Climate change and climate policy: analytical requirements and options from a central bank perspective

Ever since the start of the Industrial Revolution, the global average temperature has been increasing significantly. Most of this global warming is attributable to human activities. The effects of climate change on people and the environment are already being felt, and there is a risk of considerable damage in the long term. With that in mind, there is a broad consensus that appropriate measures need to be taken to combat climate change. Initiatives to this end are under way. Both climate change and climate policy will have far-reaching implications for macroeconomic developments, which is why central banks need to engage with this topic.

Alongside the macroeconomic effects of extreme weather events and gradually rising temperatures, attention is likely to turn to the impact of climate policy, in particular, in the near future. Measures such as significantly increasing the cost of greenhouse gas emissions are aimed at triggering far-reaching economic adjustment processes. This means that it is not only climate change itself but also climate policy that will affect different sectors to varying degrees. It stands to reason that certain regions, too, will be more heavily affected than others. These disparities could affect macroeconomic dynamics and monetary policy transmission. Climate change and climate policy may also give rise to risk concentrations that contribute to the build-up of systemic risk in the financial system and thus pose a potential threat to financial stability. The Bundesbank presented an initial analysis of the risks posed by climate action to the German financial system as part of its 2021 Financial Stability Review. Additionally, climate change and climate policy have a significant global dimension. All countries need to play their part in combating climate change. Action lacking sufficient coordination at the international level may result in distortions. All of this poses additional challenges to macroeconomic analysis, which is key to monetary policy and macroprudential decision-making. The Bundesbank is therefore adapting its analytical toolkit with the aim of being able to adequately study adjustment processes driven by climate change and climate policy, examining their sectoral and regional dimensions in an international context.

Relevance of climate change and climate policy for central banks

Global warming as a consequence of anthropogenic greenhouse gas emissions

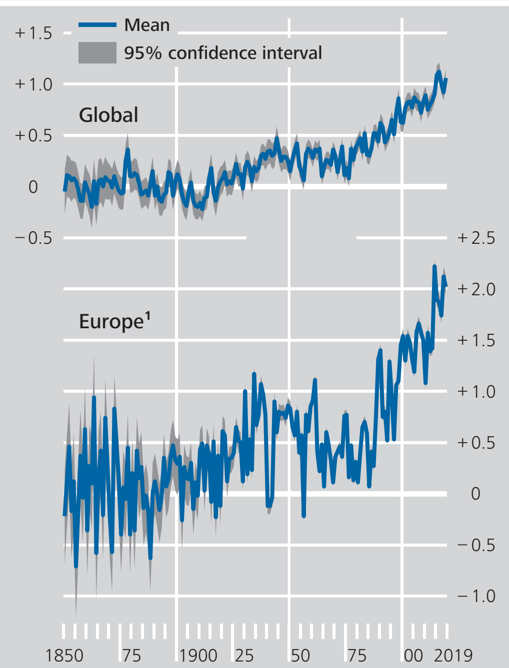
Ever since the start of the Industrial Revolution, the global average temperature has been rising significantly. It has been proven that most of this global warming is due to anthropogenic emissions of greenhouse gases.[1] There is also strong evidence to suggest that rising temperatures will spur further changes in the climate.[2]

Effects of climate change already being felt

Some of the effects triggered by global climate change are already being felt. These include the greater frequency and intensity of extreme weather events such as heat waves, dry spells and torrential rainfall.[3] Such effects are expected to be amplified as the climate continues to warm. Climate action is therefore one of the biggest challenges facing society today, and it is the task of governments and parliaments to set this in motion via climate policy.

Temperature anomaly*

°C



Sources: European Environment Agency, Met Office Hadley Centre and Climatic Research Unit. * Deviation of the annual average near-surface air temperature from the mean value for the years from 1850 to 1899. **1** Defined here as the land mass from 34°N to 72°N and −25°E to 45°E.

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Global dimension of climate problem

Particular political challenges arise from the global dimension of climate change and climate policy. Global efforts are required to combat climate change. This is why, on top of national initiatives, international agreements such as the Paris Agreement have a crucial role to play. In addition, the risk of irreversible climate change means there is greater urgency to act.[4]

Central banks, too, have to deal with climate change and climate policy

Central banks also have to deal with climate change and climate policy. Climate change and climate policy influence macroeconomic developments and may affect price and financial stability. This may make it more difficult for central banks to fulfil their tasks.[5]

Physical risks …

For example, physical risks such as rising average temperatures or more frequent extreme weather events may cause lasting harm to aggregate potential growth. Since the equilibrium real interest rate also depends on aggregate potential output, this would narrow the room for manoeuvre for conventional monetary policy measures. A lower equilibrium real interest rate increases the likelihood of monetary policy hitting the zero lower bound.[6] The consequences of climate change may also put pressure on the financial system and thereby make monetary policy transmission more difficult if, for example, extreme weather events are accompanied by substantial financial losses.

… and transition risks …

There are also transition risks associated with greening the economy. Measures such as significantly increasing the cost of greenhouse gas emissions are aimed at triggering far-reaching economic adjustment processes. This, too, may make it more difficult to safeguard price and financial stability if, for example, profound structural change triggers a widespread revalu-

1 See Intergovernmental Panel on Climate Change (2021).
2 See Intergovernmental Panel on Climate Change (2018).
3 See Intergovernmental Panel on Climate Change (2021).
4 The likelihood of irreversible climate change increases in line with average global warming. See Intergovernmental Panel on Climate Change (2021).
5 See also Deutsche Bundesbank (2021a).
6 See also Deutsche Bundesbank (2017a).

ation of assets.[7] Risks could also arise from changes in consumer behaviour brought on by the transition or from technological progress driven by climate policy.

… interact with one another

Physical and transition risks can be considered dynamic processes that interact with one another. These risks can be reduced in general by a forward-looking, predictable climate policy, whereas physical risks will mount in the face of climate policy inaction, with the threat of abrupt climate policy adjustments further down the line and ensuing transition risks.

Monetary policy analysis faced with new challenges

Climate change and climate policy therefore present monetary policy analysis with new challenges, too. Expectations or uncertainty about the occurrence and extent of climate damage as well as the future course of climate policy may influence economic activity.[8] Climate risks may also make it more difficult to identify economic drivers and prepare macroeconomic projections.[9]

In addition to global dimension, these include …

The global dimension of climate change and climate policy makes macroeconomic analysis particularly challenging. Looking at countries in isolation paints an incomplete picture of both the causes and the consequences of climate change.[10] The effects of climate action, too, are felt across national borders.

… regional and sectoral differences in importance of climate risks

The international distribution of physical and transition risks is also relevant to monetary policy because of its possible consequences, especially for a currency union such as the euro area. It is a similar story with respect to the accumulation of climate risks in certain sectors. Climate change and climate policy may give rise to risk concentrations that contribute to the build-up of systemic risk in the financial system and pose a potential threat to financial stability.[11]

Adjusting the analytical toolkit

Review of monetary policy analytical toolkit

To meet these challenges, it is necessary to review and, where necessary, adjust the monetary policy analytical toolkit. This is also true of macroeconomic analysis, which is key to monetary policy decision-making. Following the Eurosystem’s latest monetary policy strategy review, the ECB therefore announced that it would expand its analytical capacity in macroeconomic modelling with regard to climate change and climate policy.[12]

Macroeconomic climate models: modelling interactions between climate and economic activity …

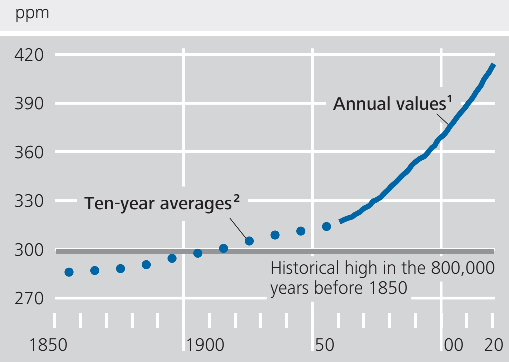
This includes, inter alia, incorporating macroeconomic climate models, known as integrated assessment models (IAMs). The combination of model elements from economics and climate research is characteristic of this model class. The idea behind this is to capture the interdependence of climate and economic activity in a relatively simple way.[13] In an IAM, it is usually assumed that greenhouse gases are emitted in the course of economic activity. This subsequently leads to an increase in the global average temperature, which in turn has an impact on economic activity. This can be represented, for example, by a functional relationship between the average global temperature and output: the damage function.

… as well as climate policy

On the basis of such models, costs and benefits can be weighed against each other to determine optimal emission pathways and thus consistent climate action.[14] Alternatively, a climate policy goal can be specified directly, for example in the form of a global average temperature or a cap on greenhouse gas emissions. The agents in the model then make their decisions subject to this constraint.

7 See, inter alia, Deutsche Bundesbank (2021b).
8 See, inter alia, Deutsche Bundesbank (2018).
9 See Drudi et al. (2021).
10 See also Hsiang and Kopp (2018).
11 See Deutsche Bundesbank (2021b).
12 See European Central Bank (2021).
13 See, inter alia, Nordhaus (2013) and Hassler et al. (2016).
14 See, inter alia, Weitzmann (2012) and Nordhaus (2013).

Atmospheric CO_2 concentration since 1850*



Sources: National Oceanic and Atmospheric Administration, Bereiter et al. (2015) and Bundesbank calculations. **1** Data from 1960 onwards are from the Hawaiian Mauna Loa atmospheric baseline observatory. **2** Reconstruction of atmospheric CO_2 concentration before 1960 based on studies of ice cores.

