

Business Cycles and Environmental Policy

Barbara Annicchiarico, Stefano Carattini, Carolyn Fischer, and Garth Heutel

May 2021

Abstract

We study the relationship between business cycles and the design and effects of environmental policies, particularly those with economy-wide significance like climate policies. First, we provide a brief review of the literature related to this topic, from initial explorations using real business cycle models to New Keynesian extensions, open-economy variations, and issues of monetary policy and financial regulations. Next, we provide a list of the main findings that emerge from this literature that are potentially most relevant to policymakers, including the impacts of policy on volatility and how to design policy to adjust to cycles. Finally, we propose several important remaining research questions.

JEL codes: Q58; E32

Keywords: Fluctuations; Climate Change; Real Business Cycles; Dynamic Stochastic General Equilibrium; Carbon Tax; Cap-and-Trade

Annicchiarico: University of Rome Tor Vergata, barbara.annicchiarico@uniroma2.it. Carattini: Georgia State University, scarattini@gsu.edu. Fischer: Vrije Universiteit Amsterdam, University of Ottawa, and Resources for the Future, fischer@rff.org. Heutel: Georgia State University and NBER, gheutel@gsu.edu. This paper is prepared for the NBER's *Environmental and Energy Policy and the Economy* conference and publication. We thank the volume's editors, Tatyana Deryugina, Matthew Kotchen, and James Stock, as well as Baran Doda, for very useful comments on a previous version of this paper. We also thank Kukhee Han for valuable research assistance.

I. Introduction

Environmental economists have long strived to identify the “optimal” level of environmental regulation for many pollutants, including, in recent decades, greenhouse gases. This “optimal” balance between the economy and the environment is usually defined based on efficiency, considering both the marginal benefits and marginal costs of regulation. Optimal pollution pricing has been one of the main activities of environmental economics as a field, an area where economists have been especially influential in shaping public policy (Hahn 1989; Fourcade et al. 2015).

Importantly, the costs and benefits of environmental regulation, as well as their distribution, may vary over the course of business cycles. Pollution is highly pro-cyclical and more volatile than GDP (Doda 2014). For example, the United States generated 11% fewer greenhouse gas emissions between 2007 and 2013, largely due to the Great Recession (Feng et al. 2015). Recent evidence from the COVID-19 pandemic is even more striking, given the exceptional circumstances of its related recession. Daily global carbon dioxide (CO₂) emissions had already decreased on average by 17% by April 2020 since the beginning of the COVID-19 pandemic (Le Quéré et al. 2020), due to the responses by governments, individuals, and firms, which all contributed to limit economic activity following the outbreak. Overall, global CO₂ emissions decreased by about 7% from 2019 to 2020 (Le Quéré et al. 2021). Since pollution varies with the business cycle, it seems reasonable to conclude that pollution policy ought to adapt to the business cycle as well, following fluctuations in marginal costs and benefits.

Some real-world environmental policies do adjust automatically to business cycles. The European Union Emissions Trading System (EU ETS) has created a Market Stability Reserve (MSR) to insulate the system from business cycle shocks (Perino et al. 2021). California and

Quebec have auction reserve prices, and the Regional Greenhouse Gas Initiative has adopted an emissions containment reserve with price-triggered quantity adjustments. However, most real-world environmental policies – whether market-based policies like taxes or cap-and-trade, or command-and-control policies – do not explicitly respond to business cycles and instead maintain a constant stringency over cycles. Several reasons may explain this phenomenon.

First, business cycle adaptations may be seen as of second-order importance in environmental policy, while getting the stringency right on average is considered of first-order importance. Environmental policies may be on average too lenient, and fixing this may be seen as more important than making sure policies adjust to business cycles. When policies are too lenient, the economic rationale for adjusting their stringency to the business cycle may be weaker.¹ Many carbon tax proposals, for example, are designed with embedded tax escalators, which may allow them to reach, after several years, a level of stringency that is compatible with the goal of maintaining global temperatures within +1.5-2°C with respect to pre-industrial levels (see Stiglitz et al. 2017; IMF 2019). In the meantime, tax rates remain below efficient levels, thus weakening the rationale for business-cycle adjustments. Cap-and-trade programs also struggle with excessive leniency, at least initially. Lacking full information about the costs of regulation, and concerned about price volatility, governments tend to err on the side of avoiding potential high-cost outcomes, and as a result consistently set caps too leniently (Burtraw and Keyes

¹ Environmental policies may be too lenient for several reasons. First, due to uncertainties arising from difficulties in estimating costs and benefits properly (e.g. Pindyck 2013), leading standard economic analysis like integrated assessment models (e.g. Nordhaus 1993) to provide estimates of optimal stringency that may be the source of important debates (e.g. Stern 2007; Pindyck 2013; Stern and Stiglitz 2021). Second, due to a consistent tendency of policymakers to overweight or overestimate costs versus benefits (Harrington et al. 2000). Third, due to similar information asymmetries between experts and citizens, leading them overestimate drawbacks and underestimate benefits of market-based instruments for environmental policy (Carattini et al. 2018; Dal Bò et al. 2019). Finally, economic efficiency or other economics-based optimization criteria may not be the primary consideration in policy design.

2018).² The fact that allowance prices react endogenously to the business cycle can in principle be a benefit of cap-and-trade schemes.³ Information limitations and political biases can thus pose challenges to ensuring that the average level of stringency is appropriate, which may prevent policy from efficiently adapting to cycles.

A second reason why environmental policy does not adapt to business cycles is a political economy concern for the potential for the rationale to be abused by regulators, leading to a persistent weakening of environmental policy. One example is the decisions taken by the Trump administration during the COVID-19 recession. By March 2020, the Environmental Protection Agency (EPA) decided to exempt facilities that release toxic chemicals from reporting their emissions to the Toxic Release Inventory (TRI), which led to an increase in pollution around TRI facilities (Persico and Johnson 2021). While the decision was motivated mostly by the inability of facilities to meet TRI requirements due to the direct effects of the COVID-19 pandemic, additional rollbacks referred explicitly to the recessionary forces generated by the pandemic.⁴ These additional rollbacks often reduced stringency to virtually zero, which is hard to justify as a business cycle adjustment. A case in point is the regulation of methane, where the federal administration in August 2020 eliminated requirements for oil and gas companies to monitor and

² An example is the European Union Emissions Trading System (EU ETS), in which allowance prices collapsed early on and remained persistently low for nearly a decade (EC 2012). While such low price outcomes were largely due to an overallocation of permits (Martin et al. 2014), the Great Recession also contributed to depress prices (Koch et al. 2014).

³ Some commentators, however, do not seem to have been able or willing to disentangle the two elements, overallocation of permits and effect of the business cycle, in their critique of the EU ETS. Fortunately, in a cap-and-trade system, the appropriate response to either price-depressing element is to tighten the cap, which recent reforms have done (see Hepburn et al. 2016), but it remains far from clear whether the accompanying reforms are sufficient to address future shocks (Fischer et al. 2020).

⁴ With the executive order “Accelerating the Nation's Economic Recovery From the COVID-19 Emergency by Expediting Infrastructure Investments and Other Activities” of June 2020, the Trump administration instructed agencies to waive long-standing environmental laws given that “Unnecessary regulatory delays will deny our citizens opportunities for jobs and economic security, keeping millions of Americans out of work and hindering our economic recovery from the national emergency.”

repair methane leaks from pipelines, storage facilities, and wells. These requirements, known as Oil and Natural Gas New Source Performance Standards, were recently reinstated by the new administration.

A final reason is simply that the literature studying this issue is so recent that it has not yet been able to address the most pressing questions or has not yet been properly communicated to policymakers. The literature on business cycles and environmental policy effectively started just about a decade ago with Fischer and Springborn (2011) and is thus relatively recent.⁵ The research has not yet addressed all dimensions of the problem nor all questions that policymakers may have about the implications of tying environmental policy to the business cycle, including distributional effects.

Our goal in this paper is threefold. First, we review the literature on environmental policy and the business cycle, with the goal of summarizing and conveying in a palatable way the economic rationale for business-cycle adjustments to environmental policy, as well as the effects of policy on economic volatility. In this respect, our paper updates early synthesis papers, including Fischer and Heutel (2013). Second, we present an assessment of the main results from this literature that are most relevant for policymakers today. This includes how different types of policy can lead to different volatilities of outcomes, and how policymakers can adapt environmental policy to cycles, ideally *ex ante*, tying their hands to limit the risk of business-cycle adjustments being abused. Third, we identify areas for future research that have currently been underexplored, with the goal of filling the current knowledge gaps that may contribute to limiting the adoption of business-cycle adjustments in environmental policy. Our general focus is on the climate externality, due to its importance in the current policy landscape, although many

⁵ Of course, there is a much larger and older literature on business cycles more generally, which is beyond this scope of this paper to discuss.

of our insights may also carry important implications for other environmental issues. We discuss the importance of considering other pollutants as well, particularly given the fact that greenhouse gases are long-lived stock pollutants, while other pollutants like particulate matter are flow pollutants for which cyclical fluctuations in emissions likely have a larger effect on damages.

We present four main sets of policy-relevant findings from the literature, described in detail in section IV. First, we discuss how different policies can impact the volatility of outcomes over the business cycle, even when those policies themselves do not vary over the cycle. A main finding here is that policy type matters—a quantity-based instrument such as cap-and-trade leads to overall less volatility, while a price-based policy such as a carbon tax leads to more volatility. Second, policy can be designed to vary over the business cycle and these adjustments affect the economy and welfare. Both the dynamically-efficient carbon tax rate and the dynamically-efficient carbon cap are procyclical—increasing during expansions and decreasing during recessions; however, the magnitude of the welfare advantages of these dynamically-efficient policies over static policies is unclear. Third, policy implications vary depending on the source of the business cycle, i.e. the type of shock triggering the business-cycle fluctuation. Almost all of the modeling literature considers aggregate productivity shocks, although some empirical literature suggests that other shocks may contribute more to emissions fluctuations. Productivity shocks may also be sector-specific. When productivity shocks are specific to energy-intensive polluting sectors, a tax may have a welfare advantage over a cap, though yielding higher volatility. Fourth and finally, we discuss how environmental policy interacts with other policies or other distortions over the business cycle. Other policies, including monetary policy, and other distortions, including labor market frictions, can affect the efficient cyclicity of policy or its effects on volatility.

The remainder of this paper is organized as follows. Section II describes the basics of the environmental dynamic stochastic general equilibrium (E-DSGE) model, the main toolbox to study business cycles in macroeconomics, and their relationship to the environment. Section III very briefly summarizes the most important extensions to the basic E-DSGE models, while the Appendix provides a more thorough literature review. Section IV summarizes what we see as the main findings of the literature most relevant to policymakers. Section V discusses the most promising and most urgent avenues for future research.

II. Description of basic E-DSGE model

In this section we describe the basic dynamic stochastic general equilibrium (DSGE) model used in the literature examining environmental policy and business cycles. DSGE models have been frequently used in the literature for decades to study business cycles (Christiano et al. 2018). Models that extend the basic DSGE model to include some aspects of the environment have been called environmental DSGE, or E-DSGE, models (Khan et al. 2019). The workhorse model is based on the real business cycle (RBC) model, where business cycles are fueled by random autocorrelated productivity shocks (Rebelo 2005). Fischer and Springborn (2011), Heutel (2012), and Angelopoulos et al. (2013) are three early papers that modify the standard RBC model by including pollution and pollution policy. Briefly, the model consists of an aggregate representative agent choosing consumption, labor, and investment to maximize total discounted utility. Capital evolves dynamically based on investment. Pollution arises from production and can negatively affect productivity or utility, but the agent's choices can affect the level of pollution. Given a series of exogenous shocks to productivity, the model can be used to find the efficient level of investment and pollution that maximizes total discounted utility. The model can also analyze pollution policies, like pollution taxes or cap-and-trade.

We first describe a centralized model, where a representative agent acts the same as a social planner would act. The representative agent chooses consumption c_t , investment i_t , and leisure l_t in each period t to maximize expected discounted lifetime utility. The single-period utility function is $U_t(c_t, l_t)$. The resource constraint is $c_t + i_t = y_t$, where y_t is the level of output or production. A capital stock evolves according to $k_{t+1} = i_t + (1 - \delta)k_t$. Time is normalized to one each period and allocated between labor (n_t) and leisure: $l_t + n_t = 1$. Production is based on the labor and capital inputs along with a productivity shock: $y_t = a_t f(k_t, n_t)$. The productivity shock a_t is exogenous and evolves according to an autoregressive process.

So far, the model described is the standard RBC model. At this point, the model can be modified to include pollution and pollution policy, and there is more than one way to do so. As in Fischer and Springborn (2011), and as is commonly done in computable general equilibrium models, one would modify the production function to also include a polluting input m_t , so that output is $y_t = a_t f(k_t, n_t, m_t)$. The polluting input is costly, so the resource constraint becomes $c_t + i_t + m_t = y_t$. The polluting input is a choice variable and so can be changed in response to economic conditions or policies (described below). An alternative way of modeling pollution, following Heutel (2012) based on the representation in the DICE model (see Nordhaus 1993; Nordhaus 2017), is to let pollution emissions e_t be a byproduct of production that can be reduced through abatement spending z_t . Emissions are $e_t = g(z_t)h(y_t)$, where the increasing function h maps how output creates emissions, holding abatement z_t fixed, and the decreasing function g maps how abatement spending reduces emissions, holding output y_t fixed. The resource constraint under this specification of pollution is $c_t + i_t + z_t = y_t$.

