Credit and Capital Markets, Volume 55, Issue 3, pp. 381 – 411
Scientific Papers

Central Bank Policies and Climate Change. Where Do We Stand?

Uwe Vollmer*

Abstract

The article reviews the literature on the relationship between climate change and central bank policies. Central banks conduct monetary policy and are responsible for macroprudential supervision. The article focuses on the consequences of transition and physical risks for financial stability and price stability. It also asks what role central banks can play in slowing climate change and what implications climate change has for the future strategy and for the monetary policy framework of the Eurosystem.

Key words: Physical risk, transition risk, monetary policy, macroprudential policy, green QE

JEL classification: E52, E58, Q54

I. Climate Change and Central Banks – the Issues

The tasks of central banks have expanded considerably since the start of the great financial crisis in 2007. While they were previously primarily entrusted with the implementation of monetary policy, they have since also become increasingly involved in (micro- and macroprudential) supervision of the financial sector. The primary objective of monetary policy is to guarantee "macro(economic) stability", what is essentially identical with price stability and usually means an inflation rate close to 2 % p. a. over the medium term. Sometimes a high level of employment is added as an additional objective. The primary objective of micro- and macroprudential supervision is to guarantee "financial stability", i. e., a state in which the financial system is able to withstand shocks and reduce financial imbalances so that it can fulfil its key economic functions.

* Prof. Dr. Uwe Vollmer, Leipzig University, Economics Department, Institute for Theoretical Economics, Grimmaische Str. 12, D-04109 Leipzig, Germany, E-Mail address: vollmer@wifa.uni-leipzig.de.

Acknowledgments: The author thanks *Jan Bruch*, MSc., and an anonymous referee for helpful comments. The paper also owes valuable insights to *Florian Bieber*'s master's thesis. The usual disclaimer applies.

Climate change refers to the long-term change in average temperature and weather conditions that have been observed since the beginning of the industrialization phase. It is essentially a consequence of consumption of fossil energy which leads to the continued emission of menthane gas and carbon dioxide. This causes a greenhouse effect in the atmosphere that leads to progressive global warming and can trigger extreme weather events (*Otto* et al. (2020)). In order to prevent climate change from progressing and to limit the average temperature increase to less than 2° C, the Paris Agreement obliges the signatory states to take appropriate measures to limit CO_2 emissions and to create incentives for the transition to emission-neutral production processes (*United Nations* (n.d.)). To achieve the 2° C target, global CO_2 emissions would have to be reduced by at least 3% p.a. from now on (*Höhne* et al. (2020)).

Monetary policy affects the business cycle and is "climate relevant" because greenhouse gas emissions fluctuate procyclically and there is a link between the business cycle and air pollution (*Annicchiarico*, et al. (2021)). Causality can go both ways: GHG emissions influence macroeconomic development, and this changes emissions. Central banks are confronted with climate change in two ways. First, they must assess the implications of climate change for the effectiveness of their policy instruments and for their ability to maintain price stability and financial stability. Second, at the normative level, central banks must decide whether and by what means they will actively intervene in the fight against climate change without compromising their legal mandate.

With respect to the first task, central banks divide the economic impact of climate change into two categories: Physical risks and transition risks (*Giuzio* et al. (2019)).[1] Physical risks follow directly from climate change and affect either price stability or financial stability. Transition risks are triggered by the transformation to a low-carbon economy and result, for example, from the policy measures taken or from technological adjustments. Transition risks are often seen as occurring already in the near future (5-years horizon), while physical risks are seen as threatening the financial sector more in the next 30 years (*Stroebel/Wurgler* (2021)). Furthermore, low transition risks today due to a delayed transformation to a low carbon-economy may cause large physical risks in the future.

Several studies try to asses empirically the impact of transition risks and physical risks on macro stability and/or on financial stability. Regarding the effects of transition risks on macro stability, most studies look at the immediate impact of climate risks on inflation rates: Higher CO_2 taxes mainly change relative prices, but have no significant impact on CPI inflation or at most have a weak deflationary effect (*Konrad/Weder di Mauro* (2021); *Moessner* (2022)). In contrast, extreme temperature increases, especially in the summer months, have an im-

[1] The distinction goes back to the former Governor of the Bank of England, *Mark Carney* (2015), who additionally mentions a liability risk.

pact on CPI inflation that persists over the medium term. Such events have become more frequent in recent decades and are expected to increase in the future (*Faccia* et al. (2021); *Mukherjee/Ouattara* (2021)).[2]

With regard to financial stability, some papers use network-based climate stress tests which assess the resilience of the financial sector under alternative climate policy scenarios (overview in *Semieniuk* et al. (2020)). They assume a hypothetical adjustment path for a carbon tax and assume different elasticities in how companies adjust their GHG emissions to the tax rate change (*Belloni* et al. (2022)). From this, one can determine the increase in the probability of firm-level default as a result of the higher carbon tax, which allows to derive the expected costs to the financial sector for different climate change mitigation scenarios. These additional costs are larger the more the CO_2 tax increases and the fewer firms respond by reducing their emissions. Table 1 shows this for the Eurozone banking sector as an example, with median banking sector losses increasing by 13.55 % if the CO_2 tax increases by 250 EUR/ton and no abatement measures are taken.[3] This suggests that there are important benefits – also for the banking system – from an immediate implementation of emissions reduction strategies.

Table 1

Loss Statistics for the European Banking Sector: Increase in Median Losses in % (compared to 2020)

Increase in CO_2 Tax in EUR/ton	*Emissions reduction by*				
	0 %	*15 %*	*30 %*	*50 %*	*80 %*
10	0.35	0.26	0.29	0.20	0.23
50	1.01	0.87	0.77	0.68	0.32
100	2.83	2.18	1.73	1.00	0.62
150	6.66	4.79	3.09	1.79	0.70
200	10.15	8.08	5.90	2.80	0.80
250	13.55	10.92	8.49	4.55	0.94

Source: Belloni et al. (2022), p. 37.

[2] In addition, there are indirect effects on macrostability when climate change threatens financial stability and the central bank therefore responds with macroprudential instruments. On these side effects of macroprudential instruments on macro stability, see the literature reviewed in *Vollmer* (2022).

[3] *Roncoroni* et al. (2021) provide similar results for Mexico and *D'Orazio* et al. (2022) for Germany. *ECB/ESRB Project Team on Climate Risk Monitoring* (2021) gives an overview of all past, ongoing and planned climate risk stress-testing and sensitivity exercises by ESRB and non-ESRB institution. For a survey of results for other countries see *D'Orazio* et al. (2022).

The consequences of physical risks are more difficult to assess, because they are unprecedented in nature and cover a long-dated horizon. For the EU, floods of rivers, forest fires or sea-level rise are likely to be the biggest risk drivers (*Kovats* et al. (2014)), affecting up to 30 % of euro area banks'exposures. These risks are not widely dispersed, because 70 % of the banking system's credit exposures to industries with high or rising climate risks are concentrated in the portfolios of only 25 banks. Moreover, these exposures to physical risk drivers are more relevant for weakly capitalised and/or less profitable banks (*ECB/ESRB Project Team on Climate Risk Monitoring* (2021)).

Several papers attempt to quantify the consequences of physical risks for the global financial sector. *Lamperti* et al. (2019) use a calibrated agent-based macroeconomic climate model (*Lamperti* et al. (2018)) in order to analyse the impact of climate change on banking crisis and bailout costs. They conclude that climate change will significantly increase the frequency of banking crises (by 26 – 248 %). Bailing out insolvent banks will cost public funds of 5 – 15 % of GDP per year, almost doubling the global public debt to GDP ratio. *Dietz* et al. (2016) estimate the "climate" value at risk (VaR) for the period from 2015 to 2100 and quantify the potential financial asset losses triggered by climate change for alternative Monte Carlo simulations. To do this, they measure the asset value as the present value of future net earnings, assume that corporate earnings represent a constant long-term percentage of GDP, and use forecasts of global GDP growth which are estimated along various climate change scenarios. The estimates yield a mean climate VaR of 1.77 % of global financial assets for the "business-as-usual scenario", corresponding to an asset loss of USD 2.5 trillion in 2013; the climate VaR is just under 17 % for the 99th percentile (or USD 24.9 trillion for the 99th percentile). In the case of a climate mitigation policy that limits global warming to 2° C compared to pre-industrialisation, the average VaR is still 1.18 % of financial assets (1.7 trillion USD) or 9.17 % (13.2 trillion USD) for the 99th percentile (Table 2).[4]

[4] As a point of reference: In 2014, the stock market capitalisation of oil & gas and coal companies amounted to nearly 5 trillion USD. See https://about.bnef.com/blog/fossil-fuel-divestment-5-trillion-challenge/

Table 2

Value at Risk of Global Financial Assets from Climate Change between 2015 and 2100

Emission scenario	*1st percentile*	*5st percentile*	*Mean*	*95st percentile*	*99st percentile*
Business-as-usual-policy[1)]	0.46 %	0.54 %	1.77 %	4.76 %	16.86 %
Mitigation-policy[2)]	0.35 %	0.41 %	1.18 %	2.92 %	9.17 %

[1)] Expected warming of 2,5° C in 2100; [2)] Limiting warming to 2° C with 2/3 probability.