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Deployment and adjustment of conventional analytical toolkit

However, the macroeconomic effects of climate change and climate policy can also be examined using modelling approaches that more closely resemble the macroeconomic analysis traditionally conducted by central banks. For example, established econometric methods can be used to estimate the macroeconomic impact of climate change.[15] In addition, structural macroeconomic models, such as dynamic stochastic general equilibrium (DSGE) models,[16] can be modified in such a way that they can be used to investigate the consequences of extreme weather and the effects of climate policy.[17] Using models of this kind, macroeconomic adjustment processes can be examined in more detail than is possible with macroeconomic climate models. The environmental multi-sector DSGE model EMuSe, which was developed at the Bundesbank, can be used in particular to analyse adjustment processes driven by climate policy in an international context and flexibly adapted to various policy questions (see the box on pp. 50 ff.).[18]

Macroeconomic effects of climate change

Greenhouse effect amplified by use of fossil fuels

The concentration of greenhouse gases in the atmosphere has been rising steadily for around 200 years.[19] This trend, which is due largely to the use of fossil fuels, is amplifying the natural greenhouse effect. In Earth's atmosphere, the balance between incoming and outgoing solar radiation is changing in such a way that net solar radiation is increasing.[20] Climate projections show that, in the absence of climate policy intervention, this trend will continue.[21] However, there is still uncertainty as to how much the heightened concentration of greenhouse gases in the atmosphere will affect the global average temperature.[22] The expected regional distribution of temperature changes is especially fraught with uncertainty. In addition to rising global temperatures, climate change is accompanied by a host of other effects, some varying quite widely from region to region. These include rising sea levels, changing precipitation patterns and more frequent and more extreme weather events.[23]

Climate change as a trigger for adjustment processes

It is already clear today that climate change will bring irreversible changes in its wake.[24] In addition to the direct effects, this will result in further adjustment processes. Both the direct consequences and the adjustment processes that they trigger will affect the economy as a whole.

15 See, inter alia, Dell et al. (2014), Burke et al. (2015) and Gallic and Vermandel (2020).
16 A characteristic feature of this model class is the approach of explaining macroeconomic relationships and developments based on the individual optimal decisions of (typically) rational economic agents. This model framework is presented in detail, inter alia, in Christiano et al. (2018).
17 See, inter alia, Gallic and Vermandel (2020), Heutel (2012) and Golosov et al. (2014).
18 A detailed description of the environmental multi-sector DSGE model EMuSe can be found in Hinterlang et al. (2021).
19 For example, the CO_2 concentration in Earth's atmosphere is almost 1.5 times higher than it was in pre-industrial times. The concentration of methane in the atmosphere saw an even larger increase in the same period, to more than 2.5 times the pre-industrial level. See Intergovernmental Panel on Climate Change (2021).
20 See North (2015).
21 See, inter alia, Intergovernmental Panel on Climate Change (2021) and Network of Central Banks and Supervisors for Greening the Financial System (2021a).
22 This uncertainty is reflected in the range of temperature increases to be expected as a result of the rising concentration of greenhouse gases, which was calculated using various climate science methods. See Intergovernmental Panel on Climate Change (2021).
23 See Intergovernmental Panel on Climate Change (2014).
24 See Intergovernmental Panel on Climate Change (2021).

Gradual temperature increase

Impact of gradual warming on labour input, productivity …

The gradual increase in average temperatures affects economic activity in a variety of ways, with the impact depending on the initial temperature. Human health and performance suffer at high temperatures.[25] As a result, when certain temperature thresholds are exceeded, it is not just productivity but also labour input that decreases.[26] Climate-related migration can also have repercussions for employment.[27] Where initial temperatures are low, however, a temperature increase could have a positive effect on labour input and productivity.[28]

… as well as natural …

The increase in average temperatures also affects the production factor capital. A distinction should be made between different types of capital. On the one hand, a lasting impact on natural capital is foreseeable. For example, increasing water scarcity may affect output in certain regions.[29] By contrast, some countries would stand to benefit temporarily from a temperature rise, since the production conditions for certain goods, such as those in agriculture, would improve.[30]

… and physical capital

On the other hand, gradual warming may have consequences for the physical capital stock. For example, infrastructure and production facilities could conceivably be damaged or age faster as a result of increased temperatures.[31] Indirect effects stem from the need to adjust the capital stock to evolving environmental conditions or from changes in investment behaviour.[32] This is detrimental if, on account of climate considerations, it comes at the expense of more productive investment alternatives and the efficiency gains that they would have brought with them have to be sacrificed.[33] A downturn in investor sentiment triggered by climate change – for example, as a result of increased uncertainty or more pessimistic expectations about the future – may even dampen the general propensity to invest, with far-reaching consequences for growth and prosperity.[34]

Effect of gradual warming on demand

A temperature increase can also have economic effects via structural changes in demand. Economic agents' preferences could conceivably change as a result of improved information about the long-term impact of consumption and investment decisions on the climate.[35]

Direction and intensity of effect of gradual temperature increase dependent on a variety of factors

The effects described here may vary significantly across regions, economic sectors and periods under consideration. For example, the adverse effects of temperature increases will be particularly evident in regions that are already hot.[36] When certain thresholds, or climatic tipping points,[37] are reached, the effects on the economy as a whole can sometimes be devastating.[38] From a sectoral perspective, there is strong evidence of adverse implications for agriculture, in particular.[39] However, there are signs pointing to output losses in manufactur-

25 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).
26 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.
27 See, inter alia, Black et al. (2011), Oppenheimer (2013) and Missirian and Schlenker (2017).
28 See also Tol (2018).
29 See, inter alia, World Bank (2016) and Dolan et al. (2021).
30 See, inter alia, Burke et al. (2015) and Tol (2018).
31 See, inter alia, Dietz and Stern (2015).
32 See, inter alia, Fankhauser et al. (1999), Batten (2018) and Andersson et al. (2020).
33 See, inter alia, Stern (2013) and Moyer et al. (2014).
34 Diminishing investment in research and development can also put the brakes on technological progress. See, inter alia, Dietz and Stern (2015) and Letta and Tol (2019).
35 See, inter alia, Moran et al. (2020) and Reisch et al. (2021).
36 See Dell et al. (2012) and Burke et al. (2015).
37 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 with an understanding that the change is irreversible. See Intergovernmental Panel on Climate Change (2018).
38 See Burke et al. (2015), Intergovernmental Panel on Climate Change (2018) and the box on pp. 39 ff.
39 See, inter alia, Deschênes and Greenstone (2007), Schlenker and Roberts (2009), Fisher et al. (2012), Graff Zivin and Neidell (2014), Burke and Emerick (2016), Colacito et al. (2018) and Acevedo et al. (2020) for the United States and Lesk et al. (2016) and Burke et al. (2015) for a global country panel.

ing and certain services sectors, too.[40] In addition, it must be borne in mind that the macroeconomic impact at the sectoral or local level is also associated with spillover effects resulting from economic and financial linkages.

Empirical findings show non-linear relationship between temperature and economic growth

The macroeconomic importance of temperature changes very much depends on whether their effects are permanent.[41] A number of empirical studies indicate that changes in the average temperature affect aggregate growth, with evidence of non-linear relationships.[42] Bundesbank estimations for a panel of European countries come to a similar conclusion (for details, see the box on pp. 39 ff.). According to these results, an increase in the annual average temperature dampens economic growth when a certain threshold is exceeded. The estimated threshold for the annual average temperature is just over 9°C.

In Europe, effects vary widely from region to region

Based on the estimations, the effects of the gradual warming observed in recent decades have varied widely across Europe. While this warming seems to have boosted economic developments in some northern European countries so far because of their lower initial temperatures, the opposite was the case for a number of southern countries. It also 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 amongst euro area economies.[43] Compared with other world regions, however, the loss in output growth in Europe would be rather small (see also the box on pp. 43 f.).[44]

Estimates of climate-related output losses fraught with considerable uncertainty

Estimates of this kind are fraught with considerable uncertainty. First, there is a fundamental degree of estimation and specification uncertainty. For example, international interdependencies are not adequately taken into account in the approach adopted here, but they can be significant. Second, it should be noted that the estimations reflect historical developments. Any statements they lead to regarding the future must come with a caveat. They would need adjusting if there were significant technological advances that had an impact on the climate or if climatic tipping points became relevant, for example.

Results correspond to findings of macroeconomic climate models, …

Nevertheless, the findings described above correspond to projections of macroeconomic climate models. According to IAM simulations, too, labour productivity in Europe would suffer as a result of progressive warming. However, losses would be significantly lower than in other regions of the world.[45] Within Europe, damage in the south would be significantly greater in the long term than in the centre or north of the continent.

… although there is model uncertainty here, too

However, IAM simulations are likewise subject to significant model uncertainty, particularly in terms of the specification of the damage function. Depending on the assumed functional relationship and the parametrisation, there can be major differences in terms of probable economic losses.[46,47]

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40 Output losses in certain services sectors are identified by Hsiang (2010) for Central and South American countries and by Colacito et al. (2018) for the United States. Effects on output in manufacturing or industry are shown by Acevedo et al. (2020) for the United States, Deschênes et al. (2018) for firms in China and Dell et al. (2012) in a global panel. Burke et al. (2015) document non-linear effects for the agricultural and non-agricultural sector.
41 See Fankhauser and Tol (2005), Stern (2013), Tol (2018) and Piontek et al. (2019).
42 See, inter alia, Dell et al. (2012), Dell et al. (2014) and Burke et al. (2015).
43 For example, the projected cumulative damage is many times higher for Spain and Portugal than for Germany.
44 Burke et al. (2015) even derive positive macroeconomic effects of a progressive rise in temperature for Europe from an estimation using global data.
45 IAM projections on the impact of climate change on labour productivity can be accessed via the NGFS CA Climate Impact Explorer: http://climate-impact-explorer.climateanalytics.org/. See also Network of Central Banks and Supervisors for Greening the Financial System (2021a).
46 In addition, the assessment of future damage can depend to a large extent on other factors, such as the social discount rate. See also Bauer and Rudebusch (2021).
47 The damage functions in macroeconomic climate models are therefore a contentious topic. See, inter alia, Weitzmann (2012) and Pindyck (2013).