The relationship between emissions in one period e_t and the total stock of pollution x_t can be given by a stock evolution equation. For example, in Heutel (2012), the pollution stock evolves according to $x_{t+1} = \eta x_t + e_t + e_t^{exog}$, where η is a pollution depreciation rate and e_t^{exog} is the exogenous level of emissions from other economies (e.g., for a global pollutant like carbon dioxide, this represents emissions from other countries). Another way of incorporating the stock of pollution is done in Angelopoulos et al. (2013), where the stock variable Q_t represents environmental quality (a good) rather than the pollution stock (a bad). The evolution of environmental quality is $Q_{t+1} = (1 - \delta^q)\bar{Q} + \delta^q Q_t - e_t + \nu z_t$, where \bar{Q} is environmental quality without any pollution and δ^q is a pollution persistence parameter. Emissions e_t negatively affects environmental quality, and abatement spending z_t positively affects environmental quality measured by the parameter ν .

We next describe how damages from pollution can be incorporated into the model. There are two places where pollution damages can enter: pollution can either negatively affect utility directly, or it can indirectly affect utility by negatively affecting output or productivity. Under the first specification, following Angelopoulos et al. (2013), we can modify the utility function to include the level of environmental quality Q_t : $U_t(c_t, l_t, Q_t)$. Under the second specification, following Heutel (2012), we can modify the production function to include the level of the pollution stock x_t : $y_t = (1 - d(x_t))a_t f(k_t, n_t)$, where d is a damage function that relates the level of the pollution stock to a reduction in output. Several integrated assessment models of climate change, including the DICE model (Nordhaus 1993, 2017, 2018), model carbon pollution as affecting output rather than utility directly.

The centralized model is now complete, and the model can be solved as a social planner's problem, where the damages from pollution are incorporated into the decision-making process. A

social planner trades off the benefits of reducing emissions (reducing pollution damages) with its costs (abatement costs). The solution represents the first-best response of all economic variables to exogenous productivity shocks. Solutions can be presented as impulse response functions, which show how all of the variables optimally respond to a one-unit innovation in the productivity shock. Or, solutions can be presented as simulations of business cycles, in which an exogenous series of productivity shocks are drawn and the economy is allowed to optimally respond. Figures 1 and 2 present results from the first-best dynamic policy simulations, based on the model in Heutel (2012), showing impulse response functions and business cycle simulations, respectively.⁶ The model used here is identical to that used in Heutel (2012), though the calibration is updated based on Gibson and Heutel (2020).⁷

Figure 1 shows impulse response functions for the productivity shock (after a one-time innovation in period 0) along with three variables related to the environment: single-period emissions e_t , the pollution stock x_t , and abatement spending z_t . The blue line shows that the productivity shock value decays exogenously at a constant rate. In response to that productivity increase, emissions are higher than their steady-state value. During an economic boom, when output increases (not shown in Figure 1), emissions also are allowed to increase. However, Figure 1 also shows that abatement spending increases above its steady-state value. While emissions are increasing during the boom, they are not increasing by as much as they otherwise would if it were not for the efficient response of the economy in increasing abatement spending.

⁶ These graphs update Figures 4 and 5 in Heutel (2012). This model (like the model in Angelopoulos et al. 2013 but unlike the model in Fischer and Springborn 2011) omits labor and leisure.

⁷ This updated calibration is based both on the most recently-available version of the DICE model's damage function, and emissions elasticity estimated from monthly emissions and GDP data through 2019. See details in Gibson and Heutel (2020).

The optimal cyclicality of emissions is thus procyclical, but less procyclical than they would be absent the dynamically-optimal policy.

Figure 2 shows business cycle simulations for the centralized model without policy, drawn from an arbitrary draw of productivity shocks. Capital is procyclical but less volatile and somewhat lagged from output due to its stock nature. Emissions are strongly procyclical, though not quite as variable as output is. The pollution stock has such a slow decay rate that these business-cycle fluctuations have very limited impact on its value (pollution here is calibrated to carbon dioxide, a stock pollutant that remains in the atmosphere for decades).

Next, we turn to a decentralized model, in which a representative firm maximizes profits and a representative consumer maximizes utility. By assuming that the firm ignores the effect that its pollution has on either productivity or utility, the decentralized model features an externality, so that the decentralized solution will generally not be first best. Either the consumer or the firm can be subject to an environmental policy, for example, a tax on emissions.

The model can also be used to analyze the effect of these policies on various economic outcomes. Fischer and Springborn (2011) analyze the effect of three environmental policies: an emissions tax, an emissions cap, and an intensity standard that fixes the ratio of emissions to output. They generate business cycle simulations and show how various economic variables respond to the draw of productivity shocks under each of the three policies. We replicate these simulations here in Figure 3. In response to an exogenous draw of productivity shocks (identical to the draw in Figure 2), Figure 3 plots the response of emissions (top panel) and output (bottom panel) under each of the three policies: the intensity standard (*IT*), the emissions cap (*Cap*), and the emissions tax (*Tax*).

The three policies are all calibrated to yield the efficient first-best level in steady state, but the policy values do not adjust to the business cycle. Consequently the three policies yield different cyclical properties. Of course, since the cap is fixed over time, it results in emissions fixed at their steady-state level, while the tax and intensity standard result in emissions that vary over the business cycle. Output is slightly less volatile under the cap policy than under the other two policies. This demonstrates that the intensity standard is more accommodating of business cycles due to its flexibility—by restricting emissions per unit output rather than total emissions, it includes a built-in cyclical adaptation.

The decentralized model can also be used to solve for the efficient level of the policy variables that internalizes the pollution externality and reaches the theoretical first best. Such an exercise is performed in Heutel (2012), which includes a specification of external damages from pollution affecting productivity, though unlike Fischer and Springborn (2011), does not include a labor decision or an intensity standard policy. Results from business cycle simulations of efficient policy are presented here in Figure 4. For the same draw of shocks simulated in Figures 2 and 3, Figure 4 shows the efficient response of both a tax policy and an emissions cap. Here, the policy values endogenously respond to the draw of the shocks and the changing economy and thus are not fixed over time as in Figure 3. Figure 4 shows that both the emissions cap and the emissions tax are procyclical. But, that means the cyclicity of the stringency of each policy is different. During an expansion, the efficient emissions tax increases, which is an increase in stringency, while the efficient emissions cap also increases, which is a decrease in stringency. As also can be seen from Figure 4, the efficient emissions tax is more procyclical than the efficient emissions cap.

III. Extensions to the basic model

In the technical Appendix, we provide an extensive literature review of the state of the E-DSGE literature. Here, we briefly summarize the broad areas where extensions have been made in the literature, relegating the details of the individual studies to the Appendix. This review motivates our discussion in the following section around the most policy-relevant findings that we identified in the literature. We discuss four categories of extensions that have been studied in the literature: (i) extensions that maintain the RBC framework, (ii) New Keynesian extensions, (iii) open economy extensions, and (iv) extensions incorporating credit market imperfections, financial regulation, and unconventional monetary policy.

Several studies maintain the RBC framework of cycles produced through autocorrelated productivity shocks but add more complications. One such study (Dissou and Karnizova 2016) develops a multi-sector economy, where shocks can be sector-specific, including shocks arising to emissions-intensive industries like the fossil fuel sector. Other papers consider different types of productivity shocks, including anticipated vs. unanticipated shocks and investment-specific shocks (Khan et al. 2019), or frictions arising from other sources like the labor market (Gibson and Heutel 2020).

The second set of extensions include New Keynesian (NK) elements. The heart of the NK framework includes imperfect competition, nominal rigidities, and non-neutral monetary policy. For instance, Annicchiarico and Di Dio (2015) modify the E-DSGE model to include imperfect price adjustments and an interest-rate rule governing monetary policy. They explore how the optimal design of the carbon tax (including its cyclicity) depends on the degree of price stickiness and on monetary policy. Several other extensions in this vein explore related issues under alternative modeling assumptions. For example, Economides and Xepapadeas

(2018) study the challenges climate change poses to monetary policy and the potential inflationary effects of carbon pricing, which are among the main concerns for central bank (NGFS 2021).

The third variant of the literature uses open-economy versions of E-DSGE models to look at cross-country pollution and policy spillovers and international environmental agreements. Several of these papers also incorporate some elements of the NK approach, including nominal rigidities and imperfect competition. For example, Annicchiarico and Diluiso (2019) develop a two-country model to explore how real and monetary policy shocks propagate across borders, and how this propagation is influenced by environmental regulation.

Finally, the fourth set of extensions considers credit market imperfections, financial regulation, and unconventional monetary policy. This strand of the literature is motivated by the concerns that climate-related risks may represent a threat to financial and macroeconomic stability. A debate exists about whether and to what extent financial regulators can or should address climate change, for example by creating new tools like green-biased regulations to encourage the transition to a low-carbon economy. A related concern is that of the transition risk that arises from an abrupt implementation of ambitious climate policy in an economy where leveraged banks have a large stake in affected industries and assets like those related to fossil fuels and other carbon-intensive industries. In this case, climate policy could create stranded assets, which may trigger financial instability risks. Several recent studies explore these and other related issues. One of the first studies in this literature is by Diluiso et al. (2020) and combines a multi-sector E-DSGE model with a model of financial frictions, and study how unconventional monetary policy like green quantitative easing can stabilize the economy in response to a potential crisis brought about by stranded assets.

IV. Policy-relevant findings from the literature

In this section we provide a brief overview of the main findings from the literature that are most relevant to policymakers, who may seek either to design policies to accommodate business cycles or to assess the impacts of business cycles on policy effectiveness or pollution. The first two subsections describe positive findings from the literature about the effect of policy on economic volatility and the design of policy over the business cycle. The last two subsections discuss caveats to these findings, pointing out that the source of fluctuations matters and that other macroeconomic market failures or distortions interact with environmental policy.

IV.a. Policy effects on volatility

Emissions are a byproduct of production and are thus naturally pro-cyclical. Empirical evidence indicates that emissions are even more volatile than GDP, indicating they arise from sectors more vulnerable to business-cycle variations (Doda 2014). The flip side of this relationship is that policies to control emissions will also influence the response of other macroeconomic factors to exogenous shocks.

A cap on emissions has a built-in dampening effect on the business cycle. A positive productivity shock will expand output and demand for emissions, but the cap will require further efforts to limit polluting inputs or abate emissions, manifesting in an increase in the emissions price. With a negative productivity shock, the cap becomes less constraining; emissions prices fall with demand, and less abatement effort is required in a downturn. Since one means of reducing emissions is reducing output, less of this output-related abatement is needed in a downturn. As a result, an emissions cap limits volatility of other macroeconomic variables. This effect becomes even more pronounced when prices are more difficult to adjust, since these rigidities tend to exacerbate business cycles (Annicchiarico and Di Dio 2015). However, the

stabilizing properties of a cap are mitigated when wages are sticky, since the effects of uncertainty on employment are greater (Jaimes 2020). On the other hand, the pro-cyclical response of emissions prices under cap-and-trade system could exacerbate inflation volatility, so monetary policy interactions matter too (Annicchiarico and Di Dio 2017).

An emissions tax, by contrast, fixes the price of emissions and allows the quantity of emissions to respond. Investment and production decisions take the emissions price into account, but a positive productivity shock will cause output and emissions to expand. A tax does little to deter this response to the business cycle, and may even exacerbate volatility by making investment more sensitive to productivity shocks (Fischer and Springborn 2011). A carbon tax is also likely to allow greater transmission of business cycles across borders (Annicchiarico and Diluiso 2019).

An emissions intensity standard – fixing emissions per unit of output – offers a road in between a tax or a cap. A positive productivity shock increases demand for emissions, but an increase in output also loosens the emissions constraint, which is set per unit of output. As a result, the emissions price rises, but to a lesser extent than with a fixed cap. The output-based allocation of emission allowances implicit in intensity targets also provides a general incentive boost to output, leading to higher levels of investment and output than a cap or tax. However, in terms of volatility, an intensity target does little to change how the macroeconomy responds to business cycles, compared to no policy (Fischer and Springborn 2011).

The above comparisons are largely based on stark policy choices. In practice, many emissions trading systems adopt provisions with banking and borrowing that will allow emissions price responses to macroeconomic shocks to be spread over time (e.g. Kollenberg and Taschini 2019). Recognizing that the economy is composed of many sectors with different

emissions intensities, the influence of climate policy on macroeconomic volatility may depend on the source of business cycle variation. For example, shocks related to the energy sector are more likely to interact with climate policies than other productivity shocks (Dissou and Karnizova 2016).

Besides the pollution policies discussed above, macroprudential financial regulations, designed to align environmental and financial stability objectives, are also shown to influence the transmission of the business cycle. Green-biased regulations may bring down the volatility of business cycle fluctuations, while favoring green investments and reducing the exposure of financial intermediaries to assets at risk of stranding (Punzi 2018, Benmir and Roman 2020, Diluio et al. 2020, Carattini et al. 2021).

IV.b. Dynamically optimal policies and welfare

Allowing policy variables to vary along with the business cycle gives more flexibility for the policy to address market imperfections and improve welfare. Some policies, like unemployment insurance, are clearly designed so that their intensity or stringency responds to business cycles. For an environmental policy like a pollution tax or cap-and-trade system, the goal would be to design it so that the stringency of the policy (the tax rate, or the level of the cap) can vary in ways that keep emissions prices better aligned with marginal environmental damages over the business cycle. However, in practice, for adaptive policies to do more good than harm relative to fixed policies, not only must the adjustments be well-targeted, but the efficiency advantages from the policy's variance over the cycle must outweigh any costs that might be incurred by allowing it to vary. These costs could include administrative costs of the cyclical adjustments, costs arising from households' or firms' uncertainties about policy values, increased trading frictions or transaction costs, or even higher political economy barriers to

implementation. We return below to the question of how policymakers can introduce simple rules requiring limited information to mimic “optimal” cyclical adjustments.