Source: Dietz et al. (2016).

Against this background, this paper reviews the growing literature on the link between climate change and central bank policy, looking at two directions of causality:[5] What is the impact of climate change on the effectiveness of monetary policy and macroprudential policy? What is the relevance of central bank policy to climate change? The paper systematises the literature and provides the answers the two questions mentioned above. It also attempts to assess the impact of climate change on the Eurosystem's monetary policy strategy and framework.

The rest is structured as follows. Section II. presents core elements of "ecological" E-DSGE models, which form the predominant analysis tool for the macroeconomic links between central banking and climate change. Section III. discusses the implications of transition risks and physical risks, respectively, for macroprudential policy and/or for monetary policy. Section IV. changes the perspective and asks what contribution central banks can make to slowing climate change. Section V. draws some implications for the Eurosystem. Section VI. concludes.

II. Core Elements of E-DSGE Models

The literature on the link between climate change and central bank policy predominantly uses "ecological" (E-)DSGE models as its analytical instrument.[6]

[5] For another review article on the topic, see *Annicchiarico* et al. (2021). In what follows, we do not consider papers that deal with transition risks and physical risks of climate change without considering monetary policy or macroprudential policy.

[6] Another type are "ecological macroeconomic models" (*Rezai* et al. (2013); *Hassler* et al. (2016)), which are often based on post-Keynesian growth theory or use physical or monetary input-output analysis, systemic dynamics, or stock-flow consistent modelling techniques (*Hardt/O'Neill* (2017)). Ecological macroeconomic models integrate physical climate models into a neoclassic growth model to understand the long-term economic impacts of CO_2 emissions. The prototype of such an integrated assessment model is the

These introduce environmental elements into a standard New Keynesian DSGE model (*Galì* (2008); *Walsh* (2017)), with which they share the following main features (*Fischer/Springborn* (2011); *Heutel* (2012); *Annicchiarico/Di Dio* (2017)): The economy comprises of perfectly competitive final good producers which compile different intermediate goods to produce a final single consumption good. Intermediate good producers act under monopolistic competition and use labour and capital inputs to produce a single differentiated intermediate good. Households supply labour services, consume the final good and save. Wages are considered as sticky. A central bank sets the nominal interest rate according to a (modified) *Taylor* rule. In addition, some models also consider a banking sector together with a macroprudential authority which sets, e. g., minimum capital requirements or other prudential instruments for commercial banks.

E-DSGE models additionally assume that producers of intermediate goods cause CO_2 emissions that trigger climate change and negatively affect the production of other intermediate goods producers. There are several model variants, which differ in whether they account for the cumulative stock of CO_2 emissions or capture the flow of new emissions. Some models also consider an energy sector. In addition to the central bank and the macroprudential authority, there is a government that sets environmental regulations for GHG emissions. The government can either impose a tax on CO_2 emissions ("carbon tax") or use a "cap-and-trade scheme" and set the overall level of emissions.[7] Firms can pay the tax or purchase pollution rights or invest in environmentally friendly technologies ("abatement"). They also have the choice to illegally circumvent such regulations and face punishment costs if discovered.

E-DSGE models can be divided into two major groups: Physical risk models address the consequences of climate change itself for monetary policy and macroprudential policy; transition risk models address the consequences of a green transition for these policy areas. The majority of physical risk models analyzes the impact of natural desasters (caused by extreme weather events) on the business cycle (*Keen/Pakko* (2011); *Gourio* (2012); *Dietrich* et al. (2021); *Cantelmo* (2022)).[8] The disaster occurs in each period with given probability p_t and has two effects: Parts of the capital stock are devalued and total factor productivity

DICE/RICE model. The purpose is to estimate the long-term impacts of emissions or evaluate alternative paths or policies. DICE is an acronym for Dynamic Integrated Model of Climate and the Economy; RICE is an acronym for Regional Integrated Climate-Economy Model and stands for its regional version of DICE. See, e. g., *Nordhaus/Sztorc* (2013).

7 In addition to such market-based instruments, command-and-control policy instruments can also be applied, but these are not considered here.

8 Although natural disasters are not always a consequence of climate change, their frequency increases as the average temperature rises.

TFP falls. The capital devaluation means that the capital stock K_t follows the following law of motion:

$$K_t = \left(\left(1-\delta\right)K_{t-1} + I_t\right)\boldsymbol{e}^{d_t \log(1-\mu_t)}, \tag{1}$$

where d_t is a dummy which takes the value zero in the absence of the natural disaster and one, otherwise. The variable $(1-\mu_t)$ names the fraction of capital not destroyed by the disaster; it captures the "capital depreciation shock" and is often modeled as an *AR*(1) process. I_t is period investment, δ the depreciation rate, and $\boldsymbol{e}$ is *Euler*'s number. For the total factor productivity A_t holds:

$$A_t = A_{t-1}\boldsymbol{e}^{d_t(1-\alpha)\log(1-\mu_t)+\Delta_A}, \tag{2}$$

where $d_t(1-\alpha)\log(1-\mu_t)$ denotes the "factor productivity shock", $\alpha \in [0,1)$ is the capital share and Δ_A is trend productivity growth. Note that $\boldsymbol{e}^{d_t \log(1-\mu_t)} \leq 1$ (in (1)) and ($\boldsymbol{e}^{d_t(1-\alpha)\log(1-\mu_t)} \leq 1$ (in (2) for $\Delta_A = 0$) .

Another group of physical risk models analyzes the long-term consequences of CO_2 emissions for total factor productivity and for price and output stability (*Economides/Xepapadeas* (2018); *Economides/Smarzcynska Javorcik* (2019)). The production of intermediate goods $Y_{j,t}$ requires as inputs the use of labour and capital as well as energy:

$$Y_{j,t} = \Lambda_t A_t f\left(L_{j,t}, K_{j,t}, E_{j,t}\right), \tag{3}$$

where $f(L_{j,t}\ K_{j,t}\ E_{j,t})$ denotes a neoclassical production technique with $L_{j,t}$ as labor input, $K_{j,t}$ as capital input and $E_{j,t}$ as energy input in sector *j*. Λ_t is the "damage coefficient" (*Golosov* et al. (2014)) that casts the impact of climate change on output:

$$\Lambda_t = \boldsymbol{e}^{-\psi(T_t - T_0)}, \tag{4a}$$

where $T_t - T_0$ denotes the temperature anomaly, i.e. the increase in average temperature T in t compared to the reference year. The coefficient ψ is called the "damage elasticity of output". The cumulative energy consumption is responsible for the temperature anomaly:

$$T_t - T_0 = \Delta \sum\nolimits_{s=0}^{t} E_s, \tag{5}$$

where the parameter Δ is referred to as a "transient climate response". A rise in energy consumption boost production (because energy is an input factor) but pushes up temperature which reduces productivity. Under these conditions, the adjustment dynamics of the economy to TFP shocks change, and climate change acts as a chain of autocorrelated negative supply shocks (*ibid.*).

The other family of E-DSGE models are transition risk models that look at the macroeconomic effects of climate change mitigation measures. They also can be further divided in two sub-groups: The first subgroup are real-sector transition risk models which explicitly consider pollution as a by-product of intermediate good production. It takes into account that fiscal environmental protection measures can lead to adjustment reactions in the form of emission reduction or in the form of illegal emissions (*Annicchiarico/Di Dio* (2015); *Annicchiaticio/Di Dio* (2017); *Chan* (2020); *Chen* et al. (2021); *Diluiso* et al. (2021)).[9] Output $Y_{j,t}$ of intermediate product j in period t is given by (3) (without an energy input), where Λ_t is now taken either as a function of the average temperature T_j in t (as in (4a)) or as a function of the stock M_t of CO_2 emissions in the atmosphere in t:

(4b) $$\Lambda_t = e^{-\chi(M_t - M_0)}$$

(each relative to the pre-industrial value T_0 or M_0). In the first case, the change in temperature is a function of either the period flow or of the total stock of CO_2 emissions:

(7b) $$T_t - T_0 = \upsilon_{temp} Z_t \quad \text{or} \quad T_t - T_0 = \lambda\left(\sum_{s=0}^{t} Z_s\right);$$

in the latter case, the flow of additional CO_2 emission $Z_{j,t}$ of firm j is given by:

(6) $$Z_{j,t} := M_t - M_{t-1} = Z_{j,t}\left(U_{j,t}, Y_{j,t}\right),$$

where $U_{j,t}$ denotes the firm's "abatement effort" and $Y_{j,t}$ its output. The cost of emission abatement C_A ("abatement cost") depends positively on the abatement effort and the output of firm j:

(7) $$C_A := C_A\left(U_{j,t}, Y_{j,t}\right).$$

"Abatement costs" together with "emission costs" $P_{Z,t}$ are part of the marginal costs of the intermediate product producer. The level of emission costs depends on the environmental policy regime: In the "no-policy regime": $P_{Z,t} = 0$ and therefore $V_{j,t} = 0$; in the "cap-and-trade system": $Z_{Z,t}$ is fixed and $P_{Z,t}$ is endogenous; in the "tax system": $P_{Z,t}$ is fixed and $Z_{Z,t}$ is endogenous. Some models also take into account that firms may engage in illegal (hidden) CO_2 emissions and have to bear positive "penalty costs" C_D when detected. These costs depends positively on the output ($Y_{j,t}$), the effectiveness of rule enforcement (Ψ) and the proportion $V_{j,t}$ of concealed/hidden emissions:

[9] An example of such hidden emissions is given by the emissions scandal of several major car manufacturers in 2015. See *Chen* et al. (2021).