The impact of changing temperatures on macroeconomic developments in Europe

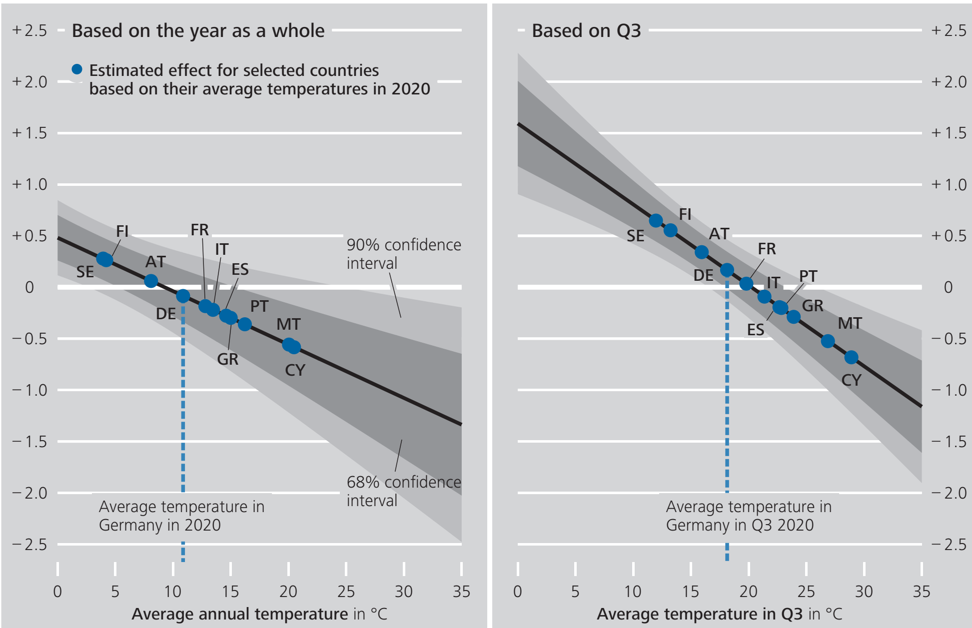
Over the last few decades, average temperatures in Europe have increased markedly. This global warming impacts upon economic activity in various ways. International studies show that high temperatures lead to reduced working hours and lower labour productivity.[1] Barely any studies of this nature have been conducted for Europe.[2]

Panel regressions provide a means of studying the impact of changing temperatures on economic growth. The growth rate of gross domestic product (GDP) in year t in country i ($\Delta y_{i,t}$) is regressed on the respective average annual temperature ($T_{i,t}$).[3] Based on relevant studies, it is assumed that temperature changes themselves are not influenced by economic growth.[4] The model also incorporates the average precipitation ($R_{i,t}$) and lagged values of the GDP growth rate ($\Delta y_{i,t-1}$), country fixed (a_i) and year fixed effects (a_t) and a residual: ($\varepsilon_{i,t}$):[5]

1 See, inter alia, Hsiang (2010), Dell et al. (2014), Graff Zivin and Neidell (2014), Deryugina and Hsiang (2014), Burke et al. (2015) and Colacito et al. (2018).
2 One exception is Holtermann and Rische (2020), which focuses on the relationship between regional growth and temperatures in the European Nomenclature of Territorial Units for Statistics (NUTS)-classified regions of the EU15 countries.
3 The model is based on earlier studies of the global impact of rising temperatures; see Burke et al. (2015) and Dell et al. (2012).
4 See Auffhammer et al. (2013).
5 In view of the strong correlation between precipitation and temperature data, it seems appropriate to include both variables (see Auffhammer et al. (2013)). The 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 GDP growth rate and in the average annual temperature from the European average (see Burke et al. (2015)).

Change in GDP growth for selected initial temperatures given a 1°C rise in the average temperature*

Percentage points



Sources: World Bank, CRU TS climate dataset and Bundesbank calculations. * The effects were estimated using a panel approach. The dataset underlying the estimation consists of data from the Member States of the European Union, Albania, Bosnia and Herzegovina, Iceland, Montenegro, Norway, Serbia, Switzerland and the United Kingdom from 1961 to 2020.
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Estimated impact of the temperature increase between 1960 and 2020 on growth in gross domestic product

Countries	Average temperature in 1960 (°C)	Average temperature in 2020 (°C)	Increase (°C)1	Average increase per year (°C)	Estimated cumulative effect on GDP growth (percentage points)2	68% confidence interval	
Malta	18.95	20.04	1.09	0.02	− 0.89	− 1.55	− 0.24
Cyprus	19.60	20.48	0.88	0.01	− 0.72	− 1.23	− 0.21
Portugal	14.74	16.22	1.48	0.02	− 0.69	− 1.37	0.00
Spain	12.95	14.60	1.65	0.03	− 0.57	− 1.30	0.15
Italy	11.98	13.46	1.48	0.02	− 0.43	− 1.09	0.23
France	10.74	12.80	2.06	0.03	− 0.39	− 1.20	0.42
Greece	14.28	14.99	0.71	0.01	− 0.33	− 0.69	0.03
Belgium	9.73	11.93	2.20	0.04	− 0.25	− 1.06	0.56
Netherlands	9.55	11.61	2.06	0.03	− 0.20	− 0.95	0.56
Germany	8.61	10.87	2.26	0.04	− 0.08	− 0.90	0.75
Ireland	9.22	9.73	0.52	0.01	− 0.01	− 0.21	0.19
Austria	6.11	8.09	1.98	0.03	0.36	− 0.34	1.06
Finland	1.64	4.21	2.57	0.04	1.10	0.42	1.78

Sources: CRU TS climate dataset and Bundesbank calculations. **1** Increase in the average annual temperature between 1960 and 2020. **2** Estimated effect on the annual GDP growth rate in 2020 that can be attributed to the change in the average annual temperature between 1960 and 2020. The calculations are based on the effect of a temperature increase on annual GDP growth estimated in a panel model. The dataset underlying the estimation consists of data from the Member States of the European Union, Albania, Bosnia and Herzegovina, Iceland, Montenegro, Norway, Serbia, Switzerland and the United Kingdom from 1961 to 2020.

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$$\Delta y_{i,t} = \rho\Delta y_{i,t-1} + \beta_1 T_{i,t} + \beta_2 T^2_{i,t} + \gamma_1 R_{i,t} + \gamma_2 R^2_{i,t} + a_i + a_t + \varepsilon_{i,t}.$$

Here, the quadratic terms allow non-linear relationships to be captured.[6] Data for 35 European countries (all 27 EU Member States as well as Albania, Bosnia and Herzegovina, Iceland, Montenegro, Norway, Serbia, Switzerland and the United Kingdom) for the period from 1961 to 2020 are included in the estimation.[7]

The regression results for the group of countries under review indicate that the average annual temperature has a marked impact on economic growth. The linear effect ($\beta_1 = 0.48$) and quadratic effect ($\beta_2 = -0.03$) of the average temperature both show a statistically significant difference from zero at the 95% confidence level. The negative quadratic effect implies that the effect of a rise in temperature is dependent on the initial temperature. Starting from a low temperature, a rise in temperature is beneficial; starting from a high temperature, it has adverse effects. The threshold differentiating low temperatures from high temperatures is 9.3°C.[8] Furthermore, the greater the gap between the initial temperature and the threshold value, the stronger the estimated impact of temperature on GDP.

More in-depth analyses show that the established temperature effect is essentially driven by the summer months. When the annual GDP growth rate is regressed on the

6 Statistical tests, too, favour a quadratic relationship between GDP growth rates and the average temperature over a linear relationship. A quadratic relationship is also supported in international studies (see Burke et al. (2015)).
7 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 GDP growth rates are taken from the World Bank's World Development Indicators. The model is estimated on the basis of an unbalanced panel dataset (for more information, see, inter alia, Cameron and Trivedi (2005)).
8 The results are in line with the findings of related studies. A negative effect on GDP growth is produced in a global panel given an average annual temperature of 13°C or above (Burke et al. (2015)) or 9.2°C or above for regional growth rates in the EU15 (Holtermann and Rische (2020)).

average temperatures and precipitation for the four quarters of the year (rather than the annual average), a statistically significant relationship is only seen for the summer quarter.[9] In addition, the estimated effect is significantly stronger than the impact of the average temperature in terms of the year as a whole. This suggests that temperature increases during the other quarters of the year tend to counteract the growth-inhibiting effect of the hotter summer months.[10]

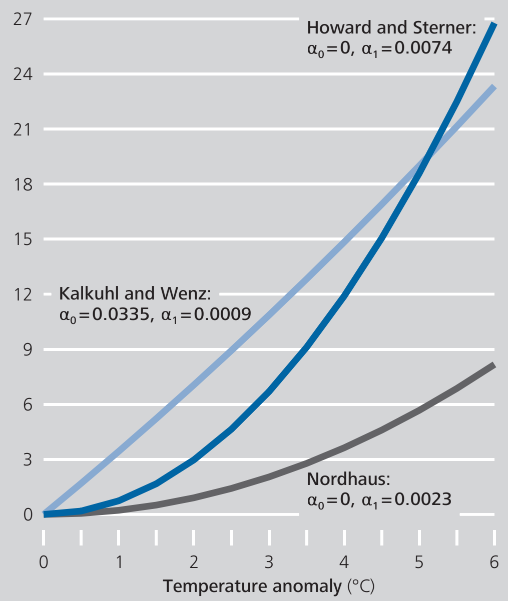
These estimation results indicate that the temperature increase has had a very varied impact on economic growth in the individual European countries to date. Between 1960 and 2020, the average rise in temperature in the European countries each year was between 0.01°C and 0.04°C. Using the estimated coefficients, the average growth effect for each country can be calculated from this.[11] While northern European countries appear to have benefited from the rising temperatures, adverse effects are found in parts of southern Europe.[12] In Finland, the annual GDP growth rate is likely to have risen by around 1.1 percentage points between 1960 and 2020 on account of the temperature effect, according to the estimates. In Cyprus or Malta, by contrast, it probably decreased by between 0.7 and 0.9 percentage point. No statistically significant effects can be seen for western and central Europe, as the average temperatures in these countries were close to the threshold value of 9.3°C during this period. Around this mark, the macroeconomic impact of a rise in temperature is either zero or very slight.

