euro area", bonds issued by entities located in Latin American countries are grouped in "Latin America", and so on). In total, 5,531 individual bonds have been sorted accordingly into the above categories. According to Refinitiv, "green bonds" are a fixed income product that offers investors the opportunity to participate in the financing of large sustainable energy green projects that help mitigate climate change and support countries in adapting to the effects of climate change.

To achieve the goals set by the European Green Deal, the European Commission has pledged to mobilise at least € 1 trillion in sustainable investment over the next decade. This will require an unprecedented shift in both public and private funds to finance the transition. According to the

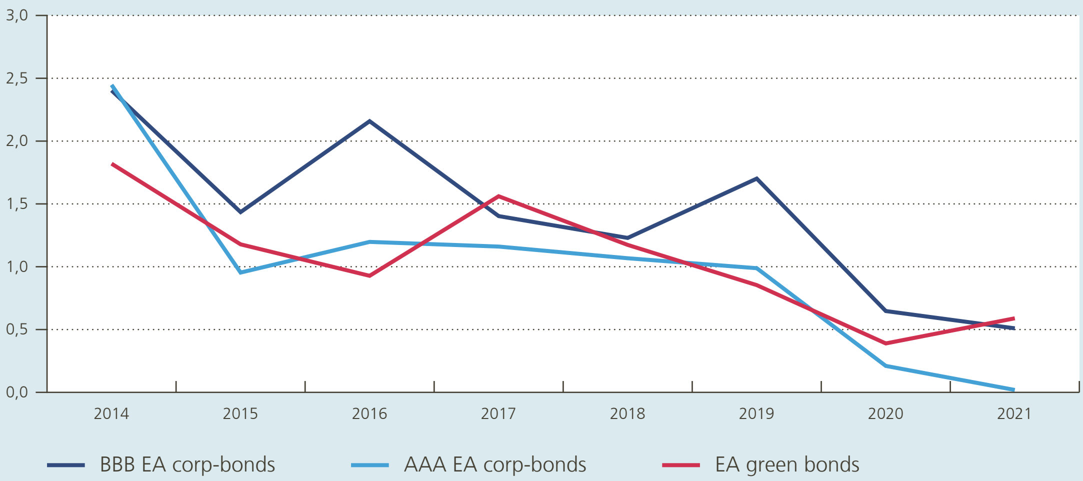
Sustainable Europe Investment Plan (also known as the European Green Deal Investment Plan), private and public sustainable investments will be mobilised over the next decade through the EU budget, together with additional funds under the InvestEU programme. It is estimated that Europe will need an additional annual investment of around € 350 billion to meet its 2030 emissions target in energy systems alone, not to mention the € 130 billion or so required for other environmental goals. A combination of funds from the EU budget, as well as public and private investments, is therefore required and capital markets are an integral part of this process.

The EU is set to become the largest green bond issuer in the world. Sustainability, along with digital growth, is at the heart of the EU's recovery plan from the coronavirus (COVID-19) pandemic as it moves towards a greener, more digital and more resilient Europe. Through its 2021-2027 long-term budget (Multiannual Financial Framework – MMF) and the Next Generation EU (NGEU) instrument, the EU intends to spend up to € 605 billion in projects to address climate crisis and € 100 billion in projects to support biodiversity. Of the € 750 billion set aside for the NGEU, the EC intends to issue up to € 250 billion, or 30 %, in green bonds by end-2026, making the EU the largest green bond issuer in the world.

Figure B

Interest rate of green and corporate bonds issued by euro area entities

(percentage)



Source : Refinitiv.

Note : The Figure shows the average coupon on green bonds issued by euro area entities per year, weighted according to the amount at issuance. This is compared to the yield of the bonds issued by euro area non-financial corporations.

The green bond market has witnessed remarkable growth, with $ 1.61 trillion in cumulative issuance since 2014. Global annual issuance has increased each year since 2014 ; accounting for a total value of $ 470 billion over the period 2014-2018 and $ 1.14 billion from 2019 to 2021 (see Figure A below). It is worth noting that in 2021 alone, green bonds totalling $ 567 billion were issued, an amount higher than the total value of issuances for the period 2007-2018 and more than double the value of green bonds issued in 2019 and 2020. Besides green bonds, sustainability and social bonds each account for about a third of total outstanding issuances on the green bond market.

The coupon charged on new green and sustainable bonds issued by euro area entities is firmly below the yield offered by BBB-rated euro area corporate bonds. This may imply either that the cost of green bond issuance is somewhat lower than that of euro area corporate bonds, or that the companies that issue green bonds are of better credit quality than the average euro area corporation. However, at the same time, the downward trend in the cost of funding of green bonds cannot be isolated from overall market conditions, as our sample includes only a period of exceptionally easy monetary and financial conditions. Overall, the above may not support the existence of a "greenium", i.e. a premium paid by investors to the issuing companies, in order to incentivise their transition towards greener forms of production.

Capital markets can provide innovative tools to close the green investment gap. At present, compared with other parts of the world, euro area non-financial corporations seem to rely more on banks than on capital markets for funding. This might be due, among other reasons, to a tax bias towards debt finance over equity and the preference for shorter-term funding commitments. However, investments for sustainable growth and innovation technologies have certain characteristics that may be less suited to bank lending, such as their relatively high risk profile and their long maturity, which may not be available in the banking sector.[1] Moreover, cross-border integration of finance in the euro area is limited, due mainly to national institutional differences, such as in insolvency laws. These create impediments to mobilising all available resources – both banking and non-banking – to finance the green transition. The green transition offers a unique opportunity to build a truly European capital market, in other words a green capital markets union (CMU).[2]

Central banks around the world are considering possible ways to incorporate the effects of climate change into their macroeconomic forecasts and financial stability monitoring. The ECB's action plan, which includes an ambitious roadmap, with a view to further integrating climate change considerations into its monetary policy, highlights the importance of developing high quality ESG (environmental, social and governance) data, ratings and research for managing climate-related risks and harnessing opportunities from the transition to a low-emissions economy.

In short, green bonds can play a significant role when it comes to financing a more sustainable European economy. Green bond issuing activity within the market to finance projects has accelerated over the past few years. Moreover, Europe is home to both green bond markets and green bond issuers and therefore plays a leading role in this respect, while private sector entities are becoming increasingly reliant on the green bond markets as a source of funding. However, given that funding from green bond market activity has been directed to relatively few sectors of the economy, there is a clear need for policy-related initiatives to involve more sectors of the economy. Lastly, the increase in green bond issuance has come during a period of easy financial conditions, which may also highlight the need for policy initiatives so as to provide investors with incentives to continue their green financing in this changing market landscape.

This box summarises Anyfantaki et al. *(2022).*

1 See, for example, De Haas and Popov (2019).
2 Speech by Christine Lagarde, "Towards a green capital markets union for Europe", May 2021.

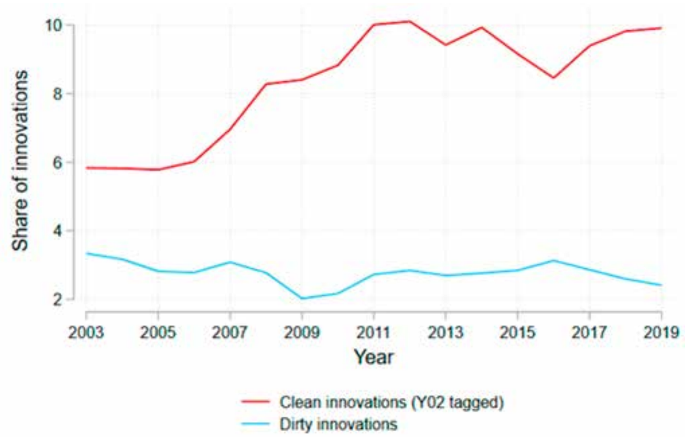
We also explore whether environmental regulation crowds out "non-green" innovations. To this end we analyse the dynamic impacts on green and "non-green" patenting by firms affected by environmental regulation. The data used for this exercise is the same as before, that is, financial accounts for about three million firms across six euro area countries merged with estimated CO_2-equivalent emissions. We then add information on patent applications retrieved from the Orbis Intellectual Property database. We use the Cooperative Patent Classification (CPC) to classify the patented technologies in different groups. "Clean innovations" refer to climate change mitigation technologies and "Dirty innovations" refer to technologies related to fossil fuel energy generation or to internal combustion engines.[81] We are able to match patent information to about 100 000 firm-year observations of our initial dataset, given that only a minority of firms patent. Over the 2003-2019 period, the share of green innovations in the dataset clearly increased, while the share of dirty innovations fell (Figure 11).

