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Climate Actions and Stranded Assets: The Role of Financial Regulation and Monetary Policy

Abstract

Limiting global warming to well below 2⁰C may result in the stranding of carbon-sensitive assets. This could pose substantial threats to financial and macroeconomic stability. We use a dynamic stochastic general equilibrium model with financial frictions and climate policy to study the risks a low-carbon transition poses to financial stability and the different instruments central banks could use to manage these risks. We show that, even for very ambitious climate targets, transition risks are limited for a credible, exponentially growing carbon price, although temporary “green paradoxes” phenomena may materialize. Financial regulation encouraging the decarbonization of the banks’ balance sheets via tax-subsidy schemes significantly reduces output losses and inflationary pressures but it may enhance financial fragility, making this approach a risky tool. A green credit policy as a response to a financial crisis originated in the fossil sector can potentially provide an effective stimulus without compromising the objective of price stability. Our results suggest that the involvement of central banks in climate actions must be carefully designed in compliance with their mandate to avoid unintended consequences.

JEL-Codes: E500, H230, Q430, Q500, Q580.

Keywords: climate policy, financial instability, financial regulation, green credit policy, monetary policy, transition risk.

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1 Introduction

Through our strategy review, we will determine where and how the issue of climate change and the fight against climate change can actually have an impact on our policies.

Christine Lagarde, President of the ECB

By signing and ratifying the Paris Agreement countries agreed to limit global warming to well below 2°C. Achieving this target requires to have a net carbon neutral economy within the next 50 years (IPCC, 2018). According to recent estimates this implies global emissions to decline by approximately 7% per year in a typical 1.5°C scenario and by 3% per year in the 2°C scenario (e.g. Höhne et al., 2020). Such strong emission reductions are historically unprecedented and partially the result of the past decade of political failure in contrasting climate change. In the absence of more stringent climate policies, global emissions are bound to keep rising (e.g. Friedlingstein et al., 2019; UNEP, 2019).¹ The current plans of expanding fossil fuel production will lead to emission levels in 2030 that are about 50% higher than those consistent with (median) cost-effective 2°C mitigation pathways (e.g. SEI et al., 2019).² There is clearly a sizable and growing discrepancy between global climate policy ambition and (inadequate) policy implementation.

The current delay in implementing ambitious policies may lead to stronger future interventions, increasing the cost of climate policy due to sunk investments in the fossil sector (e.g. Edenhofer et al., 2020; Jakob et al., 2012; Kriegler et al., 2018). To comply with the Paris Agreement goals, much of the world’s fossil fuel reserves must be left “unburned” in the ground (Jakob and Hilaire, 2015; McGlade and Ekins, 2015; van der Ploeg et al., 2020). A sudden introduction of strict climate policies would swiftly devalue these reserves, with potentially disruptive effects on fossil capital stocks and fossil financial assets. If investors currently expect these “stranded reserves” to be eventually commercialized, we are in presence of an overvaluation of fossil fuel stock. This is referred to as a “carbon bubble”.³ Whether a carbon bubble exists or not mostly depends on the credibility and timing of policy implementation. The current fossil assets value may reflect the failure to internalize the social cost of carbon and/or the beliefs of investors on the introduction of ambitious climate policies.

The extent to which financial markets are valuing climate policy risk, as well as the magnitude of the assets at risk of transition-stranding, is still unclear. The number of studies aimed at quantifying the asset losses due to a policy-induced devaluation is growing, embracing methodologies that range from different variants of accounting approaches (Carbon Tracker Initiative, 2011) and dynamic models of the economy and climate (e.g. Mercure et al., 2018; van der Ploeg and Rezai, 2020), to analyses based on input-output data (e.g. Cahen-Fourot et al., 2019; Campiglio et al., 2017) and network-based climate stress-tests as in Battiston et al. (2017).

The concerns around the alleged “carbon bubble” and stranded assets have penetrated into policy circles and kicked off a debate on transition risk, and on macroeconomic and financial stability. Among others, this has also caught the attention of a growing number of Central Banks (CBs) around the world.⁴ It is now widely accepted that transition risk poses a new

¹While the current economic crisis is projected to reduce carbon emissions by 7% in 2020 (Le Quéré et al., 2020), past recessions showed a quick rebound in emissions with even higher growth rates (Peters et al., 2020).

²Corresponding to about 120% higher emissions than those consistent with (median) cost-effective 1.5°C mitigation pathways.

³Originally, the term “carbon bubble” was introduced by Carbon Tracker Initiative (2011) to emphasize the inconsistency between observed fossil asset values and (normative) climate policy goals.

⁴See e.g., Carney (2015), Coeuré (2018), Lane (2017) and Rudebusch et al. (2019).

threat to financial stability.⁵

While there is a widely shared perception that CBs should play a role in addressing this risk, there is an increasingly heated discussion about what this role should exactly be. Is the traditional CB's mandate with its set of instruments sufficient to effectively manage transition risk or is there a need to extend the mandate and design new "green" instruments? Moreover, looking at the recent past and building on the experience of the recent financial crisis, in the words of Bolton et al. (2020, p. 17) "the sociopolitical pressure is already mounting to make central banks (perhaps again) the *only game in town*", with the risk of overburdening their mandates and at the same time discouraging the market and other players from taking action. In this respect the cautious approach of CBs in taking up climate change risks is comprehensible.⁶

Previous papers discussed the role of CBs in the transition, by proposing several new green financial and monetary tools tailored to limit systemic risk and redirecting resources toward low-carbon sectors (e.g. Campiglio, 2016; Campiglio et al., 2018; Dafermos et al., 2018; D'Orazio and Popoyan, 2019). Nevertheless, modeling attempts to study the impact of these green policies are still at an early stage.

Dynamic stochastic general equilibrium (DSGE) models have been widely used to inform CBs' interventions and could provide an important perspective in this discussion.⁷ Annicchiarico and Di Dio (2017) have been the first to explicitly focus on the relationship between monetary policy and climate policy in an environmental DSGE model.⁸ Other contributions studying the interaction between monetary policy and climate policy are Economides and Xepapadeas (2018), focusing on the implications of a negative climate externality on the conduct of monetary policy, and Annicchiarico and Diluiso (2019), exploring how the international transmission mechanism of climate policy changes in the presence of a currency union. However, they neither address transition risk, nor the role of green CB's instruments. A first contribution focusing on transition risk is provided by Spiganti and Comerford (2017). The authors study the impact of a disruptive climate policy in a DSGE model with financial frictions in the spirit of Kiyotaki and Moore (1997) and discuss the effectiveness of different government's measures in supporting a faster recovery. Donadelli et al. (2019) develop a macro asset pricing model to analyze the effects of the transition to a low-carbon economy on macroeconomic aggregates and asset prices. Punzi (2019) investigates the performance of different macroprudential policies to support green financing in the presence of macroeconomic shocks.

However, a comprehensive analysis of the role of CBs in addressing transition risk toward a greener economy is still missing.⁹ The contribution of this paper to the literature is twofold.

⁵Climate related risks have been mainly identified in physical and transition risk. While we mainly focus on the latter, the effects of physical risk on asset prices and financial markets are explored in Bansal et al. (2019), Dietz et al. (2016), Karydas and Xepapadeas (2019), van der Ploeg et al. (2020) among the others.

⁶For an overview on the inclusion of climate-related risks in CB's operational frameworks and mandates, see Dikau and Volz (2020).

⁷Features like the presence of different types of nominal and real rigidities, market failures, financial frictions, and the explicit formalization of monetary policy make DSGE models particularly suitable to reproduce short-run dynamics and thus analyze the impact of CB's policies.

⁸Previous environmental DSGE models mainly focus on the effects of different GHG mitigation policies on macroeconomic aggregates in response to standard macroeconomic shocks (e.g. Angelopoulos et al., 2013; Annicchiarico and Di Dio, 2015; Fischer and Springborn, 2011; Ganelli and Tervala, 2011; Heutel, 2012) and shocks coming from the energy sector as in Dissou and Karnizova (2016).

⁹Beyond the DSGE literature, to the best of our knowledge, Dafermos et al. (2018) is the only paper evaluating the effects of a global green quantitative easing (QE) program in reducing climate-related financial instability and global warming using a stock-flow-fund ecological macroeconomic model. While referring to green QE, they specify that the instrument suggested is very different in nature compared to the current CB's

First, we focus on transition risk and provide a comprehensive modeling framework to assess costs, benefits and side effects of different CB's instruments tailored to address this risk. We adopt a CB' perspective and explicitly explore the trade-offs in terms of output, price and financial stability that arise when adopting both conventional and green instruments. Second, we analyze a broad set of policy measures: carbon pricing schemes, conventional monetary policy, green financial regulation and green credit policy. This allows us to discuss different climate transition scenarios and the diverse role of each instrument in the transition.

We build a model with two heterogeneous energy production sectors (a low-carbon energy sector and a fossil energy sector) and a production sector, several types of nominal and real rigidities, and financial frictions in the spirit of Gertler and Karadi (2011). It is worth noting two main novelties of our set-up. First, the model includes three types of capital and three types of assets in the banks' portfolio, one for each sector. Differently from previous two-sector DSGE models, we can analyze systemic effects and not only the spillover effects between the low-carbon and the fossil sectors. This is crucial to study transition risk. Second, we explicitly model a fossil resource stock. This allows us to capture both financial and resource stranding.

The paper addresses the following questions: To what extent and under which conditions is climate policy a source of macroeconomic and financial instability? How and when can CBs use green financial regulation and green credit policy to foster the transition and preserve price and financial stability? And, finally, are green financial regulation and green credit policy in conflict with CBs' mandates?

To answer these questions we propose several policy scenarios. First, we compare a linearly-increasing carbon tax with an exponentially-increasing carbon tax. Second, we evaluate the potential effects of brown-penalizing/green-supporting financial regulation shifting financial flows toward low carbon assets. Third, we study how an asset price shock in the fossil sector transmits into the economy. Differently from the previous scenarios, where we observe the effects of a gradually implemented mitigation strategy, we explore here the role of green credit policy in stabilizing the economy following a disruptive, sudden devaluation of the fossil sector's assets (this could be generated, e.g., by a disorderly transition).

We find that a mitigation strategy based on a credible carbon price does not undermine financial stability. Even for very ambitious climate targets consistent with the 1.5°C degree target, transition risks seems to be limited. A lower initial carbon price increasing exponentially allows the markets to anticipate the effects of the mitigation plan and smoothly distribute the transition costs. Introducing a financial regulatory framework to tax and discourage the holding of fossil energy assets leads to very different results, depending on how tax revenues are redistributed. Redistribution of the revenues through lump-sum transfers enhances transition risk. Redistribution via subsidies on the low-carbon energy assets leads to expansionary effects on output, lower inflationary pressure and greater emission reductions. However, this regulatory scheme may increase the fragility of the financial market. Green credit policy implemented in response to a financial crisis in the fossil sector stabilizes financial markets and sustains the aggregate demand. However, due to the modest size of the green energy sector, the ability to stabilize the economy exclusively through this channel is limited. Further, the violation of the principle of neutrality in conducting credit policy may create excessive imbalances in the exposure of intermediaries' portfolios and be a source of undesirable consequences. Our results then suggest that CBs can facilitate a smooth transition, acting within the perimeter of their jurisdictions and consistently with their mandates. There is room for new green instruments, which, however, should be designed carefully, balancing all the trade-offs in place.

The remainder of the paper is organized as follows. Section 2 describes the model, section 3

QE programs and it has to be interpreted as long-run horizon industrial policy rather than a cyclical tool.

summarizes the calibration strategy, section 4 presents and discusses different policy scenarios, section 5 summarizes the main results and concludes.

2 Model Economy

The core framework is a New Keynesian DSGE model, modified to include (i) energy producing sectors, (ii) pollutant emissions and climate policies and (iii) financial frictions as in Gertler and Karadi (2011). The economy is composed by eight types of agents: households, who consume, supply labor to firms in the different sectors, and save in the form of bank deposits and government bonds; monopolistically competitive retailers that repackage production goods; perfectly competitive firms producing goods by combining labor and capital with energy inputs supplied by different types of energy producers; perfectly competitive energy firms that produce energy by combining labor, capital and low-carbon sources; perfectly competitive energy firms that produce energy by combining labor, capital and fossil sources; sector-specific competitive capital producers that repair the depreciated capital, build new capital and sell it to energy and goods-producing firms; banks that lend funds obtained from households to firms in the different sectors; a central authority conducting monetary policy, financial regulation and climate policy.

2.1 Households

There is a continuum of identical households of mass one. Following Gertler and Karadi (2011) within each household, a fraction $1 - f$ of members are workers and a fraction f are bankers. Workers supply labor to firms in the two energy sectors and to firms in the goods-producing sector, and return their wage to the household. Bankers manage financial intermediaries and, in turn, transfer earnings back to their respective household.

With constant probability $1 - \theta$, a banker exits next period. Upon exiting, a banker transfers retained earnings to the household and becomes a worker. Each period, $(1 - \theta)f$ workers randomly become bankers, keeping the proportion of each occupation constant.¹⁰ New bankers receive a start-up transfer from their respective household.

The representative household derives utility from consumption, C_t , and disutility from hours worked in the goods-producing sector, indexed as Y , and in the two energy sectors, the low-carbon sector, indexed as L , and the fossil sector, indexed as F . Let $\mathcal{S} \in \{Y, L, F\}$, then the expected discounted lifetime utility is of the type:

$$\mathbb{E}_0 \left\{ \sum_{t=0}^{\infty} \beta^t \left[\frac{\left(C_t - h_c \bar{C}_{t-1} \right)^{1-\varkappa} - 1}{1 - \varkappa} - \sum_{\mathcal{S}} \chi_{\mathcal{S}} \frac{N_{\mathcal{S},t}^{1+\varphi_{\mathcal{S}}}}{1 + \varphi_{\mathcal{S}}} \right] \right\}, \quad (1)$$

where \mathbb{E} is the rational expectations operator, $\beta \in (0, 1)$ is the discount factor, \varkappa is the inverse of the intertemporal elasticity of substitution, $h_c \in [0, 1)$ is the habit persistence coefficient and \bar{C}_{t-1} is the lagged aggregate consumption of households, taken as given by each household in the spirit of the “catching up with the Joneses” preferences.¹¹ The second term in the

¹⁰This assumption rules out equilibria with full internal financing (deposits equal to zero). Considering that a fraction of the earnings is retained by bankers (see section 2.6), to avoid a situation in which bankers can fund all investments from own accumulated capital, and are thus not financially constrained anymore, the model introduces a turnover between bankers and workers.

¹¹Habit formation in consumption is a standard feature of medium- and large-scale DSGE models. It allows reproducing more realistic dynamics in the behavior of consumption, matching some degree of persistence that

square brackets refers to the disutility of labor in the three sectors, where $N_{\mathcal{S},t}$ represents labor supply and $\varphi_{\mathcal{S}} > 0$ is the inverse of the Frisch elasticity, while $\chi_{\mathcal{S}}$ is a positive scale parameter measuring the relative disutility of supplying labor.

Households pay lump-sum taxes T_t to the government, and can purchase short-term debt B_t in the form of governments bonds and bank deposits (except deposits of the banks they own). We assume that both bank deposits and government bonds are one period risk-free assets paying an ex post real return adjusted for inflation, R_t .¹² Households receive net payouts D_t from the ownership of financial intermediaries and non-financial firms. D_t is net of the amount the representative household gives to its members entering the banking sector in period t . The budget constraint of households reads as:

$$C_t = \sum_{\mathcal{S}} W_{\mathcal{S},t} N_{\mathcal{S},t} + D_t - T_t + R_t B_t - B_{t+1}, \quad (2)$$

where $W_{\mathcal{S},t}$ denotes the real wage received from sector \mathcal{S} . The first-order conditions from the households' utility maximization problem are the following:

$$\left(C_t - h_c \bar{C}_{t-1} \right)^{-\varkappa} = \lambda_t, \quad (3)$$

$$\chi_{\mathcal{S}} N_{\mathcal{S},t}^{\varphi_{\mathcal{S}}} = \lambda_t W_{\mathcal{S},t} \text{ for } \mathcal{S} \in \{Y, L, F\}, \quad (4)$$

$$\beta \mathbb{E}_t \Lambda_{t,t+1} R_{t+1} = 1, \quad (5)$$

where λ_t denotes the Lagrange multiplier associated to the flow budget constraint and $\Lambda_{t,t+1} \equiv \lambda_{t+1}/\lambda_t$ is the households' real stochastic discount factor. Equation (3) is the optimal consumption choice, condition (4) represents labor supply in each of the three sectors of the economy and equation (5) is the optimal choice between present and future consumption.

2.2 Goods Producers

The goods-producing sector is made up of a continuum of perfectly competitive firms. Firms use a capital and labor composite $VA_{Y,t}$ and an energy bundle E_t , composed by low-carbon energy $E_{L,t}$ and fossil energy $E_{F,t}$. Let Y_t denote production. We assume the following functional forms for technology:

$$Y_t = \left[\varpi_{VA_Y}^{1/\varepsilon_Y} (VA_{Y,t})^{(\varepsilon_Y-1)/\varepsilon_Y} + \varpi_E^{1/\varepsilon_Y} (E_t)^{(\varepsilon_Y-1)/\varepsilon_Y} \right]^{\varepsilon_Y/(\varepsilon_Y-1)}, \quad (6)$$

where $\varepsilon_Y > 0$ is the elasticity of substitution between $VA_{Y,t}$ and E_t , and ϖ_{VA_Y} and ϖ_E are the corresponding weights. The capital and labor composite is of the form:

$$VA_{Y,t} = \Gamma_{DY,t} A_{Y,t} (U_{Y,t} \xi_{Y,t} K_{Y,t})^{\alpha_Y} N_{Y,t}^{1-\alpha_Y}, \quad (7)$$

where $A_{Y,t}$ represents the sector-specific productivity, $K_{Y,t}$ and $N_{Y,t}$ denote the amount of capital and labor used, $U_{Y,t}$ is the utilization rate of capital, $\xi_{Y,t}$ is a measure of the quality of capital, $\alpha_Y \in (0, 1)$ is the elasticity of $VA_{Y,t}$ with respect to capital, and $\Gamma_{DY,t}$ is a damage function, depending on the level of global temperature and capturing the effect of climate

we typically observe in the data.