(8) $$C_D := C_D\left(V_{j,t}, \Psi, Y_{j,t}\right).$$

The second subgroup are financial-sector transition risk models which do not consider abatement efforts or illegal emissions. They address the devaluation of property rights in energy-intensive sectors as a result of environmental policies and ask about their impact on financial stability (*Diluiso* et al. (2020), (2021); *Carattini* et al. (2021), *Comerford/Spiganti (2020*), *Annicchiarico* et al. (2022)). These models assume that CO_2 emissions are a consequence of the consumption of fossil fuels and hence consider an economy that takes into account two energy-producing sectors in addition to intermediate goods producers and a final product sector. The energy-producing sectors are split up either into a low-carbon ("green") energy and high-carbon ("fossil") energy sector or in an energy sector which uses renewable (sun and wind) or non-renewable sources (coal, oil, and gas). Furthermore, there is a banking sector that borrows funds from households and transfers them to the production sectors.

The banks are subject to an agency problem that limits the amount of funds they can raise from households (*Gertler/Karadi* (2011); *Gertler/Kiyotaki* (2011)). In particular, a banker has the opportunity to default and to transfer a share κ of total gross nominal assets $\sum_i^J Q_t S_{j,t}$ to his own household (with $S_{j,t}$ as quantities of physical assets and Q_t as asset prices). If the banker does not default, she keeps the "continuation" or "franchise" value FV_{jt} of the bank which is linear to his net worth N_{jt} (with φ_t being the linearity factor). The banker does not default iff

(9) $$FV_{jt} \geq \kappa \sum_j^J Q_t S_{j,t} \qquad \text{or}$$

(10) $$\sum_j^J Q_t S_{j,t} \leq \frac{\varphi_t}{\kappa} N_{j,t}.$$

The last equation is the borrowing constraint for banks, meaning that the bank is not able to own assets in an amount higher than the fraction $\frac{\varphi_t}{\kappa}$ of its net worth. Shocks as well as carbon taxes reduce $N_{j,t}$ and tighten the borrowing constraint. Looking at different production sectors makes it possible to assess the impact of carbon-tax increases or sudden devaluations of fossil-related assets ("stranded assets"), which lead to asset value losses and are amplified by the financial accelerator in lending. As banks hold stakes in all three productive sectors, the impact of discriminatory central bank purchases of securities can be estimated in the form of a "green QE" or minimum capital requirements that distinguish between green sectors and fossil sectors.

The models described are often calibrated using the usual parameter values as applied in conventional DSGE models. The impulse response functions are then derived to exogenous shocks for alternative values of the "climate-relevant" parameters, such as the "damage elasticity of output", to show the impact of climate on macroeconomic development. The main results are reported below.

III. Climate Change, Central Bank Policies, and Economic Stability

1. Transition Risks

Transition risks arise from climate policy measures intended to bring about a transition to environmentally friendly production methods with low-CO_2-emissions. As mentioned above, these measures essentially include the levying of a carbon emission tax or the issuance of tradable pollution rights. The use of such climate policy instruments increases production costs and acts as a negative macroeconomic supply shock, affecting inflation, output and employment. Moreover, these instruments also cause a decline in the price of property rights in CO_2-intensive industries and trigger a decline in "brown" assets prices; this "stranded assets" effect can affect financial market stability and threaten macroeconomic stability. The extent and duration of transition risks depend on the timing and speed of the instrument deployment, the climate instrument used, and the ability of agents to circumvent climate protection measures. The impact of transition risks also depends on which interest rate rule the central bank follows and how macroprudential instruments are used.

1.1 Orderly vs. Drastic Transition

As shown in *Table 1* above, the cost to the financial sector of an additional emissions tax depends on how much the CO_2 tax rate is increased and to what extent firms reduce their carbon emissions. This suggests that, in terms of financial stability, an immediate but gradual tax increase that gives companies time to react with their emissions ("orderly transition) is preferable to a delayed and drastic CO_2 tax increase. *Diluiso* et al. (2021) compare the consequences of these two transition strategies for macroeconomic stability, especially for inflation, unemployment, and output. They assume a cumulative carbon emission reduction target of 24 % in ten years (which in line with the EU Commission's target, *EEA* (2021)). The target is either announced at the beginning of the implementation period and fully credible or not announced and implemented with a delay of three (or five) years.

Three types of monetary policy rules are compared, a standard *Taylor* rule, where the CB reacts to movements in both output and inflation, and two "simple rules" where the central bank reacts only to the inflation rate (with different degrees). The increase in carbon tax impacts the economy through two channels: a reduction in the demand of energy ("real channel") and a decrease in the valuation of assets from the fossil sector ("financial channel"). The simulations in *Diluiso* et al. (2021) show that an orderly transition causes only minor disruptions in terms of macro and financial stability. These disruptions become greater the longer the transition is delayed. The strongest effects of an orderly transition are seen with regard to the inflation rate and can be avoided if the central bank – as is currently the case with the Eurosystem – follows a simple rule that stabilizes the inflation rate, only.

1.2 Quantitative Easing vs. Capital Requirements

Diluiso et al. (2021) also take into account that as a result of drastic climate protection measures, the asset value of companies in energy-intensive/polluting ("brown") sectors will decline. This will force the commercial banks invested there to write down their asset portfolios.[10] If these banks do not have a sufficient capital buffer but have to meet a regulatory minimum capital ratio, the write-downs will trigger adjustment reactions in the banks. It causes a reduction in credit and forces the banks into fire sales, which will be passed on to other banks. This can lead to a credit crunch, as a result of which overall economic activity collapses. To prevent this, the central bank can buy securities on the open market (QE) or adjust the minimum capital requirements. QE can be applied in a market-neutral manner, i.e. it can affect "green" and "brown" bonds equally, or it can only affect "green bonds". Capital requirements (CR) for banks may be the same for brown and green assets ("neutral capital requirements") or higher for brown assets than for green assets. In the last case, capital-weights for low-carbon assets can be smaller than one ("green supporting CR") or capital-weights for high-carbon assets can be larger than one ("fossil penalizing CR").

The simulations in *Diluiso* et al. (2021) show that any QE helps prevent an economic downturn, even if it only targets green assets. It prevents a fall in output and mitigates the inflationary impact of the financial shock by allowing banks to loosen their lending. However, the differences between green and neutral QE are small in terms of macroeconomic stability. Setting a neutral CR is better than no CR in terms of welfare losses. Fossil-penalising CRs are better than neutral CRs, but green supporting schemes can lead to large output losses

[10] This assumes that financial markets do not price all climate risks due to limited information or adjustment costs so that sudden price changes can occur. See *Diluiso* et al. (2021).

and significant welfare losses. From the perspective of macroeconomic stability, fossil penalizing schemes are therefore preferable to green supporting CRs.

Financial market frictions can jeopardize the achievement of climate targets, and macroprudential measures can prevent this. The unexpected introduction of a carbon tax lowers the market value of brown industries and reduces the capitalization of the banks that finance them. This reduces lending, not only to brown industries but also to green industries, so that the climate policy measure triggers an undesirable spillover effect on the green sector. These effects are weaker if the carbon tax is gradually lifted or if the tax levy is announced in advance (*Carattini,* et al. (2021); *Diluiso* et al. (2021)). Macroprudential measures, such as taxes on brown and subsidies on green bank assets, can mitigate this effect if they are introduced before the carbon tax is levied and create timely incentives for banks to increase lending to green industries (*Carattini*, et al. (2021).

1.3 Policy Coordination vs. Non-Coordination

Annicchiarico/Di Dio (2015, 2017) analyse the optimal interaction of environmental and monetary policy following an exogenous shock. They consider a *Ramsey* planner who maximizes households' expected discounted utility. The planner decides on the use of an environmental policy instrument (setting a CO_2 tax rate or a cap on pollution rights) as the institution responsible for fiscal policy and sets the interest rate as the institution in charge of monetary policy. The economy is exposed to a positive technology shock and policies can be used in a coordinated or uncoordinated way, whereby in the first case the planner chooses both instruments simultaneously, while in the second case he discretionarily determines either the environmental policy instrument alone or the monetary policy instrument alone.

Under coordination, the *Ramsey* planner simultaneously sets the interest rate and the cap on emissions (Z_t) (which is equivalent to the case in which the planner sets a carbon tax). The optimal policy reaction to a positive TFP shock implies an accomodative monetary policy, i.e., a decrease in nominal interest rates, and an increase in the emission permit price. Under non-coordination, the *Ramsey* planner controls either the monetary policy or the envorenmental policy instrument. In the first case, strict inflation targeting is optimal only when monetary policy is combined with a carbon tax. Under a cap-and-trade regime (or under a carbon tax combined with strong externalities) monetary policy should follow a standard *Taylor* rule and allow temporary deviations from price stability. In the other case, the planner's response to the TFP shock depends on the central bank's reaction function. The planner will find it optimal to cut emissions if monetary policy is highly responsive to output (*Annicchiarico/ Di Dio* (2017)).