When interpreting these results, it should be borne in mind that estimation uncertainty is high, due in part to sharply fluctuating average annual temperatures over time, in some cases. Furthermore, only historical relationships were analysed, and not all economic effects of climate change were systemically captured. This applies to the impact of extreme weather events,[13] for example, and the spillover effects of climate change in other regions of the world. Moreover, it should be noted that the impact of further rises in temperature may differ from historical relationships. For instance, the macroeconomic costs after passing a climatic tipping point could be significantly higher.[14] Adapting to climate change – say, by means of technical innovations – could, on the other hand, reduce the adverse impact on economic growth.[15] These considerations aside, however, the estimates provide clear indications that a further rise in temperatures would likely weaken economic growth in Europe and create a growth divide.

9 Similar results emerge for the United States and Central America (see Hsiang (2010) and Colacito et al. (2018)).
10 A decline in the number of icy days in the winter quarters, for instance, can have a positive impact on GDP (see Deutsche Bundesbank (2014) and Bloesch and Gourio (2015)). In the cold northern European countries, more in-depth studies identify a rise in temperature in winter and spring as having a positive effect on GDP growth.
11 Here, the aggregate impact is $\sum_{s=1961}^{2020} \rho^{2020-s}[\beta_1(T_{i,s} - T_{i,1960}) + \beta_2(T_{i,s}^2 - T_{i,1960}^2)]$. The confidence bands are calculated using the delta method.
12 Macroeconomic climate models also identify varying effects in the EU countries (see European Commission (2018)).
13 For information on the impact of extreme weather events, see, inter alia, Hsiang and Narita (2012), Lesk et al. (2016) and Deutsche Bundesbank (2017b).
14 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 with an understanding that the change is irreversible. See Intergovernmental Panel on Climate Change (2018).
15 Historically, however, such adaptation has not yet had an impact on the relationship between temperature changes and GDP growth, according to international studies (see Burke et al. (2015)).

Estimated global GDP losses caused by rising temperatures for selected damage functions*

As a percentage of GDP



Source: Bundesbank calculations based on Howard and Sterner (2017), Nordhaus (2017) and Kalkuhl and Wenz (2020). * Assumes a quadratic relationship between the global temperature anomaly τ and physical damage $D(\tau)$: $D(\tau)=\alpha_0\tau+\alpha_1\tau^2$, in which α_0 and α_1 are estimated parameters.
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Extreme weather events

Extreme weather events as …

There is mounting evidence of a link between climate change and the frequency, intensity and concurrence of weather extremes such as storms, floods and droughts.[48] Extreme weather conditions of this kind can bring about disruptions to supply and demand that are both significant in macroeconomic terms and hard to predict,[49] and which also vary across regions and across sectors.[50]

… supply-side …

Such extreme weather events have a direct impact on humans and physical capital in the regions affected.[51] There can also be indirect effects that – at least temporarily – influence economic output outside the disaster-hit regions, for example if supply chains are disrupted or migratory movements are triggered.[52]

… and demand-side disturbances

The demand side, too, can be affected by the indirect consequences of extreme weather phenomena. When households and firms (particularly banks and insurers) experience any kind of asset losses or increased need for write-downs, it acts as a potential damper on consumption and investment demand.[53] But individual regions or sectors may also see boosts to demand, for instance when requests for goods or services that at least for a time cannot be produced in the disaster-hit area are serviced elsewhere. Furthermore, individual sectors may profit from work to tackle the damage caused and to rebuild.[54] Overall, however, sudden extreme weather events are likely to mean economic losses, at least in the short term.[55]

Empirical evidence of weather extremes bringing macroeconomic strain, especially in the short and medium term

The more frequent occurrence of extreme weather conditions is likely to make aggregate output and prices more volatile.[56] Moreover, a sufficiently strong or abrupt fall in asset prices has the potential to pose a threat to financial stability.[57] Potential output may also be affected, although the direction of the effect is ambiguous theoretically. On the one hand, extreme weather events could conceivably wreak lasting damage on natural or physical capital stock, thereby weakening aggregate growth. Potential output could also suffer if private and public investment are cut, for instance due to elevated uncertainty or fiscal burdens.[58] Furthermore, climate-related adjustment measures might conceivably tie up resources – to the detriment of more productive alternative invest-

48 See, inter alia, Böhnisch et al. (2021), Intergovernmental Panel on Climate Change (2021) and Kuhla et al. (2021).
49 See, inter alia, Cavallo and Noy (2011) and Dell et al. (2014).
50 See also Jahn (2015).
51 See, inter alia, Kahn (2005), Keen and Pakko (2011), Anttila-Hughes and Hsiang (2013) and Batten (2018).
52 See, inter alia, Cavallo and Noy (2011), Strobl (2011) and Ghadge et al. (2020).
53 See, inter alia, Fankhauser and Tol (2005) and Bernstein et al. (2019).
54 See, inter alia, Hsiang (2010).
55 This has been shown in a host of empirical studies. See, inter alia, Cavallo and Noy (2011) and Botzen et al. (2019).
56 For example, simulations on the basis of DSGE models show that an increase in the distribution of unexpected extreme weather events can significantly influence the volatility of key macroeconomic variables. See Gallic and Vermandel (2020).
57 See also Deutsche Bundesbank (2021b).
58 See Deutsche Bundesbank (2018) and Deryugina (2017).

Impact of the gradual rise in temperature on trend growth in the German economy

The anticipated gradual rise in temperature raises the question as to what impact this will have on trend growth in the German economy if swift, sustainable action is not taken. The macroeconomic consequences of global warming can be assessed using the scenarios developed by the Network of Central Banks and Supervisors for Greening the Financial System (NGFS).[1] They forecast country-specific developments in average temperature and gross domestic product (GDP) for various emissions pathways.[2] Damage functions are used to establish the relationship between developments in the temperature and in GDP.[3]

The damage function in the NGFS scenarios is calibrated based on the estimation results of the interplay between these two variables in the past. The values for the calibration are taken from Kalkuhl and Wenz's global panel study (2020).[4] According to the estimation results used in the NGFS scenarios, a one-off change in temperature has a level effect on productivity.[5] However, if the average annual temperature rises continuously, the GDP growth rate is lower than the level it would be without the rise in temperature. According to these scenarios, the temperature rise expected in Germany over the course of the current decade would result in only low GDP losses.[6] As of 2030, however, if climate change continues unabated, the impact is likely to be stronger.

These estimates are subject to high uncertainty for various reasons. First, the extent of the rise in temperature for a predefined emissions pathway can only be approximated. This is why the NGFS provides GDP damage for various percentiles of potential temperature development. The median for GDP losses in Germany in 2100 is 2½%. This figure amounts to just over 5% at the 95th percentile. Second, the relationship between average temperature and GDP is unclear. As an alternative to the NGFS damage function, it is also possible to use estimation results that document a correlation between temperature levels and GDP growth rates in European countries (for

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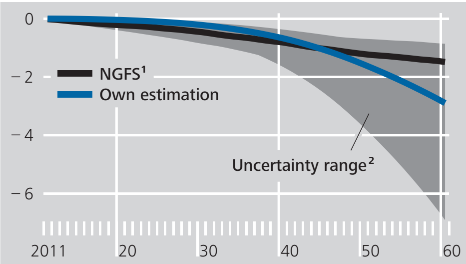
1 See Network of Central Banks and Supervisors for Greening the Financial System (2021b). The results obtained come from an international climate research consortium. Members include the Potsdam Institute for Climate Impact Research (PIK), the International Institute for Applied Systems Analysis (IIASA), the University of Maryland (UMD), Climate Analytics (CA) and the Eidgenössische Technische Hochschule in Zurich (ETH Zurich).
2 For more details on the methodology behind the scenarios and the models used, see Network of Central Banks and Supervisors for Greening the Financial System (2021c). The results presented here are based on the IAM results of the PIK's REMIND model, broken down by country.
3 The construction of the scenarios does not reflect damage that indirectly affects an economy's performance, such as changes to mortality or to the frequency of violent conflict, or damage to biodiversity and the ecosystem. The REMIND IAM can also take account of feedback loops and dynamic effects which lead to adaptations in capital accumulation or savings, or trigger policy responses to prevent emissions. However, such effects do not have a strong bearing on the size of climate costs in the NGFS calculations.
4 The dependent productivity variable in these calculations comprises labour and agricultural productivity as well as capital depreciation.
5 The impact of the temperature level on growth of per capita GDP is statistically insignificant in the estimations. The estimation equation factors in potential non-linearities in the correlation between temperature rise and GDP growth. The results demonstrate that a rise in temperature is driving economic growth in regions that were originally colder and slowing economic growth in areas that are already warmer. This is in line with the findings of other studies.
6 The NGFS' "Current Policies" scenario, which takes into consideration only containment measures that have already been implemented, is used for the scenario of unabated climate change. A hypothetical reference scenario without climate effects is used to calculate the costs of global warming. The GDP pathway in this scenario corresponds to trend growth over the past few decades, which is adjusted for the impact of the coronavirus pandemic using projections made by the International Monetary Fund (2020).

GDP level effects of the gradual rise in temperature in Germany



Sources: NGFS, Potsdam Institute for Climate Impact Research and Bundesbank calculations. **1** Damage function according to Kalkuhl and Wenz (2020). **2** Combination of overlapping uncertainty intervals according to Kalkuhl and Wenz (2020) and own estimation. The underlying developments in GDP and temperature are based on the "Current Policies" scenario in the REMIND integrated assessment model according to NGFS data.

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more details on this, see the box on pp. 39 ff.). According to this alternative method, the rise in temperature lastingly dampens economic growth. In this case, climate change would have a stronger impact on German GDP over the longer term.