Designing a policy like a tax so that its values in each period efficiently respond to business cycle conditions is often called the Ramsey problem (Chari et al. 1994). Heutel (2012) solves the Ramsey problem for both an emissions tax and cap-and-trade system, calibrated to the US economy and carbon dioxide emissions. As we showed here in Figure 4 (using an updated calibration of that earlier model), both the Ramsey-optimal carbon tax and the Ramsey-optimal carbon emissions cap are procyclical, increasing during expansions and decreasing during recessions. This implies that a carbon tax becomes more stringent during expansions and less stringent during recessions, while a cap-and-trade system becomes less stringent during expansions and more stringent during recessions. This pattern may provide a political economy advantage for taxes over cap-and-trade, given that tax relief can be communicated to the public during recessions, rather than a cap adjustment that would increase prices. However, under this calibration the Ramsey-optimal carbon tax is more volatile than the Ramsey-optimal cap, which may be a disadvantage of it.⁸

To consider specifically how to design policy to adjust to the business cycle, Heutel (2012) provides something close to “rules-of-thumb” based on GDP. Ideally, as mentioned in our introductory paragraphs, business-cycle adjustments should be a policy feature that is introduced from the start and operates according to a clear and transparent rule. Rules-based adjustments would allow timely responses, avoiding the delay of passing new legislation or promulgating amendments to regulations. They also would tie the hands of policymakers and avoid arbitrary decisions once a shock materializes. If the regulator can set the policy stringency as a function of

⁸ Gibson and Heutel (2020) and Carattini et al. (2021) also solve for Ramsey-efficient carbon taxes in response to RBC shocks, with other market failures in their DSGE models.

lagged GDP (or its deviation from trend), then what is the function mapping GDP into the efficient policy? Heutel (2012) finds that the efficient carbon tax rate increases by about 142% of the deviation of output; for example, if output is 10% higher than trend in a particular quarter, then the efficient carbon tax rate is 14.2% higher than trend in the following quarter. For the efficient emissions cap, the response is 66% of the deviation of output; if output is 10% higher than trend in a particular quarter, then the efficient carbon cap is 6.6% higher than trend in the following quarter.⁹ In addition to or instead of GDP, regulators may use leading indicators to forecast shocks. In the United States, for instance, prominent leading indicators are the Purchasing Managers Index (PMI) and the Consumer Confidence Index (CCI).¹⁰

How important are the business-cycle adjustments for welfare? Lintunen and Vilmi (2013) compare the Ramsey-optimal emissions tax with a constant tax (they do not consider cap-and-trade) and find slight differences in emissions but negligible overall economic effects. Heutel (2012) notes that the welfare comparison can depend on the shock values (see following subsection). Both papers are calibrated to greenhouse gas pollutants for which the accumulated stock matters rather than the flow of emissions in any period. For flow pollutants, business cycle policy adjustments may have larger welfare impacts than for stock pollutants, as we discuss in section V.d below.

⁹ Karp and Traeger (2021) consider a similar exercise, where the cap in a cap-and-trade scheme can endogenously adjust to macroeconomic and technology shocks, though not in a DSGE context.

¹⁰ Additional indicators that may be relevant for this exercise and could be examined in future research include jobless claims and unemployment rates, yield curves, for instance for the 10-year Treasury bond, or stock market returns. It is an open normative question whether environmental policy should be tied to GDP, rather than jobs or the unemployment rate of the most disadvantaged members of society.

IV.c. Source of shocks

Most of the papers that we have reviewed here use a real business cycle (RBC) model, where cycles are fueled by exogenous shocks to aggregate productivity. Whether or not productivity shocks are in fact a predominant driver of real-world business cycles is a question up for debate in the broader macroeconomic literature.¹¹ More specifically, two recent papers investigate the source of emissions fluctuations over the business cycle, and both find that other types of shocks besides productivity shocks—such as shocks to energy efficiency, specific technologies, or non-environmental policies—are important drivers.

Khan et al. (2019) empirically study the drivers of emissions variation in the US, including monetary and government spending shocks as additional sources of uncertainty. They consider six different shocks – anticipated and unanticipated neutral technology (TFP) shocks, anticipated and unanticipated investment-specific technology shocks, government spending policy shocks, and monetary policy shocks – and find empirically that the largest impact on pollution among these shocks comes from the anticipated investment-specific technology shock. Jo and Karnizova (2021) provide a similar analysis, including shocks to energy efficiency that can cause a negative correlation between output and emissions. Jo and Karnizova (2021) identify shocks that can cause emissions and output to be negatively rather than positively correlated with each other, and they find that these types of shocks explain almost half of the overall volatility of emissions. They argue that shocks to energy efficiency are the primary example of these negative-correlation shocks. Since other types of shocks may have different implications for the relationship between business cycles and emissions and, as Jo and Karnizova (2021) suggest, some shocks cause emissions and output to move in opposite

¹¹ For example, see Christiano et al. (2003), Galí and Rabanal (2004), and Angeletos et al. (2020).

directions, then it is likely that the optimal response of policy to these shocks is different than the optimal response to productivity shocks. Unfortunately, as of today, the literature has little to say about how policy can respond to these types of shocks, so more research is needed to shed light on this question.

In the context of E-DSGE models, some initial indication of the importance of the source of shocks is given by Dissou and Karnizova (2016), who study sector-specific productivity shocks. Their main finding is that under productivity shocks localized to energy sectors, a carbon tax outperforms a cap in welfare terms, although it leads to higher volatility of macroeconomic aggregates. However, for shocks to sectors other than energy-intensive sectors, a tax and a cap (even in the absence of intertemporal considerations like banking) have statistically equivalent welfare implications. This result indicates that including flexibility mechanisms may be more important for quantity-based policies, especially when energy sector volatility is a primary issue.

IV.d. Interaction with other policies or distortions

Policies targeting pollutants that are widespread throughout the economy, such as carbon dioxide emissions, are likely to give rise to equally pervasive effects on macroeconomic responses to other policies and market distortions. Carbon prices and regulations influence a range of household and producer behavior, which may have non-trivial implications for the frequency and severity of business cycles.

Climate change is not the only policy issue of macroeconomic importance. Policymakers must grapple with market power and barriers to competition, frictions in labor markets that result in excess unemployment, regulations or behavioral practices that impede the adjustment of prices and wages, and financial market imperfections that may elevate the cost of borrowing and limit the amount of credit. The literature has pointed out that simultaneously addressing environmental

issues and other market failures is particularly challenging in the presence of different sources of uncertainty. From this perspective, the literature on environmental policy and business cycles has drawn attention toward the interactions between environmental regulations and other policies, especially those aimed at stabilizing the economy over the business cycle, such as monetary policy, financial regulations, and labor market policies.

The underlying monetary policy affects optimal environmental policy design in response to exogenous shocks. Depending on the degree to which monetary policy reacts to the level of economic activity and stabilizes the economy, the optimal carbon price may be more or less procyclical, relative to what one would expect without monetary accommodation (see Annicchiarico and Di Dio 2015, 2017). The interaction also goes both ways: the stronger the negative environmental externality, the less accommodative—and so the more stringent—the optimal monetary policy should be to avoid excess expansion and emissions. In addition, an ambitious greening policy may produce large fluctuations in consumer prices. In this sense, unanticipated and abrupt climate actions may potentially represent a challenge for monetary stability (e.g. Economides and Xepapadeas 2018; Carattini et al. 2021).

Some unconventional monetary policies aim at changing the composition of central banks' balance sheets toward green assets. Early studies on the effects of such green-biased quantitative easing programs point to a very limited scope of these policies in greening the economy, as well as little difference in their effectiveness in reviving the economy following an adverse shock as compared to market-neutral quantitative easing programs (see Benmir and Roman 2020, Diluiso et al. 2020 and Nispi Landi and Ferrari 2020). However, emerging analyses of the effects of the introduction of non-neutral financial regulatory schemes, such as green-supporting and/or brown-penalizing regulations (see D'Orazio and Popoyan 2019),

suggest that by inducing a portfolio reallocation of financial intermediaries toward green investments, these schemes encourage the greening process and reduce the exposure of banks to climate-sensitive assets, mitigating the financial effects of stranded assets (see Punzi 2018, Benmir and Roman 2020, Diluiso et al. 2020, Carattini et al. 2021).

Finally, labor market frictions—such as the costs of searching for employment, relocating for a job, or finding suitable employees—also affect environmental policy over the business cycle. Such frictions are often represented as congestion problems: adding an unemployed worker to the pool of job seekers reduces everyone else’s probability of finding a job, but raises the probability for hiring firms of finding a good match. Similarly, more job vacancies make it harder for firms but easier for unemployed workers to find a match. Depending on how these balance out, the level of employment may be inefficiently high (too many vacancies) or low (too many job seekers). Economic efficiency then requires combining a pollution policy (e.g., carbon tax) with a labor market policy (e.g. a tax or subsidy on job creation), so as to jointly address the environmental externality and labor market imperfections. However, when the labor market instrument is unavailable, the optimal design of the emission tax is more challenging: the optimal carbon tax will be less or more procyclical depending on whether the market delivers an inefficiently high or low employment level. Gibson and Heutel (2020) find in their preferred calibration that the procyclicality of the efficient carbon tax is only half as high once labor market frictions are accounted for. The existence of labor frictions and unemployment would then provide a further rationale, based on equity as well as efficiency, for designing a state-contingent environmental policy.

V. Remaining questions

A number of important questions related to environmental policies and business cycles remain to be addressed. In this section, we categorize some promising directions for future research.

V.a. Heterogeneous agents and distribution of impacts

Over the recent decades, building on the work of Hopenhayn (1992) and Aiyagari (1994), DSGE models have gone beyond the representative firm and household assumptions to incorporate micro-level heterogeneity. This incorporation has broadened the range of problems that can be studied in business cycle analysis. The attention is no longer on the study of aggregate dynamics, rather on the analysis of the evolution of the distribution of heterogeneous agents in response to aggregate and/or idiosyncratic shocks.¹²

On the production side, firms can differ in terms of size, efficiency, products, production processes, access to credit, and innovation ability. The entry and exit of heterogeneous firms shape the aggregate fluctuations in economic activity and the associated creation and destruction of jobs. Firms can also differ in their abatement capacity, can be more or less polluting, or can differ in their innovation in clean technologies. In this context, aggregate dynamics and the performance of pollution policies will also be influenced by composition effects, due to the reallocation of market shares among heterogeneous firms. The underlying environmental regulation is likely to affect firm dynamics and eventually aggregate productivity, GDP, and employment. On the other hand, the changing composition of the production structure in response to shocks may affect policy effectiveness and optimal design.

¹² See e.g. Heathcote et al. (2009), Clementi and Palazzo (2016), and Kaplan et al. (2018).

Households, meanwhile, can differ in terms of age, wealth, skills, income, occupation, portfolio composition, access to credit, and expectations. All these dimensions matter for many of households' economic decisions and can be relevant for the propagation mechanisms of shocks and for the impact of policies falling in various domains. Incorporating heterogeneous households in an environmental business cycle model may open up, for instance, questions about the impact of pollution policies on inequality and on wealth reallocation.

The literature to date has largely avoided issues of equity, but existing results have important implications for the two main observations that follow. First, the models demonstrate that efficient emissions are less pro-cyclical than they would be in *laissez faire*. The efficient level of climate policy's stringency (e.g., the carbon tax rate) is lower in recessions than in expansions. This conclusion, however, neglects the distributional implications of policy, including carbon tax revenues. Redistributing revenues in a lump-sum way, as "carbon dividends," would be progressive (Cronin et al. 2018). The federal carbon tax of Canada, for instance, makes about 70% of Canadians financially better off, disproportionately improving the livelihood of low-income households (PBO 2019). It is not obvious, then, how reducing a carbon tax in times of recession, and thus the size of carbon dividends to households, would affect equity, especially when accounting for the fact that utility from dividends may decrease with income, so that a disproportionate impact on low-income households would disproportionately impact overall utility, even assuming a homogeneous effect of the recession on households. Such a research question could be addressed by introducing heterogeneous households, for instance to reflect income distribution, and several ways of redistributing tax revenues or revenues from auctioning permits.

Second, the efficient level of regulation, which accounts for the business cycle, implies both lower emissions and lower employment than the unregulated equilibrium (Gibson and Heutel 2020). If labor market frictions imply that vacancies are too high, then the environmental policy creates an additional efficiency benefit by reducing the labor market distortion. However, accounting for distributional effects on who is employed and who is not in a recession may lead to different policy implications, in particular if low-income households, who derive a higher utility from their salary, would be more affected by layoffs driven by recessionary forces. The standard framework could thus be extended to include distributional effects in job creation and destruction, as well as interactions with other policies, including policies aimed at fostering economic recovery (e.g. stimulus packages) or redirecting the economy toward cleaner production modes (e.g. Green New Deal).

V.b. Interaction between environmental and other public policies

Environmental policies are not the only ones that respond to market changes over the business cycle. Many topics related to the interaction between environmental and other policies remain either unexplored or still in early stages. Prime targets for further research on environmental policy interactions are fiscal policy, trade policy, monetary policy, and financial regulation.

Fiscal policy leads that list, because tax policies and government spending tend to be counter-cyclical themselves (at least at the federal level in the US). Furthermore, environmental priorities are increasingly being incorporated into fiscal responses: At present, many post-pandemic recovery plans around the world include green stimulus packages to both restart the economy and favor transition to a cleaner and more sustainable path, including the Recovery Plan for Europe, the American Rescue Plan, and the proposed American Jobs Plan. Such fiscal

responses are likely to influence the optimal adjustment of stringency of carbon pricing regulations, for example. These issues could be addressed by modelling the public sector in more detail, accounting for the composition of public spending (capital spending and current spending) and for different tax instruments.¹³ Trade policy can be intertwined with climate policy, with important business cycle implications. The most obvious example is represented by carbon border adjustments, which are currently receiving serious consideration from the European Commission in the context of the Green Deal, at least for trialing in selected sectors covered by the EU ETS. Besides the direct effects that the introduction of such a policy may have on border prices and trade flows, one may expect it to have an influence on the international propagation of the business cycle. The study of this issue requires the use of fully fledged open economy models in which countries are interlinked with each other and where the different steps of the production process are located across different countries.