¹²When saving decisions were made at time $t-1$, the risk-free gross nominal interest return, $R_{N,t-1}$, on deposits was known, while next period inflation, Π_t , was unknown. The ex-post real return on deposits B_t is then $R_t = R_{N,t-1}/\Pi_t$.

change on productivity, in the spirit of the DICE model (see e.g. Nordhaus 2018). This function represents the channels through which global warming affects the level of economic activity. $\Gamma_{D_Y,t}$ captures the idea that pollution damages interfere to some degree with the production process by reducing total factor productivity.

The energy composite is a CES aggregate of the energy inputs:

$$E_t = \left[\varpi_{E_L}^{1/\varepsilon_E} E_{L,t}^{(\varepsilon_E-1)/\varepsilon_E} + \varpi_{E_F}^{1/\varepsilon_E} E_{F,t}^{(\varepsilon_E-1)/\varepsilon_E} \right]^{\varepsilon_E/(\varepsilon_E-1)}, \quad (8)$$

where $\varepsilon_E > 0$ is the elasticity of substitution between low-carbon and fossil energy, while ϖ_{E_L} and ϖ_{E_F} are the corresponding weights.

At the end of period t firms purchase physical capital $K_{Y,t+1}$ at price $Q_{Y,t}$ to be used in production in period $t+1$. Firms finance their capital acquisition by obtaining funds from financial intermediaries and by issuing state contingent claims to their future stream of earnings, $S_{Y,t}$. Financial intermediaries are able to perfectly monitor firms and enforce contracts. The price of each claim equals the price of a unit of capital so that, by arbitrage, the value of the capital acquired is equal to the value of the issued claims, $Q_{Y,t}K_{Y,t+1} = Q_{Y,t}S_{Y,t}$. At the end of period t , after production, firms replace the depreciated capital, sell its entire capital stock and purchase capital that will be employed in the subsequent period. The replacement price of used capital is set at one. The value of the stock of capital at the end of period $t+1$ is then $(Q_{Y,t+1} - \delta_{Y,t+1})\xi_{Y,t+1}K_{Y,t+1}$, where $\delta_{Y,t}$ is the depreciation rate of capital that in turn is assumed to be a function of the capital utilization rate $\delta_{Y,t} = \delta_Y(U_{Y,t})$ with $\delta'_Y > 0$. Let $P_{Y,t}$ be the nominal price of goods and P_t the retail price. Given the zero-profit condition, at the end of period $t+1$ firms will pay out the ex post return of capital $R_{Y,t+1}$ to financial intermediaries:

$$R_{Y,t+1} = \frac{\left(\frac{\alpha_Y \frac{P_{Y,t+1}}{P_{t+1}} Y_{t+1}^{1/\varepsilon_Y} \varpi_{V_{AY}}^{1/\varepsilon_Y} V_{AY,t+1}^{(\varepsilon_Y-1)/\varepsilon_Y}}{\xi_{Y,t+1}K_{Y,t+1}} + Q_{Y,t+1} - \delta_{Y,t+1} \right) \xi_{Y,t+1}}{Q_{Y,t}}. \quad (9)$$

In each period t firms choose labor inputs, the utilization rate of capital and the demand for energy inputs. At the optimum:

$$W_{Y,t} = \frac{P_{Y,t}}{P_t} Y_t^{1/\varepsilon_Y} \varpi_{V_{AY}}^{1/\varepsilon_Y} V_{AY,t}^{(\varepsilon_Y-1)/\varepsilon_Y} (1 - \alpha_Y) \frac{1}{N_{Y,t}}, \quad (10)$$

$$\delta'_{Y,t} \xi_{Y,t} K_{Y,t} = \frac{P_{Y,t}}{P_t} Y_t^{1/\varepsilon_Y} \varpi_{V_{AY}}^{1/\varepsilon_Y} V_{AY,t}^{(\varepsilon_Y-1)/\varepsilon_Y} \alpha_Y \frac{1}{U_{Y,t}}, \quad (11)$$

$$E_t = \left(\frac{P_{Y,t}}{P_t} \right)^{\varepsilon_Y} \varpi_E \left(\frac{P_{E,t}}{P_t} \right)^{-\varepsilon_Y} Y_t, \quad (12)$$

where $P_{E,t}$ is the nominal price of the energy bundle E_t . Recalling the energy CES aggregate (8), the optimal energy mix stemming from a cost-minimization problem immediately follows:

$$E_{L,t} = \varpi_{E_L} \left(\frac{P_{E_L,t}}{P_{E,t}} \right)^{-\varepsilon_E} E_t, \quad (13)$$

$$E_{F,t} = \varpi_{E_F} \left(\frac{P_{E_F,t}}{P_{E,t}} \right)^{-\varepsilon_E} E_{j,t}, \quad (14)$$

where $P_{E_L,t}$ and $P_{E_F,t}$ denote nominal energy prices from low-carbon and fossil energy sources,

respectively. The energy price index $P_{E,t}$ is then:

$$P_{E,t} = \left[\varpi_{E_L} (P_{E_L,t})^{1-\varepsilon_E} + \varpi_{E_F} (P_{E_F,t})^{1-\varepsilon_E} \right]^{\frac{1}{1-\varepsilon_E}}. \quad (15)$$

2.3 Low-Carbon Energy Sector

The low-carbon energy sector is populated by perfectly competitive firms that employ labor and capital inputs to produce energy according to the following technology:

$$E_{L,t} = \Gamma_{D_L,t} A_{L,t} (U_{L,t} \xi_{L,t} K_{L,t})^{\alpha_L} N_{L,t}^{1-\alpha_L}, \quad (16)$$

where $A_{L,t}$ is the total factor productivity, $U_{L,t}$ denotes the utilization rate of capital $K_{L,t}$, $\xi_{L,t}$ measures the quality of capital, $N_{L,t}$ represents the labor inputs and $\alpha_L \in (0, 1)$ is the elasticity of low-carbon energy production to capital. As before, we assume that production can be affected by climate change, through the damage function $\Gamma_{D_L,t}$.

At the end of period t energy producers purchase physical capital $K_{L,t+1}$ at price $Q_{L,t}$ and finance their capital acquisition by issuing state contingent claims $S_{L,t}$, so that by arbitrage $Q_{L,t} K_{L,t+1} = Q_{L,t} S_{L,t}$. Also for this sector financial intermediaries can perfectly monitor firms and enforce contracts. At the end of period $t+1$, after production, firms replace the depreciated capital, sell their entire capital stock and purchase capital that will be employed in the subsequent period. The value of the stock of capital at the end of period $t+1$ is then $(Q_{L,t+1} - \delta_{L,t+1}) \xi_{L,t+1} K_{L,t+1}$, where $\delta_{L,t} = \delta_L(U_{L,t})$ with $\delta'_L > 0$. Letting $R_{L,t+1}$ the ex post return on capital in the low-carbon energy sector that is paid out to the financial intermediaries, then:

$$R_{L,t+1} = \frac{\left[\frac{P_{E_L,t+1}}{P_{t+1}} \alpha_L \frac{E_{L,t+1}}{\xi_{L,t+1} K_{L,t+1}} + Q_{L,t+1} - \delta_{L,t+1} \right] \xi_{L,t+1}}{Q_{L,t}}. \quad (17)$$

At the beginning of period t energy producers choose labor inputs and the rate of utilization of capital to be used in production. The first-order conditions of the profit maximization problem with respect to labor and the utilization rate are, respectively:

$$W_{L,t} = \frac{P_{E_L,t}}{P_t} (1 - \alpha_L) \frac{E_{L,t}}{N_{L,t}}, \quad (18)$$

$$\delta'_{L,t} \xi_{L,t} K_{L,t} = \frac{P_{E_L,t}}{P_t} \alpha_L \frac{E_{L,t}}{U_{L,t}}. \quad (19)$$

2.4 Fossil Energy Sector

The fossil energy sector is populated by perfectly competitive producers that employ a capital and labor composite, $VA_{F,t}$, and a fossil natural resource, X_t , to produce energy according to the following production technology:

$$E_{F,t} = \left[\varpi_{VA_F}^{1/\varepsilon_F} VA_{F,t}^{(\varepsilon_F-1)/\varepsilon_F} + \varpi_X^{1/\varepsilon_F} X_t^{(\varepsilon_F-1)/\varepsilon_F} \right]^{\varepsilon_F/(\varepsilon_F-1)}, \quad (20)$$

where $\varepsilon_F > 0$ is the elasticity of substitution between the composite and the natural resource, while ϖ_{VA_F} and ϖ_X are the corresponding weights. The capital and labor composite is of the form:

$$VA_{F,t} = \Gamma_{D_F,t} A_{F,t} (U_{F,t} \xi_{F,t} K_{F,t})^{\alpha_F} N_{F,t}^{1-\alpha_F}, \quad (21)$$

where notation is as before. Also in this case we have a negative externality due to climate change represented by the function $\Gamma_{D_F,t}$.

The stock of fossil fuel reserves M_t evolves according to:

$$M_{t+1} = (1 - g_M)M_t - X_t + \Delta_t, \quad (22)$$

where X_t is the amount of resources extracted in the period, Δ_t are exogenous discoveries and $g_M \in (0, 1)$ is a parameter capturing the part of the resource lost in the extraction process.¹³ Firms face extraction costs in units of foregone output, $\Gamma_{X,t} = \chi_0 (M_0/M_t)^{\chi_1} X_t$, where $\chi_0 > 1$ and $\chi_1 > 1$ are extraction parameters and M_0 is the initial level of fossil reserves. These costs increase as the stock of reserves diminishes, since firms need to extract from deeper and less accessible fields that are more costly to access (see e.g. Pindyck, 1978 and van der Ploeg and Rezai, 2020). If an environmental policy is implemented, firms will have to pay a carbon tax equal to $P_{X,t}$ for each unit of resource extracted. Since we will assume that emission flows are equal to X_t , this upstream tax is equivalent to a downstream tax on carbon emissions.¹⁴

Similarly to the other sectors, at the end of period t fossil energy producers issue state contingent claims $S_{F,t}$ to finance their capital acquisition $Q_{F,t}K_{F,t+1} = Q_{F,t}S_{F,t}$ and in the following period after production, they replace the depreciated capital, sell their entire capital stock and purchase new capital. The value of the stock of capital at the end of period $t + 1$ is $(Q_{F,t+1} - \delta_{F,t+1})\xi_{F,t+1}K_{F,t+1}$. The ex post return on capital in the fossil energy sector that is paid out to financial intermediaries is then:

$$R_{F,t+1} = \frac{\left[\frac{P_{E_F,t+1} E_{F,t+1}^{1/\varepsilon_F} \varpi_{V A_F}^{1/\varepsilon_F} V A_{F,t+1}^{(\varepsilon_F-1)/\varepsilon_F} \alpha_F}{\xi_{F,t+1} K_{F,t+1}} + Q_{F,t+1} - \delta_{F,t+1} \right] \xi_{F,t+1}}{Q_{F,t}}. \quad (23)$$

In period t fossil energy producers choose all the other production inputs. The first-order conditions are the following:

$$W_{F,t} = \frac{P_{E_F,t}}{P_t} E_{F,t}^{1/\varepsilon_F} \varpi_{V A_F}^{1/\varepsilon_F} V A_{F,t}^{(\varepsilon_F-1)/\varepsilon_F} (1 - \alpha_F) \frac{1}{N_{F,t}}, \quad (24)$$

$$\delta'_{F,t} \xi_{F,t} K_{F,t} = \frac{P_{E_F,t}}{P_t} E_{F,t}^{1/\varepsilon_F} \varpi_{V A_F}^{1/\varepsilon_F} V A_{F,t}^{(\varepsilon_F-1)/\varepsilon_F} \alpha_F \frac{1}{U_{F,t}}, \quad (25)$$

$$\frac{P_{E_F,t}}{P_t} E_{F,t}^{1/\varepsilon_F} \varpi_X^{1/\varepsilon_F} X_t^{-1/\varepsilon_F} - \frac{P_{X,t}}{P_t} - Q_{M,t} - \chi_0 \left(\frac{M_0}{M_t} \right)^{\chi_1} = 0, \quad (26)$$

$$Q_{M,t} = \beta \mathbb{E}_t \Lambda_{t,t+1} Q_{M,t+1} (1 - g_M) + \beta \mathbb{E}_t \Lambda_{t,t+1} \chi_1 \chi_0 \left(\frac{M_0}{M_{t+1}} \right)^{\chi_1-1} \frac{M_0}{M_{t+1}^2} X_t, \quad (27)$$

where (24)-(25) represent the optimal conditions with respect to labor and the capital utilization rate, (26) describes the optimal extraction quantity of fossil resource and (27) is the first order condition with respect to M_t , with $Q_{M,t}$ being the shadow value of the resource stock.

¹³The assumption of serendipitous discoveries ($\Delta > 0$), jointly with a positive g_M , ensure that M is a stationary process with a steady-state value larger than zero.

¹⁴In calibrating the model natural resources are expressed in carbon-equivalent units.

2.5 Capital Producers

The problem of sector-specific capital producers is standard and follows closely the specification of Gertler and Karadi (2011). At the end of each period competitive capital producers in the generic sector $\mathcal{S} \in \{Y, L, F\}$ buy capital from firms, rebuild depreciated capital and build new capital. Capital producers will then sell both the new and refurbished capital to goods and energy producers at price $Q_{\mathcal{S},t}$, commonly known as Tobin's Q. Letting $I_{net,\mathcal{S},t}$ denote net investments (i.e new capital), defined as the difference between the gross capital created $I_{\mathcal{S},t}$ and the amount of capital refurbished $\delta_{\mathcal{S},t}\xi_{\mathcal{S},t}K_{\mathcal{S},t}$, then the capital stock evolves as $K_{\mathcal{S},t+1} = \xi_{\mathcal{S},t}K_{\mathcal{S},t} + I_{net,\mathcal{S},t}$. The cost capital producers incur in refurbishing capital is equal to one, but there are investment adjustment costs associated with new capital production, $(\gamma_{\mathcal{S}}/2) \left(\frac{I_{net,\mathcal{S},t} + I_{\mathcal{S}}}{I_{net,\mathcal{S},t-1} + I_{\mathcal{S}}} - 1 \right)^2 (I_{net,\mathcal{S},t} + I_{\mathcal{S}})$, with $\gamma_{\mathcal{S}} > 0$ and $I_{\mathcal{S}}$ denoting the steady-state investment level. The first-order condition for the capital producers' optimization problem with respect to investments is then:

$$Q_{\mathcal{S},t} = 1 + \frac{\gamma_{\mathcal{S}}}{2} \left(\frac{I_{net,\mathcal{S},t} + I_{\mathcal{S}}}{I_{net,\mathcal{S},t-1} + I_{\mathcal{S}}} - 1 \right)^2 + \gamma_{\mathcal{S}} \left(\frac{I_{net,\mathcal{S},t} + I_{\mathcal{S}}}{I_{net,\mathcal{S},t-1} + I_{\mathcal{S}}} - 1 \right) \frac{I_{net,\mathcal{S},t} + I_{\mathcal{S}}}{I_{net,\mathcal{S},t-1} + I_{\mathcal{S}}} + \quad (28)$$

$$- \mathbb{E}_t \beta \Lambda_{t,t+1} \gamma_{\mathcal{S}} \left(\frac{I_{net,\mathcal{S},t+1} + I_{\mathcal{S}}}{I_{net,\mathcal{S},t} + I_{\mathcal{S}}} - 1 \right) \left(\frac{I_{net,\mathcal{S},t+1} + I_{\mathcal{S}}}{I_{net,\mathcal{S},t} + I_{\mathcal{S}}} \right)^2.$$

2.6 Banks

Banks lend funds obtained from households and retained earnings from energy and goods producers. There are no frictions in the lending process, however banks may be financially constrained. An agency problem limits the banks' leverage, and, therefore, the amount of funds they can raise from households.¹⁵

At the end of period t the balance sheet of the typical bank is equal to:

$$\sum_{\mathcal{S}} Q_{\mathcal{S},t} S_{\mathcal{S},t}^P = NW_t + B_{t+1}^P, \quad (29)$$

where $Q_{\mathcal{S},t} S_{\mathcal{S},t}^P$ denote the value of the claim issued by sector \mathcal{S} and intermediated by the bank, NW_t is the net worth and B_{t+1}^P represents the deposits the bank obtains from households.

In $t+1$ the representative bank earns the stochastic return $R_{\mathcal{S},t+1}$ on claims issued by firms in sector \mathcal{S} and pays the non-contingent real return R_{t+1} on deposits. As illustrated in the previous sections, returns on loans are sector-specific: they depend on price of capital, payoffs, and capital quality shocks. The evolution of net worth over time is given by the difference between earnings on assets and interest payments on liabilities:

$$NW_{t+1} = \sum_{\mathcal{S}} R_{\mathcal{S},t+1} Q_{\mathcal{S},t} S_{\mathcal{S},t}^P - R_{t+1} B_{t+1}^P. \quad (30)$$

Combining (29) with (30) we obtain:

$$NW_{t+1} = \left[\sum_{\mathcal{S}} (R_{\mathcal{S},t+1} - R_{t+1}) \frac{Q_{\mathcal{S},t} S_{\mathcal{S},t}^P}{NW_t} + R_{t+1} \right] NW_t, \quad (31)$$

¹⁵For simplicity the banker's problem is presented as being perfectly symmetric across banks. In Appendix A we show that all banks face the same leverage ratio, so that aggregation is straightforward.

where $R_{S,t+1} - R_{t+1}$ is the risk premium on the sector-specific assets that determines the growth in bank's wealth above the riskless return. Note that with perfect capital markets the risk premium would be zero. In this economy, risk premia are positive, due to the limited intermediary's ability to obtain funds.