1.4 Illegal CO_2 Emissions

Instead of complying with environmental regulations or switching to more environmentally friendly production processes, firms can illegally continue to emit CO_2 secretely. They then incur penalty costs whose expected value depends on the probability of detection, but avoid the costs associated with environmental regulations (carbon tax or pollution rights acquisition costs) or the abatement costs associated with switching to cleaner production technology. The potential penalty for concealed emissions is a third instrument of environmental policy, besides the carbon tax and the cap-and-trade (*Chen* et al. (2021)).

Under these conditions, a positive TFP shock leads to impulse responses by firms, which differ between a carbon tax system and a cap-and-trade scheme and depend on the effectiveness of the implementation of environmental regulations. Since in a carbon tax system the price of pollution is given, as a result of the TFP shock legal emissions become cheaper and these are expanded at the expense of abatement and illegal emissions. As a result, total emissions increase, affecting TFP, and falling effective emission costs lower marginal production costs and the price level of final goods. In contrast, the pollution price increases in a cap-and-trade system, which increases abatement effort (and allows illegal emissions to grow). At the same time, marginal production costs rise and the goods price level does not fall as much as under the carbon tax system. Thus, a cap-and-trade scheme is better suited than a carbon tax to reconcile price stability and emissions control.[11] Declining effectiveness in implementing environmental regulations does little to alter the effects of a carbon tax and, in particular, has no effect on abatement effort. In contrast, in a cap-and-trade system, the price of pollution increases less with lower effectiveness of illegal emission control, and the dynamics in the price of goods converge to those in a carbon tax system (*Chen* et al. (2021)).

2. *Physical Risks*

Physical risks arise from climate change itself. They include extreme weather events, such as droughts or floods, which directly affect economic dynamics, and are treated as shocks, or secular changes in production conditions due to climate change, which affect potential output growth and increase inflationary pressures. Normally, central banks do not respond to singular disasters or extreme weather events because their effects are temporary and do not affect trend inflation. As a result of climate change, however, such weather events could occur more frequently (*Stott* et al. (2016)) and may thus become relevant for mon-

[11] In this respect, *Chen* et al. (2021) differ from *Annicchiarico/Di Dio* (2017).

etary policy, although it is not clear a priori whether they increase inflationary pressures (because of negative supply effects) or decrease them (because household saving increases). Moreover, rising temperatures can have a significant negativ economic impact also in the short term if market participants' expectations change, even if the actual effects on economies will not occur for decades.

2.1 Natural Disaster Reactions

Keen/Pakko (2011) and *Gourio* (2012) analyze the Federal Reserve's monetary policy responses after Hurricane *Katrina* in 2005, when the Federal Reserve raised (rather than lowered) interest rates contrary to general expectations. Monetary policy follows a standard *Taylor* rule. The disaster persistently destroys productive capital and temporarily reduces TFP. Both effects act like a negative aggregate supply shock, exerting upward pressure on the price level and leading to a decline in output. After the disaster period ends, productivity returns to its initial level and the capital stock rebuilds, keeping inflation above its steady-state level for several periods. This persistent inflation effect accounts for the rise in interest rates as the optimal policy response to *Katrina*.[12]

In addition to supply-side effects, natural disasters also influence aggregate demand for goods, especially if agents expect that they occur with higher frequency. Such demand effects arise when households are sufficiently risk averse and increase their precautionary savings in response to shocks, causing the natural rate of interest and the trend rate of inflation to fall (*Cantelmo* (2020)). The negative response of the inflation rate is stronger the higher the probability of occurrence of a disaster or the stronger it turns out to be. To the extent that these demand effects are strong enough and exceed the supply effects described above, an expansionary monetary policy response is indicated.

Although the physical effects of CO_2 emissions on weather extremes and climate change only occur in the long term, they can already have a significant economic impact in the short term. One reason for this is changes in market participants' expectations of short-run consequences of climate change, which may have an impact on current economic activity and are relevant for monetary policy. *Dietrich* et al. (2021) present evidence for such changes in expectations based on US consumer surveys, and analyse the effect of an "expectation channel of climate change". They find on average a negible expected impact of climate change on economic growth, but a high perceived probability of natural desasters that causes large economic damage in the near future. Increases in the probability (and in the size of) of future natural desasters lower the natural rate

[12] The results hold in both the flex-price and the fixed-price variants of the model, only less pronounced in the latter.

of interest which causes a contraction in economic activity and reduces inflation. Like other forms of “bad news”, expectation of rare desasters increases the desire to save and reduces aggregate demand. In response, monetary policy should lower the policy rate, which requires the use of unconventional monetary policy instruments – such as forward guidance or QE – if the interest rate hits the effective lower bound.[13] Inflation and the output gap fall when monetary policy cannot perfectly track the natural rate of interest because interest rate were too low to beginn with.

2.2 Gradual Climate Change

Some papers do not consider natural disasters but analyse the consequences of gradual climate change for monetary policy. *Economides/Xepapadeas* (2018) consider an economy in which intermediate goods are produced with the help of an energy input that leads to temperature rises and reduces total factor productivity; the extent of this negative effect is captured by “damage elasticity (Ψ)”. They assume a central bank that sets the interest rate and follows either a strict inflation target or a simple *Taylor* rule; in the latter case, the central bank considers the output gap in addition to the inflation gap. The economy is exposed to a negative TFP shock, which in (3) temporarily reduces A_t (by 1 %).

The TFP shock triggers adjustment reactions of output and inflation that last longer but are weaker the larger Ψ is. This is due to the fact that energy consumption decreases with decreasing TFP, which slows down the temperature increase and improves the damage coefficient Λ_t. Thus, two effects act on the adjusted TFP ($\Lambda_t A_t$), the decrease due to the TFP shock on A_t and the gradual increase of Λ_t due to the lower energy consumption. The first effect only dominates initially and is then overlaid by the second effect until the new steady state is reached. The climate effect thus acts like a chain of autoregressive supply shocks. It moderates inflation dynamics so that the central bank has to intervene less to smooth inflation rates. This holds true when the central bank also reacts to the output gap or if one allows for trend or steady-state inflation (*ibid.*).[14]

[13] *Dietrich* et al. (2021) also point to a “paradox of communication”. By highlighting climate change, central banks increase its media presence and influence the formation of expectations about future natural disasters. This influences the natural interest rate and requires further market interest rate cuts, which are difficult to implement.

[14] For an open-economy version of the model, see *Economides/Smarzcynska Javorcik* (2019). Here, a two-country case is considered, one of which is a small country whose emissions do not affect the global temperature anomaly, but which is itself affected by global warming. The model asks to what extent a loss of monetary autonomy – by transferring monetary policy from the national to the supranational level – has an impact on stability, which is not the case.

2.3 Long-Term Effects

Because DSGE models simulate short-term impulse responses to exogenous shocks, they are ill-suited to represent the long-term, multi-decade physical risks of climate change that arise if global warming is not prevented. To fill this gap, *Dafermos* et al. (2018) consider a time span of (almost) 100 years and use a stock-flow-fund ecological macroeconomic model (*Dafermos* et al. (2017)) as the analytical tool.[15] The model contains several macroeconomic modules (including a financial sector), and a climate module which encloses an environmental damage function (*Weitzman*, 2012) and an abatement technology. The model is calibrated using global data. The baseline scenario is given by a "business-as-usual" pathway whereby the economy grows in line with recent trends and ecological efficiency improves only moderately.

Climate change negatively affects investment and consumption demand, housholds' demand for conventional corporate bonds and potential output. Economic growth declines, atmospheric temperature rises, corporate profitability declines, and corporate loan default rates rise. Bank leverage increases, capital adequacy ratios decline and credit rationing increases which feeds back into economic growth, profitability and liquidity of firms, leading to a vicious financial cycle. Eventually, banks' capital is no longer sufficient to meet regulatory requirements and banks have to be bailed out, affecting public finances. Households shift their financial assets from corporate bonds to deposits and government securities, leading to a decline in corporate bond prices and climate-induced asset price deflation.

Green finance policy can be suitable for slowing down this vicious circle. *Dafermos* et al. (2017) compare two forms of green finance policy ("GF I and GF II"), in each of which the credit rationing for "green" loans and the interest rate for these loans are lowered. Scenario GF II yields better environmental results, but economic growth is lower than under GF I. The reason is that credit rationing and the interest rate for "conventional" (brown) loans remain unchanged under GF I, but rise under GF II. Moreover, *Dafermos* et al. (2018) assess the effects of "green QE", where central banks around the globe buy 25 % of all green bonds and promise to keep this share constant. This benefits both climate change and financial stability. Because the yield on green bonds decreases, the cost of borrowing for companies falls and their dependence on bank loans decreases. This increases total investment, including green investment; it also increases the share of green investment in total investment, which reduces CO_2 emissions and slows global warming. In addition, green QE increases cor-

[15] For related models see *Bovari,* et al. (2018) who do not consider monetary policy or macro-prudential policies. Since *Dafermos* et al. (2017; 2018) do not use an E-DSGE model, they were not mentioned in section II above.