Regarding the implications for monetary policy, future research should address the challenges posed by physical and transition risks to different monetary policy regimes and study how different carbon pricing policies are likely to affect inflation dynamics. Central banks and financial regulatory authorities are increasingly interested in climate-related issues (e.g. Carney 2015, Vermeulen et al. 2018, Rudebusch 2021). The debate revolves around the need to enrich their mandate by opening the door to climate challenges in the conduct of monetary policy and in the design of the financial regulatory framework (see Campiglio et al. 2018, D’Orazio and Popoyan 2019). Hence, future research should also explore more in depth the possibility of incorporating climate objectives in the mandate of central banks. This would mainly imply

¹³ As an example, the design of the optimal dynamic carbon tax should be made in conjunction with other pre-existing tax instruments, as recently shown by Barrage (2020).

giving up market neutrality in asset buying and would enlarge the area of activity of central banks and their tools.

Concerning financial regulation, the literature on climate-related financial system risks is still nascent; further studies could contribute to move the frontier further and shed additional light on how to design a macroprudential regulatory framework able to favor green investments, reduce climate-related financial risk, and possibly also preserve financial stability. Numerous green macroprudential tools have been proposed (e.g., brown-penalizing and green-supporting capital requirements, green-biased liquidity regulation, differentiated reserves requirements), calling for further research investigating their potential ability to align environmental and financial objectives.

V.c. Suboptimal policy stringency and non-pricing policies

The E-DSGE literature tends to assume that environmental policy's stringency can be set to balance marginal costs and benefits in its steady-state, from which it should fluctuate “optimally” in response to productivity shocks. As discussed in the introduction to this paper, important constraints can prevent environmental policies from reaching their optimal level, much less adjusting with the business cycle.

In the case of climate change in particular, while economists have yet to agree on the “optimal” level of carbon pricing—for instance exactly how high the social cost of carbon is—a general consensus has formed that it should be well above current levels (Howard and Sylvan 2015). Carbon pricing remains the favorite policy tool of economists to tackle climate change (see, e.g., Goulder and Parry 2008; Aldy et al. 2010; Baranzini et al. 2017; High-Level Commission on Carbon Prices, 2017). In the decade since 2010, when it covered about 5% of global greenhouse gas emissions, carbon pricing has expanded rapidly and currently covers

about 22.5% of global greenhouse gas emissions; however, only for a few schemes do they exceed \$50 per ton of CO₂ (World Bank 2020).

Hence, an important question that the literature has arguably yet to tackle is whether, or to what extent, environmental policies that are set at a “suboptimally” low level of stringency should also adjust to the business cycle. In this context, three possible scenarios merit investigation: 1) a scenario in which the policy does not adjust to the business cycle; 2) a scenario in which the policy does adjust to the business cycle; and 3) a scenario in which the policy adjusts, upward, during economic booms, but does not adjust downward during recessions.

Additional attention should be paid to the design of environmental policies—particularly banking and borrowing provisions in cap-and-trade systems—and how they respond to business cycles. A few recent papers have already moved in this direction. For instance, Lintunen and Kuusela (2018) study emissions cap adjustments that allow banking of permits for future use, under business cycle uncertainty. Further, Pizer and Prest (2020) show in a micro model that quantity regulation can have advantages over price regulation when governments optimally adjust policies to shocks, due to the intertemporal transmission of expectations into prices. However, if governments set policy inefficiently or firms imperfectly anticipate policy changes, taxes have advantages again. In this respect, Aldy and Armitage (2020) study how cap-and-trade systems lead to price uncertainty, since shocks can affect how a given cap is priced. These issues should be explored in macro models. More generally, most of the literature to date has made stark policy comparisons between taxes and caps, but in practice many design features—such as free allocation, alternative compliance options, and international linking, as well as certain built-

in adjustment mechanisms like price floors, safety valves, and quantity-based triggers—are increasingly included and may have macroeconomic implications.

Another aspect of suboptimal policy design recognizes that a great number of environmental policies do not price carbon explicitly or even implicitly. Clean energy standards or market share mandates for renewable generation, biofuels, or zero-emission vehicles are common tools in transition policy portfolios. While they may impose an implicit tax on sources that do not qualify as clean, they do not distinguish among the carbon intensity of nonqualifying sources. Similarly, mandatory phase-outs of coal-fired generation or internal combustion engine vehicles do not differentiate among the carbon profiles of non-prohibited sources. However, these types of target-based approaches do impose constraints on the economy, and the shadow values of those constraints will respond to business cycles. The Green New Deal proposal framework in the US (H.Res.109; 116th Congress), for instance, does not even mention carbon pricing. Incorporating non-pricing mechanisms—and especially multiple and overlapping ones—into macroeconomic models is challenging, but a worthy area for future research.

V.d. Non-GHG pollutants

Most of the literature has focused on climate policy rather than policies for other environmental issues and pollutants. This view is understandable, since the broader environmental policy literature is increasingly focused on climate change and greenhouse gases. Hence, the focus of our paper is also mostly on climate change.

However, the relationship between business cycles and environmental policy may be equally or more important for non-GHG pollutants. Most GHGs, for instance such as carbon dioxide, are long-lived stock pollutants that stay in the atmosphere for decades. Business-cycle-level fluctuations in emissions have little effect on the aggregate stock of atmospheric carbon,

which is what affects climate change. This can be seen in Figure 2—over the business cycle the pollution stock (x) stays nearly constant though quarterly emissions (e) vary considerably. For this reason, the marginal benefits of climate mitigation stay relatively stable.

Many other pollutants are primarily flow pollutants, remaining in the environment and affecting the economy only for a short period. For these pollutants, business-cycle fluctuations in emissions can have serious effects on their damages. For example, ozone damages can vary considerably even over the course of a single day (Adler and Severnini 2020). As we discussed in section IV.b., this may mean that the welfare benefit of policies that dynamically adjust to business cycles is higher for non-greenhouse-gas policy, since the cyclical adjustments in the policy values are able to respond to the cyclicity of damages. E-DSGE models solving for optimal policy or evaluating the effects of policy over the business cycle should study flow pollutants like ozone or sulfur dioxide. Furthermore, even for analyses of climate policy, the co-benefits of reduced emissions of flow pollutants represent a substantial fraction of the social cost of carbon (Parry et al. 2015), meaning that incorporation of these benefits in business cycle models is crucial. Finally, regulation of pollutants other than greenhouse gases may be more likely to be closer to what economists tend to consider the appropriate level of stringency (e.g. Shapiro and Walker 2020).

However, it is not certain that business cycle considerations are always more important for non-GHG flow pollutants than for GHG stock pollutants. Because a stock pollutant accumulates, the effect on damages of a cyclical increase in emissions (from a business cycle expansionary period) will last longer, as will the effect from a cyclical decrease in emissions. If policy fails to account for these cycles, then this variation in damages will extend over a longer period than it would under flow pollutants. It is thus an open empirical question as to whether or

not cycles are more important in policy design for stock and flow pollutants, and so studying this question is crucial.

VI. Conclusion

To explore the relationship between business cycles and environmental policy, we have reviewed the growing literature using dynamic stochastic general equilibrium (DSGE) models to study the effects of policy over business cycles and the response of optimal policy to cyclical fluctuations. The majority of this literature focused on price-based climate policies, including carbon taxes and cap-and-trade, with additional economic features like new-Keynesian price rigidities. We highlight several important findings from this literature that are most relevant to policymakers, who may seek to craft policy to respond to business cycles. We also offer suggestions for important policy-relevant questions that remain unanswered, to guide the future of the literature.

References

- Adler, David, and Edson R. Severnini. *Timing Matters: Shifting Economic Activity and Intra-Day Variation in Ambient Ozone Concentrations*. IZA-Institute of Labor Economics, 2020.
- Aiyagari, S. Rao. "Uninsured idiosyncratic risk and aggregate saving." *The Quarterly Journal of Economics* 109, no. 3 (1994): 659-684.
- Aldy, Joseph E., and Sarah Armitage. "The cost-effectiveness implications of carbon price certainty." In *AEA Papers and Proceedings*, vol. 110, pp. 113-18. 2020.
- Aldy, Joseph E., Alan J. Krupnick, Richard G. Newell, Ian W. H. Parry, and William A. Pizer. "Designing Climate Mitigation Policy." *Journal of Economic Literature* 48, no. 4 (2010): 903-34.

- Angeletos, George-Marios, Fabrice Collard, and Harris Dellas. “Business-cycle anatomy.” *American Economic Review* 110, no. 10 (2020): 3030-70.
- Angelopoulos, Konstantinos, George Economides, and Apostolis Philippopoulos. “First-and second-best allocations under economic and environmental uncertainty.” *International Tax and Public Finance* 20, no. 3 (2013): 360-380.
- Annicchiarico, Barbara, and Fabio Di Dio. “Environmental policy and macroeconomic dynamics in a new Keynesian model.” *Journal of Environmental Economics and Management* no. 69 (2015): 1-21.
- Annicchiarico, Barbara, and Fabio Di Dio. “GHG emissions control and monetary policy.” *Environmental and Resource Economics* 67 no. 4 (2017): 823-851.
- Annicchiarico, Barbara, and Francesca Diluiso. “International transmission of the business cycle and environmental policy.” *Resource and Energy Economics* no. 58 (2019): 101112.
- Banque de France. “Greening the Financial System: The New Frontier.” *Financial Stability Review*. Banque de France, 2019.
- Baranzini, Andrea, Jeroen C. J. M. van den Bergh, Stefano Carattini, Richard B. Howarth, Emilio Padilla, and Jordi Roca. “Carbon Pricing in Climate Policy: Seven Reasons, Complementary Instruments, and Political Economy Considerations.” *Wiley Interdisciplinary Reviews: Climate Change* 8, no. 4 (2017).
- Barnett, Michael. “The Estimated Impacts of Climate Policy Risk,” 2020.
- Barrage, Lint. “Optimal dynamic carbon taxes in a climate–economy model with distortionary fiscal policy.” *The Review of Economic Studies* 87, no. 1 (2020): 1-39.
- Battiston, Stefano, Antoine Mandel, Irene Monasterolo, Franziska Schütze, and Gabriele Visentin. “A climate stress-test of the financial system.” *Nature Climate Change* 7, no. 4 (2017): 283-288.
- Benmir, Ghassane, and Josselin Roman. “Policy interactions and the transition to clean technology.” *Grantham Research Institute on Climate Change and the Environment, Working Paper*, no. 368, (2020).
- Burtraw, D. and A. Keyes. “Recognizing Gravity as a Strong Force in Atmosphere Emissions Markets.” *47 Agric. & Resource Econ. Rev.* 201 (2018).

- Campiglio, Emanuele, Yannis Dafermos, Pierre Monnin, Josh Ryan-Collins, Guido Schotten, and Misa Tanaka. “Climate change challenges for central banks and financial regulators.” *Nature Climate Change* 8, no. 6 (2018): 462-468.
- Carattini, Stefano, Maria Carvalho, and Sam Fankhauser. “Overcoming Public Resistance to Carbon Taxes.” *Wiley Interdisciplinary Reviews: Climate Change* 9, no. 5 (2018): e531.
- Carattini, Stefano, Garth Heutel, and Givi Melkadze. “Climate Policy, Financial Frictions, and Transition Risk.” National Bureau of Economic Research Working Paper #28525 (2021).
- Carattini, Stefano, and Suphi Sen. “Carbon Taxes and Stranded Assets: Evidence from Washington State.” CESifo Working Paper Series. CESifo Group Munich, 2019.
- Carney, Mark. “Breaking the Tragedy of the Horizon - Climate Change and Financial Stability.” London: Bank of England, 2015.
- Chari, Varadarajan V., Lawrence J. Christiano, and Patrick J. Kehoe. “Optimal fiscal policy in a business cycle model.” *Journal of Political Economy* 102, no. 4 (1994): 617-652.
- Christiano, Lawrence J., Martin S. Eichenbaum, and Mathias Trabandt. “On DSGE models.” *Journal of Economic Perspectives* 32, no. 3 (2018): 113-40.
- Christiano, Lawrence J., Martin Eichenbaum, and Robert Vigfusson. *What happens after a technology shock?*. No. w9819. National Bureau of Economic Research, 2003.
- Clementi, Gian Luca, and Berardino Palazzo. “Entry, exit, firm dynamics, and aggregate fluctuations.” *American Economic Journal: Macroeconomics* 8, no. 3 (2016): 1-41.
- Comerford, David, and Alessandro Spiganti. “The carbon bubble: climate policy in a fire-sale model of deleveraging.” Meeting Papers 734, Society for Economic Dynamics (2017).
- Cronin, Julie Anne, Don Fullerton, and Steven Sexton. “Vertical and Horizontal Redistributions from a Carbon Tax and Rebate.” *Journal of the Association of Environmental and Resource Economists* 6, no. S1 (2018): S169–208.
- Dafermos, Yannis, Maria Nikolaidi, and Giorgos Galanis. “Climate change, financial stability and monetary policy.” *Ecological Economics* 152 (2018): 219-234.
- Dal Bó, Ernesto, Pedro Dal Bó, and Erik Eyster. “The Demand for Bad Policy When Voters Underappreciate Equilibrium Effects.” *Review of Economic Studies* 85, no. 2 (2018): 964–98.
- Del Negro, Marco, Michele Lenza, Giorgio E. Primiceri, and Andrea Tambalotti. *What’s up with the Phillips Curve?*. No. w27003. National Bureau of Economic Research, 2020.