In order to limit the ability of the intermediary to expand its assets in each sector indefinitely, a moral hazard enforcement problem (derived from agency costs) is assumed: at the beginning of each period the banker can choose to divert a fraction of available funds from the banking activity. If the intermediary does not honor its debt, households (depositors) can liquidate the intermediary, by forcing it into bankruptcy and obtain the fraction of initial assets, or can limit the funds they lend to banks. Following Coenen et al. (2018) the agency problem is not symmetric across assets. The incentive compatibility constraint faced by households to be willing to supply funds to the bank is:

$$V_t \geq \rho(Q_{Y,t}S_{Y,t}^P + \psi_L Q_{L,t}S_{L,t}^P + \psi_F Q_{F,t}S_{F,t}^P), \quad (32)$$

where V_t represents the loss supported by the banker when diverting a fraction of assets (i.e. the expected discounted value of its terminal wealth) and $\rho(Q_{Y,t}S_{Y,t}^P + \psi_L Q_{L,t}S_{L,t}^P + \psi_F Q_{F,t}S_{F,t}^P)$ is the gain from diverting funds. The absconding rate varies across assets: the bank can abscond with share ρ of the investment loans in the goods-producing sector, with share $\rho\psi_L$ in the low-carbon energy sector and $\rho\psi_F$ in the fossil energy sector. Clearly, ψ_L and ψ_F represent the relative absconding rates for assets of type L and F . The higher the sectoral absconding rate, the harder to obtain funds from households to purchase assets in that specific sector.

For a given path of NW_t the banker's franchise value satisfies the Bellman equation:

$$V_t = \max_{\{S_{Y,t+1}^P, S_{L,t+1}^P, S_{F,t+1}^P\}} \mathbb{E}_t \beta \Lambda_{t,t+1} [(1 - \theta)NW_{t+1} + \theta V_{t+1}], \quad (33)$$

where the right side accounts for the fact that the bank faces a finite probability, θ , of continuing with its activity. To solve the bank's optimization problem, we conjecture that the value function is linear in net worth, that is $V_t = v_t NW_t$ with v_t measuring the expected discounted value of having an extra unit of net worth. The bank's optimization problem yields to three first-order conditions with respect to $S_{Y,t+1}^P$, $S_{L,t+1}^P$, $S_{F,t+1}^P$, an envelope condition with respect to net worth and the incentive compatibility constraint limiting the funds that households are willing to lend to the bank. See Appendix A for details.

At the optimum the following no-arbitrage relationships hold between the expected excess returns on assets Y and L , and between assets L and F :

$$\psi_L \mathbb{E}_t \Lambda_{t,t+1} [(1 - \theta) + \theta v_{t+1}] (R_{Y,t+1} - R_{t+1}) = \mathbb{E}_t \Lambda_{t,t+1} [(1 - \theta) + \theta v_{t+1}] (R_{L,t+1} - R_{t+1}), \quad (34)$$

$$\psi_F \mathbb{E}_t \Lambda_{t,t+1} [(1 - \theta) + \theta v_{t+1}] (R_{L,t+1} - R_{t+1}) = \psi_L \mathbb{E}_t \Lambda_{t,t+1} [(1 - \theta) + \theta v_{t+1}] (R_{F,t+1} - R_{t+1}). \quad (35)$$

The above conditions imply that the expected excess returns, adjusted for the relative absconding rates, must be equal. Let ϕ_t define the maximum ratio of the risk-adjusted bank assets to net worth (risk-adjusted leverage ratio) that satisfies the incentive compatibility constraint:

$$\phi_t = \frac{Q_{Y,t}S_{Y,t}^P + \psi_L Q_{L,t}S_{L,t}^P + \psi_F Q_{F,t}S_{F,t}^P}{NW_t}, \quad (36)$$

that from the bank's optimization problem can be expressed as:

$$\phi_t = \frac{v_t}{\rho}, \quad (37)$$

with

$$v_t = \frac{\rho \beta \mathbb{E}_t \Lambda_{t,t+1} [(1-\theta) + \theta v_{t+1}] R_{t+1}}{\rho - \beta \mathbb{E}_t \Lambda_{t,t+1} [(1-\theta) + \theta v_{t+1}] (R_{Y,t+1} - R_{t+1})}. \quad (38)$$

Clearly the bank's risk-adjusted leverage tolerated by depositors is increasing in v_t that measures the opportunity cost for banks to go into bankruptcy. From (36) we also observe that fluctuations in the bank capital will induce variations in the amount of assets demanded by banks.

Total net worth in the banking sector equals the sum of the net worth of existing bankers $NW_{e,t}$ and that of new bankers $NW_{n,t}$:

$$NW_t = NW_{e,t} + NW_{n,t}. \quad (39)$$

Each period households transfer a start-up fund to the new bankers. This fund is equal to a fraction $\omega/(1-\theta)$ of the value of assets of banks that exit $(1-\theta) \sum_S Q_{S,t} S_{S,t-1}^P$. The net worth of new bankers immediately follows:

$$NW_{n,t} = \omega \sum_S Q_{S,t} S_{S,t-1}^P, \quad (40)$$

while the net worth of the existing bankers is:

$$NW_{e,t} = \theta \left[\sum_S (R_{S,t} - R_t) \frac{Q_{S,t-1} S_{S,t-1}^P}{NW_{t-1}} + R_t \right] NW_{t-1}. \quad (41)$$

A deterioration of the quality of assets will then reduce the net worth of the bank, that, in turn via the incentive constraint, will be forced to reduce the amount of credit.

2.7 Retailers

This sector is made up of a continuum of monopolistically competitive retailers indexed by $k \in [0, 1]$ producing horizontally differentiated goods and using the production good as input according to a linear technology. Retail goods are combined into a final output composite Y_t , according to a constant elasticity of substitution function $Y_t = \left(\int_0^1 Y_{k,t}^{(\sigma-1)/\sigma} dk \right)^{\sigma/(\sigma-1)}$, where $\sigma > 1$ denotes the elasticity of substitution between differentiated goods. Cost minimization delivers the demand schedule for the retail good k , $Y_{k,t} = (P_{k,t}/P_t)^{-\sigma} Y_t$, where $P_{k,t}$ denotes the price of good k and P_t is the aggregate price index, $P_t = \left(\int_0^1 P_{k,t}^{1-\sigma} dk \right)^{1/(1-\sigma)}$. The objective of each retailer k is that of maximizing the sum of expected discounted profits by setting the optimal price $P_{k,t}$ subject to the available technology and the demand schedule for variety k . In re-setting their prices retailers face quadratic adjustment costs *à la* Rotemberg (1982) $\Gamma_p(P_{k,t}) = (\gamma_p/2) [P_{k,t}/(P_{k,t-1} \Pi_{t-1}^{\kappa_p} \Pi_t^{1-\kappa_p}) - 1]^2 Y_t$, where $\Pi_t = P_t/P_{t-1}$, the coefficient $\gamma_p > 0$ measures the degree of price rigidity, $\kappa_p \in [0, 1]$ denotes the weight of past inflation in the

indexation, and Π is the steady-state inflation. At the optimum the following condition holds:

$$\begin{aligned} & \frac{P_{Y,t}}{P_t} \sigma + 1 - \sigma - \gamma_p \left(\frac{\Pi_t}{\Pi_{t-1}^{\kappa_p} \Pi^{1-\kappa_p}} - 1 \right) \frac{\Pi_t}{\Pi_{t-1}^{\kappa_p} \Pi^{1-\kappa_p}} + \\ & + \beta \mathbb{E}_t \Lambda_{t,t+1} \gamma_p \left(\frac{\Pi_{t+1}}{\Pi_t^{\kappa_p} \Pi^{1-\kappa_p}} - 1 \right) \frac{\Pi_{t+1}}{\Pi_t^{\kappa_p} \Pi^{1-\kappa_p}} \frac{Y_{t+1}}{Y_t} = 0, \end{aligned} \quad (42)$$

that is the New Keynesian Phillips Curve describing the time path of inflation.

2.8 Public Sector

The public sector is composed of fiscal and monetary authorities. Monetary policy is characterized by a Taylor-type interest rate rule specified as follows:

$$\frac{R_{N,t}}{R_N} = \left(\frac{R_{N,t-1}}{R_N} \right)^{\kappa_i} \left[\left(\frac{\Pi_t}{\Pi} \right)^{\kappa_\pi} \left(\frac{Y_t}{Y_{t-1}} \right)^{\kappa_y} \right]^{1-\kappa_i}, \quad (43)$$

where R_N denotes the steady-state value of the nominal interest rate, $\kappa_i \in (0, 1)$ is the smoothing parameter, and $\kappa_\pi > 0$ and $\kappa_y > 0$ capture the responsiveness of nominal interest rate to movements in inflation and output, respectively. In addition to standard monetary policy, we also assume that the CB can facilitate lending. The credit policy we formalize tries to mimic large scale assets purchase that CBs implemented during the financial crisis to stabilize financial markets. We assume that the central bank can purchase all the three types of assets, by issuing short-term government bonds B_t^G to finance these purchases. The central bank's balance sheet identity is then:

$$\sum_{\mathcal{S}} Q_{\mathcal{S},t} S_{\mathcal{S},t}^G = B_{t+1}^G, \quad (44)$$

where the superscript G indicates central bank's assets and liabilities. The assets intermediated by the central bank represent a fraction $\gamma_{\mathcal{S},t} \in [0, 1)$ of the total intermediated assets in each sector \mathcal{S} :

$$Q_{\mathcal{S},t} S_{\mathcal{S},t}^G = \gamma_{\mathcal{S},t} Q_{\mathcal{S},t} S_{\mathcal{S},t} \text{ for } \mathcal{S} \in \{Y, L, F\}. \quad (45)$$

We further assume that the CB does not face the agency frictions that banks face but, at the same time, it is less efficient than banks in intermediating assets. To implement credit policies the central bank incurs an efficiency cost $\Gamma_{cp,t} = \tau_{cp} \sum_{\mathcal{S}} Q_{\mathcal{S},t} S_{\mathcal{S},t}^G$, where τ_{cp} represents the efficiency cost per unit of credit supplied. The consolidated budget constraint of the public sector that puts together the central bank and the government is always balanced. Letting C_t^G denote public consumption exogenously set, then we have:

$$T_t = C_t^G + \Gamma_{cp,t} - \frac{P_{X,t}}{P_t} X_t - \sum_{\mathcal{S}} (R_{\mathcal{S},t} - R_t) B_t^G, \quad (46)$$

where lump-sum taxes T_t are adjusted so as to eliminate any discrepancy between expenditures and revenues.

2.9 Equilibrium, Emissions, Temperature and Damages

Market clearing conditions on the financial market imply that $B_t = B_t^P + B_t^G$ and $S_{\mathcal{S},t} = S_{\mathcal{S},t}^P + S_{\mathcal{S},t}^G$ for $\mathcal{S} \in \{Y, L, F\}$. Final output is divided between consumption, government spending

for consumption, investments in the three sectors, costs of financial intermediation, extraction costs and adjustment costs on investment flows and price changes. The resource constraint of the economy is thus given by:

$$Y_t = C_t + C_t^G + \sum_S I_{S,t} + \Gamma_{cp,t} + \Gamma_{X,t} + \sum_S \frac{\gamma_S}{2} \left(\frac{I_{net,S,t} + I_S}{I_{net,S,t-1} + I_S} - 1 \right)^2 (I_{net,S,t} + I_S) + \frac{\gamma_p}{2} \left(\frac{\Pi_t}{\Pi_{t-1}^{\kappa_p} \Pi^{1-\kappa_p}} - 1 \right)^2 Y_t. \quad (47)$$

The level of carbon emissions in the atmosphere, Z_t , evolves as:

$$Z_t = \eta Z_{t-1} + X_t, \quad (48)$$

where $\eta \in (0, 1)$ measures the natural rate at which the atmosphere recovers and X_t is the emission flow of the period, equal to the amount of fossil resources extracted and used to produce fossil energy, directly expressed in terms of carbon dioxide.

Following a well established literature on climate science (e.g. Dietz and Venmans, 2019 and IPCC, 2015), we assume that the global temperature $Temp_t$ is proportional to cumulative emissions:

$$Temp_t = \overline{Temp} + \vartheta_{temp} Z_t, \quad (49)$$

where \overline{Temp} is the current temperature and ϑ_{temp} is the transient climate response to cumulative carbon emissions (TCRCE).¹⁶

We include only a single damage channel in the model, namely a level impact channel affecting productivity of firms via the damage factors $\Gamma_{D_Y,t}$, $\Gamma_{D_L,t}$ and $\Gamma_{D_F,t}$. Level impact damages are specified as in Nordhaus (2017):

$$\Gamma_{D_S,t} = \frac{1}{1 + \lambda_{S,0} Temp_t^2} \text{ for } S \in \{Y, L, F\}, \quad (50)$$

with $\lambda_{S,0} > 1$.

3 Calibration

This section presents the benchmark calibration of the model. Table 1 reports the calibration details. The model frequency is quarterly. We start with the preferences parameters set consistently with the existing literature. The subjective discount factor β is set to 0.99. Following Smets and Wouters (2007) the inverse of the intertemporal elasticity of substitution \varkappa is set at 1.4 and the habit persistence coefficient h_c to 0.7, while the inverse of the Frisch elasticities of labor supply are all set to 1 which represents an intermediate value in the range of macro and micro data estimates, therefore $\varphi_Y = \varphi_L = \varphi_F = 1$. The overall fraction of time spent at work in the three sectors is 0.17, and N_Y , N_L and N_F are a fraction of it, consistently with the relative size of each sector. The scale coefficients measuring the disutility of labor, χ_Y , χ_L and χ_F , are then implied.

Consider now the production side of the economy. Output Y is normalized to 1, so that all the other variables can be expressed as shares of GDP. For the energy share on GDP we used

¹⁶This streamlined temperature module is included to have a consistent environmental model closure. However, for the analyses carried out in this paper, climate damages could be disregarded as their impact is negligible for the time frame considered, and studying physical risk is beyond the scope of the paper.

the data for 2017 provided by the U.S. Energy Information Administration (EIA). The capital shares α_Y , α_L and α_F are set equal to $1/3$. From the new version of the PRIDE model (see Kalkuhl et al., 2012) we partially borrow the calibration for the CES aggregates (8) and (20).¹⁷ In function (8) the elasticity ε_E is set to 5 so implying that two energy sources are imperfectly substitutes. The weights are such that $\varpi_{E_F} = 0.75$, with $\varpi_{E_L} = 1 - \varpi_{E_F}$. For the fossil energy sector we set $\varepsilon_F = 0.3$, $\varpi_{V_{A_F}} = 0.7$ and $\varpi_X = 1 - \varpi_{V_{A_F}}$. For the CES function of the production sector (6), we set the elasticity of substitution, ε_Y , between energy and the bundle of capital and labor inputs to 0.5, as in PRIDE and other energy-macro models, implying that the two components are imperfect complements. The two weights are $\varpi_{V_{A_E}} = 0.09$, $\varpi_Y = 1 - \varpi_{V_{A_E}}$ in order to match the contribution of the energy sector to GDP both in terms of economic value and energy intensity. For the extraction costs we follow van der Ploeg and Rezai (2020), setting $\chi_1 = 1.25$, while the scale coefficient χ_0 is implied. The stock of fossil reserves M_0 is set consistently with BGR (2019) data at 3359 GtCo2 and then converted in model units as a share of the world GDP. The parameter g_M capturing the part of the resource lost in the extraction process is calibrated at 0.0001. The flow of natural resources X , and therefore emissions, are anchored to the world wide level of extraction at 39.75 GtCo2, according to BGR (2019) data, and then converted in model units as a share of the world GDP. Consistently with Reilly and Richards (1993) the quarterly rate at which the atmosphere recovers, η , is 0.9979.

We now discuss the parametrization of the damage specification and of the temperature process. In the new version of the DICE model (see Nordhaus, 2017) damages are 2.1% of global income at 3°C warming. From this assumption we can retrieve the coefficients $\lambda_{Y,0}$, $\lambda_{F,0}$ and $\lambda_{L,0}$ that are all set equal to 0.00238. \overline{Temp} is normalized to 0. In the simulations we assume that initially the temperature is equal to 1, and that the TCRE is such that at current emissions we would have a temperature increase by 0.2 degrees Celsius every decade. The implied value for ϑ_{temp} is then 0.17.

As in Gertler and Karadi (2011) the functional form of the rate of depreciation of physical capital in all the three sectors is of the form $\delta_{S,t} = \delta_{0,S} + \frac{\delta_{1,S}}{1+\delta_{2,S}} U_{S,t}^{1+\delta_{2,S}}$ for $S \in \{Y, L, F\}$. In steady state we normalize U_S at 1. We set δ_S so as to deliver an annual depreciation rate of 7.5% in the goods-producing sector, in line with the DSGE literature. We assume an annual depreciation rate equal to 3.75% for the fossil energy sector and to 6% for the low-carbon energy sector. The range of variation between the depreciation rates is consistent with Baldwin et al. (2020) and is meant to capture the specificity of energy infrastructure in the two sectors.¹⁸ The elasticity of marginal depreciation with respect to capital utilization $\delta_{1,S}$ is equal to 7.2 as in Gertler and Karadi (2011). The remaining coefficients are implied. The coefficients governing the investment adjustment costs associated with new capital production γ_S are all set at 1.728. In the retail sector the elasticity of substitution between differentiated goods, σ , is set at 9, as in Galí (2015). The adjustment cost parameter of the Rotemberg pricing, γ_p , is set so that the slope of the log-linearized version of the New Keynesian Phillips curve is equal to the one that would arise under a Calvo pricing scheme in a baseline New Keynesian model for a probability that price will stay unchanged of 0.75 at quarterly frequency. We assume a degree of past inflation indexation in the pricing scheme of 50%, so $\kappa_p = 0.5$.