In addition, it is important to note that the NGFS scenarios do not model climate damage as a result of more frequent extreme weather events or of tipping points. Yet, as global warming intensifies, these will become more likely and entail considerable macroeconomic consequences. Another factor to be considered is the impact of cross-border trade and migration links which might cause climate-related GDP losses in other countries to spill over into Germany.[7] Moreover, the comparatively small GDP losses in Germany should not blind observers to the fact that massive global GDP damage is expected.[8]

The NGFS calculations also indicate the extent to which macroeconomic damage can be limited by climate policy measures. In the scenario calculations, measures to reduce emissions that are introduced early and are intensified evenly over time (shown in the orderly NGFS scenarios) can considerably reduce both the costs of intervention as well as the costs arising as a result of global warming. If global greenhouse gas neutrality can be achieved in this way by 2050 and global warming can thereby be limited to 1.5°C, the GDP losses expected as a result of the gradual rise in temperature could be limited to 0.6% in 2100 instead of 2.7%. Even if global warming can only be capped at just under 2°C, climate-related GDP losses in Germany will still be significantly lower at 0.8%. If only those national contributions to climate protection pledged at present are implemented, the average temperature is likely to rise by about 2.5°C and GDP losses will be perceptibly greater, estimated at 1.6%. These scenarios assume that the measures implemented do not give rise to considerable GDP losses.[9] GDP losses would be larger if measures to reduce emissions are implemented late or abruptly, or are poorly coordinated. Although the costs would then be incurred at a later point in time, they would be higher overall. From a macroeconomic perspective, these results indicate that the best option is to take decisive steps to implement climate policy action at an early stage.

7 Even if this approach is coupled with the NiGEM model, the country-specific NGFS scenarios do not factor in the additional spillover effects via international trade.
8 According to the calculation by Burke et al. (2015), whose estimation equation is based on a similar specification to that on pp. 39 ff., global GDP losses in 2100 amount to 23%.
9 The assumption that at least some of the tax revenue from carbon pricing is used to finance productive investment plays a major role here (see Etzel et al. (2021)). The information for more stringent climate protection measures refers to the NGFS' "Net Zero 2050" and "Below 2°C" scenarios. The information pertaining to national contributions to climate protection pledged at present refers to the "Nationally Determined Contributions" scenario.

ments. On the other hand, weather extremes could act as an indirect stimulus to aggregate growth, by encouraging innovation and the use of more productive substitute capital. In keeping with this, the empirical evidence on the long-term macroeconomic implications of extreme weather events also paints a mixed picture. While there are indications of macroeconomic effects of a negligible or even stimulating nature, there are also a host of studies pointing towards longer lasting negative pressures.[59]

Other factors alongside geographical location decisive in determining macroeconomic significance of weather extremes

The macroeconomic significance of weather extremes is also dependent on how vulnerable a particular country is. Geographical location is a central factor. For instance, in the past the concentration of extreme weather events in the Asia-Pacific region was many times higher than that in western Europe.[60] Besides geography, a country's vulnerability is further influenced by demographics, agglomeration patterns and other socioeconomic factors.[61] The structure of the economy is also likely to play a significant role, for example on account of the economic relevance of sectors that are particularly vulnerable to extreme weather, such as agriculture.

Significant differences between countries and regions in level of damage from extreme weather

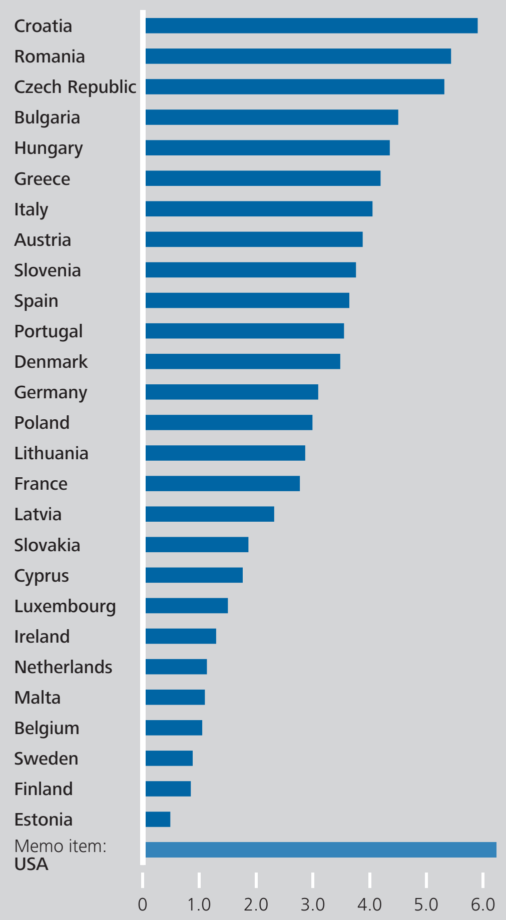
It follows that estimates for the macroeconomic damage caused by weather extremes are different for different regions of the world.[62] So far, economic damage in Asia has been many times higher than that seen on the continent of Europe.[63] There have also been differences throughout Europe, however. Relative to respective GDP, the cumulative economic damage of the last 40 years was significantly lower in Estonia and Finland and considerably higher in Greece, Spain and Italy than in the rest of the euro area. That said, the measured losses were far lower even in the worst-hit euro area countries than in other parts of the world.[64]

From a monetary policy perspective, the primary question when it comes to shocks such as the occurrence of extreme weather events is whether and to what extent the associated disruptions to supply and demand widen or narrow the output gap in the short and medium term and increase or reduce inflationary pressures.[65] Looking at the average level of eco-

No crucial significance for monetary policy in euro area in view of economic losses experienced thus far

Cumulative damage in the EU caused by extreme weather and climate change*

As a percentage of 2019 GDP



Sources: European Environment Agency, Haver Analytics, Munich Re, NOAA's National Climate Data Center and Bundesbank calculations * Cumulative economic damage resulting from meteorological disasters (including extreme temperatures and storms), hydrological disasters (including floods) and climatological disasters (including droughts) from 1980 to 2019.

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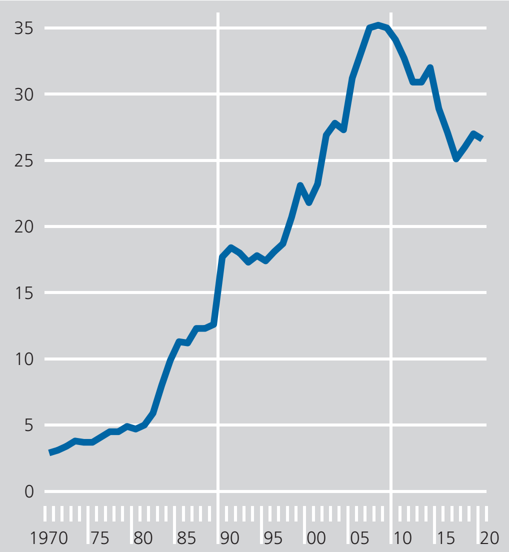
59 See Cavallo and Noy (2011), Jahn (2015) and Botzen et al. (2019).
60 See Cavallo and Noy (2011) and Centre for Research on the Epidemiology of Disasters (2020).
61 See, inter alia, Intergovernmental Panel on Climate Change (2012).
62 See, inter alia, Wallemacq et al. (2018).
63 According to the Emergency Events Database (EM-DAT), the recorded cumulative absolute economic damage resulting from meteorological, hydrological and climatological disasters was roughly three times higher in Asia than in Europe for the period from 2000 to 2020. The data are available at https://www.emdat.be/
64 See Wallemacq et al. (2018).
65 See also Deutsche Bundesbank (2021c).

Number of recorded extreme weather events and wildfires in Europe*

Rolling average of the last ten years



Sources: Emergency Events Database and Bundesbank calculations. * Extreme weather events refer to meteorological disasters (including extreme temperatures and storms), hydrological disasters (including floods) and climatological disasters (including droughts). The data used cover the following European countries: Albania, Austria, Belgium, Bulgaria, France, Germany, Greece, Italy, the Netherlands, Norway, Poland, Portugal, Romania, Switzerland, Spain and the United Kingdom.

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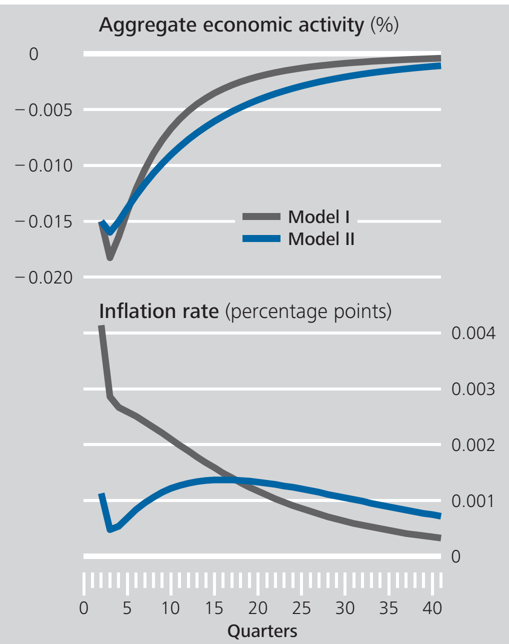
Simulated impact of an extreme weather event under different sectoral disaggregation approaches*

Deviation from deterministic equilibrium



* Impulse responses of aggregate economic activity and annualised inflation rate when using a DSGE model with (model 1) and without (model 2) sectoral production linkages.