Green patent applications made by polluting firms increase significantly after the tightening of environmental policies, though without crowding out other types of innovation. The first column of Figure 12 shows the cumulative increase, in percentage points, in the number of green patent applications made by high-polluting firms following a change in environmental policy, as defined above. The second column shows the change in non-green patents (all other applications), to analyse whether there are crowding-out effects. The first row shows the impact of more stringent environmental policies (as measured by the composite EPS indicator), while the following rows look at the separate impact of tightening market, non-market and technology support policies. The positive impact of tightening environmental policies on green patent applications is driven by non-market and, above all, R&D support policies. Market-based policies appear to have relatively little effect on the patenting behaviour of firms. We do not see any evidence of crowding-out impacts as non-green patent applications either do not change or even increase slightly. This could be due to complementarities across different types of technologies. That is, to introduce a new green technology, a firm might need a new software, which explains the slight positive impact of environmental regulation on non-green patenting. These results confirm the weak version of the Porter hypothesis, which holds that stringent environmental policy can increase overall innovation.

Figure 11

Share of green and dirty innovations over time

(percentage of total patent applications)



Source: ECB calculations on Orbis IP data.

81 See Dechezleprêtre et al. (2014).

Our results show that while firm-level TFP growth declines in the aftermath of a change in environmental policy, it could increase over the long term following a significant increase in patenting. The time horizon in the first part of this analysis, given available data, spanned "only" five years after the change in policy. Maybe this is too short to reliably gauge the productivity impacts of a change in policy. Our patent analysis shows that green patent applications increase significantly after environmental policies are made more stringent. While patents have an immediate impact upon market values, they take time to affect productivity.[82] One potential explanation is that the new products and processes covered by the patents must be embodied in new capital equipment and training. Firms may also need to undertake further research and development, as well as expensive marketing and advertising to promote their new products. Taken together, the results in this section show that firms react to more stringent environmental policy by increasing research and development in green technologies, which results in an increase in green patent applications.[83] Although TFP growth declines in the aftermath of the policy change, in the long term (beyond five years), the surge in new green technologies might start to feed through to firm efficiency.

Green innovation might also be fostered by internal factors, such as reputation and demand, in contrast to external or policy-induced factors. Box 5 uses Community Innovation Survey (CIS) data to further explore the motivations of European firms in undertaking green innovations.

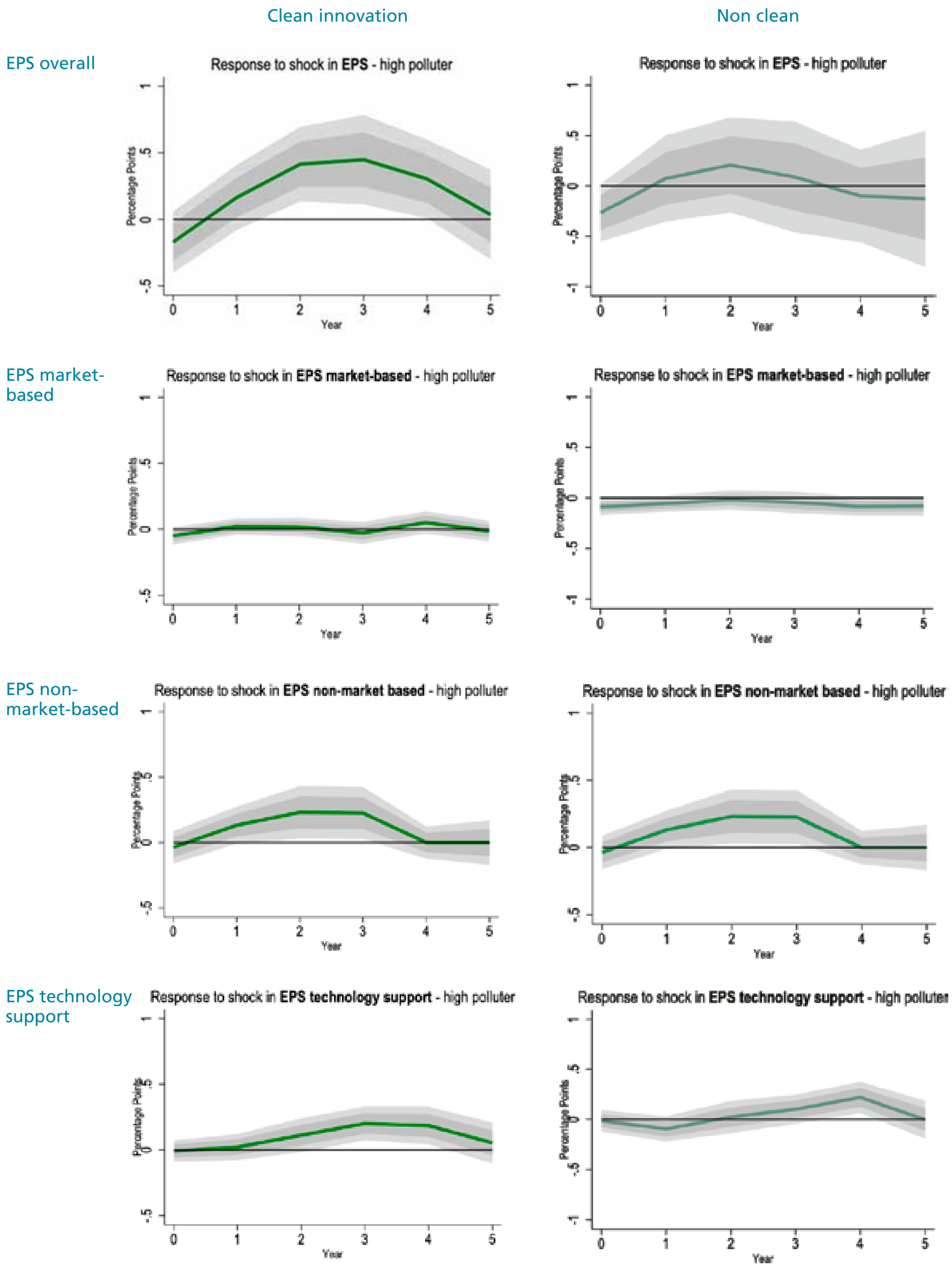
82 See Bloom and Van Reenen (2002).

83 Hasna et al. (2023) showed that when countries expand their climate policy portfolio, they tend to have more patents related to reducing climate impact, trade involving low-carbon technologies and foreign investments in environmentally friendly projects. This mitigates potential costs from climate policies over the medium term.

Figure 12

Firm-level impulse response functions of positive environmental policy stringency (EPS) changes on patent applications, by patent type

(in percentage points)



Source : ECB calculations on Orbis IP data.

BOX 5

What drives environmental innovation? Industry-level analysis using CIS data

Environmental innovations are new ideas, behaviours, products and processes that help to reduce negative environmental effects of economic activities. They are driven by factors such as regulation, technology push, market pull, and firm-specific factors. This box examines the drivers of EU environmental innovation using the 2020 Community Innovation Survey (CIS) data on innovative activities with environmental impacts.[1] The results show that environmental policy is supported by other factors such as a firm's image and voluntary actions, which also motivate firms to introduce environmental innovations.

Previous work on environmental innovation drivers distinguishes between internal (e.g. training) and external (e.g. regulation, technology, market) drivers. Most studies, including those cited in Section 4, focus on external drivers, most notably regulation, technology, and market pull factors. However the literature[2] extends the determinants of environmental innovation beyond those factors, classifying them into supply-side factors (technological capabilities, market characteristics), demand-side factors (customer demand, social awareness) and institutional and political influences (policy, institutional structure). Although environmental regulation, technology, market, and firm-specific factors are considered the main drivers of environmental innovation, demand-side factors such as public opinion and customer demand play a crucial role, and supply-side factors such as technology and cost-saving are also conducive to environmental innovation. Public concern about the environment stimulates the development of new cleaner technologies and complementarity may exist between supply and demand-side policies.