Turning to the financial sector we start by setting the risk premia. We use FRED data for the spread related to the assets of production sector Y . By using data for the Federal fund rate and the Corporate Bond Yield for the years 2016 – 2018 we set the quarterly risk premium $R_Y - R$ at 0.0066. We allow for a slightly higher risk associated to the energy related assets consistently

¹⁷Documentation available at <https://www.pik-potsdam.de/forschung/transformationspfade/models/pride/pride-policy-and-regulatory-instruments-in-a-decentralized-economy>.

¹⁸Results for a depreciation rate equal to 7.5% in all the sectors are available from the authors upon request.

with financial data for the U.S. provided by Damodaran Online, setting $R_F - R = 0.00815$ and $R_L - R = 0.00824$.¹⁹ The weights ψ_L, ψ_F measuring the relative absconding rate are then set consistently. The constant probability that a banker survives next period θ is 0.94.²⁰ The steady-state ratio between bank's liabilities (deposits) and assets are set consistently with U.S. data at 0.87. In particular, we use FRED data on bank credit and deposits for commercial banks and use the mean ratio for 2000-2019. The parameters ρ and ω are implied.²¹

Finally, government consumption C^G is equal to 0.1, consistently with government consumption as share of GDP observed at world wide level for the period 2000-2018 according to the World Bank Indicators database. Steady-state inflation is normalized to 0, so the inflation target Π is set at 1. Consistently with a baseline New Keynesian model, the policy parameters of the interest rate rule (43) are set as follows: $\kappa_\pi = 1.5$, $\kappa_y = 0.125$, $\kappa_i = 0$. See e.g. Galí (2015). In the baseline calibration the policy variables related to credit policy are zero, $\gamma_Y = \gamma_F = \gamma_L = 0$.

4 Climate Actions and Stranded Assets

In this section we analyze climate policy and CBs' policies proposing several scenarios.²² The first simulation studies the financial and the macroeconomic implications of introducing a carbon tax. We assume that carbon price becomes tighter over time and represents the only action to reduce emissions. Understanding the dynamic implications of this policy and the magnitude of transition risks associated to mitigation strategies is a precondition to seriously discuss the impact and the role of additional measures, as financial regulation or unconventional monetary policy. We assume as benchmark a 50% emissions reduction plan implemented in 10 years, largely consistent with the IPCC yearly emissions reduction targets to remain on a 1.5°C-compatible pathway, and the projections made in Rockström et al. (2017) for the period 2020-2030, to limit warming to "well below 2°C" in the long run, in line with Paris Agreement's goals. The mitigation plan is announced at the beginning of the implementation and is fully credible.²³

The second set of scenarios shows the potential role of financial regulation as an additional instrument to foster the transition and decarbonize banks' balance sheets, further discouraging fossil investments. We study the joint effect of carbon tax and climate financial regulation implemented according to two different schemes: a brown-penalizing factor in the form of a charge on fossil assets in the banks' portfolio (tax scheme), and a brown-penalizing factor coupled with a green-supporting factor for low-carbon assets (tax-subsidy scheme).

Table 2 depicts present value output losses, cumulative emissions and temperature under the mitigation scenarios introduced above and a no-policy scenario, in which emissions are kept constant and the concentration of pollutant in the atmosphere increases leading to rise in the temperature of 1 degree Celsius in 50 years. The table is meant to describe the main climate-economic trade-offs associated to different mitigation strategies and provide a proxy to

¹⁹See <http://pages.stern.nyu.edu/~adamodar/>.

²⁰In setting this parameter we are constrained by the fact that we have positive spreads in steady state.

²¹The endogenous share of fossil energy assets in the banks' portfolio is around 6%, in line with the estimate of Battiston et al. (2017).

²²The model is solved using Dynare. For details, see <http://www.dynare.org/> and Adjemian et al. (2011).

²³The model is solved under the rational expectations hypothesis. Forward looking agents in the face of a fully announced and credible mitigation plan immediately start to react and revise optimally their consumption, production and pricing decisions. Simulations can be done under different hypotheses regarding credibility, degree of agents' rationality and policymakers' commitment. For an analysis on time inconsistency problems that may arise when delaying climate actions, see Kalkuhl et al. (2020).

measure the transition risk, here summarized by the present value of output losses expressed in percentage deviation from the no-policy scenario output levels. As additional measures of transition risks, and to better address the issues of financial fragility and of monetary stability, Table 3 also reports the effects of the various mitigation policies on the net worth of banks and on inflation.

The last set of scenarios studies the implications of a sudden devaluation of fossil fuel assets and the role of unconventional monetary policies. We introduce a capital quality shock in the fossil sector that can be interpreted as a policy tipping point (i.e. sudden ban on fossil reserves in line with the carbon budget) or as a modification in the expectations of market participants, following a policy shock or a disruptive climate event. With this approach we are able to address the concerns related to a “disorderly” climate transition, having sudden or unanticipated effects. While carbon pricing and financial regulation are instruments designed to modify the structure of the market and direct the economy toward a sustainable path, and thus involve medium-run choices, monetary policy is an instrument tailored to stabilize the economy in the short-run. The perspective of the analysis in this simulation is, therefore, slightly different and aims at understanding how CBs can intervene to contrast recessionary effects or financial instability, following a shock coming from the fossil sector.

4.1 Transition Risk and Carbon Pricing

Figure 1 depicts two mitigation scenarios in which emissions are halved over 10 years, under different carbon pricing paths.²⁴ The continuous line refers to a carbon tax following an exponential rule (our baseline scenario), while the dashed line represents a carbon tax, entailing a linear reduction of emissions, as proposed by Rockström et al. (2017) among others.²⁵ All variables are expressed as percentage deviations from the initial steady state. On the x-axes time is in quarters. By means of this experiment we are able to observe the re-allocation costs associated with an orderly and credible mitigation plan, and explore the joint role played by speed of transition and expectations in eventually moderating these costs. We also explore the implications of the two mitigation strategies on inflation and interest rate, capturing the interaction between climate policy and conventional monetary policy.

The first channel through which the carbon tax impacts the economy is via its effects on the energy market, where both substitution and income effects are in place. Following the introduction of a higher carbon tax, there is a decrease in the demand for fossil energy due to the higher price of this production input. The demand for low-carbon energy, that is now relatively cheaper, increases (substitution effect), but the total energy demand decreases along the time path due to the price increase of fossil energy (income effect), reaching a decrease of almost 9% at the end of the simulation period. The income effect prevails due to the imperfect substitution between energy inputs and the larger share of fossil energy in the energy mix.²⁶ The increase in the price of energy gives rise to a first-round contractionary effect on output

²⁴In the exponential case the rate of increase of the carbon tax is set so as to meet the mitigation target given the initial level of emissions and does not reflect any optimizing behavior of the public sector. The implied increasing rate for the carbon tax is 0.14.

²⁵Due to the time horizon of the analysis we abstract from carbon budget considerations. We have opted to make the policies comparable in terms of emissions reduction targets, in line with the way in which policies are set in the short- medium-run in many countries. The level of cumulative emissions slightly differs during the simulation period between the two scenarios. In details, cumulative emissions are 17.2% higher under the exponentially-increasing carbon tax.

²⁶In Figure D-1 in Appendix D results are shown for different degrees of substitution between energy inputs. For an elasticity of substitution, ε_E , lower than one the two energy sources become imperfect complements and the effects of a mitigation policy are less disruptive in the energy sector.

and investment in the final good sector. The increase in the price of energy acts as a cost push shock that raises marginal costs.

The second channel of transmission of the mitigation plan works through the financial side of the economy, where two effects interplay.²⁷ On the one hand, the contraction in the demand for fossil energy reduces the effective quantity of capital used by this sector, depressing fossil investment and the value of the related assets. On the other hand, the policy directly impacts the shadow value of fossil reserve underground, that represents the main source of value for fossil companies. The value of fossil reserves permanently and steadily decreases over 10 years, further reducing investment and investment value in the fossil sector.²⁸ A reduction in the value of fossil assets, in turn, induces a decline in the net worth of the banks. The weakening of intermediary balance sheets induces a drop in fossil asset demand, further reducing asset price and fossil investment. Via the financial channel we also observe second-round contractionary effects on output. The net worth channel and the leverage constraint triggers a deleveraging mechanism that involves also production sector's assets. Coupled with the drop in intermediary capital is an increase in the spread between the expected return on capital and the risk-free interest rate. This boosts the user cost of capital, which leads to a further contraction of investment and output. The only sector where both assets value and investment increase is the low-carbon energy sector.

After 10 years investments in the fossil energy sector are around 69% lower in the baseline case, compared to the steady state. On the other side, we observe an increase in investment in the low-carbon energy sector around 111%. Overall, after 10 years we find a fall of output of around 1%. The present value output loss over the mitigation period is around 0.2%, compared to a 0.4% observed in the linear case.

Even if the dynamic effects described so far are common to the two scenarios, the magnitude of the reaction is different, especially at the earlier stages of the transition period. The effects materialize immediately under a linearly-increasing carbon tax, and are delayed and smoothed under an exponentially-increasing tax. In the energy market, initially we observe an energy demand above the steady-state level and a lower energy price. The costs imposed by the carbon tax in this scenario are initially smaller. This generates a crowding out effect of low-carbon energy during the first year after the implementation of the policy, but at the same time, guarantees a smoother increase in energy price and a smoother decrease in energy demand during the rest of the transition period. Under an exponentially-increasing carbon tax, in fact, energy producers face a slow increase in production costs and are not forced to immediately curb production by a large amount. At the same time firms in the goods-producing sector can revise their production plan consistently with the new mitigation scheme in a gradual way.

As a result of the lower initial carbon price, we observe a temporary expansion of the fossil energy sector and of extraction activities. Emissions increase temporarily and then start to decline. This temporary “green paradox” phenomenon is due to the fact that the owners of the fossil energy resource anticipate the mitigation plan and find it optimal to accelerate resource extraction for a limited period of time.²⁹ The initial increase in the value of fossil assets

²⁷In Appendix D we present the benchmark simulation scenario with and without financial frictions, where this second channel is shut down.

²⁸In a model in which these fossil reserves would directly be the collateral for securities lending the effects of the mitigation process conveyed by the financial channel would probably be much larger.

²⁹In Appendix D we show that the same phenomenon occurs in the case of announced climate actions for policy actions to be taken sufficiently far in the future. During the policy implementation lag, the anticipation effects of agents lead to more extractions, and so emissions, at the beginning, and to disinvestments from fossil energy at later stages. However, at a later stage the disinvestment effects do prevail over the “green paradox” effects, consistently with the findings of Bauer et al. (2018).

has the same origin.³⁰ In fact, looking at the financial side of the economy, the differences among the two mitigation timings are even stronger. Under a linear carbon tax the value of assets in the fossil sector decreases on impact, while under an exponentially-increasing carbon tax, the value of fossil assets stays above the steady-state level until period sixteen.³¹ We observe a reverse dynamics in the behavior of the low-carbon assets value. This reflects in the dynamics of investments and their final value: at the end of the simulation period the level of investment in the low-carbon sector is higher compared to the linear tax scenario, while the level of investment in the fossil sector is lower. The decrease of net worth is milder under our baseline scenario, suggesting a greater stability on the financial side. See also Table 3. Another remarkable difference between the two carbon taxes arises if we look at consumption. In this economy retailers, by virtue of their market power, can shift part of the cost induced by the policy to households by charging higher prices. Under an exponentially-increasing carbon tax adjustment costs are smoothed out more efficiently and the mitigation plan becomes less costly also for households.³²

Finally, looking at the behavior of inflation and interest rate in the two scenarios, it is possible to notice that mitigation policies are inflationary, due to the pressure they exert on productions costs, via the increase in energy price. CBs clearly face a trade-off between output and price stability in reacting to the effects of the carbon pricing that is a source of a cost-push shock.³³ Emissions reductions gains in this context are achieved at the price of higher inflation. Also in this case a tax increasing exponentially performs better, leaving room for a smoother reaction of the monetary policy, as shown by the dynamics of the nominal interest rate. Over a 40-quarter time horizon inflation volatility, measured by its annualized standard deviation is around 0.24% in the baseline case, with a mean of 0.14%, while in the linear case the volatility is around 0.26% with a mean of 0.32%. See Table 3.

Three important results have emerged from this experiment. A first result is that a credible medium-term mitigation strategy implemented only through a carbon tax imposes some costs in terms of output, inflation and financial wealth. These costs seem to be containable, suggesting that, if properly handled, the transition to a low-carbon economy is not disruptive for the economic system.

A second result concerns the importance of the choice of the implementation speed, given a common final goal in terms of emissions reduction. A too rapid and ambitious mitigation plan can exacerbate the transition risk, increasing inflation, financial instability and output losses. Giving the markets the time to react and adjust to the mitigation plan is crucial to smooth the transition costs. We find that an exponentially-increasing carbon tax entailing small initial reduction in emissions at the beginning and larger reductions in the future is able to reduce transition costs by means of a major inter-temporal smoothing of the adjustment costs. From this perspective, we provide a new rationale for a gradual ramp-up of climate policy, showing that, due to the presence of short-run frictions, gradual and smooth adjustments in the dirty and clean capital stocks are less costly than sharp increases.³⁴ Our exponentially-increasing carbon

³⁰See van der Ploeg and Rezai (2020) who show how “green paradox” effects may emerge in different scenarios of climate policies.

³¹This is the consequence of the forward looking nature of this variable. The asset price jumps upward on impact and then steadily depreciates. Agents are aware that the user cost of capital in this sector will be much higher in the future because of the carbon tax.

³²It can be shown that in the case of a “cold turkey” implementation of the climate policy the transition costs are much higher. See Appendix D.

³³Notably cost-push shocks represent a dilemma for CBs since they can either ease their monetary policy to reduce the negative effects on output or tighten it to fight the inflation rise.

³⁴Nordhaus (2007) introduced the expression “climate policy ramp” suggesting, as general principle, to start

price better reflects this principle, while the linear tax requires too sharp initial adjustments that increase the overall transition costs.

A third result regards the fact that interaction effects between monetary and climate policy are in place. The mitigation policy represents a cost-push shock simultaneously creating an upsurge in inflation and a drop of output. However, a gradual ramp-up of climate policy seems to drastically reduce also the policy trade-off faced by the monetary authorities.

4.2 Transition Risk, Carbon Pricing and Financial Regulation

We now consider the potential role of financial regulation in the mitigation process. Since climate change represents a threat to the stability of the financial system, environmental issues fall squarely in the domain of financial regulators and CBs. We address this issue by proposing two different regulatory schemes designed to incentivize the decarbonization of the banks' balance sheets and align financial stability with sustainability goals. To this purpose we introduce a tax and subsidy scheme that pushes banks to adjust their liability structure away from "brown" assets, so as to reduce banks' exposure to climate risks, and favor lending toward the low-carbon energy sector.³⁵ Under this assumption, the flow of funds of the banks evolves as follows:

$$NW_{t+1} = \sum_{\mathcal{S}} (R_{\mathcal{S},t+1} - \tau_{\mathcal{S},t}) Q_{\mathcal{S},t} S_{\mathcal{S},t}^P - R_{t+1} B_{t+1}^P, \quad (51)$$

that replaces (30), where for $\mathcal{S} \in \{Y, L, F\}$ $\tau_{\mathcal{S},t}$ represents taxes (if positive) or subsidy (if negative) per unit of assets. In the initial steady state all tax rates are set at zero. See Appendix C for more details. We consider two simulation scenarios where a tax/subsidy scheme is introduced at the onset of the baseline mitigation process described in the previous section. A first scenario in which the government imposes a tax on assets of the fossil energy sector (tax scheme) and the tax revenues so obtained are redistributed as lump-sum transfers to households, and a second scenario in which the tax revenues are used to finance a subsidy in favor of assets issued by low-carbon energy sector (tax-subsidy scheme). The tax rate $\tau_{\mathcal{S}_F,t}$ is permanently set at 0.0025 at the beginning of the simulation, while in the second scenario $\tau_{\mathcal{S}_L,t}$ is adjusted in order to neutralize the impact of the increase in $\tau_{\mathcal{S}_F,t}$ on the bank's flow of funds.³⁶

Figure 2 displays the three mitigation scenarios with and without the integration of climate-related risks into the financial regulatory frameworks. Important differences arise among the three sets of results. Consider first the case of an introduction of a tax on fossil energy assets that discourages the holdings of these assets. We observe a sharper drop of output and energy, while consumption initially increases as result of the stronger contraction of investments in the fossil energy sector. At later stages consumption will drop as well, by more than in the baseline scenario. A similar pattern can be observed for investments in the goods-producing sector. In accord with a substitution effect banks reallocate their assets away from fossil energy assets in favor of the other assets. The effects on emissions, however, do not seem to differ significantly from the baseline case. The mitigation gain seems to be modest. At the same time, the

with low carbon prices and increasing them over time rather than starting immediately with high prices. Our results are consistent with the findings of the literature on optimal carbon prices. See e.g. Dietz and Venmans (2019) and Kalkuhl and Edenhofer (2014). However, these works usually neglect short-run adjustment costs.

³⁵This is a straightforward way to reproduce regulations that make the holdings of 'brown' assets relatively more costly. Tax and subsidy schemes are very often used to study the effects of macroprudential regulation designed to reduce banks' exposure to risks. See e.g. Gertler et al. (2012).