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nomic losses to date, it appears that weather extremes are of at least no crucial significance for monetary policy in the euro area.[66]

Relevance for monetary policy in currency area may grow in future though, …

That said, the significance of weather extremes for monetary policy in the euro area could grow.[67] There has already been a considerable increase in the frequency of extreme weather events in Europe in recent decades. It is also conceivable that the rise in weather events of macroeconomic significance in other parts of the world will lead to increasing spillover effects for Europe in future. Furthermore, the mounting incidence of weather extremes could lead to abrupt adjustments in climate policy and thereby to unexpected changes with a bearing on the economy as a whole.[68]

… which would have a bearing on macroeconomic analysis

In addition, the increased frequency of weather extremes is likely to make macroeconomic analysis harder for central banks. This applies both to the identification of relevant economic drivers and the preparation of projections, for instance due to the uncertainty surrounding the horizon over which extreme weather events will exert an effect. Moreover, the established analytical tools may not adequately capture the transmission mechanisms of weather-related disturbances. For example, using a DSGE model, it can be shown that the magnitude of the consumer price response following a weather-induced supply-side shock is heavily dependent on the assumed sectoral structure.[69] A model version without sectoral linkages, of the kind typically used for macroeconomic an-

66 See also Dafermos et al. (2021).
67 See also Böhnisch et al. (2021) and Kuhla et al. (2021).
68 For instance, the series of accidents at the Japanese nuclear power plant Fukushima Daiichi set off by a tsunami had far-reaching implications for economic policy in Germany.
69 The analytical framework used here is a prototypical closed-economy New Keynesian model with physical capital, imperfect competition and nominal price rigidities (see, inter alia, Woodford (2003)). The model is calibrated for the European Union together with the United Kingdom. The specification of the multi-sectoral variant is based on the EMuSe model. See the box on pp. 50 ff.

alysis to date, shows considerably weaker effects than the multi-sectoral variant.[70]

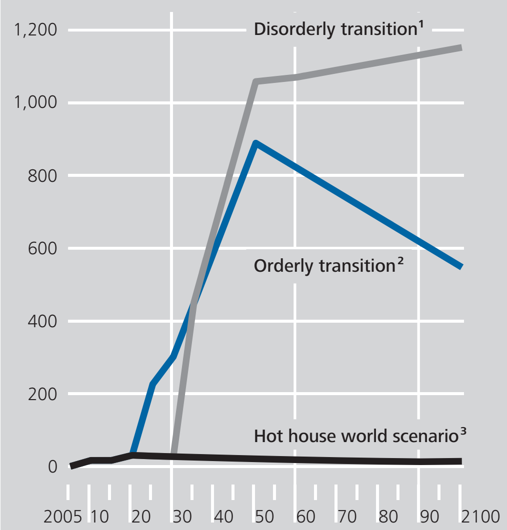
Macroeconomic impact of climate policy

Objectives behind climate policy initiatives

It is not just climate change itself but also the measures introduced with a view to mitigating it that are likely to have a significant macroeconomic impact. In December 2015, 196 countries adopted the Paris Agreement, setting the minimum goal of limiting the increase in the global average temperature to well below 2°C compared to pre-industrial levels.[71] Global greenhouse gas emissions need to be significantly reduced over the coming years if these goals are to be achieved.[72] With this in mind, various measures are being considered. These include a sometimes substantial increase in the cost of greenhouse gas emissions, for example, by introducing emissions taxes or an emissions trading scheme, setting emissions caps or even completely banning certain emissions-intensive economic activities or products.

Projected annual carbon prices in the EU for selected transition scenarios*

US$ per tonne of CO_2 in 2010 prices



Source: NGFS. * The carbon price projections were generated using the Potsdam Institute for Climate Impact Research's REMIND model. **1** It is assumed that far-reaching climate action with a view to limiting global warming to less than 2°C compared with pre-industrial levels is not implemented until 2030. **2** Climate policy's level of intervention is assumed to increase steadily up to the middle of the century with the aim of limiting the rise in the global average temperature to 1.5°C above pre-industrial levels. **3** Only currently implemented climate policies are preserved.
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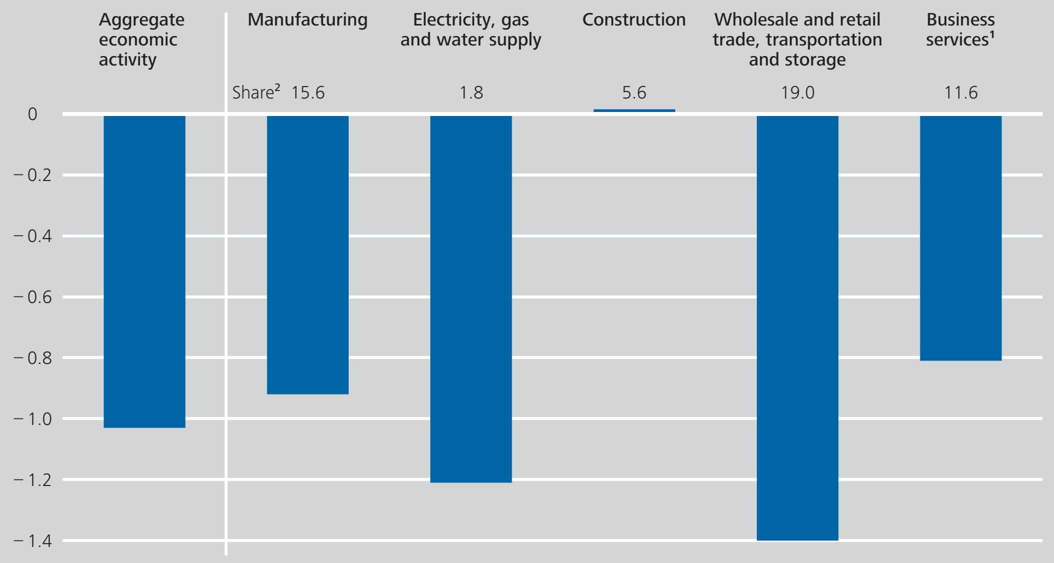
Supply-side effects

The transition to a less carbon-intensive economy may give rise to considerable supply-side strains.[73] These include direct costs as a result of emissions pricing but also increased prices for emissions-intensive intermediate inputs, outlay to avoid emissions or expenses incurred in aligning production with new policies, and losses due to asset repricing.[74] The economic ramifications for firms are likely to depend on the type and nature of interventions as well as the characteristics of the particular economic sector they belong to. This includes the specific emissions and energy intensity as well as the respective market position, the latter being a pivotal factor governing the extent to which costs can be passed on, for example.[75] However, climate policy initiatives may also be designed with a view to incentivising green innovation by firms. This can foster technological advances that boost productivity.[76]

70 The extreme weather event is modelled as a temporary negative supply-side shock, the strength of which is specified such that when the shock occurs value added falls by 0.015% in the first quarter (i.e. 0.06% on an annual basis) in both model versions. This calibration is based on the estimates of Dafermos et al. (2020).
71 Ideally, global warming should be limited to 1.5°C as this would significantly reduce the risks associated with climate change compared with a 2°C scenario. See United Nations (2015).
72 The Intergovernmental Panel on Climate Change (IPCC) describes various scenarios compatible with meeting the goals agreed upon in Paris 2015. In a core scenario, achieving the 1.5°C goal would require global net CO_2 emissions to be cut by 45% compared to 2010 levels by 2030 and brought to zero by 2050. The 2°C goal would require a 25% reduction by 2030 and net zero by 2070. See Intergovernmental Panel on Climate Change (2018).
73 See also Batten (2018) and Andersson et al. (2020).
74 There is a risk of regulatory intervention leading to the sudden or gradual devaluation of a firm's capital ("stranded assets"). This might happen if the firm is no longer permitted to use that capital in production or if production processes cease to be economically viable due to increased emissions prices, for example. See also Deutsche Bundesbank (2021a, 2021b) and the article on pp. 63 ff.
75 See, inter alia, Ryan (2012), Bushnell et al. (2013) and Känzig (2021).
76 Initial findings suggest that carbon pricing introduced as part of the EU Emissions Trading System has spurred innovation in the field of low-carbon technologies. See Calel and Dechezleprêtre (2016) and Känzig (2021). For information on the macroeconomic significance of green innovation, see, inter alia, OECD (2011, 2017a) and European Commission (2019, 2021).

Difference in gross value added between a disorderly and an orderly transition in 2050*

Percentage points



Source: Bundesbank calculations based on the DSGE model EMuSe and projections by the NGFS. * The model is calibrated for the European Union together with the United Kingdom. The entire simulation period extends from 2005 to 2100. The chart shows the respective difference in real gross value added – expressed in relation to the baseline – between a disorderly and an orderly transition. The assumed paths of CO_2 emissions intensity and the carbon price are based on projections by the NGFS (REMIND model). Physical damage caused by emissions is not taken into account. In an orderly transition, climate policy's level of intervention is assumed to increase steadily up to the middle of the century with the aim of limiting the rise in the global average temperature to 1.5°C above pre-industrial levels. In a disorderly transition, it is assumed that far-reaching climate action with a view to limiting global warming to less than 2°C compared with pre-industrial levels is not implemented until 2030. **1** NACE sections M to N: Professional, scientific and technical activities as well as administrative and support service activities. **2** Percentage share of the economic sector in aggregate gross value added in 2019.

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Impact on demand side

Climate policy measures are also likely to have an impact on the demand side. Higher energy costs due to emissions pricing will squeeze the budgets of households and firms. This will tend to dampen consumption and investment, which in turn may affect wages and employment, bringing corresponding consequences for aggregate demand.[77] Individual households and firms may be affected to very different degrees, which would then have a bearing on macroeconomic developments.[78] On the other hand, demand-stimulating effects could stem from investment incentives, the distribution to households of revenue from emissions pricing or from additional public investment.