Table 3

Climate Risks and Central Bank Policies: Main Results

Transitory risks		
1. Timing and speed of carbon tax introduction?	Swift but gradual tax increase outperforms delayed but drastic tax increase	*Carattini* et al. (2021); *Diluiso* et al. (2021)
2. Optimal monetary policy: standard *Taylor* rule (TR) or strict inflation target?	a) Carbon tax: Simple rules (where CB reacts to inflation only) outperforms standard TR	*Diluiso* et al. (2021)
	b) Cap-and-trade: Standard TR	*Annicchiarico/Di Dio* (2015, 2017)
	c) Behavioral agents: Strong interest reactions to inflation and output	*Annicchiarico* et al. (2022)
3a. Supportive role of green QE and green capital requirements (CRs)?	Any QE helps preventing an economic downturn; neutral CR is better than no CR	*Diluiso* et al. (2021); *Carattini* et al. (2021)
3b. Neutral CRs, green supporting CRs or fossil penalizing CRs?	Fossil penalizing CRs are preferable to green supportive CRs	*Diluiso* et al. (2021)
4. Efficiency of carbon tax vs. cap-and-trade system under illegal emissions?	It is easier for the central bank to achieve price stability under a cap-and-trade system	*Chen* et al. (2021)
Physical risks		
1. Optimal monetary policy reactions to natural disasters?	Interest rate increases if supply side effects dominate; interest rate decreases, otherwise	*Keen/Pakko* (2011); *Cartelmo* et al. (2021)
	“Paradox of communication”	*Dietrich* et al. (2021)
2. Optimal monetary policy to TFP shocks?	Weaker interest rate reactions by the central bank under gradual climate change	*Economides/Xepapadeas* (2018)
3. Supportive role of green QE	Green QE lowers default rates and reduces bank leverage	*Dafermos* et al. (2017, 2018)

Source: Author’s compilation

porate profitability and reduces corporate liquidity problems because economic damages from slower global warming decrease and corporate green investment is less dependent on bank credit. This improves financial stability.

3. *Transition and Physical Risks: Interim Conclusion*

Table 3 summarises the implications of transitory and physical climate risks for central bank policy. In response to the transitory risks, an early but gradual introduction of an emissions tax is preferable to a delayed and drastic increase. However, it is easier for the central bank to achieve price stability if environmental policy uses a cap-and-trade system instead of an emissions tax. As for monetary policy, simple interest rate rules are preferable to a *Taylor* rule; capital requirements should be used as a penalty rather than an incentive. With regard to physical risks, an increase in interest rates as a result of natural disasters is indicated, only if supply side effects dominate. For physical risks, the response of interest rates after natural disasters depends on whether supply-side or demand-side effects predominate. Gradual climate change reduces optimal interest rate responses to TFP shocks. Green QE lowers default rates, reduces bank leverage and benefits both climate change and financial stability.

IV. Monetary Policy and the Fight Against Climate Change

We now change the direction of analysis and ask about the possibilities of monetary policy (and macroprudential policy) to influence CO_2 emissions and to slow-down (or even stop) climate change. In most developed countries, the legal mandate of central banks is to guarantee price stability, sometimes supplemented by secondary objectives such as promoting economic growth, maintaining full employment or guaranteeing financial stability (*D'Orazio/Popoyan* (2022)). This narrow mandate guarantees institutional and operational independence, prohibits central banks from directly aligning monetary policy with climate objectives and allows instruments to be calibrated for climate policy only as long as price stability is not affected. In contrast, central banks in developing countries or emergings markets often have a broader mandate that is more closely linked to development goals and allows monetary policy instruments to be aligned with sustainability objectives (*Campiglio* et al. (2018); *Dikau/Volz* (2021)).[16]

[16] So far, only the People's Bank of China has introducing a range of measures aimed at greening its policy. The central banks of Brazil, India (and Japan) have introduced credit facilities which favor priority sectors, such as renewable energy (*Campiglio* et al. (2018)).

Nevertheless, some contributions analyse what happens when a central bank proactively addresses climate change and applies, for example, a "climate-adjusted" *Taylor* rule (*Chen* et al. (2021)). This rule adds an emissions gap as a third target to the traditional *Taylor* rule besides inflation and output gap. The associated intensity coefficient measures the responsiveness of the policy interest rate to deviations of CO_2 emissions from their steady-state value. In this case, the central bank could face a dilemma between climate protection and price stability if a climate target is included in the monetary policy rule; the central bank should thus take other measures "to help the climate" (*Chen* et al. (2021).

Chan (2020) asks how fiscal and monetary policy can interact with carbon taxation in order to stabilize carbon emissions. A policymaker follows (*Taylor*-like) policy rules simultanously for carbon taxes, for government expenditures, and for the nominal interest rate, where all three rule are carbon-dependent. Alternatively, a carbon dependent tax rule is combined with a situation where the government and the central bank do not take environment degration into consideration. The analysis shows the optimality of an active carbon tax rule, where regulators increase (decrease) the carbon tax rate during periods when carbon emissions are above (below) a target. Such a rule allows emissions to temporarily deviate from the target value. It should be combined with similar rules for fiscal and monetary policy, i. e., government spending should decrease (increase) when CO_2 emissions are above (below) the target. Similarly, interest rates should react to the fulfilment of CO_2 emission targets. Unless such rules can be realised for fiscal or monetary policy, an active carbon tax is only optimal in the context of a conventional monetary policy, but not in the context of a conventional fiscal policy.

One way for central banks to prevent climate change would be a targeted privileging of "green" bonds which finance "green projects" that promote climate goals or serve environmental protection. The privileged treatment could either consist of preferential treatment of such bonds within the central bank's collateral framework (*Brunnermeier/Landau* (2020)) or it could be done through a green bond purchase programme ("green QE"). All this lowers the financing costs for green projects, which could facilitate the transition to climate-neutral value creation. Moreover, central banks are thus pointing the way to environmentally sustainable investments for other investors and signalling to the market that this category of assets is more liquid and less risky (*Schoenmaker* (2019)).

Green QE is only effective if green and brown bonds are imperfect substitutes for households. There is often a negative interest rate premium ("greenium") between the two types of investment, which is influenced by the central bank.[17]

[17] Households realize a benefit from holding green bonds and are therefore willing to hold them at an interest rate discount. Cf. *Zerbib* (2019), *Fatica* (2021).

Ferrari/Nispi Landie (2020) study the impact of a temporary QE in the following scenarios: the central bank keeps its total securities holdings constant and sells brown bonds in exchange for green bonds; it increases its total securities holdings and acquires green bonds by issuing its own liabilities. In both cases, the green sector's financing costs decrease; however, the brown sector's costs increase only in the first scenario, resulting in a decrease in (new) CO_2 emissions. Accodringe to the simulations, the emission reduction does not lead to a significant decrease in the (cumulative) CO_2 stock in the atmosphere (for similar results see also *Abiry*, et al. (2022)).

Ferrari/Nispi Landie (2022) compare the effects of a permanent green QE in two scenarios, namely gradually increasing securities purchases and a front loaded green QE. A third szeanrio is a temporary green QE, i. e., the central bank buys green bonds and then allows their holdings to decline. The impact on CO_2 emissions is greater with front loading, but even in this case the impact on the total stock of CO_2 in the atmosphere is small. Moreover, there is the possibility that green QE increases (new) CO_2 emissions, provided that green and brown consumer goods are complements and the production expansion of green goods also increases the production of brown goods (*ibid.*).

Giovanardi et al. (2022) analyze the preferential treatment of green bonds in the collateral framework of the central bank.[18] The framework identifies the assets that the central bank accepts as collateral when financial institutions want to raise liquidity and defines the amount they can raise. By tilting the collateral framwork towards green bonds, the central bank affects the relative price of green and brown bonds because banks can use green bonds more easily to settle liquidiy deficits. This may initiate a permanent shift towards green technology but this shift is small and accompanied by adverse side effects, such as higher risk-taking by banks.[19] This is avoided if *Pigou*vian taxes on pollution are used which promise large welfare gains that exceed the gains from optimal collateral policy considerably (*ibid*).

Campiglio (2016) discusses whether it makes sense to differentiate the minimum reserve requirements for banks according to the carbon footprint of their liabilities subject to minimum reserves. He assesses the potential use of such "green reserve requirements" (GRR) as rather low because banks in most OECD countries currently have high excess liquidity as a result of quantitative easing,

[18] See also *Monnin* (2018). A green collateral framework was introduced by the People's Bank of China in 2018 (*Macaire/Naef* (2022)). Some central banks (such as the Reserve Bank of New Zealand) have also started to include green bonds into their frameworks for managing foreign exchange reserves (*Fender* et al. (2019); *Fender* et al. (2020)).

[19] Such a risk-taking effect is als reported in *Van Bekkum* et al. (2017) as a consequence of lowered rating requirement for eligible residential mortgage-backed securities in the Netherlands.

so that changes in reserve ratios are hardly effective. Alternatively, *van't Klooster/van Tilburg* (2020) propose "green targeted long-term refinancing operations (green T-LTROs)" that provide banks with cheap funding if they lend to sustainable activities. Critics object that this approach will take years to become technically feasible. They propose a program which binds refinancing to energy efficient housing renovation (*Batsaikhan/Jourdan* (2021)). *Böser/Colesanti Senni* (2021)) propose climate risk-adjusted refinancing operations which help to address misallocations of ressources and financial instability coming from inappropriately priced climate risks.