³⁶The tax-subsidy scheme is designed to be budget neutral at all times, so the subsidy rate is time varying. However, the no-arbitrage conditions still depend on the tax rate and so do the portfolio allocation decisions of banks. See Appendix C.

introduction of a financial regulation that discourages the holdings of fossil energy assets seems to render more severe the mitigation process, actually exacerbating the transition risk. The net worth of banks falls persistently, giving rise to a stronger contraction of investments in the goods-producing sector at later stages of the adjustment. Table 2 shows how present value output losses significantly increase compared to the baseline scenario.

The results differ substantially when the revenues of taxes on “brown” financial assets are used to finance subsidies on low-carbon energy assets. In this case the effects on output becomes expansionary, while the sharper increases in investments in the low-carbon energy sector and in the goods-producing sector explain the initial drop of consumption consistently with a substitution effect. Investments in the fossil sector fall almost to zero after the 5th year, before starting recovering slowly to keep the fossil energy sector running.³⁷ The effects on emissions are now larger, and consistently the value of the natural resources declines more sharply than in the other two experiments. In this case the price of energy increases by less, thanks to the major expansion of the low-carbon energy sector supported by the subsidy scheme. This type of policy proves to reduce the transition risk: the present value of output losses is now equal to 0.062% after 10 years, well below the baseline scenario. As a side effect, however, we observe a major decline in the net worth of banks that in our simulations seem to have repercussions only on investments in the fossil energy sector. See Table 3. The enhanced fragility of the balance sheets of banks caused by this regulatory scheme could then magnify the potential risks to the financial system, since the decline of the net worth could trigger a chain of unintended consequences. In other words, as a result of this regulatory scheme banks could become more vulnerable. From this perspective there seems to be a trade-off between climate ambition and financial stability.

Finally, consider the effects on inflation, also summarized in Table 3. As anticipated in the previous section, the decarbonization policy through the increase in the price of energy and so of the production costs, exerts slight inflationary pressures, after a deflationary phase. In the presence of a financial regulation scheme we observe more inflation in the case of a simple tax scheme on fossil energy, while for the mixed regulatory scheme inflation initially reduces and then recovers, following a path lying below the baseline case. In the 40-quarter time interval considered the standard deviation of annual inflation is around 0.24% in the baseline case, 0.26% in the case of a simple tax scheme and of 0.23% in the tax-subsidy scheme. These results would suggest that a carefully designed “green” financial regulation may be introduced without compromising the objective of price stability.

4.3 Transition Risk, Financial Instability and Credit Policy

In this section we explore the impact of a sudden and persistent devaluation of fossil energy related assets and study the potential role of unconventional monetary policy in alleviating the effects. Notably, financial market pricing of climate risk appears to be limited by informational inefficiencies, economic incentives and limited rationality.³⁸ From this perspective financial markets would be unable to reflect the risks associated with climate change and the transition costs related to mitigation and structural change. In the previous section we have studied the

³⁷van der Ploeg et al. (2020) find that the share of dirty assets stabilizes around 50% and 30% in the long-run. They show that it is not optimal to fully close down carbon-intensive sectors as they serve as a hedge in the long run and allow a faster build-up of green assets in the short run, intrinsically driven by assets holding diversification motive. According to their results, in the short-run diversification and climate action are complementary goals, since agents tend to reach a balanced portfolio. Only if policy makers want to speed up the process, they must take extra action.

³⁸In this respect Godin et al. (2017) talk of “market apathy”.

implications of smooth mitigation scenarios in which forward looking agents have the time to adapt and gradually shift toward a low-carbon energy source. In those scenarios the financial impact of transition costs was limited. However, what if following an acute climate-change related event market sentiments abruptly change and the value of fossil energy related assets drop dramatically? Notably, instability of financial markets can have strong repercussions on the real side of the economy. The sudden and expected drop in the value of these assets would lead to a sharp deterioration of intermediary capital with disruption on the flow of funds between lenders and borrowers, and possible contagion and cascade effects on all sectors of the economy.³⁹

The financial crisis experiment is designed as a sharp decline in capital quality of the fossil energy sector, reflected by the exogenous process $\xi_{F,t}$. This capital-quality shock is introduced in DSGE models to trigger a recession originating from an adverse shock on the asset price. See e.g. Gertler and Karadi (2011). The size of the initial shock is fixed at 10% with a quarterly autoregressive coefficient of 0.85. To account for the indirect financial exposure of intermediaries to climate-change relevant sectors and factor in potential contagion effects due to the financial dislocation, we also assume a reduction in capital quality of the goods-producing sector assuming an indirect exposure of non-fossil related funds of 7.5%.⁴⁰ The exogenous process $\xi_{Y,t}$ is then initially reduced by 0.75%. For this process we also assume an autoregressive factor of 0.85. To make our analysis more transparent and focus only on the disruptive effects of financial instability we deliberately abstract from the climate-related shocks that could be at the origin of this instability, but that would entail a drop in assets' value.⁴¹ The results of the simulation are shown in Figure 3, where for now we focus on continuous lines representing the response of the main macroeconomic variables to the financial crisis shock in the absence of any further feedback policies besides the standard Taylor rule.

The initial decline in the value of capital in the fossil energy sector, and partially in that of the goods-producing sector, leads to a decline in net worth of banks and indirectly affects future investments by changing their expected return. Given the leverage ratio constraint, the weakening of intermediary balance sheets gives rise to a drop in the demand of the devalued assets and to a partial reallocation in favor of assets related to the low-carbon energy sector. This mechanism explains the sharp decreases of the asset prices Q_F and Q_Y , and the increase in Q_L . Associated with the worsening of the balance sheets of the intermediary we observe a sharp increase in the risk premia that lead to a contraction of investments in the goods-producing sector and in the fossil energy sector.⁴² As a consequence, output declines and so does consumption.⁴³ The overall demand for energy declines, but the production of low-carbon energy expands. The downsizing of the fossil energy sector leads to a sharp fall in the shadow value of the natural resource. However, the contraction of the fossil energy sector pushes the price of energy upward, that is why after the initial deflationary effects of the shock due to the sharp contraction of aggregate demand, inflation starts to increase. The inflationary consequences of the shock are due to the nature of the shock itself that hits a production input

³⁹In this respect, Battiston et al. (2017) show that the fragility of the financial markets in the face of climate risks and actions depends on both direct and indirect exposure of investors' equity portfolios.

⁴⁰On the relevance of contagion effects see Roncoroni et al. (2019). In Appendix D we show the response of the economy to an adverse shock hitting exclusively fossil energy assets in the absence of contagion.

⁴¹In this exercise, τ_{cp} , the efficiency cost per unit of credit supplied is set at 0.0001. Since any discrepancy in the government balance is offset by changes in lump-sum taxes, the size of this cost is irrelevant for our results.

⁴²Recall that the financial assets are imperfect substitutes, but their returns are related by the no-arbitrage relationships (34) and (35).

⁴³Notably this kind of shock is able to generate co-movement of output, consumption and investment.

(fossil energy) and translates into a sort of cost-push shock for the goods-producing sector. The nominal interest rate declines sharply getting closer to its lower bound during the first quarters of the adjustment process.

We now consider the possibility of credit interventions designed to reduce the disruptive effect of the crisis. In particular, we explore the potential stabilizing effects that may derive from the direct purchase of assets as part of credit easing programs. In doing so, however, we assume that monetary authorities are willing to align different objectives, namely that of financial stability with that of environmental sustainability. In other words, we remove the assumption of market neutral corporate bond purchases and of the balanced market presence of the CB. A commitment of CBs against fossil asset could be useful to prevent anticipation effects that would lead to moral hazard risks leading banks to raise further their fossil risk exposure. To this purpose we consider two kinds of sector-specific interventions where credit easing programs are designed so as to exclude carbon-intensive financial assets: (i) a green credit policy program, where the central bank is assumed to purchase only assets issued by the low-carbon energy sector, (ii) and a credit policy program on sector Y , where the CB is assumed to purchase assets issued by only by the goods-producing sector. Following Gertler et al. (2012) we assume that the CB reacts to changes in credit spreads according so that the coefficient $\gamma_{S,t}$ following a simple feedback rule:

$$\gamma_{S,t} = \varrho_S E_t [\log (R_{S,t+1}/R_{t+1}) - \log (R_S/R)], \quad (52)$$

where $S \in \{Y, L, F\}$ and the feedback parameter $\varrho_S > 0$ measures the intensity of the response to variations in interest rate risk premium. Under a green credit policy experiment we set $\varrho_L = 200$, and $\varrho_Y = \varrho_F = 0$; under a credit policy program concentrating only on assets issued by firms in sector Y , we set $\varrho_L = 0$, $\varrho_Y = 4.43$ and $\varrho_F = 0$ so that the over a 20-quarter time horizon the size of the intervention, measured as the average share of assets purchased by the CB over the total assets value, is the same in the two scenarios, that is around 0.4%. According to rule (52) as the financial crisis unfolds and the credit spreads rise, the CB injects credit in the economy. The amount of credit that the CB can inject through the green energy sector is however constrained by the size of this sector itself that still represents a small size the of overall assets of the economy. For the green credit policy over the simulation time horizon the average value of the share $\gamma_{L,t}$ is around 21%, while for the credit policy involving only assets of sector Y the share $\gamma_{Y,t}$ is around 0.4%.

The dashed and the dashed-dotted lines of Figure 3 represent these two simulations. As expected, the credit policy mitigates the contraction of output and the negative effects on consumption. The beneficial effects of unconventional monetary policy are substantial even if the zero lower bound constraint on the nominal interest rate is not binding. Given the non-neutral nature of the interventions, however, the shadow value of the natural resources diminishes by more on impact. Both credit policy interventions are sufficiently aggressive to reduce the rise in the spreads and moderate the fall of the asset price Q_Y , while increasing the positive reaction of Q_L . As a result the net worth of bank falls by less. Concerning the price of energy and inflation, we observe that while credit policy does not seem to affect the reaction of the former, it is able to mitigate the initial deflationary pressures while reducing the later inflationary effects of the shock. The credit policy, even when biased toward “green” assets, is able to provide a sufficient stimulus to the economy so sustaining aggregate demand at the onset of the crisis and diminishing the drop of output, moderating in this way the subsequent inflationary effects of the crisis. These results show how it is possible for CBs to align the objective of financial stability with that of environmental sustainability, consistently with their

mandate of price stability. However, two words of caution are in order here. First, as long as the green energy sector will be small selective credit policies targeting only this sector will have a very limited scope. Second, the violation of the principle of neutrality in asset purchasing programs may give rise to a series of unintended consequences, such as moral hazard problems pushing banks to diversify less their portfolios, and as the emergence of “green” market bubbles.

5 Conclusion

This paper contributes to the increasing literature on stranded assets and climate transition risk, and to the debate on the actions that CBs could implement to help reaching the climate objectives and safeguard financial stability.

We analyze the macroeconomic and financial impact of several climate actions. The following results arise. If mitigation plans implemented through carbon pricing policies are orderly and credible, even if ambitious, transition risks seem to be limited. Timing and expectations play a crucial role in shaping transition costs and limiting financial instability. With an exponentially-increasing carbon price implemented according to an announced time schedule, agents are able to anticipate the effects of the mitigation plan and can smoothly distribute the transition costs. The lower initial level of the tax may lead to a temporary “green paradox” phenomenon. Disinvestment effects fully prevail at later stages of the transition and lead to a sharp contraction of the fossil energy sector. A linearly-increasing carbon tax does not lead to “green paradox” effects but results in substantially higher output losses, inflation and financial losses.

The integration of climate-related risks into the financial regulatory framework leads to very different outcomes depending on the scheme implemented. Taxing fossil assets and redistributing the revenues outside the financial sector as lump-sum transfers results in modest mitigation gains at the price of higher transition risk. If the tax revenues on fossil assets are used to subsidize low-carbon assets, instead, the mitigation gains are higher and the effects on output expansionary. The objective of price stability is not compromised but, as a side effect, we observe a sharper deterioration of intermediary capital. If not carefully tailored, this regulatory scheme may then enhance the fragility of the financial system during the transition.

In response to a crisis originated in the fossil energy sector, green credit policy proves to be effective in mitigating the contraction of output and in reducing financial instability. This policy is also compatible with price stability objectives and can be implemented in compliance with CBs’ mandate. The rationale for this non-neutral unconventional monetary policy could be that of reducing *ex ante* the exposure of banks to carbon intensive assets and so to climate risk. However, the anticipation of non-neutral credit policy interventions may create risky imbalances in the financial exposure of intermediaries. It is worth noting that CBs’ credit policies have been used only in times of economic distress. Therefore, green credit policies should only be considered as a tool to react to financial instability that may emerge during the transition, but they should not be invoked as a standalone mitigation instrument to reshape the economy in normal times.

Some final remarks are in order. Despite the growing pressure on CBs to embrace sustainability actions, the fundamental responsibility for addressing climate change challenges and guide the transition lies with governments. Financial regulation can support carbon pricing policies but is insufficient *per se* to reallocate capital and could have unintended consequences if not well designed. To clearly evaluate the potential of green finance instruments, a better understanding of the exposure of the financial sector to fossil assets and a clear taxonomy distinguishing green from brown assets are required. In this respect, building a consensus around

the definition of low-carbon investments is pivotal to understand the size and the potential of the sector and, thus, to come up with effective and well-targeted instruments. CBs could be part of a common and coordinated policy effort to deal with climate change hazards, but new green instruments may be considered only after evaluating all the trade-offs and in compliance with CBs' core mandates.

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Table 1: Parametrization

Parameter	Description	Value
A. Preferences		
β	discount factor	0.99
h_c	habit parameter	0.7
\varkappa	inverse of the intertemporal elasticity of substitution	1.4
$\varphi_Y, \varphi_L, \varphi_F$	inverse of the Frisch elasticity	1
B. Emissions, Temperature and Damages		
ϑ_{temp}	TCRCE	0.17
η	emissions decay rate	0.9979
$\lambda_{0,Y}, \lambda_{0,L}, \lambda_{0,F}$	level impact damage parameter	0.0024
C. Production		
$\alpha_Y, \alpha_L, \alpha_F$	capital share	1/3
$\gamma_Y, \gamma_L, \gamma_F$	investment adjustment costs parameter	1.728
γ_p	degree of price rigidities	93.2
δ_Y	depreciation rate of capital in sector Y	0.0188
δ_L	depreciation rate of capital in sector L	0.015
δ_F	depreciation rate of capital in sector F	0.0088
ε_Y	elasticity of substitution between VA_Y and E	0.5
ε_E	elasticity of substitution between E_L and E_F	5
ε_F	elasticity of substitution between VA_F and X	0.3
κ_p	price backward indexation	0.5
σ	elasticity of substitution between final goods varieties	9
χ_1	extraction cost parameter	1.25
g_M	resource lost in the extraction process	0.0001
ϖ_{VA_Y}	factor share of value added sector Y	0.91
ϖ_E	factor share of energy	0.09
ϖ_{E_L}	factor share of low-carbon energy	0.25
ϖ_{E_F}	factor share of fossil energy	0.75
ϖ_{VA_F}	factor share of value added in sector F	0.7
ϖ_X	factor share of natural resource	0.3
D. Financial Intermediaries		
θ	survival rate of the bankers	0.94
ρ	absconding rate	0.6755
ψ_L	relative absconding rate sector L	1.2405
ψ_F	relative absconding rate sector F	1.0819
ω	start-up transfer	0.003
F. Monetary policy		
κ_i	smoothing parameter of the Taylor rule	0
κ_y	output variation coefficient of the Taylor rule	0.125
κ_π	inflation coefficient of the Taylor rule	1.5

Table 2: Output Loss and Temperature under Different Mitigation Scenarios

		No Policy	Mitigation		Mitigation and Financial Regulation	
			<i>Baseline</i>	<i>Linear</i>	<i>Tax Scheme</i>	<i>Tax-Subsidy Scheme</i>
10 Years	Output Loss	-	0.197	0.400	0.302	0.062
	Cumulative Emissions	-	-12.107	-25.000	-13.037	-15.074
	Temperature Variation	0.235	0.195	0.153	0.192	0.185
20 Years	Output Loss	-	0.576	0.679	0.695	0.436
	Cumulative Emissions	-	-31.305	-37.346	-32.306	-34.663
	Temperature Variation	0.450	0.253	0.218	0.247	0.232
50 Years	Output Loss	-	0.743	0.788	0.873	0.590
	Cumulative Emissions	-	-42.9320	-44.900	-43.948	-46.466
	Temperature Variation	1.000	0.403	0.383	0.389	0.355