These considerations are confirmed by CIS data, which show that the most significant drivers for EU environmental innovation activities are (i) the improvement of a firm's reputation and (ii) the high cost of energy, water, and materials. Table A below shows the share of innovative firms who reported each of the nine drivers as highly important for their introduction of environmental innovations. The most frequently cited driver was the resulting improvement in the firm's reputation, followed by the high cost of energy, water, and materials. Regulations were found to be significantly less important drivers compared to voluntary undertakings. We ran a factor analysis to simplify the nine drivers into common factors, suggesting that just two factors should be used, which explain 64 % of the variation in innovation drivers for both industry (mining, manufacturing, electricity, water and waste) and services (construction, trade, transport, hotels and restaurants, ICT, financial, real estate, professional services, and administration).[3] The first factor, "Regulation & Costs", shows that regulation, taxes, costs and grants share much in common and should therefore be grouped together, while the second factor, "Reputation & Demand", brings together the determinants of reputation, voluntary actions and market demand. Table B further below shows the factor loadings, showing the extent to which each of these

1 The Community Innovation Survey (CIS) 2020 is a commonly used data source for measuring innovation in enterprises across the European Union and other countries. The CIS 2020 includes an optional module on environmental innovation, which asks firms to rate the factors affecting their decision to introduce innovations with environmental benefits.

2 See, for example, Horbach (2008), Horbach et al. (2012) and De Marchi (2012).

3 This analysis is conducted at the level of NACE two-digit industries.

two factors relates to the original environmental innovation driver. The factor loadings are similar for industry and services, with only slight differences in the weight given to regulations and taxes.

Our results suggest that environmental policy and demand-side factors are complementary drivers of environmental innovation. Most sectors in both industry and services score high for both "Regulation & Costs" and "Reputation & Demand": correlation coefficients between the two factors are 0.37 and 0.44, respectively, in the cross-country average industry-level data. The complementarity between policy factors, costs and demand-pull factors can also be seen across countries, with Nordic countries and Germany showing both factors as significant drivers in services. However, correlation coefficients between the two factors in the cross-industry average country-level data are 0.08 and 0.58 respectively. The weaker complementarity in industry could be due to the looser link between production and end users in industry or the differences in the sectoral mix across countries.

Table B

Rotated factor loadings, 2018-2020

	Industry, n = 334		Services, n = 274	
	Factor1 Regulations and costs	Factor2 Reputation and demand	Factor1 Regulations and costs	Factor2 Reputation and demand
Existing regulations	0.829	0.223	0.403	0.674
Existing taxes, charges or fees	0.828	0.171	0.510	0.492
Expected regulations or taxes	0.782	0.380	0.799	0.352
Government grants, subsidies or other financial incentive	0.671	0.402	0.819	0.075
Existing or expected market demand	0.387	0.593	0.408	0.560
Improving the enterprise's reputation	0.384	0.813	0.148	0.858
Voluntary actions or initiatives within the sector	0.069	0.889	0.108	0.795
High cost of energy, water or materials	0.669	0.077	0.774	0.244
Need to meet requirements for public procurement	0.570	0.283	0.774	0.137

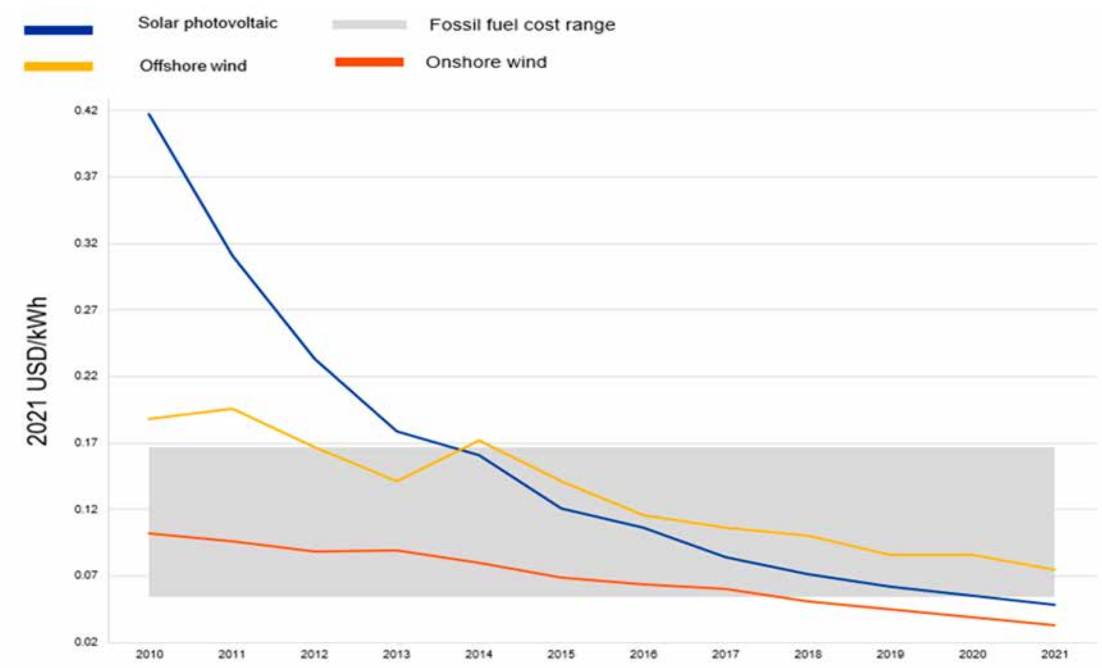
Sources: Eurostat table INN_CIS12_ENVF and authors' own calculations.

Our findings confirm that environmental regulation is driving environmental innovation within the EU. However, formal regulation receives complementary support from voluntary activities and demand-driven pull towards environmental innovation, which often go hand in hand with formal regulation, especially in the services sectors. We build on the existing research, which has already shown that a firm's decision to introduce environmental innovations is influenced by a variety of factors, including technology push, market pull, policy and firm-specific aspects.

One key sector where green innovation and regulation resulted in competitive technology is electricity generation. Technological improvements and economies of scale have caused the price of electricity generated by wind and solar technologies (particularly onshore) to plummet over the past decade. Both renewables sources are now markedly cheaper than fossil fuel sources of electricity on a levelised cost basis (Figure 13). While challenges remain in handling intermittency, particularly at high penetration rates, a substantial switch from fossil fuel to renewable electricity generation would at present result in both lower carbon intensity and lower costs.

Figure 13

Levelised costs of renewable energy



Source: IRENA, Renewable Energy Statistics 2022.
Note: Levelised costs represent the net present value of average revenue per unit of electricity required to recover the costs of constructing and operating a new project over an assumed financial and operating lifetime.

4.3 Reallocation of resources

In addition to individual firms becoming less-carbon intensive, reallocation of resources within and between sectors will be inevitable. Climate policies generally focus on developing innovative technology and processes and ensuring their adoption across Europe. In addition to this green innovation, emission reduction targets can also be met via "green reallocation", by shifting economic activity away from the worst performing firms with respect to emission efficiency towards the best performers. Reallocation is equally as important as innovation, if not more, in explaining traditional aggregate productivity growth [84] and will undoubtedly be a driver as well in making firms more "carbon productive".

84 Foster et al. (2001).

Climate-driven reallocation may also change measured economy-wide productivity. If carbon-intensive sectors and firms set to shrink have higher productivity than green sectors and firms likely to grow, then the reallocation mechanism would lead to lower economy-wide productivity in aggregate (and vice versa). The impact may then vary between individual economies and depends on the country's industrial structure.

At given sectoral productivity levels, reallocation between sectors would mechanically lower productivity given that high carbon-intensive sectors are, on average, relatively more productive. The reallocation of production factors across sectors during the green transition would dampen overall productivity growth due to the differences in sectoral productivity levels.[85] Sectors such as mining, refineries and air transport, which are expected to shrink due to higher relative prices, have higher labour productivity compared to sectors like construction, which is expected to (at least temporarily) grow but has lower labour productivity. This shift in sectoral demand will result in a decline in aggregate labour productivity, estimated to be around −1 % based on input-output and employment data analysis.98

The effects of within-sector reallocation are less clear. There is a substantial difference between the carbon intensity of firms even within sectors.[86] For EU ETS firms in the metals and chemicals sector, the 20 % most carbon-intensive firms account for around three quarters of total sector carbon emissions, but only 20-30 % of employment. Even for cement and lime manufacturers, where the technology is much more homogenous, the 20 % most emissions-intensive firms account for 30 % of emissions, but only 10 % of employment.[87] If we conduct a thought experiment where the 20 % most emission-intensive firms (known as "brown zombies"[88]) had their output reallocated to the remaining firms within the narrowly-defined sector, such that output within the sector remained unchanged and individual firms' carbon intensity also remained unchanged, there would be a 15 % to 35 % drop in emissions.[89]

There is some evidence to suggest that reallocating output towards less emissions-intensive firms within an industry would be positive for productivity. Firm-level carbon intensity and productivity are not necessarily correlated, so reallocating output between firms of different carbon intensity would not necessarily lead to unchanged productivity overall. We analyse approximately 2 500 firms within the EU ETS over the period 2005-2020 and find a negative relation between labour productivity and emission intensity. This finding is confirmed when regressing labour productivity on emission intensity whilst controlling for a wide range of fixed effects, as negative and significant coefficients are found. A 10 % decrease in firm-level emissions per unit of output is associated with a labour productivity increase of 1 % to 2 %. This result confirms the earlier finding that environmental tightening predominantly benefits firms that already had a relatively high productivity.