- Diluiso, Francesca, Barbara Annicchiarico, Matthias Kalkuhl, and Jan Christoph Minx. “Climate Actions and Stranded Assets: The Role of Financial Regulation and Monetary Policy.” CESifo WP no. 8486 (2020).
- Dissou, Yazid, and Lilia Karnizova. “Emissions cap or emissions tax? A multi-sector business cycle analysis.” *Journal of Environmental Economics and Management* 79 (2016): 169-188.
- Doda, Baran. “Evidence on business cycles and CO₂ emissions.” *Journal of Macroeconomics*, 40 (2014): 214-227.
- D’Orazio, Paola, and Lilit Popoyan. “Fostering green investments and tackling climate-related financial risks: Which role for macroprudential policies?” *Ecological Economics* 160 (2019): 25-37
- Economides, George, and Anastasios Xepapadeas. “Monetary policy under climate change.” Bank of Greece Working Paper no. 247 (2018).
- Economides, George, and Anastasios Xepapadeas. “The effects of climate change on a small open economy.” Bank of Greece Working Paper 267 (2019).
- European Commission (EC). 2012. Report From the Commission to the European Parliament and the Council: The state of the European carbon market in 2012. Brussels, 14.11.2012 COM(2012) 652 final.
- Feng, Kuishuang, Steven J. Davis, Laixiang Sun, and Klaus Hubacek. “Drivers of the US CO₂ Emissions 1997–2013.” *Nature Communications* 6, no. 1 (2015): 7714.
- Ferrari, Alessandro, and Valerio Nispi Landi. “Whatever it takes to save the planet? Central banks and unconventional green policy.” ECB WP no. 2500 (2020).
- Fischer, Carolyn, and Garth Heutel. “Environmental macroeconomics: Environmental policy, business cycles, and directed technical change.” *Annual Review of Resource Economics* 5, no. 1 (2013): 197-210.
- Fischer, C., L. Reins, D. Burtraw, D. Langlet, A. Lofgren, M. Mehling, S. Weishaar, L. Zetterberg, H. van Asselt, and K. Kulovesi. The Legal and Economic Case for an Auction Reserve Price in the EU Emissions Trading System. *Columbia Journal of European Law* 26 (1) (Spring 2020): 1–35.

- Fischer, Carolyn, and Michael Springborn. "Emissions targets and the real business cycle: Intensity targets versus caps or taxes." *Journal of Environmental Economics and Management* 62, no. 3 (2011): 352-366.
- Fourcade, Marion, Etienne Ollion, and Yann Algan. "The Superiority of Economists." *Journal of Economic Perspectives* 29, no. 1 (2015): 89–114.
- Galí, Jordi, and Pau Rabanal. "Technology shocks and aggregate fluctuations: How well does the real business cycle model fit postwar US data?." *NBER Macroeconomics Annual* 19 (2004): 225-288.
- Gertler, Mark, and Peter Karadi. "A model of unconventional monetary policy." *Journal of Monetary Economics* 58, no. 1 (2011): 17-34.
- Gibson, John, and Garth Heutel. *Pollution and Labor Market Search Externalities Over the Business Cycle*. No. w27445. National Bureau of Economic Research, (2020).
- Goulder, Lawrence H. "Environmental Taxation and the Double Dividend: A Reader's Guide." *International Tax and Public Finance* 2, no. 2 (1995): 157–83.
- Goulder, Lawrence H., and Ian W. H. Parry. "Instrument Choice in Environmental Policy." *Review of Environmental Economics and Policy* 2, no. 2 (2008): 152–74.
- Hahn, Robert W. "Economic Prescriptions for Environmental Problems: How the Patient Followed the Doctor's Orders." *Journal of Economic Perspectives* 3, no. 2 (1989): 95–114.
- Harrington, Winston, Richard D. Morgenstern, and Peter Nelson. "On the Accuracy of Regulatory Cost Estimates." 19 *J. POL'Y ANALYSIS & MGMT.* 297 (2000).
- Heathcote, Jonathan, Kjetil Storesletten, and Giovanni L. Violante. "Quantitative macroeconomics with heterogeneous households." *Annual Review of Economics* 1, no. 1 (2009): 319-354.
- Hepburn, Cameron, Karsten Neuhoff, William Acworth, Dallas Burtraw, and Frank Jotzo. "The Economics of the EU ETS Market Stability Reserve." *Journal of Environmental Economics and Management*, 80 (2016): 1–5.
- Heutel, Garth. "How should environmental policy respond to business cycles? Optimal policy under persistent productivity shocks." *Review of Economic Dynamics* 15, no. 2 (2012): 244-264.
- High-Level Commission on Carbon Prices. *Report of the High-Level Commission on Carbon Prices*. Washington, DC: World Bank (2017).

- Holladay, J. Scott, Mohammed Mohsin, and Shreekar Pradhan. “Environmental Policy Instrument Choice and International Trade.” *Environmental and Resource Economics* 74, no. 4 (2019): 1585-1617.
- Hopenhayn, Hugo A. “Entry, exit, and firm dynamics in long run equilibrium.” *Econometrica* 60, no. 5 (1992): 1127-1150.
- Howard, Peter H., and Derek Sylvan. “The Economic Climate: Establishing Consensus on the Economics of Climate Change.” *2015 AAEA & WAEA Joint Annual Meeting, July 26-28, San Francisco, California*. 2015 AAEA & WAEA Joint Annual Meeting, July 26-28, San Francisco, California. Agricultural and Applied Economics Association, 2015.
- IMF. “Fiscal Monitor: How to Mitigate Climate Change.” Washington, DC: IMF, 2019.
- Jaimes, Richard. “The dynamic effects of environmental and fiscal policy shocks.” University of Tilburg, mimeo (2020).
- Jo, Soojin, and Lilia Karnizova. “Energy Efficiency and CO₂ Emission Fluctuations.” Working Paper, (2021).
- Kaplan, Greg, Benjamin Moll, and Giovanni L. Violante. “Monetary policy according to HANK.” *American Economic Review* 108, no. 3 (2018): 697-743.
- Karp, Larry, and Christian Traeger. “Smart Caps.” Centre for Economic Policy Research Discussion Paper 15941 (2021).
- Khan, Hashmat, Konstantinos Metaxoglou, Christopher R. Knittel, and Maya Papineau. “Carbon emissions and business cycles.” *Journal of Macroeconomics* 60 (2019): 1-19.
- Koch, Nicolas, Sabine Fuss, Godefroy Grosjean, Ottmar Edenhofer. 2014. Causes of the EU ETS price drop: Recession, CDM, renewable policies or a bit of everything?—New evidence, *Energy Policy* 73: 676-685.
- Kollenberg, Sascha, and Luca Taschini. “Dynamic supply adjustment and banking under uncertainty in an emission trading scheme: The market stability reserve.” *European Economic Review* 118 (2019): 213-226.
- Le Quéré, Corinne, Robert B. Jackson, Matthew W. Jones, Adam J. P. Smith, Sam Abernethy, Robbie M. Andrew, Anthony J. De-Gol, et al. “Temporary Reduction in Daily Global CO₂ Emissions during the COVID-19 Forced Confinement.” *Nature Climate Change* 10, no. 7 (2020): 647–53.

- Le Quéré, Corinne, Glen P. Peters, Pierre Friedlingstein, Robbie M. Andrew, Josep G. Canadell, Steven J. Davis, Robert B. Jackson, and Matthew W. Jones. “Fossil CO₂ Emissions in the Post-COVID-19 Era.” *Nature Climate Change* 11, no. 3 (2021): 197–99.
- Lintunen, Jussi, and Olli-Pekka Kuusela. “Business Cycles and Emission Trading with Banking.” *European Economic Review* 101 (2018): 397–417.
- Lintunen, Jussi, and Lauri Vilmi. “On optimal emission control—Taxes, substitution and business cycles.” Bank of Finland Research Discussion Paper 24 (2013).
- Martin, Ralf, Mirabelle Muûls, Laure B. de Preux, and Ulrich J. Wagner. “Industry Compensation under Relocation Risk: A Firm-Level Analysis of the EU Emissions Trading Scheme.” *American Economic Review* 104, no. 8 (2014): 2482–2508.
- Michel, Philippe, and Gilles Rotillon. “Disutility of pollution and endogenous growth.” *Environmental and Resource Economics* 6, no. 3 (1995): 279–300.
- NFGS “Adapting Central Bank Operations to a Hotter World – Reviewing Some Options”, Network for Greening the Financial System, 2021.
- Nordhaus, William. “Optimal Greenhouse-Gas Reductions and Tax Policy in the ‘Dice’ Model.” *American Economic Review* 83, no. 2 (1993): 313–17.
- Nordhaus, William “Revisiting the Social Cost of Carbon.” *Proceedings of the National Academy of Sciences* 114, no. 7 (2017): 1518–23.
- Nordhaus, William. “Evolution of modeling of the economics of global warming: Changes in the DICE model, 1992–2017.” *Climatic Change* 148, no. 4 (2018): 623–640.
- Parry, Ian, Chandara Veung, and Dirk Heine. “How Much Carbon Pricing Is in Countries’ Own Interests? The Critical Role of Co-Benefits.” *Climate Change Economics* 06, no. 04 (2015): 1550019.
- PBO. “Fiscal and Distributional Analysis of the Federal Carbon Pricing System.” Office of the Parliamentary Budget Officer, 2019.
- Perino, Grischa, Michael Pahle, Fabian Pause, Simon QuminQuminQumin, Hannah Scheuing, and Maximilian Willner. “EU ETS stability mechanism needs new design.” Chaire Économie du Climat Policy Brief 2021-1 (2021).

- Persico, Claudia L., and Kathryn R. Johnson. 2021. "The Effects of Increased Pollution on COVID-19 Cases and Deaths." *Journal of Environmental Economics and Management*, 102431.
- Pindyck, Robert S. "Climate Change Policy: What Do the Models Tell Us?" *Journal of Economic Literature* 51, no. 3 (2013): 860–72.
- Pizer, William A. and Brian C. Prest. "Prices versus Quantities with Policy Updating." *Journal of the Association of Environmental and Resource Economists* 7 (3) (2020): 483–518.
- Punzi, Maria T. "Role of bank lending in financing green projects: A dynamic stochastic general equilibrium approach." In Sachs, J., Woo, W. T., Yoshino, N., and Taghizadeh-Hesary, F., editors, *Handbook of Green Finance: Energy Security and Sustainable Development, Sustainable Development*. Springer, (2019).
- Ramelli, Stefano, Alexander F Wagner, Richard J Zeckhauser, and Alexandre Ziegler. "Investor Rewards to Climate Responsibility: Evidence from the 2016 Climate Policy Shock." Working Paper. National Bureau of Economic Research, 2018.
- Rebelo, Sergio. "Real Business Cycle Models: Past, Present and Future." *Scandinavian Journal of Economics* 107, no. 2 (2005): 217-238.
- Rudebusch. "Climate Change Is a Source of Financial Risk." *FRBSF Economic Letter*, 2021.
- Sen, Suphi, and Marie-Theres von Schickfus. "Climate Policy, Stranded Assets, and Investors' Expectations." *Journal of Environmental Economics and Management* 100 (2020): 102277.
- Shapiro, Joseph S., and Reed Walker. "Is Air Pollution Regulation Too Stringent?" National Bureau of Economic Research, 2020. Stern, Nicholas. *The Economics of Climate Change: The Stern Review*. Cambridge, UK; New York: Cambridge University Press, 2007.
- Stern, Nicholas, and Joseph E. Stiglitz. "The Social Cost of Carbon, Risk, Distribution, Market Failures: An Alternative Approach." No. w28472. National Bureau of Economic Research, 2021.
- Stiglitz, Joseph E., Nicholas Stern, Maosheng Duan, Ottmar Edenhofer, Gaël Giraud, Geoffrey Heal, Emilio Lèbre la Rovere, et al. "Report of the High-Level Commission on Carbon Prices." Carbon Pricing Leadership Coalition, 2017.