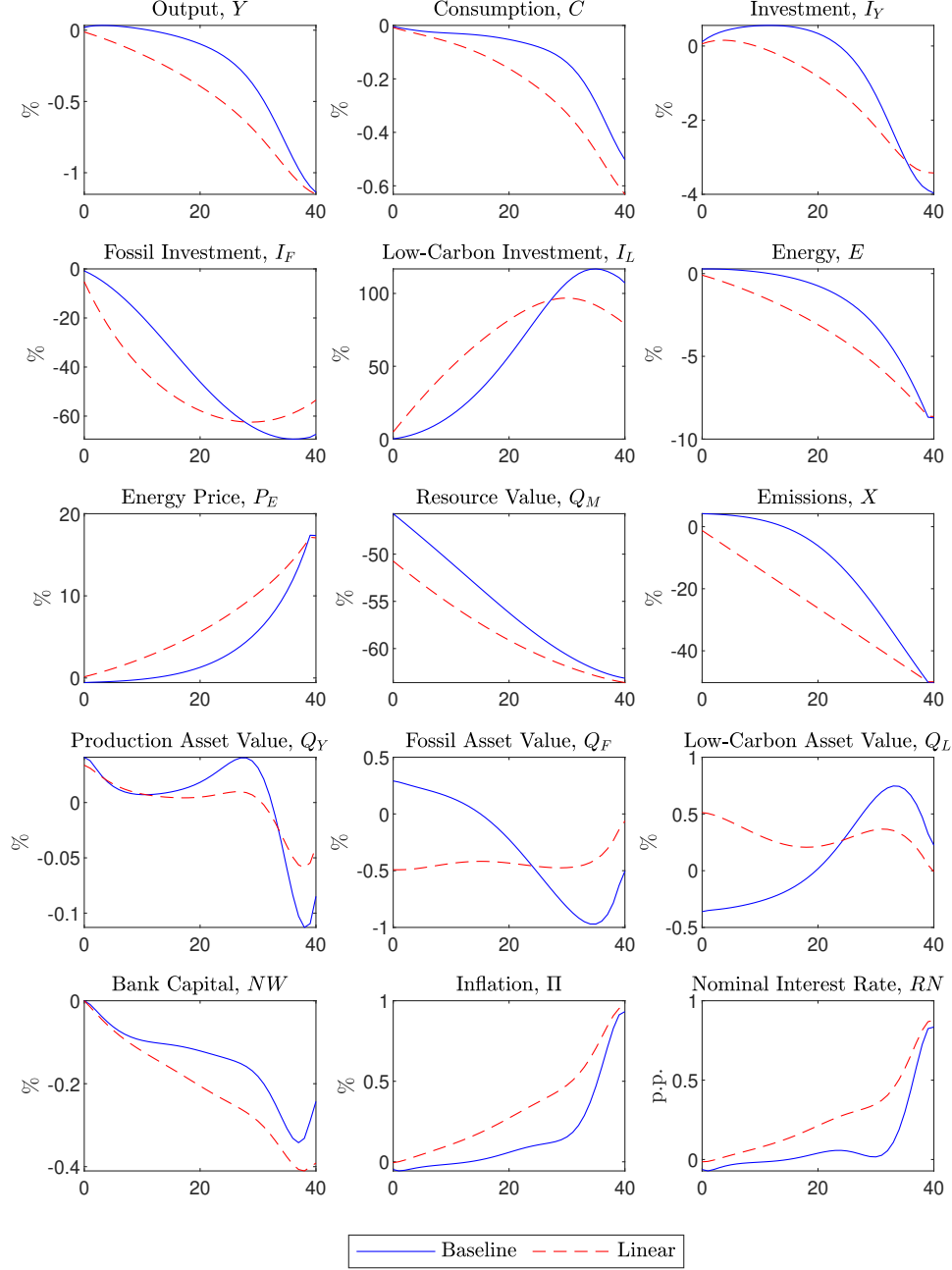
Note: the table reports the present value of output loss (% from the no policy case), the variation in the cumulative emissions (% from the no policy case) and the variation of temperature in Celsius degrees after different time horizons.

Table 3: Banks' Net Worth and Inflation under Different Mitigation Scenarios

	Net Worth		Inflation	
	Mean	SD	Mean	SD
Mitigation				
<i>Baseline</i>	-0.143	0.089	0.137	0.242
<i>Linear</i>	-0.205	0.116	0.318	0.264
Mitigation and Financial Regulation				
<i>Tax Scheme</i>	-0.334	0.199	0.199	0.260
<i>Tax and Subsidy Scheme</i>	-0.664	0.391	0.031	0.226

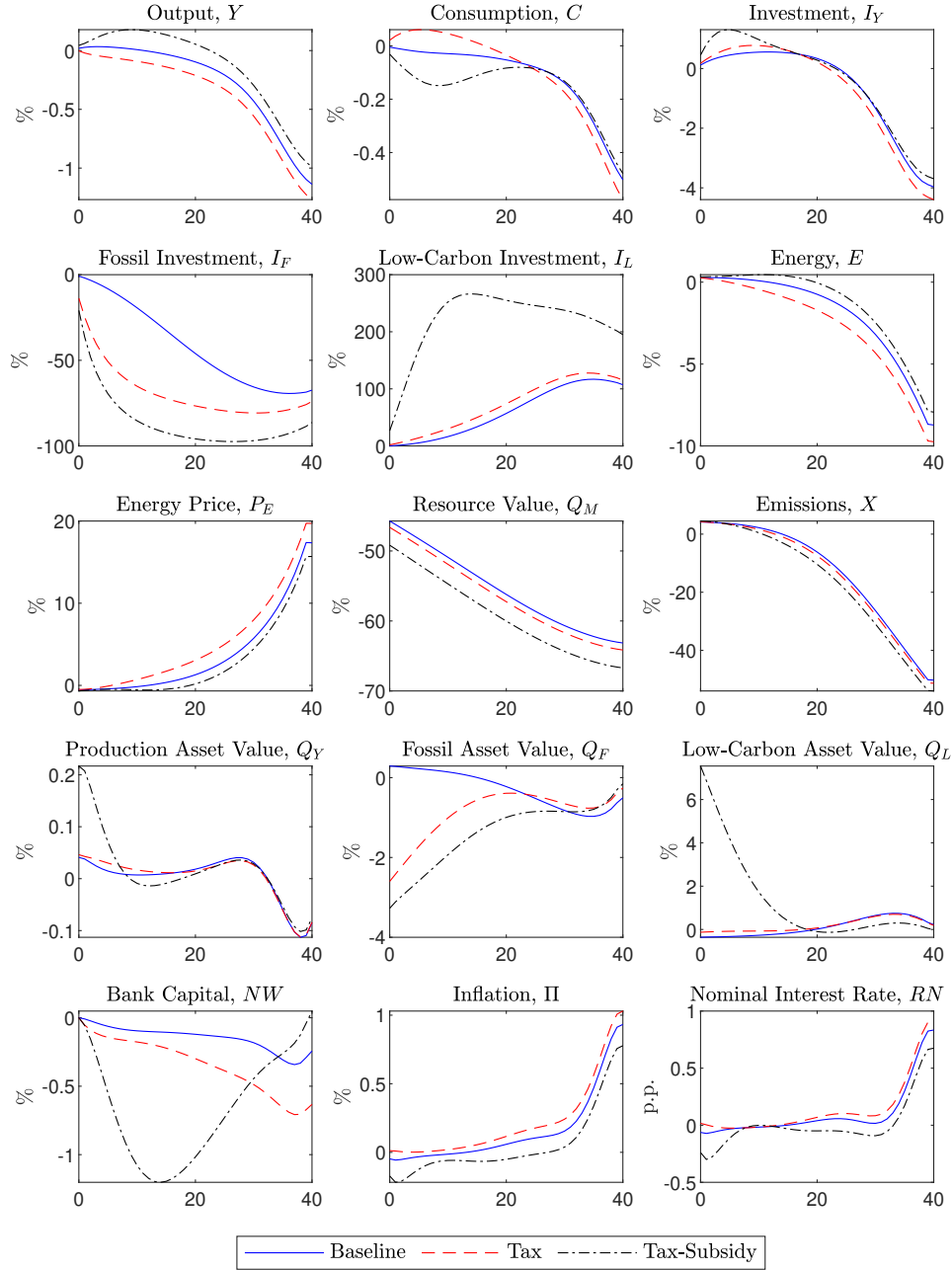
Note: the table presents moments for the net worth of banks (measured as deviation from the steady state) and the annualized inflation rate (in %) computed over a 10-years time horizon.

Figure 1: Transition Risk and Time Profile of Carbon Pricing Schemes



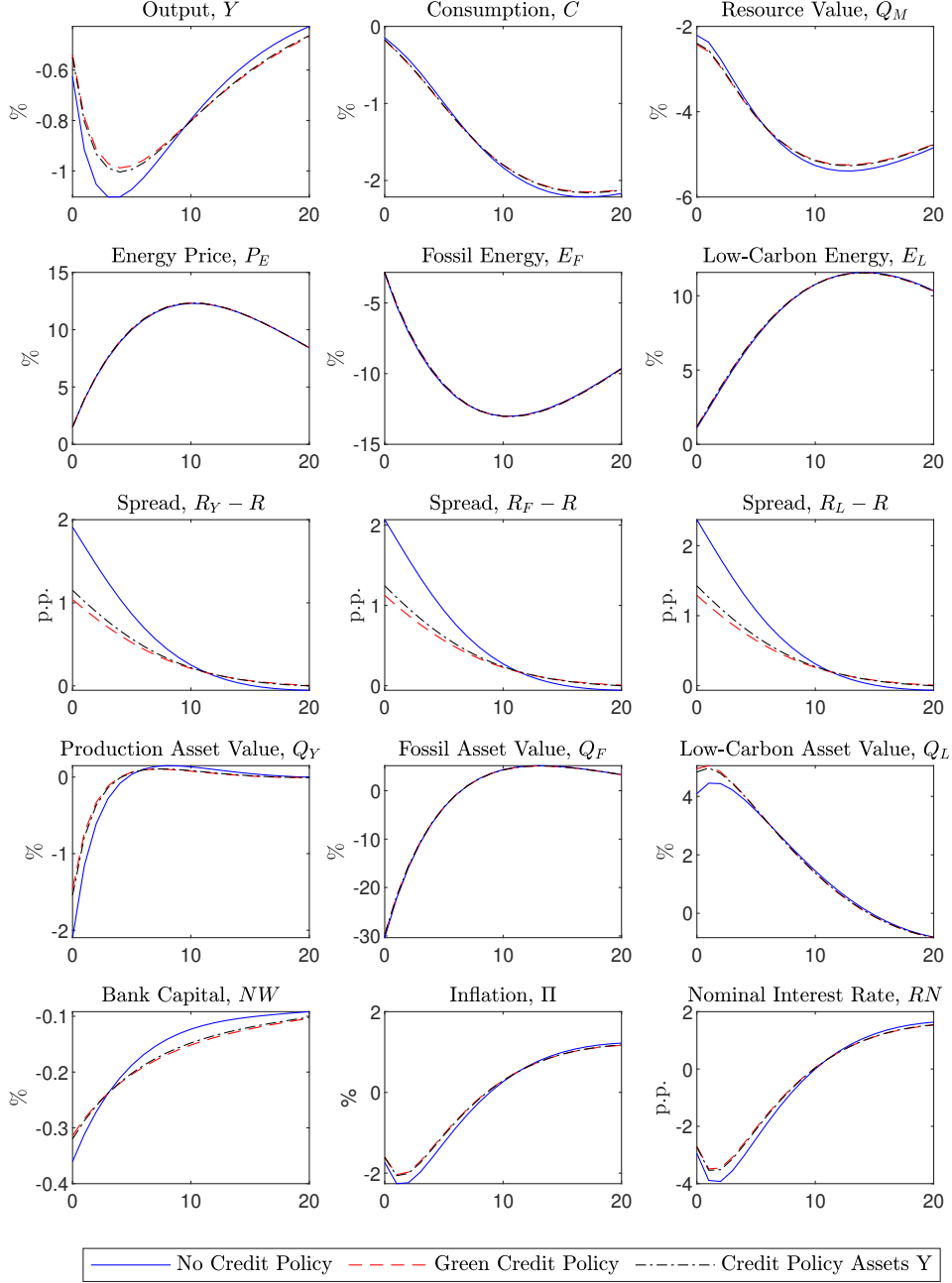
Note: the 50% emission reduction takes place in 10 years. The figure plots the simulated time path of the main macroeconomic and financial variables for an exponentially-increasing carbon price (continuous line) and a carbon price consistent with a linear reduction of emissions (dashed line). All variables are expressed as percentage deviations from the steady state, with the exception of inflation, reported as annualized inflation rate, and of the risk-free nominal interest rate, reported as annualized percentage point deviations from the steady state. Time is in quarters.

Figure 2: Transition Risk and Financial Regulation



Note: the 50% emission reduction takes place in 10 years. The figure plots the simulated time path of the main macroeconomic and financial variables for an exponentially-increasing carbon price with and without financial regulation. Dashed line depicts a mitigation scenario in which a tax rate on fossil assets is set at 0.0025 and tax revenues are redistributed as lump-sum transfers to households. Dashed-dotted line represents a mitigation scenario in which a tax rate on fossil assets is set at 0.0025 and there is a budget-neutral redistribution of the tax revenues in the form of subsidies on low-carbon assets. All variables are expressed as percentage deviations from the steady state, with the exception of inflation, reported as annualized inflation rate, and of the risk-free nominal interest rate, reported as annualized percentage point deviations from the steady state. Time is in quarters.

Figure 3: Transition Risk, Financial Instability and Credit Policy



Note: the figure plots the impulse response of the main financial variables to a 10% reduction of the value of fossil capital for different monetary policy interventions: (i) Taylor rule only (continuous line), (ii) Taylor rule and credit in support of low-carbon assets (dashed line), (iii) Taylor rule and credit policy in support of production assets (dashed-dotted line). All variables are expressed as percentage deviations from the steady state, with the exception of inflation, reported as annualized inflation rate, and of the interest rate spreads and the risk-free nominal interest rate reported as annualized percentage point deviations from the steady state. Time is in quarters.

Appendix A

In this Appendix we derive the equilibrium conditions describing banks' behavior. We focus on bank j and then aggregate across banks. At the end of period t the balance sheet of bank j is:

$$Q_{Y,t}S_{Y,j,t} + Q_{L,t}S_{L,j,t} + Q_{F,t}S_{F,j,t} = NW_{j,t} + B_{j,t+1}, \quad (\text{A-1})$$

where the time path of net worth is given by the difference between earnings on assets and interest payments on liabilities:

$$NW_{j,t+1} = R_{Y,t+1}Q_{Y,t}S_{Y,j,t} + R_{L,t+1}Q_{L,t}S_{L,j,t} + R_{F,t+1}Q_{F,t}S_{F,j,t} - R_{t+1}B_{j,t+1}. \quad (\text{A-2})$$

Solving (29) for $B_{j,t+1}$ and substituting in (A-2) we deliver:

$$NW_{j,t+1} = \left[\sum_S (R_{S,t+1} - R_{t+1}) \frac{Q_{S,t}S_{S,j,t}}{NW_{j,t}} + R_{t+1} \right] NW_{j,t}. \quad (\text{A-3})$$

The banker's objective is that of maximizing its expected terminal wealth. For a given path of net wealth, then the banker's franchise value satisfies the Bellman equation:

$$V_{j,t} = \max_{\{S_{Y,j,t+1}^P, S_{L,j,t+1}^P, S_{F,j,t+1}^P\}} \mathbb{E}_t \sum_{i=0}^{\infty} (1-\theta)\theta^i \beta^{i+1} \Lambda_{t,t+1+i} NW_{j,t+1+i}, \quad (\text{A-4})$$

$$\begin{aligned} &= \max_{\{S_{Y,j,t+1}^P, S_{L,j,t+1}^P, S_{F,j,t+1}^P\}} \mathbb{E}_t (1-\theta) \beta \Lambda_{t,t+1} NW_{j,t+1} + \theta \beta \Lambda_{t,t+1} \mathbb{E}_t V_{j,t+1}, \\ &= \max_{\{S_{Y,j,t+1}^P, S_{L,j,t+1}^P, S_{F,j,t+1}^P\}} \mathbb{E}_t \beta \Lambda_{t,t+1} [(1-\theta) NW_{j,t+1} + \theta \mathbb{E}_t V_{j,t+1}]. \end{aligned} \quad (\text{A-5})$$

The agency problem limits the amount of resources the banker can obtain from households, so the incentive compatibility constraint faced by bank j is:

$$V_{j,t} \geq \rho(Q_{Y,t}S_{Y,j,t} + \psi_L Q_{L,t}S_{L,j,t} + \psi_F Q_{F,t}S_{F,j,t}). \quad (\text{A-6})$$

To solve bank j problem we conjecture that the value function is a linear function of net wealth, that is $V_{j,t} = v_t NW_{j,t}$. We assume that the function is the same across banks. Under this guess solution and given the accumulation equation (A-3), (A-5) can be written as:

$$V_{j,t} = \max \mathbb{E}_t \left\{ \beta \Lambda_{t,t+1} [(1-\theta) + \theta v_{t+1}] \left[\sum_S (R_{S,t+1} - R_{t+1}) \frac{Q_{S,t}S_{S,j,t}}{NW_{j,t}} + R_{t+1} \right] NW_{j,t} \right\}. \quad (\text{A-7})$$

At the optimum we have the following first-order conditions (FOC):

$$\text{FOC wrt } S_{Y,j,t} : \beta \mathbb{E}_t \Lambda_{t,t+1} [(1-\theta) + \theta v_{t+1}] (R_{Y,t+1} - R_{t+1}) = \vartheta_t \rho, \quad (\text{A-8})$$

$$\text{FOC wrt } S_{L,j,t} : \beta \mathbb{E}_t \Lambda_{t,t+1} [(1-\theta) + \theta v_{t+1}] (R_{L,t+1} - R_{t+1}) = \vartheta_t \rho \psi_L, \quad (\text{A-9})$$

$$\text{FOC wrt } S_{F,j,t} : \beta \mathbb{E}_t \Lambda_{t,t+1} [(1-\theta) + \theta v_{t+1}] (R_{F,t+1} - R_{t+1}) = \vartheta_t \rho \psi_F, \quad (\text{A-10})$$

the envelope's condition:

$$\beta \mathbb{E}_t \Lambda_{t,t+1} [(1-\theta) + \theta v_{t+1}] R_{t+1} = v_t - \vartheta_t v_t, \quad (\text{A-11})$$

and the incentive constraint:

$$v_t NW_{j,t} = \rho(Q_{Y,t} S_{Y,j,t} + \psi_L Q_{L,t} S_{L,j,t} + \psi_F Q_{F,t} S_{F,j,t}). \quad (\text{A-12})$$

Combining (A-9) and (A-10) with (A-8) delivers the no-arbitrage conditions (34) and (35) of the main text. Now let define a risk-weighted leverage of bank:

$$\phi_{j,t} = \frac{Q_{Y,t} S_{Y,j,t} + \psi_L Q_{L,t} S_{L,j,t} + \psi_F Q_{F,t} S_{F,j,t}}{NW_{j,t}}, \quad (\text{A-13})$$

that given (A-12) can be expressed as:

$$\phi_{j,t} = \phi_t = \frac{v_t}{\rho}. \quad (\text{A-14})$$

Substituting this result into the first-order condition (A-8) and then using (A-11) we get the expression for v_t (38).