85 According to the estimates of the Output Gaps Working Group of the European Commission in an unpublished working document.

86 The complex system that the EU ETS uses to distribute free emission rights among industrial installations is based on a benchmark set by the best-performing installations producing a similar product. It therefore acknowledges that there is a certain dispersion in carbon performance within narrowly-defined sectors. Vieira et al. (2021) also come to this same finding. Rising carbon prices in conjunction with the phasing-out of free emissions allowances would therefore stimulate not only investment in abatement technology but also reallocation of output towards the most carbon-efficient firms.

87 See Bijnens and Swartenbroekx (2022).

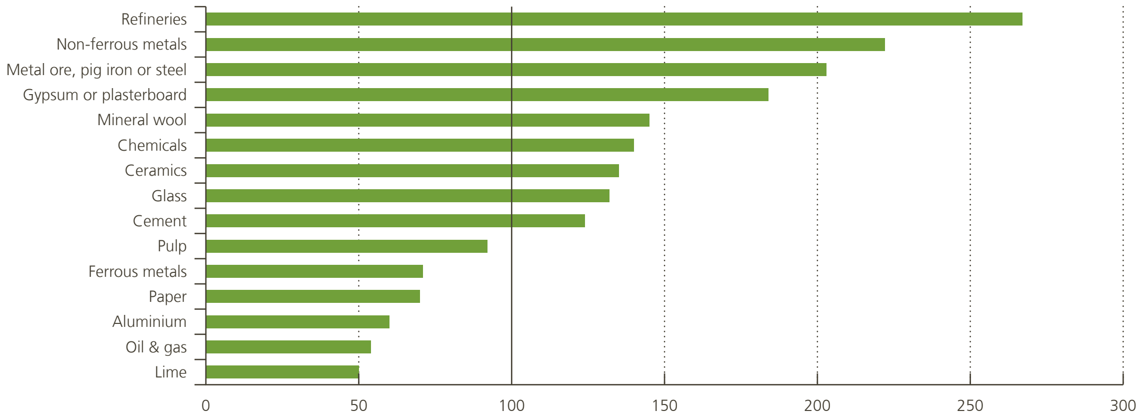
88 The concept of "zombie" firms" – defined as low-productivity firms that would typically exit in a competitive market – is well-known in the productivity literature. Due to their increasing survival rates over the past decade, they tie up scarce capital and therefore constrain the growth of more productive firms. In other words, zombie firms impede productivity-increasing reallocation. Much like zombies, "brown zombies", or firms with low carbon productivity, tie up capital that could otherwise be allocated to more carbon-productive firms. See Bijnens and Swartenbroekx (2024).

89 Based on an analysis of firms within the EU ETS, excluding power generation. See the table in Appendix 1 for calculations per industry.

Figure 14

Labour productivity of the 80 % most carbon-efficient firms versus the 20 % least carbon-efficient firms

(percentage)



Sources: EUETS.info, Orbis and Nationale Bank van België analysis.
Note: Firms refers to firms within the EU-ETS.

Nevertheless, the productivity gains to be had from moving output to the most carbon-efficient firms depend on the characteristics of the sector. Continuing the same thought experiment in which we compare the 80 % most carbon-efficient with the 20 % least-carbon efficient EU ETS firms, we can indeed observe that in most sectors the most carbon-efficient firms are also the most productive. However, in several sectors, such as pulp, paper and ferrous metals, the most carbon-efficient firms are less productive (Figure 14). As such this finding does not differ from the stylized fact that sectoral productivity dispersion is high within European countries, possibly driven by slow technology diffusion. [90] This implies that reallocating output to these carbon-efficient firms would lead to lower productivity for the sector. For the economy as a whole, however, this thought experiment would increase overall labour productivity.

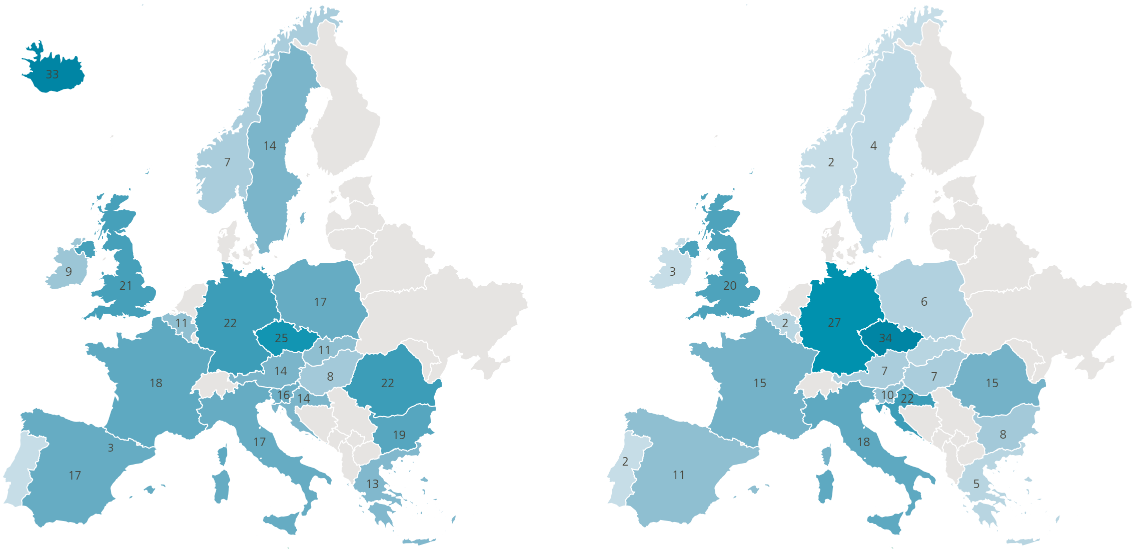
Reallocation of factors of production within firms away from energy may lead to lower productivity. In models where energy is included in the production function, higher energy prices can result in firms substituting away from energy and increasing their use of capital and labour. However, due to diminishing marginal returns, the overall impact is lower productivity and output. For example, one estimate for the EU of a net zero by 2050 scenario suggests an increase in the capital-labour ratio of 1.2-1.5 % in the long run, but a decline in labour productivity of 0.2-0.7 %. [91] Recent OECD work [92] does foresee medium-term TFP growth stemming from higher energy prices triggered by energy-abating investment. In the short term, however, following an energy price shock firms pare back their capacity utilisation and their productivity declines. OECD estimates suggest that a 5 % increase in energy prices would reduce productivity by approximately 0.4 % one year later. The firms most affected are those operating in energy-intensive sectors, as well as firms that are financially constrained.

90 See Berlingieri et al. (2020) and CompNet (2023).
91 See Varga and Roeger (2021).
92 See OECD (2023).

Figure 15

Share of ETS manufacturing firms (left) and employment (right) at risk with an ETS price of €150/ton

(percentage)



Sources: EUETS.info, Orbis and Nationale Bank van België analysis.
Note: Scenario based on firm-level profitability and estimates for carbon intensity for 2019.

Triggering a reallocation of production through a sharp increase in carbon prices could put many firms at risk of becoming loss-making. A sudden rise in ETS carbon prices to €150 payable for all emissions within the EU ETS, assuming constant carbon intensity and no pass-through of the increased carbon cost, would have put at least a tenth of manufacturing firms currently covered by the ETS in major euro area economies at risk of making losses in 2019, rising to a fifth of German manufacturers currently covered by the ETS (Figure 15, left). The share of total employment currently covered by the ETS at risk follows a similar pattern (Figure 15, right).[93]

This carbon price-driven cleansing might bankrupt low-carbon intensity firms with low profitability, and therefore be less successful at reducing emissions. Allocating the output of firms at risk of losses across the remaining firms results on average in a roughly 10% reduction in emissions (Figure 16). Yet this reduction is not constant across sectors, with some showing an increase in emissions. This means that firms with the lowest cash flows per tonne emitted are not necessarily the ones with the highest carbon intensity. In other words, the least carbon-intensive firms are not necessarily also more profitable. Furthermore, carbon-intensive activities are generally carried out by older, and therefore less financially-constrained, firms.[94, 95] A steep increase in carbon prices might therefore drive some low carbon firms out of the market ahead of their more carbon-intensive (and more profitable or less credit-constrained) competitors. This example, where economic cleansing does not fully overlap with carbon cleansing, also reveals that there might be limitations on the effectiveness of pure market-based policy instruments such a carbon pricing. Box 6 further explores the impact of carbon pricing on the entry and exit of firms and shows that an increase in carbon taxes also affects firm entry, given that the productivity threshold needed to enter the market increases.