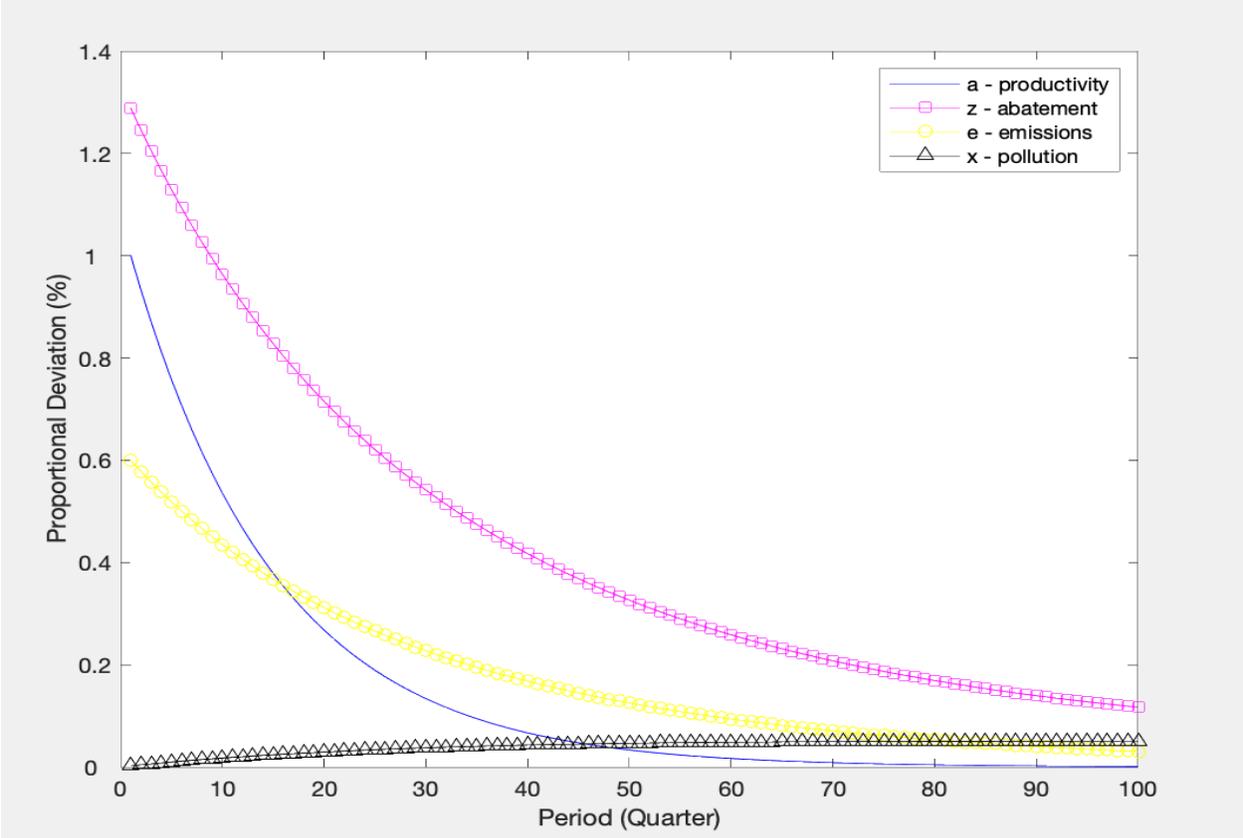
van den Bijgaart, Inge M., and Sjak Smulders. “Does a recession call for less stringent environmental policy? A partial-equilibrium second-best analysis.” *Environmental and Resource Economics* 70, no. 4 (2018): 807-834.

Vermeulen, Robert, Edo Schets, Melanie Lohuis, Barbara Kolbl, David-Jan Jansen, and Willem Heeringa. “An Energy Transition Risk Stress Test for the Financial System of the Netherlands.” *DNB Occasional Studies*. DNB Occasional Studies. Netherlands Central Bank, Research Department, 2018.

World Bank. “State and Trends of Carbon Pricing—2020.” Washington, DC, 2020.

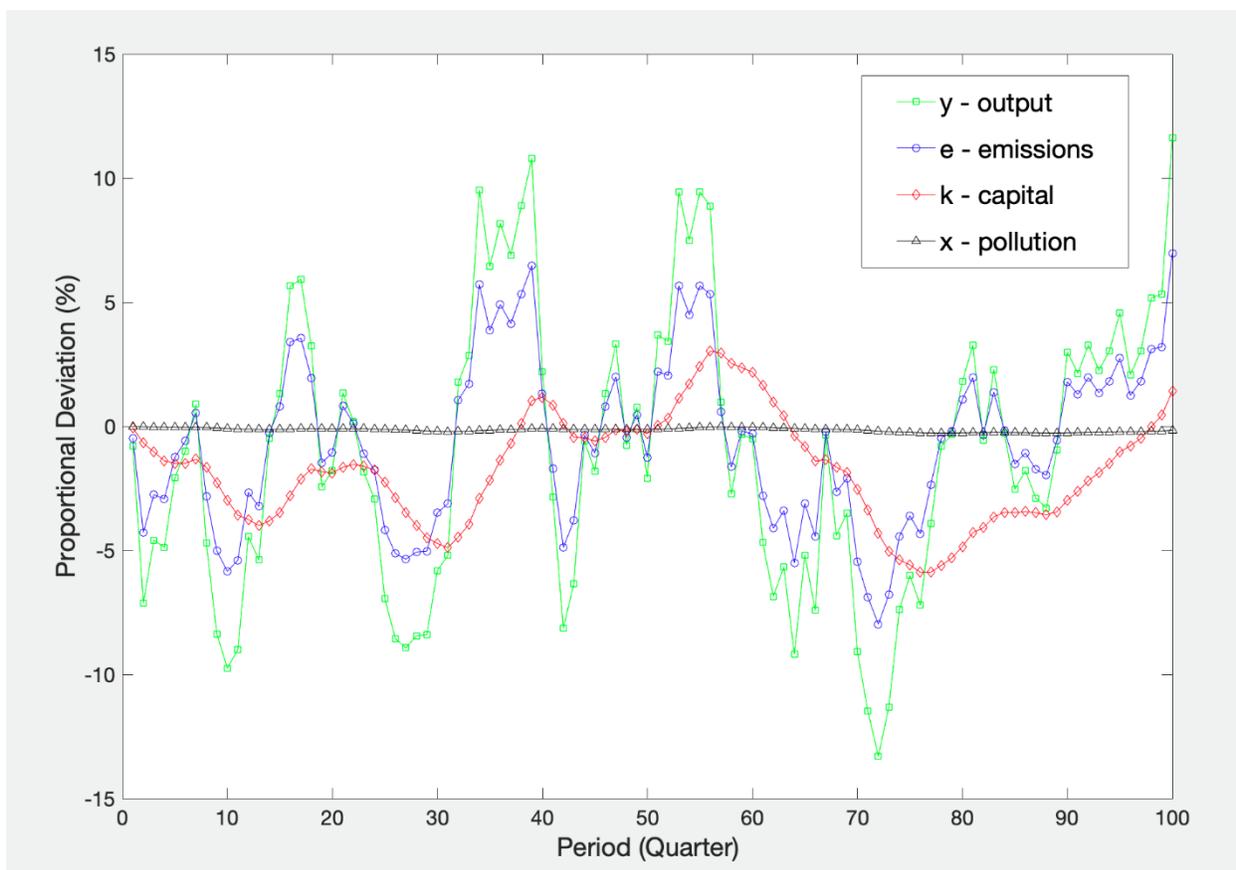
Figures

Figure 1—Impulse Response Functions – Centralized Efficient Model



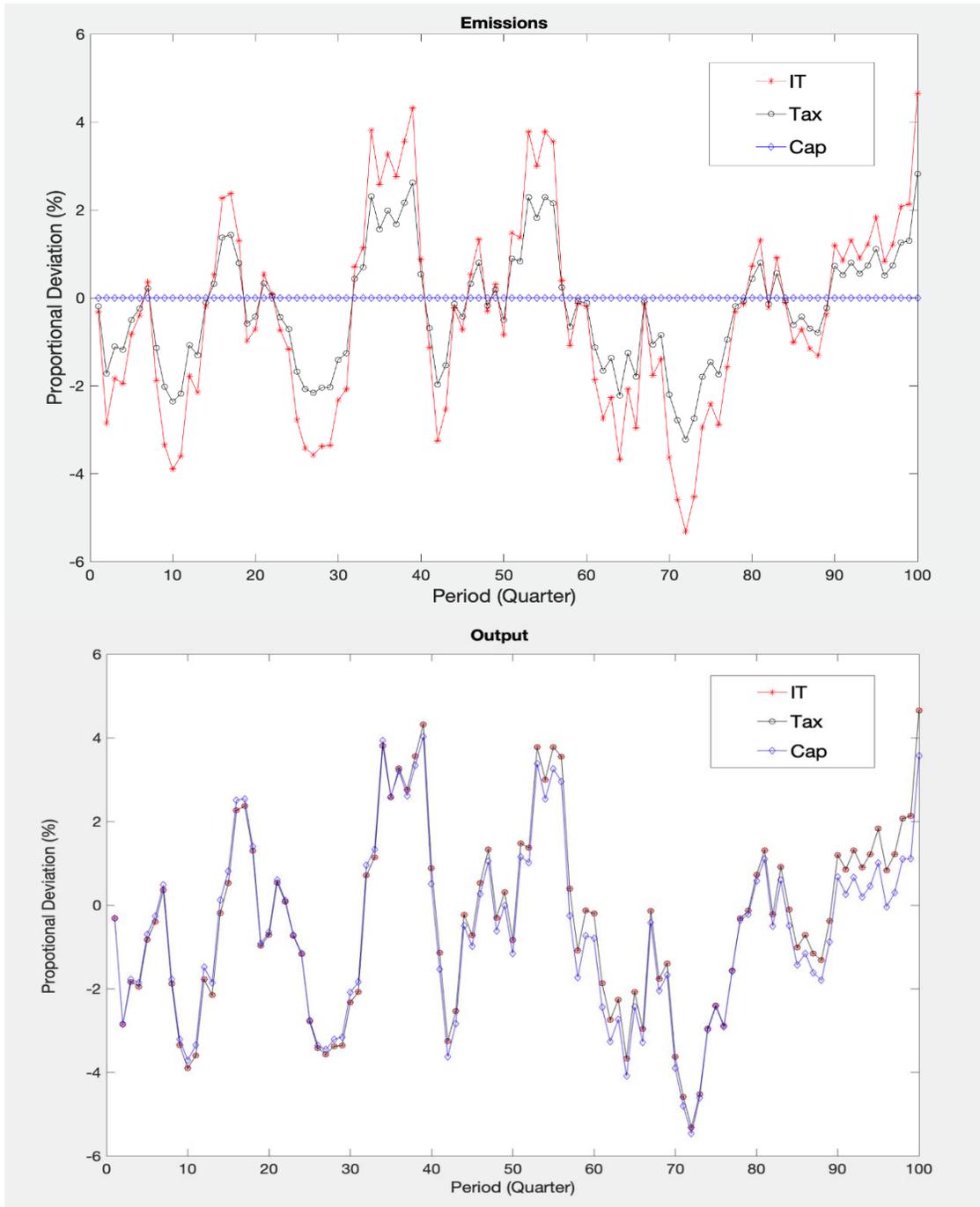
Note: The productivity shock a increases exogenously in period 0, and all other variables respond endogenously. The y-axis units are the percentage deviation from each variable's steady-state value. The simulations are from the E-DSGE model in Heutel (2012) with updated calibration as described in the text.

Figure 2—Business Cycle Simulation – Centralized Efficient Model



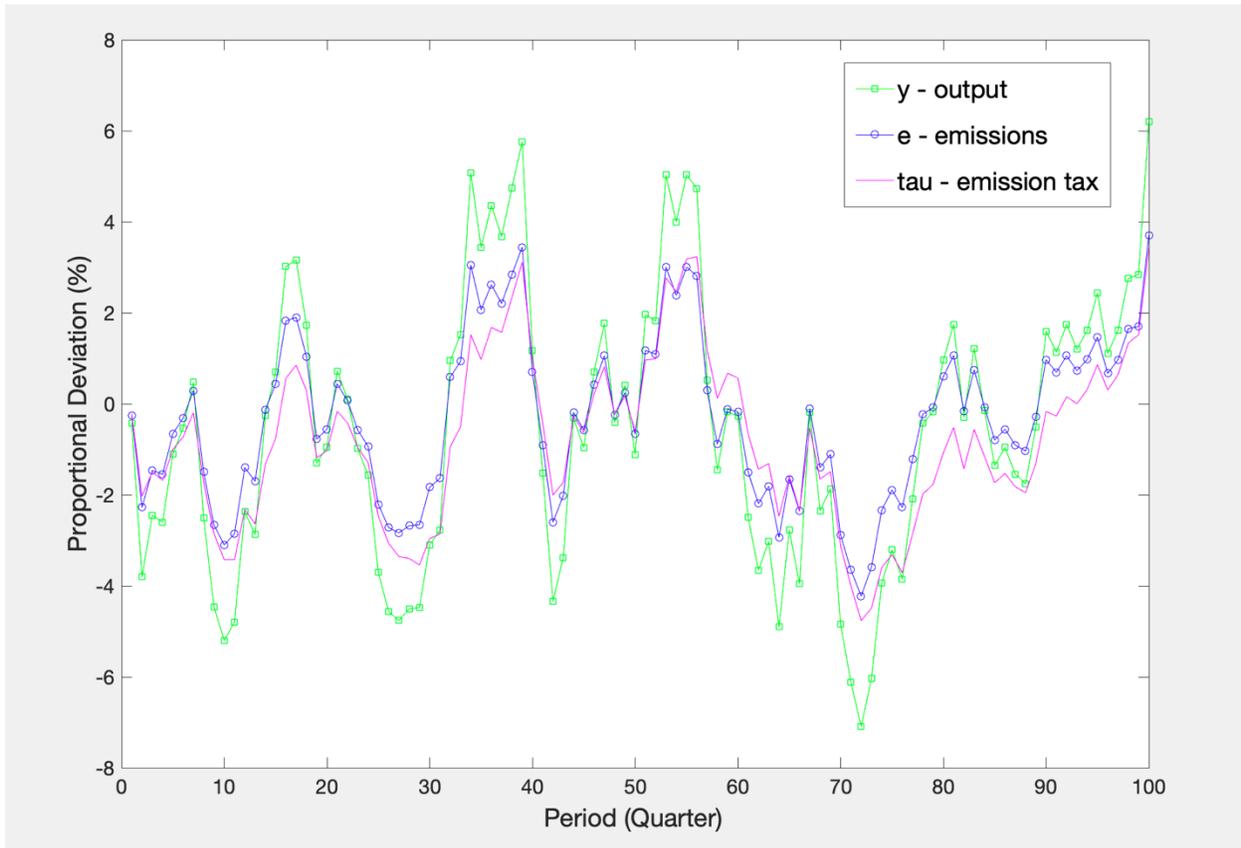
Note: Productivity shocks (not graphed here) are exogenously generated, and all other variables respond endogenously. The y axis units are the percentage deviation from each variable's steady-state value. The simulations are from the E-DSGE model in Heutel (2012) with updated calibration as described in the text.