Finally, *Dafermos/Nikolaidi* (2021) ask to what extent minimum capital requirements are suitable as an instrument to initiate a "green transition". They distinguish between two types of capital regulation, namely those with a "green supporting" factor and those with a "green penalising" factor. In the first case, commercial banks must back loans for projects that lead to CO_2 savings with less equity capital; in the second case, loans to finance CO_2-intensive projects must be backed by more equity capital. The result of the simulations is that "green differentiated capital requirements" (GDCR) can slow down climate change and therefore also reduce the associated physical risks. However, the effect is rather small and increases when GDCRs are used together with a green fiscal policy. Table 4 summarizes the main results of this section.

Table 4

Monetary Policy Instruments and Fight Against Climate Change: Capabilities and Boundaries

Instrument/Source	*Concept*	*Capabilities*	*Boundaries*
Green QE *Ferrari/Nispi Landie* (2021), (2022)	Alternative QE sce-narios: gradual in-creasing and permanent; front loaded and perma-nent; front loaded and transitory	Green QE helps re-ducing emissions if it is front-loaded; overall impact on the stock of pollu-tion is small in all scenarios	Green QE *increases* emissions if green and brown goods are complements
Climate risk criteria for collateral frame-work *Monnin* (2018); *Gio-vanardi* et al. (2021);	Accepting green bonds as collateral on preferential terms	Small shift towards green technologies and reducions in CO_2 emissions	Adverse effects on risk-taking and fi-nancial stability Inferior to Pigouvi-an pollution taxes
Green T-LTROs/Cli-mate risk-adjusted refinancing opera-tions (CARO) *van't Klooster/ van Tilburg* (2020); *Batsaikhan Jourdan* (2021); *Böser/Cole-santi Senni* (2021)	Refinaning opera-tions which offers cheap funding if banks fulfil climate criteria	Correction of dis-torted loan alloca-tions CAROs allow the central bank to re-duce bank lending to sectors exposed to climate risk and eliminates financial instability	Unclear green asset taxonomy Only 1.3 % of fi-nanced economic activities can be classified as "green"
Green reserve re-quire-ments (GRR) *Campiglio* (2016)	Reserve require-ments differentiat-ed according to carbon footprint	dito	Low effectiveness due to currently high excess liquidi-ty
Green differentiated capital requirements (GDCR) *Dafermos/Nikolaidi* (2021)	Green supporting factor vs. dirty pe-nalising factor	GDCRs can reduce the pace of global warming	Reduction is likely to be quantitatively small

Source: Own compilation.

V. Implications for the Eurosystem

The results of the literature allow some thoughts on the influence of climate change on the Eurosystem's monetary policy strategy and the future design of its monetary policy framework. Conversely, they also enable some conclusions to be drawn about the possibilities for monetary policy in the euro area to influence climate change. With a view to the first point, the following perspectives emerge:

- As the primary objective is to maintain price stability, the Eurosystem currently focuses on the inflation rate when setting interest rates; while economic activity indicators were the focus of the ECB's interest prior to the financial crisis, their importance has declined over the past decade (*Gross/Zahner* (2021)). The advantageousness of such a simple interest rate rule is confirmed by the literature as long as climate policy is characterized by a carbon tax. If climate policy were to switch to a cap-and-trade system, the need for the Eurosystem to switch to a standard TR would increase. While only a few member states of the European Union have introduced a CO_2 tax, all EU countries participate in the EU-wide emissions trading system (ETS). This covers just over 10,000 stationary installations, and coverage is expected to increase further by 2030 (*Lagarde* (2021)). This should increase the need for the Eurosystem to move away from the simple interest rule to a *Taylor* rule and to give output fluctuations a greater weight in setting interest rates.
- In the past, the Eurosystem has engaged in QE because its conventional monetary policy instruments became ineffective when the effective interest rate floor was reached. It had announced that it would stop QE as soon as interest rates started to rise again (which happened in the summer of 2022). However, this moratorium could become obsolete in the future if climate policy measures lead to a decline in the value of assets of "brown" industries and securities purchases become necessary to maintain macroprudential stability. In this case, the Eurosystem is likely to deviate from its previous maxim of buying the market and to see the need for green QE.[20]
- The Eurosystem will have to adapt its communication policy to climate change. Since central banks enjoy a high level of credibility and have a great deal of media coverage, they should explain their forecasts on the impact of climate change on monetary policy accurately and in a way that the public can understand. Otherwise, there is a risk of misunderstandings that changes households' propensity to save and influence the natural rate of interest, which further reduces the efficiency of interest rate steps.

---

[20] However, it is easier said than done to distinguish brown from green industries, which requires extensive expertise. Moreover, if a green QE is launched, the pressure on the Eurosystem to align a QE not only with climate policy requirements could grow.

Climate change will also influence the Eurosystem's macroprudential policy. The macroprudential instruments currently used by the Eurosystem hardly take climate-related risks into account, although these risks are concentrated in low-capitalized and low-profit banks. Nevertheless, regulatory capital buffers do not capture climate-related financial risks, as the risk weights used to calculate regulatory capital buffers do not yet fully reflect climate-related risks (*Baranovic*, 2022)). However, the ECB banking supervisor plans to conduct a comprehensive supervisory review of banks' practices to incorporate climate risks into their risk frameworks in the near future. Moreover, it already conducts climate risk stress tests for the commercial banks it supervises and plans to make access to its credit facilities conditional on the outcome of such stress tests (*Carattini* et al. (2021)).

Less comprehensive are the contributions monetary policy can make to slowing climate change. Already from a legal point of view, the possibilities for the Eurosystem to actively participate in the fight against climate change are rather limited. According to Article 127 of the "Treaty on the Functioning of the European Union (TFEU)", the primary objective of the Eurosystem shall be to maintain price stability. While there is a duty to support general economic policies in the European Union to help achieve their objectives, which include combating climate change, this applies only to the extent that price stability is not jeopardized. Thus, monetary policymakers should choose from a range of policy options the one that contributes most to price stability. If two or more policy alternatives contribute equally to price stability, they can be prioritized according to their support for secondary objectives (*Breitenfellner/Pointner* (2021)). The Eurosystem's policy mandate can only be changed by a unanimous decision of the EU member states, which is unlikely to be achieved. Thus, climate policy goals can currently only be pursued to the extent that they do not conflict with price stability.

Within this mandate, the Eurosystem has few options to gear its instruments more closely to climate policy and to launch, e. g., a "green" QE. The Eurosystem divides its securities holdings into two categories, namely "other securities" and "securities held for monetary policy purposes". The "other securities" include the ECB's own securities portfolio, which corresponds to the paid-up share capital by the national central banks, and a pension portfolio, from which pensions are paid. Both portfolios are already composed according to ecological criteria, but only account for just under ten percent of the total securities holdings of the Eurosystem.[21]

[21] The ECB and the 19 National Central Banks of the Euro Area countries manage separate non-monetary policy portfolios under their own responsibility. However, they have defined a common stance for applying sustainable and responsible investment principles.

Quantitatively much more significant are the "securities held for monetary policy purposes", which are acquired within the framework of the securities purchase programmes for public and private debt instruments (PSPP and CSPP) and in summer 2022 comprised a volume of € 2,800 billion. Here, the Eurosystem deliberately defines the criteria for the eligibility of securities to be purchased broadly and environmental aspects play neither a positive nor a negative role. The Eurosystem "buys the market" – in order to avoid price distortions in individual capital market segments and not to contradict the principle of an open market economy with free competition (*De Santis* et al. (2018)). Until mid-2018, the Eurosystem had purchased only a small amount of "green bonds" (of € 16 billion).

Critics argue that this makes the Eurosystem market neutral, but not climate neutral, because the programmes in their current form favour CO_2-intensive investments (*Matikainen* et al., (2017); *Dafermos* et al. (2021); *Papoutsi* et al. (2021)). They call for the Eurosystem to significantly expand its purchases of green bonds and abandon the principle of market neutrality in favour of a climate-neutral orientation of the purchase programmes. This is, however, countered by the fact that the available volume of green bonds is currently far too small to play a significant role in the Eurosystem's asset purchase programmes.[22]

As part of the review of its monetary policy strategy, the Eurosystem has announced that it will adjust its monetary policy framework and give greater weight to climate criteria in climate change-related disclosures, risk assessment, corporate sector asset purchases and the monetary policy collateral framework (*Work Stream on Climate Change* (2021)).[23] This requires a classification system to assess which economic activities can be considered environmentally sound and sustainable. The EU has developed such a green taxonomy, which is intended to prevent "green washing" and to enable companies, investors and policy-makers to draw up a list of environmentally sound economic activities. However, so far only a very small proportion (of 1.3 %) of fnanced economic activities comply with the taxonomy and can be classified as "green" (*Alessi/Battiston* (2022)).

---

[22] At the end of August 2018, the volume of PSPP-eligible bonds outstanding was about € 8,000 billion, of which only about € 50 billion (about 0.5 %) were green bonds. At the same time, the volume of CSPP-eligible bonds outstanding was about 1,000 billion euros, of which 31 billion euros (3 %) were green bonds. The global green bond market, while still relatively small, is growing rapidly. In 2014, global green bond issuance was 0.2 % of total bond issuance; it is expected to increase to 2.85 % of total issuance by 2019. See *Boneva/Tamburri* (2020).