93 For the sake of simplicity, firms at risk are firms that would have reported negative EBITDA in 2019 if the carbon price was € 150/tonne instead of € 20/tonne, there were no free carbon allowances, no pass-through of carbon prices into sales prices, no reduction of emissions driven by an increasing carbon price, and no change in the volumes sold. Hintermann et al. (2020) find that firms pass on shocks to materials costs completely, or even more than completely, whereas the pass-through of energy costs is around 35-60%.

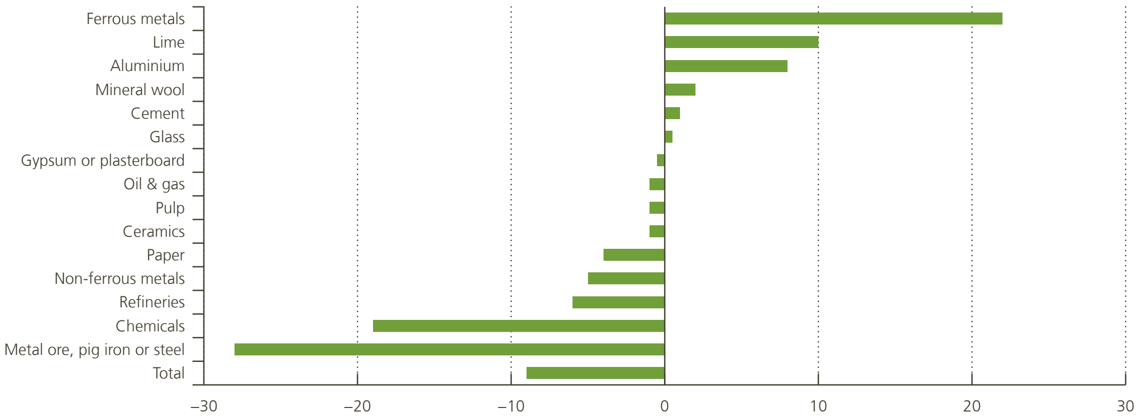
94 See Cloyne et al. (2018).

95 The importance of green finance is discussed in Box 4.

Figure 16

Scenario for emissions savings per sector from a carbon price-driven reallocation

(percentage)



Sources: EUETS.info, Orbis and National Bank of Belgium analysis.

BOX 6

Carbon taxation and business dynamism

Business dynamism driven by carbon taxation will affect productivity, with carbon taxation potentially affecting productivity through at least two channels. The first one is structural change. By altering the price of energy produced with a fossil resource, carbon tax has an asymmetric effect on the profitability of industries using energy with different intensities. As a result, carbon tax will reallocate profit opportunities across industries and, through this channel, change the relative size of sectors. Given the heterogeneity in sectoral productivity, this would have an impact on aggregate productivity. The effect on productivity resulting from structural change is unclear a priori. As a second channel, the carbon tax could improve sectoral productivity via standard selection and through a cleansing effect at the sectoral level, more precisely by inducing the exit of less productive businesses and the entry of more productive businesses Thus, business dynamism produces a composition effect – both within and between sectors – that is important in shaping the dynamics of sectoral and aggregate productivity.

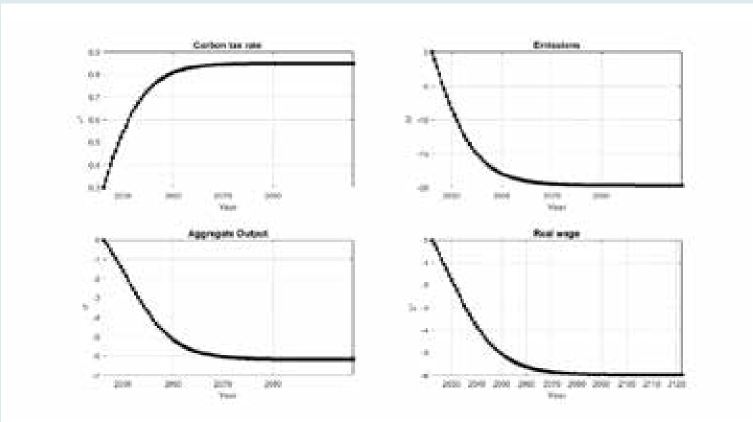
We develop a model that captures the effects of carbon taxation on business dynamism with the following features:

- Potential entrants face initial uncertainty concerning their future productivity when making an investment decision to enter the market. A firm enters the market in expectation of future profits.
- Productivity levels differ across firms and firms face fixed production costs. As a result, given aggregate conditions, firms with productivity levels below a specific threshold will be forced to discontinue production and remain inactive until production becomes profitable again.

- We model a two-sector economy: manufacturing and services, with the former being energy-intensive and latter labour-intensive. Both are populated by an endogenous mass of heterogeneous firms that produce differentiated goods, which are aggregated into sectoral goods. As a result of varying intensities in the use of energy, a change in the price of the energy bundle will have an asymmetric effect on the two sectors.
- We add an energy sector to our model. The final bundle of energy, which is used in the production of final goods, is a constant elasticity of substitution (CES) aggregator that bundles clean and dirty energy. The former is produced from a renewable source, while the latter is produced from a fossil resource.
- The government imposes a linear carbon tax on the revenues of producers of dirty energy and rebates the proceeds to households in a lump sum fashion.
- The final good is a CES aggregator of manufacturing goods and services.
- Emissions are a by-product of output.
- We assume nominal rigidities in the form of sticky wages. Monetary policy is described by a Taylor rule that features a policy response to inflation and to the output gap.

Figure A

Increase in carbon tax to reduce emissions by 20 % with respect to the status quo – Key aggregates

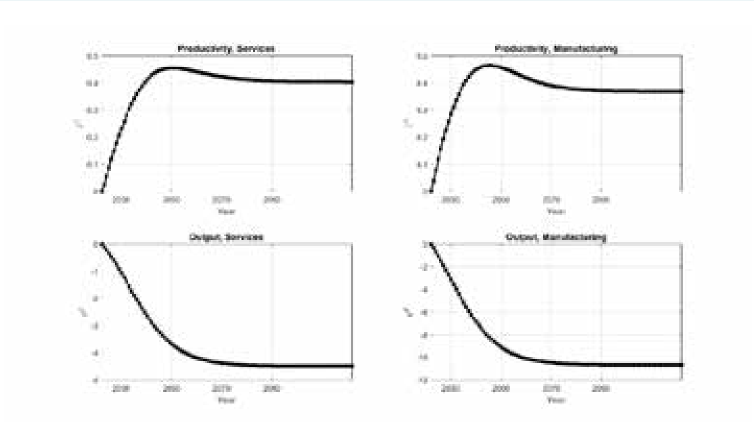


Source: Authors' calculations.

The carbon tax increases productivity, as firms need to become more productive to break even, but comes with an output loss. Figure A depicts the transition implied by our model economy in response to an increase in the carbon tax aimed at achieving a permanent 20 % emissions reduction with respect to the status quo. Variables are expressed in percentage deviations from the initial steady state, where the revenues from the carbon tax represent 1 % of GDP. The carbon tax rate is expressed as a percentage. Meanwhile, time on the horizontal axes is shown in years. The carbon tax imposed on producers of dirty energy must increase from 30 % to 80 % to induce the required reduction in emissions. This entails large costs in terms of both output and real wages. The energy mix (not shown) is such that the production of dirty energy halves while that of clean energy doubles with respect to the initial production structure. Figure B below shows the effects of the increase in the carbon tax on sectoral productivity and output. Both manufacturing and the services sector shrink in response to the tax increase. However, manufacturing, being the most energy-intensive sector, suffers a heavier output reduction than services. Both sectors experience a permanent increase in productivity. Indeed, in both sectors firms need to be more productive to break even on their costs.