Figure 3—Business Cycle Simulation – Effects of Policies Set ex ante



Note: Productivity shocks (not graphed here, identical to those in Figure 2) are exogenously generated, and all other variables respond endogenously. The top panel plots emissions, and the bottom panel plots output, both in percentage deviation from each variable's steady-state value. "IT," "Cap," and "Tax" denote the intensity standard, the emissions cap, and the emissions tax, respectively.

Figure 4—Business Cycle Simulations—Efficient Policy



Note: Productivity shocks (not graphed here, identical to those in Figure 2) are exogenously generated, and all other variables respond endogenously. The y-axis units are the percentage deviation from each variable's steady-state value. The simulations are from the E-DSGE model in Heutel (2012) with updated calibration as described in the text.

Appendix – Extensions to the E-DSGE Model

The basic E-DSGE RBC model has been extended to include several features and market failures used in business cycle analysis. In this appendix we provide a review of this literature. We first discuss the main extensions of the RBC environmental model with perfectly competitive markets and flexible prices, where supply shocks are the main source of economic fluctuations. We then consider the New Keynesian contributions that offer an alternative to the flexible price framework of the RBC analysis. Finally, we consider other extensions focusing on open economy issues and credit market imperfections. The explicit consideration of additional market failures besides environmental damage may lead to important implications for the design of second-best policies and to non-trivial interactions with short-run stabilization policies.

A.a. RBC extensions

A first important extension of the business cycle model with environmental regulation is represented by the modelling of a multisector economy. From a business cycle perspective, the departure from the one-sector theoretical scheme and the modelling of sectoral interlinkages can be critical to examine the propagation of shocks of different sources and the impact of pollution policy. Dissou and Karnizova (2016) develop a model economy with six sectors where uncertainty comes from sector-specific productivity shocks. They consider three energy sectors differing in their emission intensity (coal, oil and gas, and electricity), two manufacturing sectors (low- and high-energy intensive), and a sector providing services. The analysis focuses on restricting emissions generated as a by-product of the fossil energy sectors. Two environmental regulations are compared to each other: cap system and carbon tax. The cap system is designed

as an upper limit on the emissions and is introduced into the model as an occasionally binding constraint.¹⁴ When the cap constraint is not binding, the price of the emission permit is zero. This feature drives an asymmetry in the response to negative and positive shocks. The extra revenues generated by environmental policies are then rebated to households as lump-sum transfers. In response to a more stringent pollution policy the economy adjusts through three channels: (i) the shift from fossil-fuel to cleaner energy; (ii) the reduction of the use of energy in production; (iii) the substitution of energy inputs for other production inputs. The model abstracts from other mechanisms of mitigation, such as abatement technology, and does not include environmental damage, similarly to Fischer and Springborn (2011).

With this tool, Dissou and Karnizova (2016) evaluate the performance of price and quantity policy instruments in the presence of persistent productivity shocks originated in different sectors, and then use welfare and the volatility of the main macroeconomic variables as metrics. Their main findings are the following. First, they show that the impact of a carbon mitigation policy on aggregate variables is lower in a multisector model, where it is possible to vary the energy mix in response to regulation, than the impact observed in an aggregate model. Second, consistently with Fischer and Springborn (2011), they find that the cap system leads to lower volatility of the main macroeconomic variables relative to the carbon tax. However, they demonstrate that two policy tools lead to statistically different results only for productivity shocks in the energy sectors. Third, in contrast to previous findings, a tax policy is less costly in terms of welfare than the cap, but the welfare costs are statistically different only in the case of energy-related shocks. This result seems quite puzzling, since a tax policy delivers higher

¹⁴ Bosetti and Maffezzoli (2014) explore in detail the implications of having occasionally binding constraints on emissions in a baseline E-DSGE RBC model with bankable permits for the control of environmental pollution.

volatility than does the cap. The reason is that, in this model, the occasionally binding constraint on emissions under the cap delivers an asymmetry in response to shocks of opposite signs. The cap limits the expansionary effects of positive productivity shocks, reducing not only the volatility of economic variables, but also their means. The lower volatility improves welfare, while the negative effects on the mean of variables like consumption worsens welfare. The latter effect prevails and leads to statistically significant welfare differences between the two environmental regulations under energy-related shocks.

Another study related to the baseline RBC E-DSGE model is Khan et al. (2019), which extends the model to include four types of technology shocks: anticipated and unanticipated technology shocks, and anticipated and unanticipated investment-specific shocks. Investment-specific shocks directly affect the marginal efficiency of investments and, as shown by Justiniano et al. (2010) and Furlanetto and Seneca (2014), are important drivers of business cycle fluctuations. In addition, their model features investment adjustment costs that are a source of inertia for investments. These costs reduce the investment volatility generated by the baseline RBC model and reproduce a hump-shaped response of the main macro variables to shocks, as observed in the data. Khan et al. (2019) show that emissions are procyclical in response to all shocks considered, because abatement becomes relatively more expensive during expansions. When pollution externalities are not fully internalized in the decentralized equilibrium case, the policy is too weak, and emissions will be even more procyclical than in the social planner's solution.

Finally, all the RBC models discussed so far are silent about labor force participation and the unemployment rate. Work has also begun on the task of introducing labor market frictions in RBC models with a pollution externality. Gibson and Heutel (2020) integrate the Diamond-

Mortensen-Pissarides search and matching framework of unemployment into the RBC E-DSGE model of Heutel (2012) and examine the interaction between labor market and environmental policies. Labor search frictions generate two congestion externalities of opposite signs that under certain conditions may perfectly offset each other. On the one hand, each unemployed worker searching for a job reduces the probability of a match of all the other unemployed workers, while increasing the probability of a match for all hiring firms. On the other hand, firms posting a vacancy increase the probability of finding a job for unemployed workers, while reducing the probability of filling a vacancy for all the other firms. When these externalities do not offset each other, the model generates a level of employment that is above or below the socially efficient level, in addition to the market failure from emissions.

In Gibson and Heutel (2020), the calibrated DSGE model delivers a decentralized equilibrium with inefficiently high pollution and employment. The efficient allocation can then be achieved by imposing a pollution tax and a tax on vacancy creation. When the vacancy tax is unavailable, the Ramsey planner has only the pollution tax as a policy instrument to address both sources of externalities. In the steady state equilibrium, the optimal emission tax rate is found to be much higher than its first-best counterpart. The cyclical properties are also very different: the optimal emission tax is only half as volatile as the first best emission tax. These results suggest that in an economy where the decentralized equilibrium would deliver unemployment, the Ramsey planner, in the attempt to strike the balance between search and environmental externalities, would set a lower emission tax in steady state, while responding more vigorously to business cycle fluctuations.

A.b. New Keynesian extensions

The E-DSGE RBC model has been enriched by New Keynesian (NK) elements in the spirit of the so-called New Neoclassical Synthesis.¹⁵ At the heart of the baseline NK framework are three main elements: (i) imperfectly competitive markets, (ii) nominal rigidities (imperfect price and/or wage adjustment), and (iii) non-neutrality of monetary policy. In RBC models, monetary policy is essentially unimportant for real activity, while in NK economics the presence of nominal rigidities makes monetary policy central to the dynamics of real activity and to the propagation of the business cycle.¹⁶

Annicchiarico and Di Dio (2015) propose an NK E-DSGE model with pollution, abatement technology, environmental regulations, and pollution damage, as in Heutel (2012). The model maintains the RBC framework as its underlying structure and features imperfect price adjustment *à la* Calvo (1983), while monetary policy is described by an interest-rate rule.¹⁷ The Calvo pricing scheme introduces a further distortion in the decentralized equilibrium since staggered prices generate price dispersion which, in turn, results in an inefficiency loss in aggregate production. In this model, the higher price dispersion is, the more polluting inputs are needed to produce a given level of output. As in Fischer and Springborn (2011), the paper seeks to understand the role of different environmental policy regimes (cap, tax, and intensity target) as a further conditioning factor of the business cycle, here driven by technological, fiscal, and monetary policy shocks.¹⁸ However, in this model imperfectly competitive markets and

¹⁵ See Goodfriend (2004).

¹⁶ For a comprehensive introduction to the fundamentals of the New Keynesian model, see Woodford (2011) and Galí (2015).

¹⁷ Starting from the New Open Economy Macroeconomics literature (see Lane 2001 for a survey), the early contribution of Ganelli and Tervala (2011) incorporates environmental policy in a two-country model with New Keynesian elements. This paper does not deal with business cycle and uncertainty, yet it presents a framework of analysis of environmental regulation that can be easily extended along several dimensions.

¹⁸ Xiao et al. (2018) use a slightly different framework, with pollutant emissions treated as a by-product of energy inputs, to examine the performance of various pollution policies in a model economy calibrated to China.

imperfect price adjustments further condition the performance of pollution policy and the design of the optimal carbon tax. The key findings of their analysis can be summarized as follows. Consistent with previous contributions, an emission cap tends to mitigate the impact of the main macroeconomic variables to shocks. The ability of the cap to dampen business cycle fluctuations is increasing in the degree of nominal rigidities. These stabilizing properties of the cap are welfare improving when nominal rigidities are strong, while the differences with the other environmental policies become negligible under flexible prices. This is because since nominal rigidities amplify business cycle fluctuations a regulation that forces a smoothed response of real variables tends to be preferred. The paper also explores optimal environmental policy in response to shocks for different levels of price stickiness and for different monetary policy conducts, although this second aspect is only touched upon in this paper. Consistent with the results of Heutel (2012) and Angelopoulos et al. (2013), Annicchiarico and Di Dio (2015) show that the optimal emissions tax is strongly procyclical. However, they also show that the optimal response of the tax is stronger with a higher degree of nominal rigidities. Again, the distortions induced by nominal rigidities make the decentralized equilibrium less efficient, requiring a stronger reaction of the optimal tax policy in response to shocks.

Jaimes (2020) further explores the role of nominal rigidities by also considering the implications of sluggish wage adjustments. The baseline NK E-DSGE model with abatement and environmental externality is extended to include an imperfectly competitive labor market, where wage setters with market power adjust wages according to a Calvo-pricing scheme as in Erceg et al. (2000). The model is used to analyze the interdependence between environmental and fiscal policy in an economy hit by shocks on the abatement technology and on public spending, where the carbon tax or permit revenue is used to cut consumption or labor income tax rate (see

Goulder 1995 for a primer on the “double dividend” of environmental taxation), rather than redistributed via lump-sum transfers. The redistribution of environmental policy revenues to reduce distortionary taxes is shown in Jaimes (2020) to have a stabilizing effect in the face of uncertainty, while the result regarding the major stabilizing effect of a cap-and-trade under price rigidities, as already found in Annicchiarico and Di Dio (2015), is robust to different recycling schemes. By contrast, wage stickiness leads to a higher output volatility, especially under a cap-and-trade scheme and when prices are flexible. This is because wage rigidities amplify the impact of uncertainty on employment. On the other hand, in presence of wage stickiness, the use of revenues raised from emissions pricing system to lower labor taxes has stronger stabilizing properties than under a carbon tax. The presence of nominal rigidities and the non-neutrality of monetary policy are two distinctive features of NK models, therefore it is not surprising that these frameworks are also used to study the potential role of monetary policy under climate change and explore the interactions of monetary and environmental policies. Although monetary policy and environmental regulations are two distinct areas of intervention, climate or pollution control policy may have an impact on monetary policy and a bearing on price stability. For instance, more ambitious climate actions could induce inflationary pressure through different channels, such as higher production costs, higher abatement costs, and tax pass-through. In the presence of economic uncertainty, a cap-and-trade system could lead to higher inflation volatility as the price of permits would fluctuate with market conditions. On the other hand, monetary policy may affect the design of the optimal environmental policy in an economy hit by shocks. These issues have been studied by Annicchiarico and Di Dio (2017), Economides and Xepapadeas (2018).

Annicchiarico and Di Dio (2017) propose a simple variant of the baseline NK model including pollutant emissions, abatement technology and environmental damage to study several combinations of second-best environmental and monetary policies in response to productivity shocks. Emissions are found to be more or less procyclical depending on the instruments available to the planner. With a Ramsey planner having access to both monetary and environmental policy instruments, emissions tend to be less procyclical than when pollution policy is set according to a carbon tax. When the Ramsey planner controls the level of emissions and monetary policy obeys a simple monetary rule, the optimal environmental policy depends crucially on the monetary policy. If monetary policy is strongly responsive to output, then the optimal environmental policy will deliver a strong increase in the carbon price in reaction to a positive shock, delivering countercyclical emissions. Under the assumption that the Ramsey planner controls only monetary policy, price stability turns out to be optimal only when environmental regulation is implemented in the form of a carbon tax, provided that the negative externality of pollution is small, otherwise under a quantity restriction on emissions, or a strong negative pollution externality, the optimal policy requires deviations from price stability in response to technology shocks.¹⁹

Economides and Xepapadeas (2018) build an NK model embodying a climate module and energy produced by the processing of fossil fuels. Energy is a production input, and the processing of fossil fuels generates pollution, which damages the economy. Productivity shocks trigger economic fluctuations, while endogenous climate change introduces a new propagation mechanism limiting the expansionary effects of positive shocks. In this context, monetary policy should be less reactive to inflation, and therefore less expansionary in response to positive

¹⁹ A different approach to the study of pollution and monetary policies is proposed by Chan (2020), who introduces state-contingent monetary, fiscal, and carbon tax rules reacting to the level of emission.

productivity shocks, the stronger the negative environmental externality. Economides and Xepapadeas (2018) also explore the effects of the introduction of a carbon tax showing how an ambitious greening policy may generate large fluctuations in the price levels. In this sense, Annicchiarico and Di Dio (2017) and Economides and Xepapadeas (2018) are some of the first studies to integrate monetary and environmental policy features and conclude that ambitious climate actions may potentially represent a challenge for monetary authorities.²⁰

A.c. Open economy

Open economy variants of E-DSGE models allow analysis of cross-country spillovers of pollution policies and the performance of international environmental regulation. It is also possible to study the response of additional macroeconomic indicators (e.g. trade balance, exchange rate, measures of competitiveness) to different environmental regulations. In particular, we focus on the contributions by Annicchiarico and Diluiso (2019), Economides and Xepapadeas (2019), and Holladay et al. (2019). The first two papers propose open-economy E-DSGE models that incorporate imperfect competition and nominal rigidities, all features that, as discussed in the previous section, alter the transmission mechanism of shocks, and provide a role for monetary policy and the chosen exchange rate regime.²¹ Holladay et al. (2019) reconsider

²⁰ More recent advances in the E-DSGE literature embodying financial frictions further expand on this potential challenge, offering new perspectives on the relationship between monetary and environmental policies, and on the role that central banks and financial regulators may have in the green transition process. This research area is discussed in subsection III.d.