Since all the components of ϕ_t do not depend on bank-specific factors, one can sum up across banks' total assets and net wealth:

$$NW_t \phi_t = Q_{Y,t} S_{Y,t} + \psi_L Q_{L,t} S_{L,t} + \psi_F Q_{F,t} S_{F,t},$$

describing the total intermediary demand for assets and the aggregate quantity of intermediary equity capital. The remaining equations of section 2.6 immediately follow from aggregation across banks.

Appendix B

This Appendix reports the equilibrium conditions of the economy. Let $p_{E,t} = \frac{P_{E,t}}{P_t}$, $p_{E_L,t} = \frac{P_{E_L,t}}{P_t}$, $p_{E_F,t} = \frac{P_{E_F,t}}{P_t}$, $p_{X,t} = \frac{P_{X,t}}{P_t}$, $p_{Y,t} = \frac{P_{Y,t}}{P_t}$. Given the exogenous processes and the policy variables, the equilibrium conditions of our decentralized economy can be summarized and regrouped as follows.

Households

$$(C_t - h_c \bar{C}_{t-1})^{-\alpha} = \lambda_t, \quad (\text{B-1})$$

$$\chi_S N_{S,t}^{\varphi_S} = \lambda_t W_{S,t} \text{ for } S \in \{Y, L, F\}, \quad (\text{B-2})$$

$$\beta \mathbb{E}_t \Lambda_{t,t+1} R_{t+1} = 1, \quad (\text{B-3})$$

$$\Lambda_{t,t+1} = \frac{\lambda_{t+1}}{\lambda_t}, \quad (\text{B-4})$$

$$R_t = R_{N,t-1} / \Pi_t. \quad (\text{B-5})$$

Goods Producers

$$Y_t = \left[\varpi_{VA_Y}^{1/\varepsilon_Y} V A_{Y,t}^{(\varepsilon_Y-1)/\varepsilon_Y} + \varpi_E^{1/\varepsilon_Y} E_t^{(\varepsilon_Y-1)/\varepsilon_Y} \right]^{\varepsilon_Y/(\varepsilon_Y-1)}, \quad (\text{B-6})$$

$$V A_{Y,t} = \Gamma_{D_Y,t} A_{Y,t} (U_{Y,t} \xi_{Y,t} K_{Y,t})^{\alpha_Y} N_{Y,t}^{1-\alpha_Y}, \quad (\text{B-7})$$

$$E_t = \left[\varpi_{E_L}^{1/\varepsilon_E} E_{L,t}^{(\varepsilon_E-1)/\varepsilon_E} + \varpi_{E_F}^{1/\varepsilon_E} E_{F,t}^{(\varepsilon_E-1)/\varepsilon_E} \right]^{\varepsilon_E/(\varepsilon_E-1)}, \quad (\text{B-8})$$

$$R_{Y,t+1} = \frac{\left(\frac{\alpha_Y p_{Y,t+1} Y_{t+1}^{1/\varepsilon_Y} \varpi_{VA_Y}^{1/\varepsilon_Y} V A_{Y,t+1}^{(\varepsilon_Y-1)/\varepsilon_Y}}{\xi_{Y,t+1} K_{Y,t+1}} + Q_{Y,t+1} - \delta_{Y,t+1} \right) \xi_{Y,t+1}}{Q_{Y,t}}, \quad (\text{B-9})$$

$$W_{Y,t} = p_{Y,t} Y_t^{1/\varepsilon_Y} \varpi_{VA_Y}^{1/\varepsilon_Y} V A_{Y,t}^{(\varepsilon_Y-1)/\varepsilon_Y} (1 - \alpha_Y) \frac{1}{N_{Y,t}}, \quad (\text{B-10})$$

$$\delta'_{Y,t} \xi_{Y,t} K_{Y,t} = p_{Y,t} Y_t^{1/\varepsilon_Y} \varpi_{VA_Y}^{1/\varepsilon_Y} V A_{Y,t}^{(\varepsilon_Y-1)/\varepsilon_Y} \alpha_Y \frac{1}{U_{Y,t}}, \quad (\text{B-11})$$

$$E_t = p_{Y,t}^{\varepsilon_Y} \varpi_{EP}^{-\varepsilon_Y} Y_t, \quad (\text{B-12})$$

$$E_{L,t} = \varpi_{E_L} \left(\frac{p_{E_L,t}}{p_{E,t}} \right)^{-\varepsilon_E} E_t, \quad (\text{B-13})$$

$$E_{F,t} = \varpi_{E_F} \left(\frac{p_{E_F,t}}{p_{E,t}} \right)^{-\varepsilon_E} E_t. \quad (\text{B-14})$$

Low-Carbon Energy Sector

$$E_{L,t} = \Gamma_{D_L,t} A_{L,t} (U_{L,t} \xi_{L,t} K_{L,t})^{\alpha_L} N_{L,t}^{1-\alpha_L}, \quad (\text{B-15})$$

$$R_{L,t+1} = \frac{\left[p_{E_L,t+1} \alpha_L \frac{E_{L,t+1}}{\xi_{L,t+1} K_{L,t+1}} + (Q_{L,t+1} - \delta_{L,t+1}) \right] \xi_{L,t+1}}{Q_{L,t}}, \quad (\text{B-16})$$

$$W_{L,t} = p_{E_L,t} (1 - \alpha_L) \frac{E_{L,t}}{N_{L,t}}, \quad (\text{B-17})$$

$$\delta'_{L,t} \xi_{L,t} K_{L,t} = p_{E_L,t} \alpha_L \frac{E_{L,t}}{U_{L,t}}. \quad (\text{B-18})$$

Fossil Energy Sector

$$E_{F,t} = \left[\varpi_{VA_F}^{1/\varepsilon_F} V A_{F,t}^{(\varepsilon_F-1)/\varepsilon_F} + \varpi_X^{1/\varepsilon_F} X_t^{(\varepsilon_F-1)/\varepsilon_F} \right]^{\varepsilon_F/(\varepsilon_F-1)}, \quad (\text{B-19})$$

$$V A_{F,t} = \Gamma_{D_F,t} A_{F,t} (U_{F,t} \xi_{F,t} K_{E_F,t})^{\alpha_F} N_{F,t}^{1-\alpha_F}, \quad (\text{B-20})$$

$$M_{t+1} = (1 - g_M) M_t - X_t + \Delta_t, \quad (\text{B-21})$$

$$R_{F,t+1} = \frac{\left[\frac{p_{E_F,t+1} E_{F,t+1}^{1/\varepsilon_F} \varpi_{VA_F}^{1/\varepsilon_F} V A_{F,t+1}^{(\varepsilon_F-1)/\varepsilon_F} \alpha_F}{\xi_{F,t+1} K_{F,t+1}} + Q_{F,t+1} - \delta_{F,t+1} \right] \xi_{F,t+1}}{Q_{F,t}}, \quad (\text{B-22})$$

$$W_{F,t} = p_{E_F,t} E_{F,t}^{1/\varepsilon_F} \varpi_{VA_F}^{1/\varepsilon_F} V A_{F,t}^{(\varepsilon_F-1)/\varepsilon_F} (1 - \alpha_F) \frac{1}{N_{F,t}}, \quad (\text{B-23})$$

$$\delta'_{F,t} \xi_{F,t} K_{F,t} = p_{E_F,t} E_{F,t}^{1/\varepsilon_F} \varpi_{VA_F}^{1/\varepsilon_F} V A_{F,t}^{(\varepsilon_F-1)/\varepsilon_F} \alpha_F \frac{1}{U_{F,t}}, \quad (\text{B-24})$$

$$p_{E_F,t} E_{F,t}^{1/\varepsilon_F} \varpi_X^{1/\varepsilon_F} X_t^{-1/\varepsilon_F} - p_{X,t} - Q_{M,t} - \chi_0 \left(\frac{M_0}{M_t} \right)^{\chi_1} = 0, \quad (\text{B-25})$$

$$Q_{M,t} = \beta \mathbb{E}_t \Lambda_{t,t+1} Q_{M,t+1} (1 - g_M) + \beta \mathbb{E}_t \Lambda_{t,t+1} \chi_1 \chi_0 \left(\frac{M_0}{M_{t+1}} \right)^{\chi_1 - 1} \frac{M_0}{M_{t+1}^2} X_t. \quad (\text{B-26})$$

Capital Accumulation and Capital Producers

$$K_{S,t+1} = \xi_{S,t} K_{S,t} + I_{net,S,t} \text{ for } S \in \{Y, L, F\}, \quad (\text{B-27})$$

$$I_{net,S,t} = I_{L,t} - \delta_{S,t} \xi_{S,t} K_{S,t} \text{ for } S \in \{Y, L, F\}, \quad (\text{B-28})$$

$$Q_{S,t} = 1 + \frac{\gamma_S}{2} \left(\frac{I_{net,S,t} + I_S}{I_{net,S,t-1} + I_S} - 1 \right)^2 + \gamma_S \left(\frac{I_{net,S,t} + I_S}{I_{net,S,t-1} + I_S} - 1 \right) \frac{I_{net,S,t} + I_S}{I_{net,S,t-1} + I_S} + \quad (\text{B-29})$$

$$- \mathbb{E}_t \beta \Lambda_{t,t+1} \gamma_S \left(\frac{I_{net,S,t+1} + I_S}{I_{net,S,t} + I_S} - 1 \right) \left(\frac{I_{net,S,t+1} + I_S}{I_{net,S,t} + I_S} \right)^2 \text{ for } S \in \{Y, L, F\},$$

$$\delta_{S,t} = \delta_{0,S} + \frac{\delta_{1,S}}{1 + \delta_{2,S}} U_{S,t}^{1 + \delta_{2,S}} \text{ for } S \in \{Y, L, F\}. \quad (\text{B-30})$$

Banks

$$Q_{S,t} K_{S,t+1} = Q_{S,t} S_{S,t} \text{ for } S \in \{Y, L, F\}, \quad (\text{B-31})$$

$$\sum_S Q_{S,t} S_{S,t}^P = NW_t + B_{t+1}^P, \quad (\text{B-32})$$

$$NW_t = NW_{e,t} + NW_{n,t}, \quad (\text{B-33})$$

$$NW_{n,t} = \omega \sum_S Q_{S,t} S_{S,t-1}^P, \quad (\text{B-34})$$

$$NW_{e,t} = \theta \left[\sum_S (R_{S,t} - R_t) \frac{Q_{S,t-1} S_{S,t-1}^P}{NW_{t-1}} + R_t \right] NW_{t-1}, \quad (\text{B-35})$$

$$\phi_t = \frac{Q_{Y,t} S_{Y,t}^P + \psi_L Q_{L,t} S_{L,t}^P + \psi_F Q_{F,t} S_{F,t}^P}{NW_t}, \quad (\text{B-36})$$

$$v_t = \frac{\rho \beta \mathbb{E}_t \Lambda_{t,t+1} [(1 - \theta) + \theta v_{t+1}] (R_{t+1})}{\rho - \beta \mathbb{E}_t \Lambda_{t,t+1} [(1 - \theta) + \theta v_{t+1}] (R_{Y,t+1} - R_{t+1})}, \quad (\text{B-37})$$

$$V_t = \nu_t NW_t, \quad (\text{B-38})$$

$$\psi_L \mathbb{E}_t \Lambda_{t,t+1} [(1 - \theta) + \theta v_{t+1}] (R_{Y,t+1} - R_{t+1}) = \mathbb{E}_t \Lambda_{t,t+1} [(1 - \theta) + \theta v_{t+1}] (R_{L,t+1} - R_{t+1}), \quad (\text{B-39})$$

$$\psi_F \mathbb{E}_t \Lambda_{t,t+1} [(1 - \theta) + \theta v_{t+1}] (R_{L,t+1} - R_{t+1}) = \psi_L \mathbb{E}_t \Lambda_{t,t+1} [(1 - \theta) + \theta v_{t+1}] (R_{F,t+1} - R_{t+1}), \quad (\text{B-40})$$

$$\phi_t = \frac{v_t}{\rho}. \quad (\text{B-41})$$

Retailers

$$p_{Y,t}\sigma + 1 - \sigma - \gamma_p \left(\frac{\Pi_t}{\Pi_{t-1}^{\kappa_p} \Pi^{1-\kappa_p}} - 1 \right) \frac{\Pi_t}{\Pi_{t-1}^{\kappa_p} \Pi^{1-\kappa_p}} +$$

$$+ \beta \mathbb{E}_t \Lambda_{t,t+1} \gamma_p \left(\frac{\Pi_{t+1}}{\Pi_t^{\kappa_p} \Pi^{1-\kappa_p}} - 1 \right) \frac{\Pi_{t+1}}{\Pi_t^{\kappa_p} \Pi^{1-\kappa_p}} \frac{Y_{t+1}}{Y_t} = 0. \quad (\text{B-42})$$

Public Sector

$$\frac{R_{N,t}}{R_N} = \left(\frac{R_{N,t-1}}{R_N} \right)^{\kappa_i} \left[\left(\frac{\Pi_t}{\Pi} \right)^{\kappa_\pi} \left(\frac{Y_t}{Y_{t-1}} \right)^{\kappa_y} \right]^{1-\kappa_i}, \quad (\text{B-43})$$

$$Q_{S,t} S_{S,t}^G = \gamma_{S,t} Q_{S,t} S_{S,t} \text{ for } S \in \{Y, L, F\}, \quad (\text{B-44})$$

$$\sum_S Q_{S,t} S_{S,t}^G = B_{t+1}^G, \quad (\text{B-45})$$

$$B_t = B_t^P + B_t^G, \quad (\text{B-46})$$

$$S_{S,t} = S_{S,t}^P + S_{S,t}^G \text{ for } S \in \{Y, L, F\}, \quad (\text{B-47})$$

$$T_t = C_t^G + \Gamma_{cp,t} - p_{X,t} X_t - \sum_S R_{S,t} Q_{S,t} S_{S,t}^G + R_t B_t^G. \quad (\text{B-48})$$

Equilibrium, Emissions, Temperature and Damages

$$Y_t = C_t + C_t^G + \sum_S I_{S,t} + \Gamma_{cp,t} + \Gamma_{X,t} +$$

$$+ \sum_S \frac{\gamma_S}{2} \left(\frac{I_{net,S,t} + I_S}{I_{net,S,t-1} + I_S} - 1 \right)^2 (I_{net,S,t} + I_S) + \frac{\gamma_p}{2} \left(\frac{\Pi_t}{\Pi_{t-1}^{\kappa_p} \Pi^{1-\kappa_p}} - 1 \right)^2 Y_t, \quad (\text{B-49})$$

where $\Gamma_{cp,t} = \tau_{cp} \sum_S Q_{S,t} S_{S,t}^G$, $\Gamma_{X,t} = \chi_0 (M_0/M_t)^{\chi_1} X_t$.

$$Z_t = \eta Z_{t-1} + X_t, \quad (\text{B-50})$$

$$Temp_t = \overline{Temp} + \vartheta_{temp} Z_t, \quad (\text{B-51})$$

$$\Gamma_{D,S,t} = \frac{1}{1 + \lambda_{S,0} Temp_t^2} \text{ for } S \in \{Y, L, F\}. \quad (\text{B-52})$$

Appendix C

With financial regulation and in the absence of credit policy equations, (B-35), (B-37), (B-39), (B-40) and (B-48) are respectively replaced by:

$$NW_{e,t} = \theta \left[\sum_S (R_{S,t} - \tau_{S,t-1} - R_t) \frac{Q_{S,t-1} S_{S,t-1}^P}{NW_{t-1}} + R_t \right] NW_{t-1}, \quad (\text{C-1})$$

$$v_t = \frac{\rho \beta \mathbb{E}_t \Lambda_{t,t+1} [(1 - \theta) + \theta v_{t+1}] R_{t+1}}{\rho - \beta \mathbb{E}_t \Lambda_{t,t+1} [(1 - \theta) + \theta v_{t+1}] (R_{Y,t+1} - \tau_{S_Y,t} - R_{t+1})}, \quad (\text{C-2})$$

$$\begin{aligned} \psi_L \mathbb{E}_t \Lambda_{t,t+1} [(1-\theta) + \theta v_{t+1}] (R_{Y,t+1} - \tau_{S_Y,t} - R_{t+1}) = \\ \mathbb{E}_t \Lambda_{t,t+1} [(1-\theta) + \theta v_{t+1}] (R_{L,t+1} - \tau_{S_L,t} - R_{t+1}), \end{aligned} \quad (\text{C-3})$$

$$\begin{aligned} \psi_F \mathbb{E}_t \Lambda_{t,t+1} [(1-\theta) + \theta v_{t+1}] (R_{L,t+1} - \tau_{S_L,t} - R_{t+1}) = \\ \psi_L \mathbb{E}_t \Lambda_{t,t+1} [(1-\theta) + \theta v_{t+1}] (R_{F,t+1} - \tau_{S_F,t} - R_{t+1}), \end{aligned} \quad (\text{C-4})$$

$$T_t = C_t^G - \sum_S \tau_{W_S,t} W_{S,t} N_{S,t} - \tau_{L,t} p_{E_L,t} E_{L,t} - \tau_{F,t} p_{E_F,t} E_{F,t} + \quad (\text{C-5})$$