[23] A climate stress test has also been announced for 2022 to show how robust the financial sector in the euro area is to climate-related risks. The stress test is an exercise for banks and regulators alike and not intended as a pass or fail exam, nor does it have any direct impact on banks' capital adequacy.

VI. Conclusions

Although our knowledge of the relationship between climate change and central bank policy has increased considerably in the last decade, several questions remain unanswered. First of all, it is still unclear which economic activities are to be classified as "green" and which as "brown". Especially the classification of fossil gases and nuclear energy is controversial. Second, the question of international coordination of climate protection measures, which also concerns central banks, was not addressed here. It is likely that the goal to limit the average temperature increase to less than 2° C would not be attainable in absence of international cooperation even with the support of monetary policy (*Ferrari/Sole Pagli* (2021)). Third, it is unclear what supportive role central banks play as catalysts in the emergence of markets for pricing environmental risks.

Climate change will have an influence on the way monetary policy will be conducted in the future, but the possibilities for central banks to actively participate in the fight against climate change are rather limited. Although monetary policy instruments can be calibrated to be climate-sensitive and thus influence CO_2 emissions from brown industries, the impact on the stock of greenhouse gases is rather small in the best case (and green QE can even increase emissions in the worst case). Because of the uncertain climate policy transmission of monetary policy instruments, it is also not prudent to impose additional climate targets on central banks, which may conflict with the actual mandate. Ultimately, climate change is driven by the real economy and can only be tackled efficiently by regulatory instruments of the real sphere (such as environmental and fiscal policy).

References

Abiry, R./*Ferdinandusse*, M./*Ludwig*, A./*Nerlich*, C. (2022): Climate change mitigation: How effective is green quantitative easing?, ECB Working Paper No. 2022/2701, Frankfurt/M.

Alessi, L./*Battiston*, S. (2022): Two sides of the same coin: Green taxonomy alignment versus transition risk in financial portfolios, in: International Review of Financial Analysis, 102319.

Annicchiarico, B./*Carattini*, S./*Fischer*, C./*Heutel*, G. (2021), Business cycles and environment policy: Literature review and policy implications, Working Paper 29032, Cambridge/Mass.

Annicchiarico, B./*Di Dio*, F. (2015): Environmental policy and macroeconomic dynamics in a new Keynesian model, in: Journal of Environmental Economics and Management, Vol. 69, pp. 1 – 21.

Annicchiarico, B./*Di Dio*, F. (2017): GHG emissions control and monetary policy, in: Environmental and Resource Economics, Vol. 67(4), pp. 823 – 851.

Baranovic, I./*Busies*, I./*Coussens*, W./*Grill*, M./*Hempell*, H. (2022): The challenge of capturing climate risks in the banking regulatory framework: Is there a need for a macroprudential response?, in: ECB Macroprudential Bulletin, 2021, Vol. 15.

Batsaikhan, U./*Jourdan*, S. (2021): Money looking for a home. Technical report, Positive Money Europe.

Belloni, M./*Kuik*, F./*Mingarelli*, L. (2022): Euro area banks' sensitivity to changes in carbon price, European Central Bank, WP 2654, Frankfurt/M.

Böser, F./*Colesanti Senni*, C. (2021): CAROs: Climate risk-adjusted refinancing operations, mimeo, ETH Zürich.

Boneva, I./*Tamburri*, F. (2020): Box 1: The role of the euro in global green bond markets, in: European Central Bank, The International Role of the Euro, Frankfurt/M., p. 20–22.

Bovari, E./*Giraud*, G./*McIssak*, F. (2018): Coping with collapse: A stock-flow consistent monetary macrodynamics of global warming, in: Ecological Economics, Vol. 147, pp. 383–398.

Breitenfellner, W./*Pointner*, W. (2021): The impact of climate change on monetary policy, OeNB, Monetary Policy & the Economy Q3/21, pp. 59–80.

Brunnermeier, M./*Landau*, J.-P. (2020): Central Banks and Climate Change, https://voxeu.org/article/central-banks-and-climate-change.

Campiglio, E. (2016): Beyond carbon pricing: The role of banking and monetary policy in financing the transition to a low-carbon economy, in: Energy Economics, Vol. 121, pp. 220–230.

Campiglio, E./*Dafermos*, Y./*Monnin*, P./*Ryan-Collins*, J./*Schotten*, G./*Tanaka*, M. (2018): Climate change challenges for central banks and financial regulators, in: Nature Climate Change, Vol. 8, pp. 462–468.

Cantelmo, A. (2022): Rare disasters, the natural interest rate and monetary policy, in: Oxford Bulletin of Economics and Statistics, 473–496.

Carattini, S./*Heutel*, G./*Melkadze*, G. (2021): Climate policy, financial frictions, and transition risk, NBER Working Paper No. 28525.

Carney, M. (2015): Breaking the tragedy of the horizon – climate change and financial stability, Speech at Lloyd's of London, 29 September.

Chan, Y. T. (2020): Are macroeconomic policies better in curbing air pollution than environmental policies? A DSGE approach with carbon-dependent fiscal and monetary policies, in: Energy Policy, Vol. 141, June 2020.

Chen, C./*Pan*, D./*Huang*, Z./*Bleischwitz*, R. (2021): Engaging central banks in climate change? The mix of monetary and climate policy, in: Energy Economics, Vol. 103, 105531.

Comerford, D./*Spiganti*, D. (2020): The carbon bubble: Climate policy in a fire-sale model of deleveraging, EUI MWP, 2020/04, https://hdl.handle.net/1814/67434.

Dafermos, Y./*Gabor*, D./*Nikolaidi*, M./*Paeloff*, A./*Van Lerven*, F. (2021), Greening the Eurosystem Collateral Framework. How to Decarbonise the ECB's Monetary Policy, New

Economic Foundation. https://neweconomics.org/2021/03/greening-the-eurosystem-collateral-framework.

Dafermos, Y./*Nikolaidi*, M. (2021): How can green differentiated capital requirements affect climate risks? A dynamic macrofinancial analysis, in: Journal of Financial Stability, Vol. 54, 100871.

Dafermos, Y./*Nikolaidi*, M./*Galanis*, G. (2017): A stock-flow-fund ecological macroeconomic model, in: Ecological Economics, Vol. 131, pp. 191 – 207.

Dafermos, Y./*Nikolaidi*, M./*Galanis*, G. (2018): Climate change, financial stability and monetary policy, in: Ecological Economics, Vol. 152, pp. 219 – 234.

De Santis, R. A./*Hettler*, K./*Roos*, M./*Tamburrini*, F. (2018): Purchases of green bonds under the eurosystem's asset purchase programme, in: Economic Bulletin, 7/2018.

Dietrich, A./*Müller*, G./*Schoenle*, R. (2021): The expectations channel of climate change: Implications for monetary policy, CEPR Discussion Paper 15866.

Dietz, S./*Bowen*, A./*Dixon*, C./*Grandwell*, F. (2016): 'Climate value at risk' of global financial assets, in: Nature Climate Change, Vol. 6, pp. 676 – 679.

Dikau, S./*Volz*, U. (2021): Central bank mandates, sustainability objectives and the promotion of green finance, in: Ecological Economics, Vol. 84.

Diluiso, F./*Annicchiarico*, B./*Kalkuhl*, M./*Minx*, J. (2021): Climate actions and macro-financial stability: The role of central banks, in: Journal of Environmental Economics and Management, Vol. 110, October, 102548.

D'Orazio, P./*Hertel*, T./*Kasbrink*, F. (2022): No need to worry? Estimating the exposure of the German banking sector to climate-related transition risks, Ruhr Economic Papers No. 946, Essen.

D'Orazio, P./*Popoyan*, L. (2022): Realising Central Banks' Climate Ambitions Through Financial Stability Mandates, in: Intereconomics, Vol. 57 (2), pp. 103 – 111.

ECB/ESRB Project Team on Climate Risk Monitoring (2021): Climate-related risk and financial stability, Frankfurt/M., https://www.ecb.europa.eu/pub/pdf/other/ecb.climateriskfinancialstability 202107~87822fae81.en.pdf.

Economides, G./*Smarzcynska Javorcik*, B. (2019): The Effects of Climate Change on a Small Open Economy, CESifo Working Paper No. 7582, Munich.

Economides, G./*Xepapadeas*, A. (2018): Monetary policy under climate change, CESifo WP No, 7021, Munich.

European Energy Agency – EEA (2021): Greenhouse gas emission targets, trends, and member states MMR projections in the EU, https://www.eea.europa.eu/ims/total-greenhouse-gas-emission-trends.

Faccia, D./*Parker*, M./*Stracca*, L. (2021): Feeling the heat: Extreme temperatures and price stability, ECB Working Paper Series No. 2626, Frankfurt/M.

Fatica, S./*Panzica,* R./*Rancan*, M. (2021): The pricing of green bonds, in: Journal of Financial Stability, Vol. 54, 100873.