²¹ Recall that Ganelli and Tervala (2011) incorporate environmental elements in a two-country model in which pollution may either affect productivity or utility. The aim of the paper is to study the international transmission of a unilateral implementation of a more ambitious environmental policy. Although the intent of this paper is not that of studying the business cycle, it falls squarely within this literature since it offers a useful framework to explore cross-country spillovers of pollution policies in the presence of uncertainty. The authors explicitly refer to the so-called New Open Economy Macroeconomics. See Lane (2001) for a survey.

the debate on prices-versus-quantities regulations under uncertainty in a small open-economy RBC model.

Annicchiarico and Diluiso (2019) use a two-country NK E-DSGE model with international trade and perfect capital mobility, and show how the cross-border propagation of asymmetric real and monetary shocks is influenced by the underlying environmental regulations (carbon tax and international cap and trade). The main channels of international transmission of the business cycle are the “demand channel” (any change in domestic expenditure implies changes in the demand for foreign production) and the “competitiveness channel” (changes in relative prices of domestic and foreign production influence trade flows). The strength of these channels depends on the underlying environmental regime. The cross-border spillover effects of business cycle uncertainty from real and monetary shocks are stronger under a carbon tax, where for shocks hitting only the home country foreign output is relatively more volatile than in other policy regimes, since both the demand and competitiveness channels are stronger. By contrast, under a cap-and-trade regime, where countries can exchange emission permits, the effects of asymmetric shocks are mitigated and the cross-border spillovers are less strong, while home and foreign outputs move in opposite directions. An international market of emissions permits further allows to smooth out the spillover effects of international trade. The degree of openness, the trade pattern, and the underlying exchange rate regime (i.e. currency union or flexible exchange rates) affect the conditioning role of environmental regulations in the transmission of shocks.

Economides and Xepapadeas (2019) show that the underlying exchange rate regime does not significantly affect the implications of climate change in a small open economy. They use a NK model calibrated to Greece to investigate the impact of the damage deriving from a continuous increase in temperature on output and competitiveness. Irrespective of the type of the

exchange rate regime considered, climate change, by reducing total factor productivity, entails significant output losses, reduction of competitiveness, and a deterioration of the external balance. In this model, having an autonomous monetary policy does not seem to make any difference in the face of climate change.

Holladay et al. (2019) study the properties of pollution taxes, cap-and-trade, and emission intensity targets in a small open economy RBC model calibrated to Canada. The model features free trade, but imperfectly mobile capital. Pollution is generated by processing a fossil fuel input in the production sector, while business cycle fluctuations are triggered by unanticipated shocks on productivity and on the price of imports. The results in Holladay et al. (2019) suggest that a cap-and-trade regulation is likely to dampen business cycle fluctuations due to productivity shocks, consistently with the findings obtained by Fischer and Springborn (2011) in a closed economy. The extension of the core E-DSGE model to an open economy allows the authors to examine the impact of business cycles on the trade balance. Holladay et al. (2019) find that a cap-and-trade regulation mitigates the effects of the business cycle on the trade balance by reducing imports during a recession and exports during an expansion. In particular, in response to a shock on the price of imports the cap-and-trade system would work as a barrier to trade limiting the expansion of demand for imports in response to a decline in foreign prices.

A.d. Credit market imperfections, financial regulation, and unconventional monetary policy

Early studies in the E-DSGE literature explore the behavior and the effects of different pollution policies on macroeconomic aggregates in response to standard macroeconomic shocks and to shocks coming from the energy sector. However, following the Global Financial Crisis of

2008, increasing attention has been devoted by the macroeconomic literature to financial shocks and to the implications of imperfectly functioning financial markets in the propagation of business cycle shocks, for instance, with the studies by Gertler and Karadi (2011), Gertler and Kiyotaki (2015), or Cúrdia and Woodford (2016).

Recently, several authors have started to study the effects of credit market imperfections in environmental macroeconomic models of the business cycle, focusing on the additional policy trade-offs that inevitably emerge when other market failures are factored in, as shown in van den Bijgaart and Smulders (2018), which we discuss below. Particular attention has been paid to the macro-financial consequences of climate change and carbon transition, and to the implications for monetary policy and financial regulators. The potential for important interactions between climate change and financial markets, including for macroeconomic stability, raised to prominence following an influential speech by then Bank of England's governor Mark Carney (Carney 2015), which highlighted three sources of systemic risk. First, physical risk, related with the impact of climate damages on assets' financial valuations. Second, transition risk, related with the revaluation of carbon-intensive assets during the transition to a cleaner economy. Third, liability risks, related to the exposure of some firms to legal action concerning their role in opposing climate action.

In this section, we focus mostly on transition risks. As markets move toward a low-carbon economy, transition risk arises when unanticipated policy measures, new technologies or sudden changes in public sentiment lead to abrupt changes in market valuation and risk of stranded assets. A sudden slump in the value of carbon-related assets could be a source of uncertainty, leading to higher default risks in the carbon-intensive sectors, precipitate a fire-sale of assets across the economy, and trigger procyclical market dynamics generating fall in output

and investment. Two main empirical observations support concerns about transition risk. First, evidence suggesting that carbon-intensive stocks make up a substantial portion of a standard financial institution's portfolio (e.g. Battiston et al. 2017). Second, evidence pointing to the imperfect ability of financial markets to price in transition, with stock markets reacting mostly to short-term changes in the probability of ambitious climate policy being implemented (Ramelli et al. 2018, Carattini and Sen 2019, Barnett 2020, Sen and von Schickfus 2020).

The management of transition risk represents a challenge for central banks and regulatory authorities. Following Carney's speech, several other central banks and prudential authorities expressed concerns, in particular about transition risk, including in France, the Netherlands, and the United States (Vermeulen et al. 2018; Banque de France 2019; Rudebusch 2021). As a result, several jurisdictions have started implementing climate-related stress tests, while both the United Kingdom and the United States mandate carbon disclosure for large firms or large polluters, under the Streamlined Energy and Carbon Reporting regulations and the Greenhouse Gas Reporting Program, respectively. In the United States, Senator Elizabeth Warren's Climate Risk Disclosure Act would require all public companies to disclose critical information about their exposure to climate-related risks.

Currently, the academic and policy debate revolves around the need to extend the mandate of both central banks and financial regulatory authorities to address climate change. In this respect, there is need to design new "green" tools ranging from green-biased financial regulations, aimed at favoring green investments and/or discouraging brown investments, to unconventional monetary policy such as the so-called "green quantitative easing", that is defined as a central bank's purchase of assets issued to finance environmentally friendly projects (see Campiglio et al. 2018 and D'Orazio and Popoyan 2019). The intent of this policy is that of

reducing the cost of borrowing for green projects. On these more specific aspects, this section discusses first the contributions of Comerford and Spiganti (2017) and Punzi (2018), and then those of Benmir and Roman (2020), Diluio et al. (2020), Ferrari and Nispi Landi (2020), and Carattini et al. (2021).

Van den Bijgaart and Smulders (2018) study second-best optimal environmental policy responses to technology and financial shocks in a model with two market failures, credit constraints and an environmental externality. The analysis is conducted in a simple two-period partial equilibrium business cycle model with heterogeneous firms that may invest in pollution-saving technologies. The level of investments in clean technologies is sub-optimal because of credit market imperfections. In this context, more ambitious environmental policies undermine the borrowing capacity of firms through the negative effects these policies have on profits. The environmental regulator faces a trade-off between limiting emissions and relaxing credit constraints, and this trade-off changes along the business cycle. The degree of procyclicality of the optimal pollution tax then crucially depends on the effects of regulation on firm's access to credit and on the strength of credit market imperfections. When the economy is in a recession, credit constraints are more binding and the best policy response requires a reduction of the pollution tax so as to alleviate hardship for business. E-DSGE models incorporating a financial sector can provide a different perspective to the study of the potential role of 'green' financial regulations for banks and other financial intermediaries in reducing the risk of financial instability from stranded assets and in supporting green investments.

Comerford and Spiganti (2017) construct a model economy with a credit amplification mechanism *à la* Kiyotaki and Moore (1997), where credit market imperfections arise from collateral constraints on borrowing, and study the effects of the implementation of a climate

policy on the value of brown assets. In this model, ambitious climate actions may cause a sudden fall in the value of these assets and precipitate a fire-sale of assets across the economy, triggering a recession. Policies tailored to mitigate the impact of stranded assets upon investors' balance sheets, such as investment subsidies, debt take-over, or government guarantee, can be welfare-enhancing and support a faster recovery.

Punzi (2018) develops an E-DSGE model of the NK type with a formalized banking sector similar to that of Kollmann et al. (2011) to study the effects of total factor productivity, monetary, and credit shocks in a two-sector economy (green firms and non-green firms) and provide a first attempt to investigate the role of different macroprudential measures to support green financing. She finds that only differentiated capital requirements can help to sustain green investments, while lowering the volatility of business cycle fluctuations.

Next, we discuss four recent papers that all combine an E-DSGE model with financial frictions *à la* Gertler and Karadi (2011). In this setup, an agency problem limits the amount of funds banks can raise from households.²² First, Benmir and Roman (2020) incorporate this into a two-sector (green and dirty) NK-DSGE model. Their results suggest that, by rendering dirty and green assets imperfect substitutes and by favoring a rebalancing of intermediaries' portfolio toward green assets, macroprudential regulation could be designed to favor the expansion of the green sector with a minimal welfare cost. This paper also examines the effects of green biased quantitative easing policies, showing that these unconventional monetary policies can be used as short-term countercyclical tool, rather than as an instrument to favor the structural change toward a greener economy.

²²Banks have an incentive to divert funds from the assets they hold and households (depositors) recognizing this incentive limit the amount they lend. See Gertler and Karadi (2011).

Diluiso et al. (2020) build up a three-sector NK-DSGE model with heterogeneous energy production sectors (a low-carbon energy sector and a fossil energy sector), financial frictions in the spirit of Gertler and Karadi (2011) and a climate module. Policy and financial shocks hitting the fossil energy sector weaken banks' balance sheets and propagate in the economy through a financial accelerator mechanism. Diluiso et al. (2020) show that the transition risks are limited for orderly and credible mitigation plans, while tax-subsidy schemes designed to encourage the decarbonization of banks' balance sheets may significantly reduce the transition risks.

In Diluiso et al. (2020) unconventional monetary policies, such as green quantitative easing programs, prove to be effective in stabilizing the economy in response to a crisis generated by the stranding of fossil assets and do not seem to compromise the objective of price stability.²³ However, the effectiveness of green-biased quantitative easing programs in reviving the economy is not significantly different from that of market-neutral programs.

These results in Diluiso et al. (2020) are consistent with those obtained by Ferrari and Nispi Landi (2020), who also propose a two-sector NK-DSGE model with green and carbon assets and financial frictions as in Gertler and Karadi (2011). This paper elucidates the potential effects and the scope of temporary green quantitative easing policy shocks, and shows that the imperfect substitutability between green and brown assets is a necessary condition for the effectiveness of non-neutral asset purchasing programs in greening the economy, although the welfare gains of these policies seem limited. When brown and green assets are perfect substitutes their returns must be the same in equilibrium. In this case, green quantitative easing policies are still expansionary, because they ease the credit constraint on banks and improve lending

²³ In a stock-flow-fund ecological macroeconomic model, Dafermos et al. (2018) explore the potential effects of a global green quantitative easing program in reducing climate-related financial instability and global warming risks.

conditions. However, banks exploit arbitrage opportunities and expand their assets holdings also in the brown sector, frustrating any attempt to green the economy through this policy. As a result of the same intuition, green and neutral asset purchasing programs behave similarly in stimulating the economy after an adverse financial shock, as shown by Diluiso et al. (2020).

Finally, Carattini et al. (2021) also develop an E-DSGE model that features financial frictions *à la* Gertler and Karadi (2011). While the other papers that do this focus primarily on the transition risk of introducing carbon policy, Carattini et al. (2021) consider both the transition risk, in particular from the abrupt implementation of ambitious climate policy (Carney's "hard landing"), as well as the long-run and business cycle implications of the relationship between the climate externality and the financial market frictions. They consider both a carbon tax to address the climate externality and macroprudential policies, in the form of taxes or subsidies on banks' assets, to address the financial frictions. Over the business cycle, the first-best level of both policies varies, and the Ramsey planner dynamically optimizes both policies. If one policy is constrained or absent, then the second-best solution is where the remaining policy adjusts as best it can to the business cycle. Despite current debates, in Europe as well as in the United States, on whether central banks should also make tackling climate change part of their mandate, Carattini et al. (2021) find that macroprudential policies alone, without an accompanying climate policy, are not very effective at reducing greenhouse gas emissions. Macroprudential policies can, however, limit the risk of a recession with the abrupt implementation of carbon taxes, thus clearing the way for ambitious policies.