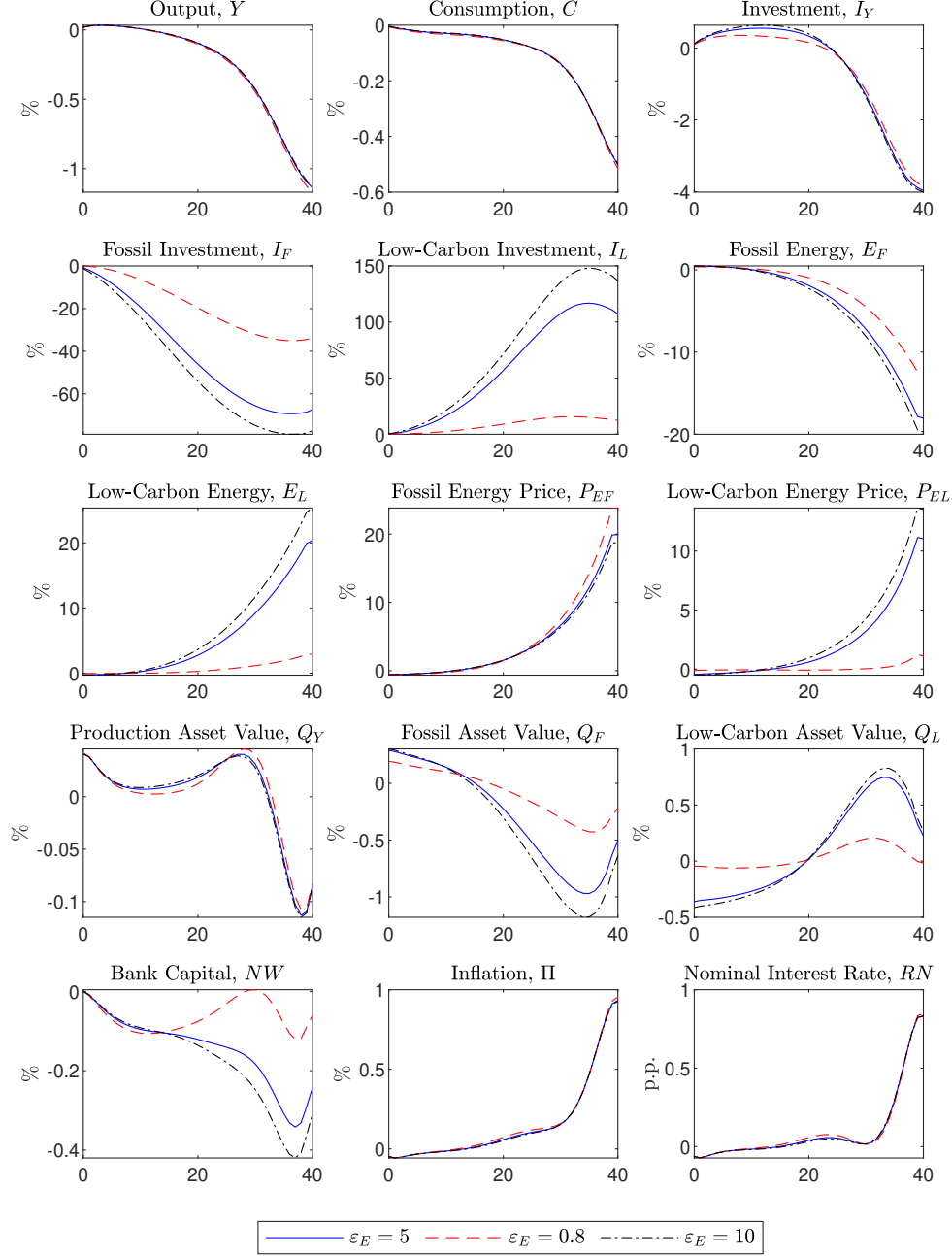
$$-p_{X,t} X_t - \sum_S \tau_{S,t} Q_{S,t} S_{S,t}^P. \quad (\text{C-6})$$

Appendix D

This Appendix reports some additional results.

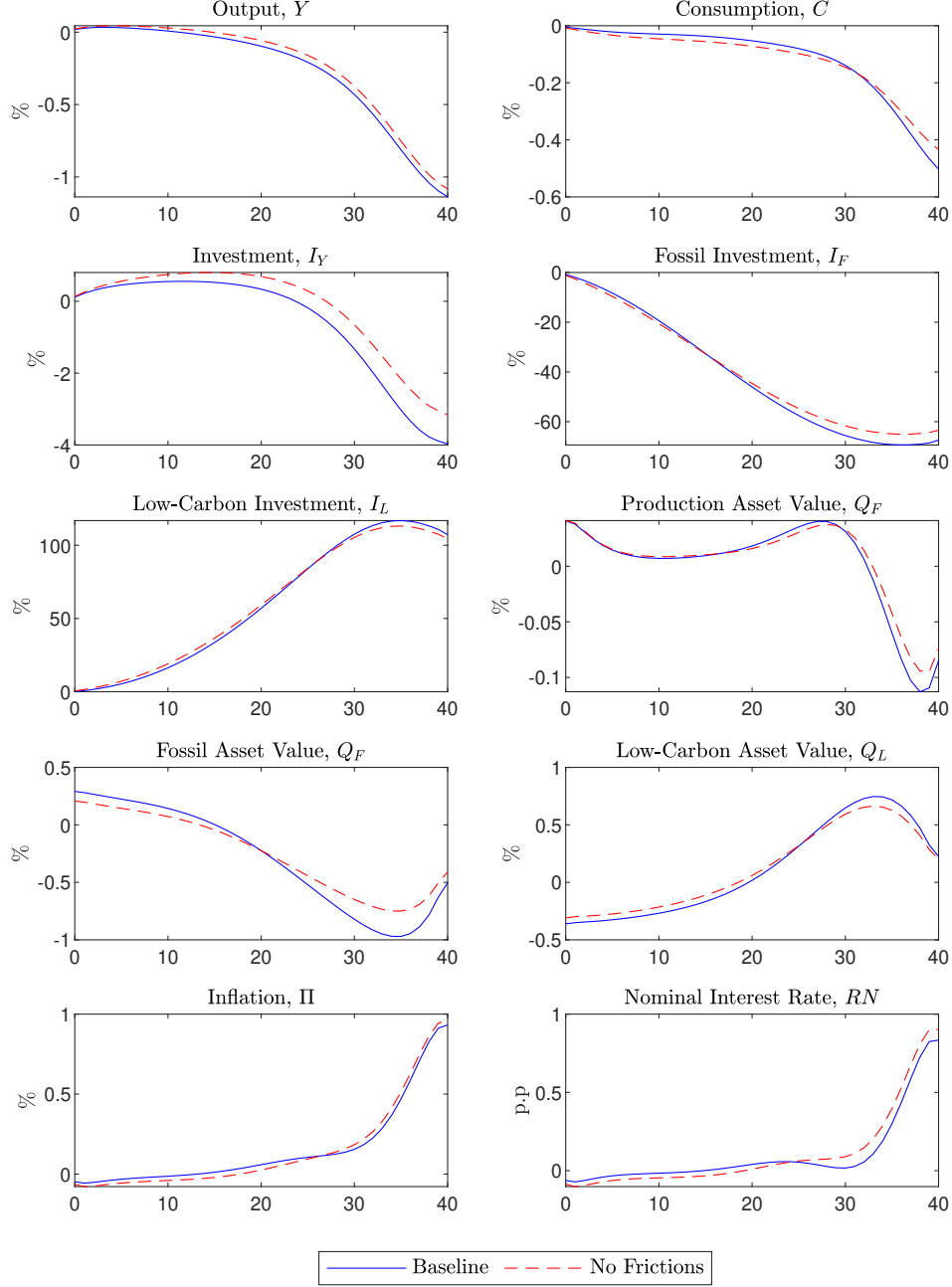
Figure D-1 shows the role of the elasticity of substitution ε_E between the two energy sources in shaping the response to the baseline (exponentially-increasing) carbon price discussed in Figure 1. Figure D-2 depicts simulation results of the baseline mitigation scenario in the absence of financial frictions. Since the financial impact of the policy is very limited, the role of financial frictions in amplifying the results is small. Figure D-3 presents three different timings of implementation of a drastic policy inducing a sudden decrease of emissions by 30%. In the delayed scenarios policy makers announce in period zero zero that at some future date in time a carbon tax will be set to drastically reduce emissions. This experiment shows the role of anticipation effects for the emergence of “green paradox” phenomena. Figure D-4 depicts two crisis scenarios triggered by a sudden devaluation of fossil energy assets with and without contagion.

Figure D-1: Transition Risk and Degree of Substitution of Energy Inputs



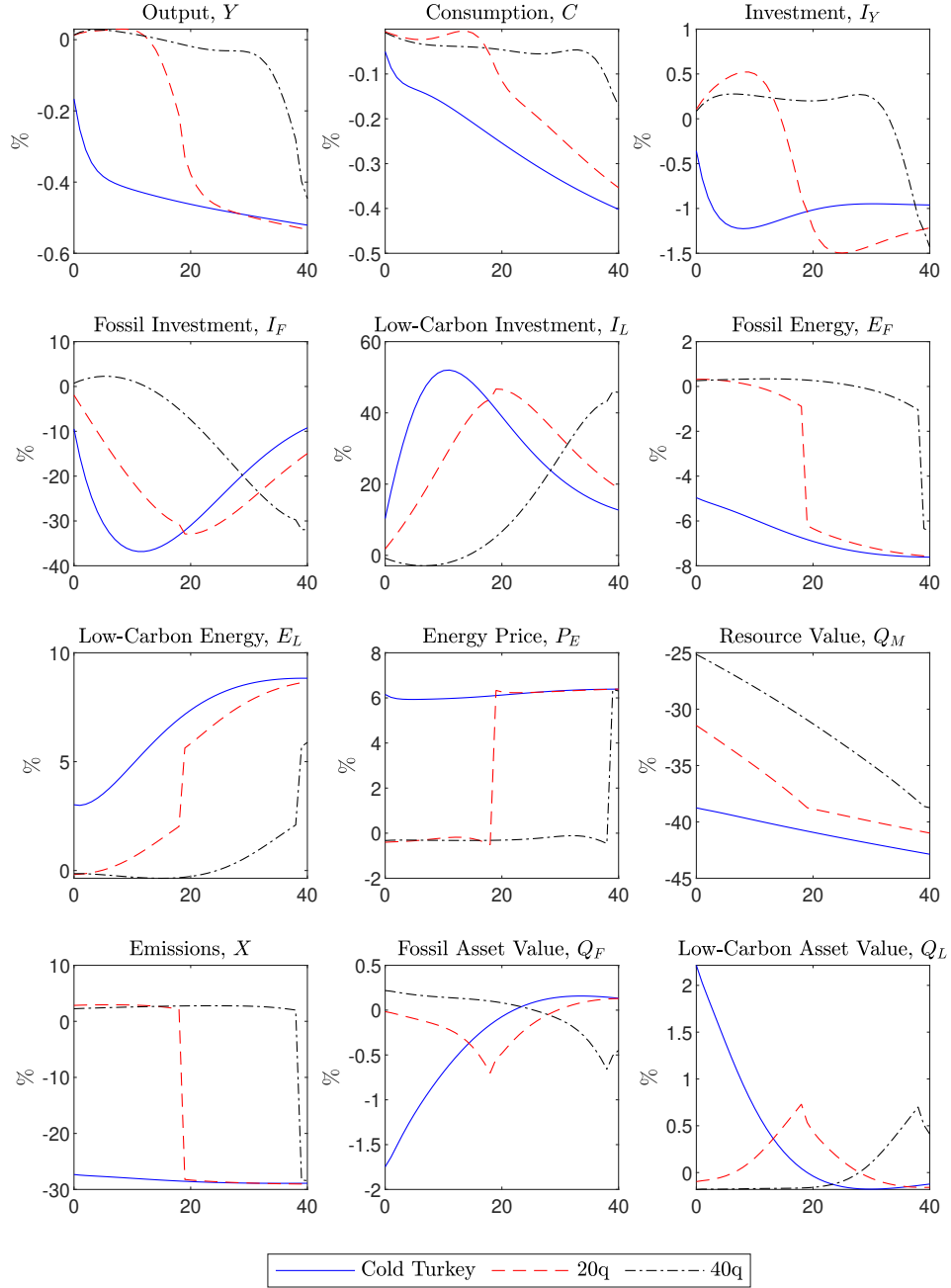
Note: the 50% emission reduction takes place in 10 years. The figure plots the simulated time path of the main macroeconomic variables for an exponentially-increasing carbon price for different values of the elasticity of substitution ε_E . All variables are expressed as percentage deviations from the steady state, with the exception of inflation, reported as annualized inflation rate, and of the risk-free nominal interest rate, reported as annualized percentage point deviations from the steady state. Time is in quarters.

Figure D-2: Transition Risk and Financial Frictions



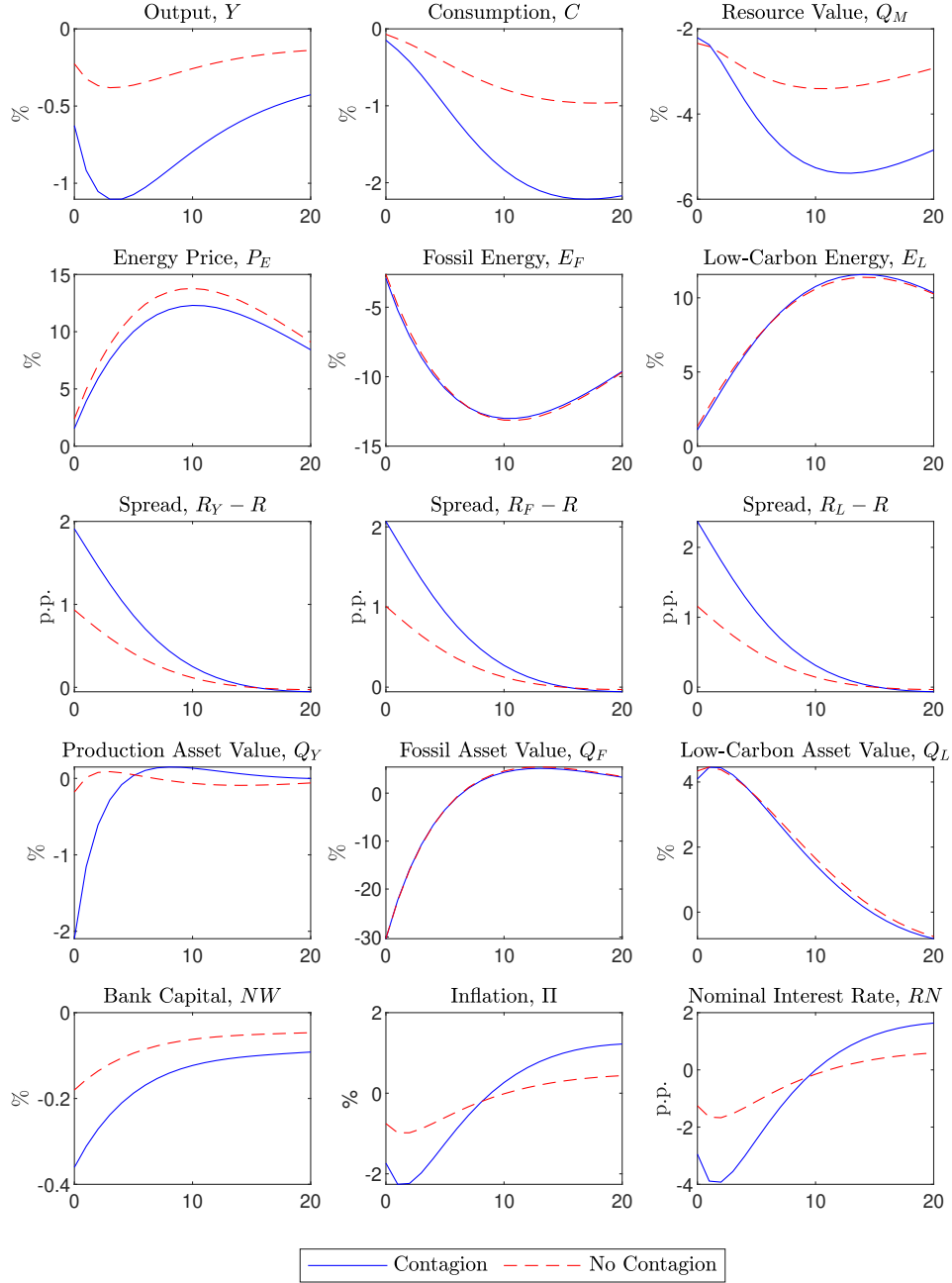
Note: the 50% emission reduction takes place in 10 years. The figure plots the simulated time path of the main macroeconomic variables for an exponentially-increasing carbon price with (continuous line) and without (dashed line) financial frictions. All variables are expressed as percentage deviations from the steady state, with the exception of inflation, reported as annualized inflation rate, and of the risk-free nominal interest rate, reported as annualized percentage point deviations from the steady state. Time is in quarters.

Figure D-3: Transition Risk and Announcement Effects



Note: the figure plots the simulated time path of the main macroeconomic and financial variables under three scenarios of abrupt implementation of a carbon price entailing a 30% emission reduction: (i) sudden implementation or cold turkey (continuous line), (ii) implementation in 5 years (dashed line), (iii) implementation in 10 years (dashed-dotted line). All variables are expressed as percentage deviations from the initial steady state. Time is in quarters.

Figure D-4: Transition Risk, Financial Instability and Contagion



Note: the figure plots the impulse response of the main financial variables to a 10% reduction of the value of fossil capital in the presence (continuous line) and in the absence (dashed line) of contagion. All variables are expressed as percentage deviations from the steady state, with the exception of inflation, reported as annualized inflation rate, and of the interest rate spreads and the risk-free nominal interest rate, reported as annualized percentage point deviations from the steady state. Time is in quarters.