Figure B

Increase in carbon tax to reduce emissions by 20 % with respect to the status quo – Productivity and structure of the economy

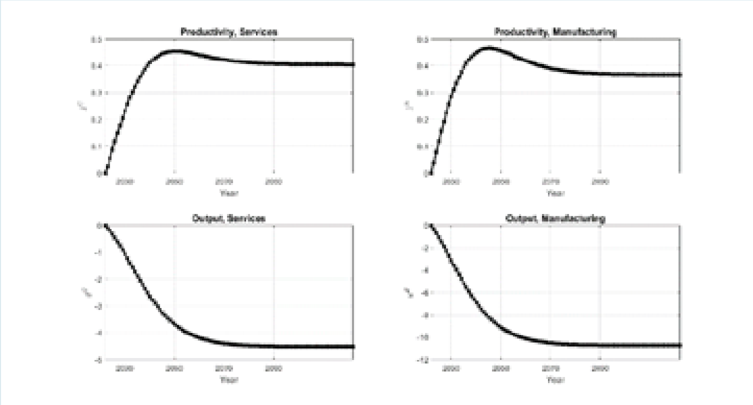


Source : Authors’ calculations.

Entry and exit are permanently reduced. Figure C below displays sectoral entry together with the trend in the number of firms that actively produce in each sector. The increase in productivity required to break even on costs induces a permanent reduction in the entry rate and a further reduction in the number of active firms in each market. The carbon tax is an effective instrument in forcing a greener energy mix in our multi-sector industry dynamics model. Additionally, an increase in the carbon tax leads to productivity gains due to selection and cleansing along the entry and exit margins, despite presenting significant output costs. For the time being, we have not considered productivity growth in the production of energy from renewable sources (which in the data is high), or research and development by incumbents. Considering these aspects may induce a faster transition in response to a higher carbon tax, with lower output costs.

Figure C

Increase in carbon tax to reduce emissions by 20 % with respect to the status quo. Business dynamism



Source : Authors' calculations.

This box is based on ongoing research by Boris Chafwehé, Andrea Colciago and Romanos Priftis. The model used is calibrated based on US aggregate data.

Economic theory indeed suggests that carbon pricing promotes a structural shift towards a less carbon-intensive economy, with a possible impact on potential output growth. However, empirical literature on the macroeconomic effects of carbon pricing is thin and apathetic to its structural impact. That said, ongoing research at the ECB suggests that increases in carbon taxes would have relatively little impact on potential output in Europe, implying that the negative side effects described earlier remain limited for now.

The transition inevitably involves reallocation of labour from carbon-intensive jobs to green ones, both between and within sectors. That reallocation may impair effective labour supply if the new jobs created during the transition are a poor match skill-wise or geography-wise for the jobs that are destroyed. Recent research using US and UK data finds that low-carbon jobs have higher skill requirements across a broad range of skills, including technical, managerial and social. Furthermore, high-carbon manual jobs are extremely spatially concentrated, whereas low-carbon vacancies are more dispersed in both the United States and the United Kingdom. This holds true for both high- and low-skill occupations. [96] This could result in protracted unemployment and skill atrophy, the human equivalent of stranded assets.

There are potential impacts on individual regions within Europe where carbon-intensive jobs are particularly concentrated. Regional heterogeneity is also observed for employment in energy-intensive industry within Europe that is heavily concentrated within certain regions (Figure 17). [97] Around 5 % of EU NUTS2 regions have more than 20 % of employment in carbon-intensive jobs and in seven regions (all of them located in Greece

96 See Sato et al. (2023).
97 See Bijnens et al. (2021) and Bijnens et al. (2022).

and Romania), the share exceeds 25 %.[98] A sudden "climate shock" to certain regions could potentially lead to long-lasting negative local labour market effects akin to the "China syndrome" used to describe the heterogeneous exposure among US regions to rising import competition from China.[99] A further example would be previous episodes of declining local coal production, which resulted in increased rates of poverty within regions.[100] In summary, the impact of the green transition is likely to have an uneven effect not only on regions, but also on sectors and population groups. The distributional aspects of the climate transition are further discussed in Box 7 below.

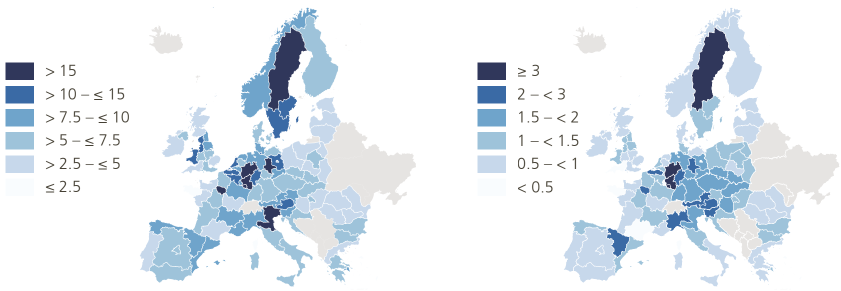
Yet overall available evidence points to few constraints to labour reallocation that are unique to the green transition and that extend beyond the normal constraints to workers moving between firms and industries. Most European jobs are so called "white jobs", which are relatively neutral in their environmental impact.110 Furthermore, most "green" jobs are only partly so, with many skills that are common to "dirty" or "brown" jobs and most of the unique skills obtainable through on-the-job training. Notably, 44 % of US workers are currently in non-green jobs that have similar skill profiles to green jobs.[101] The International Energy Agency estimates that in the energy sector, most carbon-intensive jobs have skills that would transfer smoothly to the green sector. Moreover, it estimates that more than half of the 7.5 million energy sector workers in Europe already work in the clean energy sector.[102]

With respect to the reallocation of human resources, the longer-term impact of migration on productivity remains uncertain. Climate change will inevitably lead to a change in the comparative advantage and specialisation of agricultural and industrial regions alike. Together with flows from climate-related asylum seekers, this will generate migration flows within Europe and with other parts of the world and lead to altered population densities. A recent meta-study suggests that a 1 % increase in population density would lead to a positive impact on TFP of 0.06 %.[103] Due to these positive agglomeration effects, denser regions are likely to experience higher productivity growth. However, the positive effect of these spatial effects on productivity will be highly influenced by composition effects related to migration and trade policies, and by how proceeds from carbon taxes are redistributed.[104]

Figure 17

Share of the workforce employed by sectors with very high energy intensity, as a share of manufacturing employment (left) and total employment (right)

(percentage)



Sources: EUETS.info, Orbis and National Bank of Belgium analysis.

Notes: Geographical areas defined based on NUTS1 code. Sectors with high energy intensity include NACE 17 (Paper), 19 (Coke & petrol), 20 (Chemicals) and 24 (Basic metals). Sector-specific employment figures gathered from Eurostat SBS; total manufacturing employment and overall employment gathered from Eurostat LFS. Figures for 2016.

98 See Vandeplas et al. (2022).

99 Autor et al. (2013) show that various US regions were exposed differently to Chinese import competition and that "rising exposure increased unemployment, lowered labour force participation, and reduced wages in local labour markets." Exposure to Chinese competition affected not only local manufacturing employment but also numerous other sectors. In Autor et al. (2014), they note that "earnings losses are larger for individuals with low initial wages, low initial tenure, and low attachment to the labour force." Pressure on China-exposed industries and regions led to the fact that a part of the labour force was worse off than before, even many years after the shock occurred.

100 See, for example, Betz et al. (2015).

101 See Bowen et al. (2018).

102 See International Energy Agency (2022).

103 See Ahlfeldt and Pietrostefani (2019).

104 See Desmet and Rossi-Hansberg (2021) and Conte et al. (2022).

BOX 7

Distributional impacts of transition policies on Portugal

A carbon tax triggers non-trivial distributional effects at sectoral and individual levels. Our analysis points to asymmetric effects across sectors and individuals; workers with a comparative advantage in dirty energy sectors who do not reallocate experience the largest welfare loss. As climate change mitigation policies elicit heterogeneous responses among individuals, sectors, or geographies, understanding the distributional effects is key, as they are very likely to influence future climate policies.

We document the distributional effects of a carbon tax in Portugal by relying on a multi-sector model. The model combines the skill distribution among workers with the sectoral composition of the economy. It also features endogenous occupational choice and human capital accumulation. Individuals take into account their sector-specific productivities when choosing their sector of work and investing in schooling. On the production side of the economy, there are various sectors, including four energy-producing activities: oil, coal, natural gas and green energy production. The policy experiments involve introducing a carbon tax on the "dirty" energy sectors (oil, coal and natural gas). The model-based estimates needed for Portugal to achieve its Paris Agreement pledges of a 35 % and a 70 % [1] reduction in emissions imply a 32.9 % and an 80.4 % carbon tax, respectively. [2] Given the intersectoral linkages in the economy, carbon taxation induces changes in relative prices, thus leading to reallocation of inputs across sectors, including labour. We consider four different revenue recycling schemes under which the government uses carbon tax revenues in four different ways: (i) wastefully spent, i.e. not rebated back to the economy ("Wasteful spending"); (ii) used to subsidise green energy, such as wind projects ("Green subsidy"); (iii) used to subsidise all non-dirty sectors ("Useful spending"); or (iv) used to subsidise education expenditures for all non-dirty sectors in the economy ("Education subsidy").