Predictability of climate policy highly relevant

The predictability of climate policy is likely to be highly relevant when it comes to macroeconomic effects. This is because uncertainty weighs on the consumption and investment decisions of households and firms. Developments that come as a surprise can also trigger extensive revaluations of financial assets, with corresponding consequences for financial stability.[79]

The overall result is a complex layering of supply and demand-side effects whose macroeconomic net impact is not always clear up front.[80]

77 But regulatory requirements, tax incentives and subsidies, higher use costs and changes in preferences may also have a lasting impact on the consumption and investment decisions of households and firms.
78 Empirical studies suggest that low-income households take a comparatively greater hit from the effects of an increase in energy prices. See Känzig (2021).
79 The article on pp. 63 ff. of this report (entitled "Scenario-based equity valuation effects induced by greenhouse gas emissions") quantifies the emissions-related changes in the valuation of global joint stock companies in the event of a swing in market expectations from a scenario where Nationally Determined Contributions are being implemented to a transition scenario in line with the Paris Agreement. See also Deutsche Bundesbank (2021b).
80 Quantitative studies also arrive at correspondingly differing results. In the context of its model analyses, the IPCC concludes that scenarios with a likelihood of limiting global warming to 2°C compared to pre-industrial levels would entail losses in consumption amounting to 2% to 6% of global GDP in 2050. By contrast, the OECD, for example, anticipates a positive growth effect from such a transformation in an ideal case. See Intergovernmental Panel on Climate Change (2014) and OECD (2017a).

Net macroeconomic effect of climate policy measures not always clear

Depending on how it is designed, climate policy may, in the short to medium term, go hand in hand with either a shrinking or a growing output gap and commensurately lower or higher inflationary pressures. Taken by itself, decisive action to mitigate climate change would probably have an initial dampening effect on aggregate growth, but climate-related damage would be reduced in the longer term. The medium-term impact on economic growth also hinges on the design of climate policy and its predictability.[81]

Higher carbon pricing likely to fuel consumer price inflation, at least temporarily

It is likely that a tighter carbon pricing regime would at least temporarily lead to higher inflation. The magnitude of the effect depends primarily on the timing of the climate policy measures, as shown, for example, by macroeconomic climate model projections performed as part of work by the Network of Central Banks and Supervisors for Greening the Financial System (NGFS). The carbon price pathway of an orderly transition where the degree of climate policy intervention is gradually increased exhibits considerable differences from the carbon price pathway under a disorderly climate policy, where it is assumed that intervention comes much later but is then all the more stringent.[82]

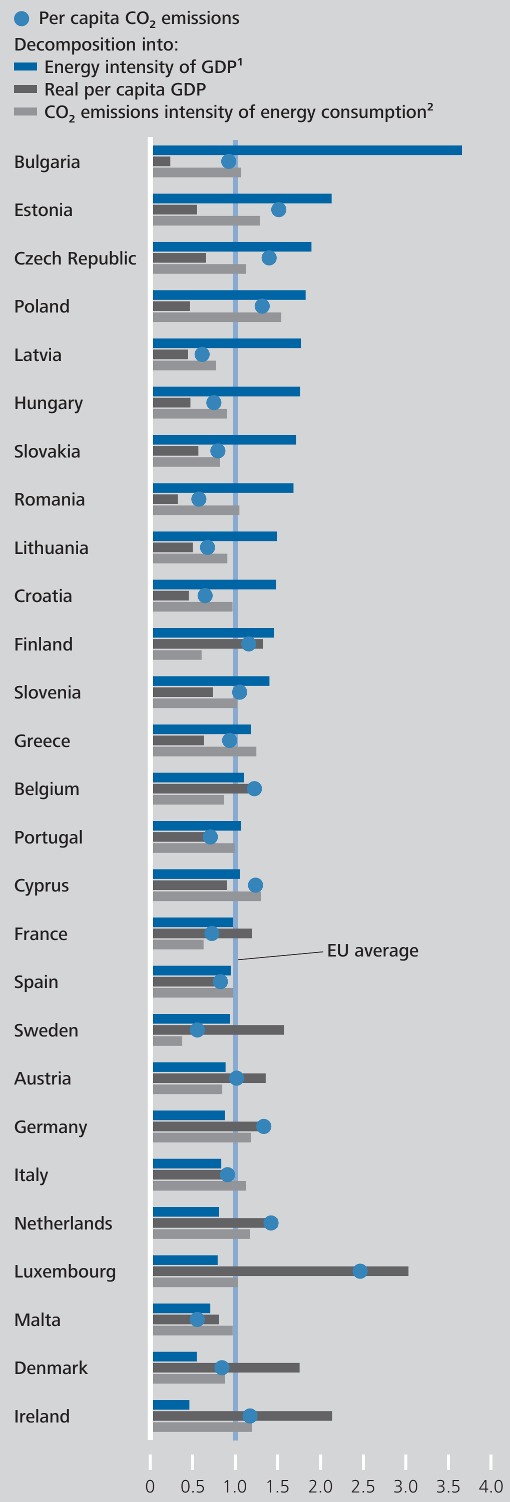
Climate policy has varying …

It must be borne in mind that the burden of climate policy measures varies from one economic sector to the next, a fact that can be illustrated by simulations using the environmental multi-sector DSGE model EMuSe (see the box on pp. 50 ff.). Especially in the case of

81 One factor here is the extent to which carbon revenues are channelled into productive investment.
82 Simulations on the basis of the NiGEM global economic model developed by the National Institute of Economic and Social Research suggest that even an orderly transition scenario could imply significant price increases in the euro area for a time. According to the model projection, consumer price inflation would sit approximately 1 percentage point above the baseline on an average for 2025 to 2035, before moving back towards it over the course of the following decade. The projections are based, amongst other things, on an average carbon price calculated as the arithmetic mean of the carbon price pathways from three of the IAMs used in the NGFS climate scenarios (see Network of Central Banks and Supervisors for Greening the Financial System (2021a)). For further information on NiGEM, see https://nimodel.niesr.ac.uk

Decomposition of per capita CO_2 emissions for the EU Member States in 2019

In relation to EU average



Sources: Eurostat and Bundesbank calculations. **1** Ratio of primary energy consumption to GDP. Primary energy consumption comprises gross domestic consumption and does not include non-energetic use of energy carriers. **2** Ratio of CO_2 emissions caused by energy consumption to primary energy consumption.

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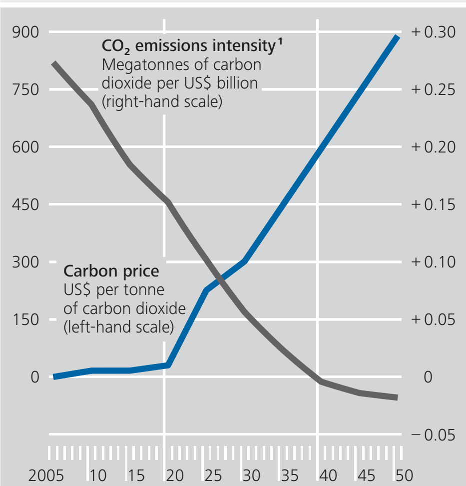
On the role of sectoral linkages when analysing transition risks: the environmental multi-sector DSGE model EMuSe

Climate action may hit certain economic sectors especially hard,[1] which could have far-reaching consequences for financial stability, monetary policy transmission and aggregate growth. This is why it is important to keep an eye on sectoral developments and their macroeconomic implications when analysing climate action. Given the high level of aggregation of economic sectors in prototypical dynamic macroeconomic models, this is either not possible or possible to only a limited extent. Meanwhile, traditional multi-sector models are generally static and focus on long-term equilibria. They are not suitable for analysing key adjustment processes. The Bundesbank therefore developed a dynamic stochastic general equilibrium (DSGE) model with a multi-sector production structure.[2]

Projections of annual carbon prices and CO_2 emissions intensities in the European Union in an orderly transition*

2010 prices



Sources: NGFS and Bundesbank calculations. * The carbon price and CO_2 emissions intensity projections were generated for the European Union together with the United Kingdom using the REMIND model developed by the Potsdam Institute for Climate Impact Research. In an orderly transition, climate policy's level of intervention is assumed to increase steadily up to the middle of the century with the aim of limiting the rise in the global average temperature to 1.5°C above pre-industrial levels. **1** Ratio of CO_2 emissions to macroeconomic activity.
Deutsche Bundesbank

This model contains both key economic and ecological variables such as CO_2 emissions. In addition, it can analyse international linkages between up to three countries or regions. This allows the model, named EMuSe (Environmental Multi-Sector),[3] to be adapted flexibly to various policy questions.[4]

The EMuSe model allows for a relatively detailed examination of the interrelationship between the economy and climate policy. Particularly significant in this regard is the fact that, in the EMuSe model, enterprises use not only capital and labour but also intermediate inputs to produce output. These can come from any sector, although the extent to which various inputs are substitutable is limited. The composition of the intermediate input bundles varies depending on the sector.

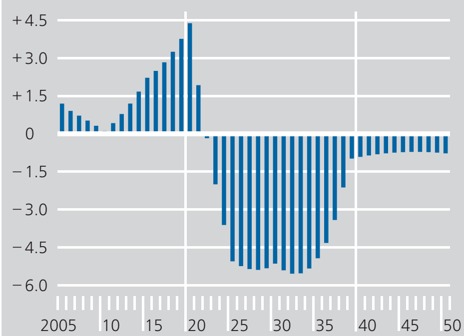
The role played by intersectoral linkages can be illustrated by comparing the simulation results for the multi-sector model with a version without a sectoral breakdown or the corresponding linkages.[5] The impact of carbon pricing on aggregate growth and CO_2 emissions for the European Union and the United Kingdom is analysed here as an

1 See also the remarks on this topic on p. 49.
2 A typical feature of this model class is the way it seeks to explain relationships and developments based on the individual optimal decisions of (typically) rational economic agents. For a detailed explanation of this model framework, see, inter alia, Christiano et al. (2018).
3 A detailed description of the EMuSe model can be found in Hinterlang et al. (2021).
4 Both flexible prices and price rigidities can be assumed, for example.
5 Both models are parametrised to depict the European Union along with the United Kingdom. The aggregate emissions level and aggregate economic activity are identical at the start of the simulation in both versions of the model. The production structure of the multi-sector model comprises ten sectors.

example. For the purposes of simplification, external trade links are excluded and the European Union and the United Kingdom are depicted together as one region. The assumed trajectory for the carbon price is based on the projections made by the Network of Central Banks and Supervisors for Greening the Financial System (NGFS) for an orderly climate policy transition. In these projections, climate policy's level of intervention is assumed to increase steadily up to the middle of the century with the aim of limiting the rise in the global average temperature to 1.5°C above pre-industrial levels.[6] From 2020 onwards, in particular, the carbon price rises sharply.