Fender, I./*McMorrow,* M./*Sahakyan,* V./*Zulaica*, O. (2019): Green bonds: The reserve management perspective, BIS Quarterly Review, September, Basel.

Fender, I./*McMorrow*, M./*Sahakyan*, V./*Zulaica*, O. (2020): Reserve management and sustainability: The case for green bonds? BIS Working Paper No. 849, Basel.

Ferrari, A./*Nispi Landi*, V. (2020): Whatever it takes to save the planet? Central banks and unconventional green policy, ECB Working Paper Series No 2500, Frankfurt/M. December.

Ferrari, A./*Nispi Landi*, V. (2022): Toward a green economy: The role of central bank's asset purchases, Banca D'Italia WP.

Ferrari, M./*Sole Pagli*, M. (2021): No country is an island: International cooperation and climate change, ECB WP 2568, Frankfurt/M.

Fischer, C./*Springborn*, M. (2011): Emissions targets and the real business cycle: Intensity targets versus caps or taxes, in: Journal of Environmental Economics and Management, Vol. 62(3), pp. 352 – 366.

Galì, J. (2008): Monetary policy, inflation, and the business cycle: An introduction to the new Keynesian framework, 2. ed., Princeton.

Gertler, M./*Karadi*, P. (2011): A model of unconventional monetary policy, in: Journal of Monetary Economics 58(1), pp. 17 – 34.

Gertler, M./Kiyotaki, N. (2011): Financial intermediation and credit policy in business cycle analysis, in: Friedman, B. and Woodford, M., eds., Handbook of Monetary Economics, ed., Vol. 3A, pp. 547 – 599.

Giovanardi, F./*Kaldorf*, M./*Radke*, I./*Wicknig*, F. (2022): The preferential treatment of green bonds, mimeo, University of Cologne.

Giuzio, M./*Krusec*, D./*Levels*, A./*Sofia Melo*, A. S./*Mikkonen*, K./*Radulova*, P. (2019): Climate change and financial stability, in: Financial Stability Review, Vol. 1, May.

Golosov, M./*Hassler*, J./*Krusell*, P./*Tsyvinski*, A. (2014): Optimal taxes on fossil in general equilibrium, in: Econometrica, Vol. 82(1), pp. 41 – 88.

Gourio, F. (2012): Disaster Risk and Business Cycles, in: American Economic Review, Vol. 102 (6), pp. 2734 – 2766.

Gross, J./*Zahner*, J. (2021): What is on the ECB's mind? Monetary policy before and after the global financial crisis, in: Journal of Macroeconomics, Vol. 68, June, 103292.

Hardt, L./*O'Neill*, D. W. (2017): Ecological macroeconomics models: Assessing current developments, in: Ecological Economic, Vol. 134, pp. 198 – 211.

Hassler, J./*Krusell*, P./*Smith Jr.*, A. A. (2016): Environmental macroeconomics. Handbook of Macroeconomics, Vol. 2, pp. 1893 – 2008.

Heutel, G. (2012): How should environmental policy respond to business cycles? Optimal policy under persistent productivity shocks, in: Review of Economic Dynamics, Vol. 15(2), pp. 244 – 264.

Höhne, N./*den Elzen*, M./*Joeri Rogelj*, J./*Metz*, B./*Fransen*, T./*Kuramochi*, T./*Olhoff*, A./ *Alcamo*, J./*Winkler*, H./*Fu*, S./*Schaeffer*, M./*Schaeffer*, R./*Peters*, G. P./*Maxwell*, S./ *Dubash*, N. K. (2020): Emissions: world has four times the work or one-third of the time, in: Nature, Vol. 579, pp. 25 – 28.

Keen, B./*Pakko*, M. R. (2011): Monetary policy and natural desasters in DSDE models, in: Southern Economic Journal, Vol. 77(4), pp. 973 – 990.

Konradt, M./*Weder di Mauro*, B. (2021): Carbon taxation and inflation: Evidence from Canada and Europe, CEPR Discussion Paper Series, No 16396.

Kovats, R. S./*Valentini*, R./*Bouwer*, L. M./*Georgopoulou*, E./*Jacob*, D./*Martin*, E./*Rounsevell*, M./*Soussana*, J.-F. (2014): Europe, in: Barros, V. R./Field, C. B./Dokken, D. J./Mastrandrea, M. D./Mach, K. J./Bilir, T. E./Chatterjee, M./Ebi, K. L./Estrada, Y. O./Genova, R. C./Girma, B./Kissel, E. S./Levy, A. N./MacCracken, S./Mastrandrea, P. R./White, L. L. (eds.), Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge/New York, pp. 1267 – 1326.

Lagarde, C. (2021): Climate change and central banking. Keynote speech at the ILF conference on Green Banking and Green Central Banking, Frankfurt/M.

Lamperti, F./*Bosetti*, V./*Roventini*, A./*Tavoni*, M. (2019): The public costs of climate-induced financial instability, in: Nature Climate Change, Vol. 9, pp. 829 – 835.

Lamperti, F./*Dosi*, G./*Napoletano*, M./*Roventini*, A./*Sapio*, A. (2018): Faraway, so close: Coupled climate and economic dynamics in an agent-based integrated assessment model, in: Ecological Economics, Vol. 150, pp. 315 – 339.

Macaire, C./*Naef*, A. (2022): Greening monetary policy: Evidence from the People's Bank of China, in: Climate Policy, DOI: 10.1080/14693062.2021.2013153.

Matikainen, S./*Campiglio*, E./*Zenghelis*, D. (2017): The climate impact of quantitative easing. Grantham Research Institute on Climate Change and the Environment Policy Paper. https://www.lse.ac.uk/granthaminstitute/wp-content/uploads/2017/05/ClimateImpactQuant Easing_Matikainen-et-al.pdf.

Moessner, R. (2022): Effects of carbon pricing on inflation, CESifo WP 9563, Munich.

Monnin, P. (2018): Central banks and the transition to a low-carbon economy, Council of Economic Policies. Discussion Note.

Mukherjee, K./*Ouattara*, B. (2021): Climate and monetary policy: Do temperature shocks lead to inflationary pressures?, in: Climatic Change, Vol. 167, 32. https://doi.org/10.1007/s10584-021-03149-2.

Nordhaus, W./*Sztorc*, P. (2013): DICE 2013R: Introduction and User's Manual, 2. ed., mimeo, Yale University.

Otto, F. E. L./*Harrington*, L./*Frame*, D./*Boyd*, E./*Lauta*, K./*Wehner*, M./*Clarke*, B./*Raju*, E./*Boda*, C./*Hauser*, M./*James*, R./*Jones*, R. (2020): Toward an inventory of the impacts of human-induced climate change, in: Bulletin of the American Meteorological Society, Vol. 101(11), pp. E1972 – E1979.

Papoutsi, M./*Piazzesi*, M./*Schneider*, M. (2021): How unconventional is green monetary policy?, https://web.stanford.edu/~piazzesi/How_unconventional_is_green_monetary_ policy.pdf.

Rezai, A./*Taylor*, L./*Mechler*, R. (2013): Ecological macroeconomics: An application to climate change, in: Ecological Economics, Vol. 85, pp. 69 – 76.

Roncoroni, A./*Battsiton*, S./*Farfan*, E./*Leonardo*, L. O./*Jaramillo*, S. M. (2021): Climate risk and financial stability in the networks of banks and investment funds, in: Journal of Financial Stability, Vol. 54, 100870.

Schoenmaker, D. (2019): Greening monetary policy, VoxEU, 17. April 2019.

Semieniuk, G./*Campiglio*, E./*Mercure*, J.-F./*Volz*, U./*Edwards*, N. (2020): Low-carbon transition risks for finance, in: WIREs Climate Change, Vol. 11, pp. 1 – 24.

Stott, P. et al. (2016): Attribution of extreme weather and climate-related events, in: WIREs Climate Change, Vol. 7(1), pp. 23 – 41.

Stroebel, J./*Wurgler*, J. (2021): What do you think about climate finance?, in: Journal of Financial Economics, Vol. 142 (2), pp. 487 – 498.

United Nations (n.d.): What is climate change?, https://www.un.org/en/climatechange/what-is-climate-change.

Van Bekkum, S./*Gabarro*, M./*Irani*, R. M. (2017): Does a larger menu increase appetite? Collateral eligibility and credit supply, in: Review of Financial Studies, Vol. 31(3), pp. 943 – 979.

van't Klooster, J./*van Tilburg*, R. (2020): Targeting a sustainable recovery with green TLTROs. Technical report, Positive Money Europe.

Vollmer, U. (2022): Monetary policy or macroprudential policies: What can tame the cycles?, in: Journal of Economic Surveys, Vol. 36(5), pp. 1510 – 1538.

Walsh, E. (2017): Monetary theory and policy, 4. ed., Cambridge, London.

Weitzman, M. L. (2012): GHG targets as insurance against catastrophic climate damages, in: Journal of Public Economic Theory, Vol. 14(2), pp. 221 – 244.

Work Stream on Climate Change (2021): Climate change and monetary policy in the euro area, European Central Bank, Occasional Paper Series, Frankfurt/M.

Zerbib, O. D. (2019): The effect of pro-environmental preferences on bond prices: Evidence from green bonds, in: Journal of Banking & Finance, Vol. 98, S. 39 – 60.