Imposing a carbon tax causes the oil, coal and natural gas sectors to shrink, with a loss in employment of 20-40 %. A carbon tax makes dirty sectors more expensive relative to others. As a result, these sectors shrink and labour demand and wages fall. Workers reoptimise their occupational decisions and some switch sectors. Figure A shows the changes in equilibrium labour by sectors. Employment in the oil, coal and natural gas sectors drops, with losses ranging from 20 % to 40 %, depending on the revenue recycling scheme. With a clean energy subsidy, inputs are reallocated from the dirty energy sectors to the green sector to equalise marginal returns. This yields an increase in employment in this sector of more than 30 %. With an education subsidy, human capital rises because education becomes relatively cheaper, thus reinforcing the increase in effective labour to the sectors not directly affected by the carbon tax. The occupational decision of workers is driven by their innate abilities and the wage offered by each occupation. Marginal workers with relatively low productivity in the dirty energy sectors reallocate to other sectors of the economy. Workers with a comparative advantage in the dirty energy sectors remain in these sectors following the policy change. Therefore, due to a selection effect, the average productivity of workers in the taxed sectors rises (Figure B). In the green subsidy

1 Portugal originally pledged a reduction target of 30 % to 40 % by 2030, below 2005 levels. Later on, it assumed a reduction target of 65 % to 75 % by 2040, below 2005 levels. Hence, in our experiments we target the mid-points of these intervals, respectively, meaning 35 and 70 %.

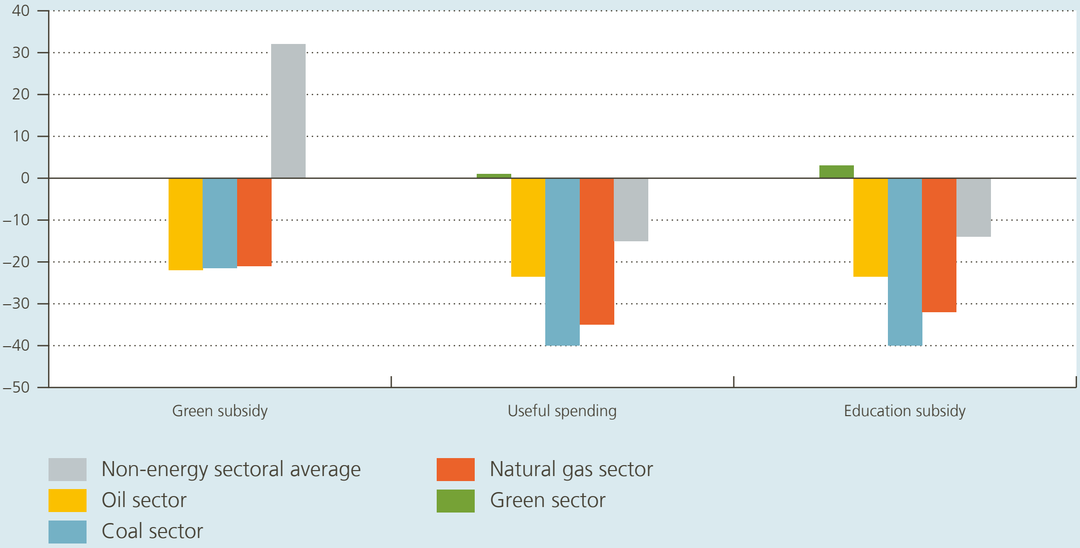
2 The carbon tax is introduced as a sales tax for each energy type and is equivalent to 53 and € 129.5 per tonne of CO_2 in Portugal.

scenario, average productivity drops by 10 % in the green sector due to the larger prevalence of workers in this sector, as depicted in Figure A.

Figure A

Change in effective labour upon increasing the carbon tax from 0 % (benchmark) to 32.9 %

(percentage)



Source: Hasna et al. (2022).
Notes: For the sake of space, the results obtained for an 80.4 % carbon tax are not reported. The effects across sectors and tax rebate schemes are qualitatively similar, but naturally amplified.

The welfare of "stayers" in the dirty sectors declines the most. To study the distributional effects at the individual level, workers are split into four categories: (i) those who remain in the non-dirty energy sectors; (ii) those who reallocate from the non-dirty energy sectors; (iii) those who remain in the dirty energy sectors; and (iv) those who reallocate from the dirty energy sectors. Following the policy implementation, welfare changes are tracked. Table A shows that workers who remain in the dirty sectors (oil, coal and natural gas) experience the largest decline in welfare. In the wasteful spending scenario of a 32.9 % carbon tax (Panel A), for instance, the welfare of stayers in the dirty sectors declines by 16.8 %. This loss is almost twice as much as the loss experienced by those who managed to switch out of the dirty sectors (9.7 %) and almost five times the loss endured by non-dirty workers (stayers and switchers). However, these most heavily affected workers account for less than 0.5 % of the Portuguese labour force. This decline in welfare is due to the reduction in labour demand and wages in the taxed sectors. Due to general equilibrium effects, labour reallocation also takes place in the non-dirty sectors. Faced with a higher carbon tax (Panel B), workers who remain in the dirty sectors are hit harder and experience welfare losses ranging from 30 % to 42 %, compared to a welfare loss of 17 % to 23 % among workers who managed to reallocate out of the dirty sectors and of 11 % to 12 % among workers not present in the dirty energy sectors. As such, workers with a comparative advantage in dirty energy production are still the hardest hit, but now constitute only 0.2 % of the Portuguese labour force.

Figure B

Welfare analysis

Source: Hasna et al. (2022).
Notes: CE denotes consumption equivalent variation; LFP stands for labour force participation.

This box is based on Hasna et al. *(2022).*

5. Concluding remarks

The impacts of climate change and the green transition are likely to be heterogeneous across geographical areas. Certain regions heavily reliant on carbon-intensive industries may experience more significant short-term disruptions, while others with a strong focus on renewable energy and sustainable practices may benefit from the transition. The impact of rising temperatures on labour productivity is likely to be positive for Northern European countries but negative for Southern European countries. Meanwhile, extreme weather events, having an almost entirely negative impact on output and productivity, are likely to have a relatively higher impact on Southern Europe.

Shifting towards a greener economy is important for mitigating climate change, but could temporarily decrease overall labour productivity. An orderly transition where carbon prices gradually rise ensures that industries and firms have sufficient time and resources to adapt to new regulations and invest in sustainable practices and technologies. Although there may be some short-term productivity setbacks as marginal costs increase and demand decreases, the long-term outlook is more favourable. In contrast, a disorderly transition, where the authorities are late in implementing the policies needed to enable the transition, could have severe long-term consequences, particularly for the energy sector. In such a scenario, longer-term emissions costs must be significantly higher than they would have been under an orderly transition and are therefore more distortionary.

Stricter environmental protection is beneficial for industry-level productivity growth in countries that are at the technology frontier. The impact of climate policies on resource reallocation across sectors is likely negative, as the more carbon-intensive sectors are currently more productive than the sectors that are expected to grow due to the green transition. On a longer-term horizon, there is evidence of technology diffusion from leading industries to lagging ones and of catch-up for other country-industry pairs.

Tighter environmental regulation can be negative for productivity growth in the short term, but provides the right incentive to invest in green innovation which could support productivity growth in the long run. The impact, however, on firms' innovation capabilities and productivity growth is heterogeneous across firms. Smaller firms that have a harder time in securing finance and less experience in creating or adapting new innovations may initially face challenges and see a decline in their productivity growth. However, their productivity outlook improves as they gradually adjust and gain access to support mechanisms, such as financial assistance and technological expertise. Environmental regulations can spur green innovation, without crowding out other types of innovation. This investment in green technology might lead to productivity gains capable of offsetting compliance costs in the long term. Market-based instruments, like carbon taxes, are not enough in themselves to spur investment in green innovation and productivity growth. As others have found, the green transition also calls for an increase in green R&D efforts and non-market policies such as standards and regulations, where carbon pricing is less adequate. Survey-based evidence shows that other factors related to reputational risks and demand are also important in driving corporate green performance.