Difference in real gross value added in an orderly climate policy transition under different sectoral disaggregation approaches*

Percentage points



Source: Bundesbank calculations based on the DSGE model EMuSe and NGFS projections. * The model is calibrated for the European Union together with the United Kingdom. Calculated as the deviation of a ten-sector variant of the model from the one-sector version. The total simulation period spans from 2005 to 2100 and depicts the deviation from a situation without a carbon price and with constant CO_2 emissions intensities in 2005. The development of the CO_2 emissions intensities and the carbon price assumed for the simulation is based on the NGFS projections for an orderly transition scenario according to the REMIND model. In an orderly transition, climate policy's level of intervention is assumed to increase steadily up to the middle of the century with the aim of limiting the rise in the global average temperature to 1.5°C above pre-industrial levels.

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The costs arising from carbon pricing for enterprises within a sector depend on the carbon price, the sector-specific CO_2 emissions intensity and output level. 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.[7] Changes in the emissions intensity over time can be understood here as an approximation of the impact of exogenous environmentally friendly technological progress.[8] In the multi-sector version of the model, it is assumed, for simplicity, that the emissions intensity will change to the same extent across all sectors.

Although the development of CO_2 emissions is very similar in both model versions under these assumptions, there are significant differences in terms of aggregate growth. This is due to the shifts in the production structure triggered by climate action and the consequential effects of these shifts, which are disregarded in the single-sector version. The possibilities of substituting goods in individual sectors with the products of other economic sectors in the production process, as well as complementarities, play a pivotal role. The energy sector, for instance, is particularly affected by carbon pricing, which means that the price of energy will rise faster than many other prices. However, there are limits to the extent that energy can be substituted with other goods as there are complementarities between energy and other intermediate goods. This is why demand for all types of intermediate inputs drops following a strong rise in energy prices, and output is scaled back.

6 The NGFS's carbon price and CO_2 emissions intensity projections were generated using the REMIND-MAgPIE model developed by the Potsdam Institute for Climate Impact Research. See Network of Central Banks and Supervisors for Greening the Financial System (2020).
7 The trajectory of the emissions intensity is also taken from the NGFS's projections. The changes in the carbon price and sectoral emissions intensities thus enter EMuSe exogenously. By contrast, the aggregate emissions intensity (the ratio of aggregate emissions to aggregate economic activity) is endogenous.
8 See also Csereklyei et al. (2016).

According to the simulation, in the multi-sector version, it was possible to make use of the relief provided by the scope for substitution when carbon prices were still low initially. From around 2020 onwards, however, complementarities weighing down on the economy dominate on account of the considerable rise in the carbon price.[9]

The simulation results show that taking into account the sectoral linkages of an economy can be important not only to structural analysis and considerations of financial stability, but also to macroeconomic analysis.[10] This is especially true for larger sectoral shocks, such as the occurrence of physical climate risks or unexpected climate action.

9 Although the level of detail is relatively high, the version of EMuSe used here has been simplified, in some ways considerably. Simplifications include the assumption of homogeneous household preferences that remain constant over time, the omission of endogenous technological progress and the assumption of a closed economy. The results should therefore be interpreted with caution.
10 See also Baqaee and Farhi (2020).

a disorderly transition, it becomes apparent that risk concentrations develop in specific economic sectors. This can contribute to the build-up of systemic risk in the financial system, which could jeopardise financial stability and thus the fulfilment of the monetary policy mandate.[83]

… and sometimes long-lasting impact on individual sectors

It is also probable that climate policy will bring about lasting structural changes, with some economic sectors gaining in importance and others losing ground. This could have repercussions for economic growth and price developments as well as indirect ramifications for monetary policy transmission. The extent to which this will be the case is contingent on sector-specific characteristics such as emissions and energy intensity or how sensitive demand is to changes in price. The degree of friction in product and financial markets is also likely to play a role. Analytical tools such as the EMuSe model can supply helpful insights here.

Regional differences in impact of climate policy

How intense the effects of a harmonised climate policy are can also differ on a regional basis. For example, a decomposition of per capita CO_2 emissions in the European Union (EU) reveals significant differences between Member States with respect to the energy intensity of gross domestic product (GDP) and the CO_2 emissions intensity of energy production.[84] For instance, the average energy inten-

83 See also Deutsche Bundesbank (2021b).
84 In formal terms, the decomposition is expressed as $\widetilde{CO2_i/POP_i} = \widetilde{GDP_i/POP_i} * \widetilde{Energy_i/GDP_i} * \widetilde{CO2_i/Energy_i}$, where $\widetilde{X}_i = X_i/X_{EU}$ is the ratio of a factor in country i to the average for the EU. The decomposition makes it possible to break the annual per capita CO_2 emissions ($CO2_i/POP_i$) in the EU Member States down into different determinants. These include overall output, measured as per capita GDP (GDP_i/POP_i), the energy intensity of GDP ($Energy_i/GDP_i$), given by the ratio of primary energy consumption to GDP, as well as the CO_2 emissions intensity of energy consumption ($CO2_i/Energy_i$), which represents the ratio of CO_2 emissions to primary energy consumption. Primary energy consumption is gross domestic energy consumption excluding energy carriers used for non-energy purposes; the CO_2 emissions are those resulting from the use of energy. In the interests of comparability, the factors are normalised by placing them in relation to the EU-wide average. See also Kaya and Yokobori (1997).

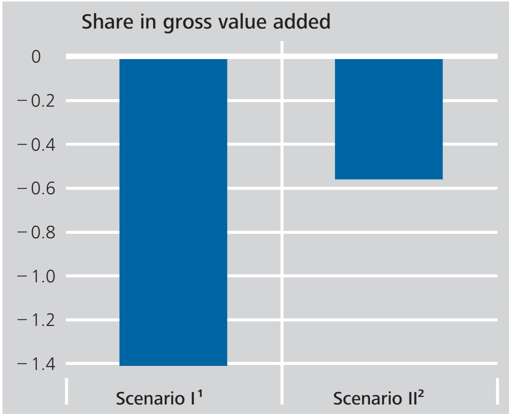
sity of GDP is much higher in the central and eastern EU Member States than in the rest of the EU.

Influence of international climate policy

It is not just domestic climate policy that is expected to exert a considerable influence on macroeconomic developments; climate policy abroad is also likely to be highly influential. For example, unilateral climate policy measures could lead to goods with high emissions and energy intensity profiles increasingly being sourced from overseas. The sector mix at home and abroad would alter, affecting macroeconomic developments and the efficiency of climate policy measures. This is also borne out by EMuSe simulations specifying a carbon pricing regime for the EU while the rest of the world takes no climate policy action. As a result, the share of value added accounted for by the EU manufacturing sector would drop distinctly, partly because of the sector's emissions-intensive products being increasingly sourced from other countries. Emissions would therefore be shifted abroad. Possibilities for counteracting this include a countervailing charge in the form of a climate tariff or alternatively the development and application of new, greener technologies that boost carbon productivity at home.[85]

Effects of unilateral introduction of a carbon price in the EU on manufacturing*

Percentage point change, 2050 versus 2019



Source: Bundesbank calculations based on a two-region version of the DSGE model EMuSe and projections by the NGFS. * The model is calibrated for the European Union (together with the United Kingdom) and for the rest of the world. The simulation period extends from 2005 to 2100. In the rest of the world, no carbon price is introduced, and the sectoral CO_2 emissions productivity, which gives the ratio of economic output to emissions, is constant. The paths of CO_2 emissions productivity and of the carbon price in the EU assumed for the simulation are based on projections by the NGFS for an orderly transition scenario. In an orderly transition, climate policy's level of intervention is assumed to increase steadily up to the middle of the century with the aim of limiting the rise in the global average temperature to 1.5°C above pre-industrial levels. **1** Constant sectoral emissions productivity in the EU. **2** Rising sectoral emissions productivity in the EU.

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Monetary policymakers should closely monitor climate policy processes

Climate policy measures can therefore have significant macroeconomic effects, the specifics of which will hinge on their precise design, the economy's capacity to adapt and the external setting. Central banks need to pay heed to all of this when conducting their analyses. This requires the right kind of data and the right kind of analytical tools.[86]

Outlook

Impact of climate change and climate action likely to pose greater challenges to monetary policy in future

The Eurosystem's monetary policy is geared towards safeguarding price stability and helping to ensure a stable financial system. To achieve these goals, it is important to adequately assess short and long-term economic developments. Global climate change and climate action pose new challenges in this context. It is therefore necessary to review and, where required, adjust the analytical toolkit available to monetary policymakers. This is also true of macroeconomic analysis, which is key to monetary policy decision-making. Alongside the impact of extreme weather events and gradually rising temperatures, it is notably the macroeconomic repercussions of climate policy that are likely to become significant in the near future. Climate policy measures may trigger far-reaching structural adjustment processes that also transcend national borders; if their macroeconomic implications are to be adequately gauged, models with sufficient regional and sectoral differentiation are needed. This article presents EMuSe, a multi-sector environmental DSGE model that can be adapted flexibly to varying requirements

85 Carbon productivity measures the ratio of economic output to emissions. See also OECD (2017b).
86 See also Deutsche Bundesbank (2021a, 2021b).

and used to analyse a number of issues, including in an international context.

Fulfilment of monetary policy mandate crucial foundation for transition to a climate-neutral economy

Climate and economic policy can play a vital part in mitigating risks and uncertainties, particularly through long-term focus, consistency and efficiency. But the reduction of structural rigidities could likewise help smooth the transition to a climate-neutral economy. Both of these factors would also support a stability-oriented monetary policy. The Eurosystem has a role to play in ensuring the success of climate action by fulfilling its monetary policy mandate and thus providing a crucial foundation for the transition to a climate-neutral economy: price stability is a key prerequisite for price signals to take effect.

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