The positive cleansing effects within a sector are likely dampened at the aggregate level as less productive sectors could grow more. Stricter regulation and higher carbon prices are indeed likely to induce clean-up effects within a sector, as the least productive firms are pushed out of the market. Nevertheless, since overall demand is likely to shift towards greener, yet less productive, industries, between-sector reallocation is likely to produce opposite productivity effects.

In conclusion, while shifting towards a greener economy can lead to temporary declines in labour productivity in the shorter term, it could yield several long-term productivity benefits. These rewards would include a lower risk of stranded assets, thus minimising the disruption and driving productivity improvements through innovation and efficiency gains. Market-based policies, such as carbon taxes, and support mechanisms for firms can help mitigate the adverse short-term impacts of the green transition on labour productivity. While the reallocation of production factors during the transition period may initially have a negative impact on productivity, firms can gradually adapt and optimise their operations to fall in line with sustainable practices, resulting in long-term productivity gains.

However, the economics surrounding climate change and the transition towards sustainability entail significant uncertainties and gaps in knowledge. The paths of transition can vary; the scenarios for climatic changes are uncertain; future technologies and their costs remain unknown; and comprehending the economic consequences remains a challenging task. Crucially, the lessons learned from past climate-related events and policies must be effectively extrapolated to address more significant changes and bolder policy trajectories in the future.

Annex

Table A

A limited reallocation from the 20 % most emission-intensive firms ("brown zombies") toward the 80 % least intensive firms within sectors can decrease emissions by 15-38 % ; this reallocation concerns 6-10 % of output

(in units, unless otherwise stated)

	80 % least emission-intensive firms				20 % most emission-intensive firms "brown zombies"				Emission savings	
	# firms	Value added	Emissions	Intensity	# firms	Value added	Emissions	Intensity	Emissions	Total (in %)
Combustion	621	165 062	17 760 229	108	159	4 449	27 136 280	6 099	26 657 580	59
Refining	40	24 166	56 603 202	2342	10	1148	23 755 133	20 693	21 066 212	26
Coke	4	57	1 377 279	24 163			49 870	49 870	25 707	2
Metal ore	10	899	2 420 491	2692	2	749	5 775 289	7 711	3 758 662	46
Iron or steel	83	5 211	8 299 130	1 593	21	5 076	74 718 476	14 720	66 634 348	80
Ferrous metals	89	7381	3 112 029	422	22	1 009	7 291 526	7 226	6 866 105	66
Primary aluminium	9	1686	3 865509	2 293	2	123	1 047 211	8 514	765 208	16
Secondary aluminium	13	712	730 186	1026	3	56	159 716	2852	102 286	11
Non-ferrous metals	43	3 981	1 945 098	489	10	304	2 407 031	7918	2 258 498	52
Cement clinker	64	4 957	69 913 969	14 104		367	15 243 223	41 535	10 067 022	12
Lime	52	1 441	14 975 566	10 392	13	46	2 059 478	44 771	1 581 424	9
Glass	137	6 894	10 357 700	1 502	35	853	3 985 795	4 673	2 704 229	19
Ceramics	278	5 356	7 888 791	1 473	71	291	2 058 235	7 073	1 629 624	16
Mineral wool	30	1 143	1 616 682	1 414	7	37	138 774	3 751	86 440	5
Gypsum or plasterboard	20	1 100	1 020 474	928		76	169 498	2 230	98 993	8
Pulp	88	7 335	4 254 649	580	22	342	1 307 165	3822	1 108 789	20
Paper or cardboard	192	8 184	9 069 570	1 108	49	966	4 300 574	4 452	3 230 046	24
Carbon black		1 085	1 503 299	1386		2	94 671	47 336	91 900	6
Nitric acid		542	1 627 898	3 004		1	22 488	22 488	19 484	1
Adipic acid	1	35	95 214	2 720						
Ammonia		749	10 146 416	13 547		16	694 956	43 435	478 210	4
Bulk chemicals	83	7 383	10 192 048	1 380	21	2 320	15 245 741	6 571	12 043 039	47
Hydrogen	11	1 507	2 405 103	1 596	2	58	1 846 508	31 836	1 753 943	41
Soda ash	4	200	1 378 128	6 891		95	1 008 094	10 612	353 483	15
Other		335	769 002	2 296		32	301 929	9435	228 472	21
Oil and gas	81	13 230	11 714743	885	20	665	8 103 617	12 186	7 514 781	38
Total	1 983	270 631	255 042 405	942	496	19 082 6,6 % [2]	198 921 278 42,8 % [2]	10 425	171 124 485	38
Total (excluding activities with high heterogeneity of intensity) [3]	499	26 916	112 665 406	4 186	123	3 371 11,1 % [2]	32 874 929 22,6 % [2]	9 752	21 898 758	15

Sources : EUETS.info, Orbis, Bijnens and Swartenbroekx (2024).

Notes : Based on analysis of firms within the EU ETS. Figures for 2019. Value added in € millions, emissions in tCO_2-eq, emission intensity tCO_2-eq per € million value added. Sectors refers to activities defined within the EU ETS. Oil and gas are not an activity listed within the EU ETS. Firms with NACE 2-digit code 6 are attributed to oil and gas.

1 Emission savings (in tCO_2-eq, in the percentage of total emissions) if the bottom 20 % most emission-intensive firms would produce the same output, but with the average intensity of the 80 % least intensive firms.

2 Represents the share in the percentage of value added or emissions of the 20 % most emission-intensive firms in the value added or emissions of all firms.

3 Excludes activities where the ratio of emission intensity of the bottom 20 % and top 80 % by performance is above the median ratio (4.3). This includes coke, metal ore, primary and secondary aluminium, cement clinker, glass, mineral wool, gypsum and plasterboard, paper or cardboard box, ammonia, soda ash and other.

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Conventional signs

€	euro
%	per cent
°C	Celsius
excl.	excluding
e.g.	*exempli gratia* (for example)
EUR	euro
et al.	*et alia* (and others
i.e.	*id est* (that is)
pp.	percentage point
USD	US dollar

List of abbreviations

Countries or regions

BG	Bulgaria
CY	Cyprus
DE	Germany
DK	Denmark
EE	Estonia
ES	Spain
FR	France
HR	Croatia
HU	Hungary
LT	Lithuania
LU	Luxembourg
MT	Malta
PL	Poland
PT	Potugal
RO	Romania
SE	Sweden
SI	Slovenia
SK	Slovakia
EA	Euro area
EU	European Union
US	United States
UK	United Kingdom

Abbreviations

ACEA	European Automobile Manufacturers' Association
BACH	Bank for the Accounts of Companies Harmonized
CBAM	Carbon Border Adjustment Mechanism
CCATs	Climate Change Adaptation Technologies
CCMTs	Climate Change Mitigation Technologies
CCPs	Climate Change Policies
CCTPs	Climate Change Technologies/Policies
CCTs	Climate Change Technologies
CES	Constant Elasticity of Substitution
CIS	Community Innovation Survey

CMU	Capital Markets Union
CPC	Cooperative Patent Classification
CO_2	Carbon dioxide
COVID-19	Coronavirus disease-19
CRU	Climate Research Unit
CTCN	Climate Technology Centre and Network
DSGE	Dynamic stochastic general equilibrium
EBITDA	Earnings Before Interest, Taxes, Depreciation, and Amortization
ECB	European Central Bank
EC-JRC/OECD	European Commissions's Joint Research Center of The Organization for Economic Cooperation and Development
ELV	Emission limit value
EMuSe	Environmental Multi-Sector
EPS	Environmental Policy Stringency
ESCB	European System of Central Banks
ESG	Environmental, Social and Governance
EU-ETS	European Union Emissions Trading System
Eurostat	European Statistical Office
ETS	Emissions Trading System
FTSE	Financial Times Stock Exchange
GDP	Gross Domestic Product
GHGS	Greenhouse Gasses
IAMs	Integrated Assessment Models
IP	Intellectual Property
IRENA	International Renewable Energy Agency
IRF	Impulse Response Function
MMF	Multiannual Financial Framework
NACE	Nomenclature générale des Activités économiques dans les Communautés Européennes
NGEU	Next Generation EU
NGFS	Network of Central Banks and Supervisors for Greening the Financial System
NUTS	Nomenclature of Territorial Units for Statistics
OECD	Organisation for Economic Cooperation and Development
R&D	Research and Development
SBS	Structural Business Statistics
UN	United Nations
TFP	Total Factor Productivity
WDI	World Development Indicators
WGI	Worldwide Governance Indicators

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