Climate Policy, Financial Frictions, and Transition Risk*

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Abstract

We study climate and macroprudential policies when financial frictions are present. Using a dynamic stochastic general equilibrium model featuring both a pollution market failure and a market failure in the financial sector, we explore transition risk – whether ambitious climate policy can lead to macroeconomic instability. It can, but the risk can be alleviated through macroprudential policies – taxes or subsidies on banks' assets. Then, we explore efficient climate and macroprudential policy in the long run and over business cycles. The presence of financial frictions affects the steady-state value and dynamic properties of the efficient carbon tax. In a second-best world, macroprudential policy can be used to address the pollution externality, but not very effectively.

JEL Classifications: E32; G18; Q58

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1 Introduction

Achieving the Paris Agreement's goal to maintain global temperature increases within 2°C above pre-industrial levels will likely demand ambitious and quick climate policy action, rather than the gradual "ramp-up" approach to policy favored by some integrated assessment models like DICE. Such an ambitious and sudden policy may create macroeconomic risks given the financial sector's investment in fossil fuel reserves and polluting industries. A non-trivial fraction of financial intermediaries' asset portfolios is currently represented by carbon-intensive assets at a high risk of becoming "stranded", or losing most of their economic value (e.g. Battiston et al. 2017; see also the reviews by Monasterolo 2020, van der Ploeg and Rezai 2020, van der Ploeg 2020, and Semienuk et al. 2020). This risk is what Mark Carney's influential speech at Lloyd's (Carney 2015) identified as "transition risk," stemming from an unanticipated ambitious climate action.[1] Could a climate policy large and sudden enough to achieve the 2°C goal cause a recession because of the financial sector's exposure to risky assets? And if so, could some other policy mitigate this risk?

Beyond its impact on the transition risk, the financial sector can also have important implications for the efficient design of climate policy in the long run and over business cycles. The Great Recession has illustrated that financial and credit market frictions play a crucial role in driving business cycles. It has also emphasized the need for macroprudential regulation to manage financial stability risk (Gertler and Kiyotaki 2010, Bernanke 2019). Given market failures associated with both greenhouse gas pollution and financial frictions, and given banks' non-trivial exposure to carbon-intensive assets, understanding the interactions between climate policy and macroprudential policy is important for the efficient design of such policies.

The purpose of this paper is to study how the presence of financial market frictions affects the efficient design of climate policy and the possibility of transition risk. We answer the following questions: (i) Could a sudden and ambitious climate policy create transition risk,

[1] See also ESRB (2016), Bank of England (2018), Banque de France (2019), Rudebusch (2019), NGSF (2020).

and can macroprudential policy alleviate this risk? (ii) How do financial frictions affect the efficient design of climate policy and of macroprudential financial policy in the long run and over business cycles? We develop a dynamic stochastic general equilibrium (DSGE) model with 'brown' (polluting) and 'green' (non-polluting) production sectors, and two types of market failures: a climate pollution externality, and an externality from financial frictions in a banking sector. We allow for two types of policies: a carbon tax to target the climate externality, and macroprudential policies in the form of a tax or a subsidy on banks' assets to target financial frictions.

At the core of our model are banks that raise deposits from households and make loans to non-financial firms in green and brown sectors. The firms in turn rely on bank credit to finance capital purchases. Financial frictions between banks and depositors constrain the amount of investment in the economy by banking sector equity (or net worth). Therefore, when banks are in financial stress (i.e., when their net worth is low), real economic activity falls. This is a newly-identified channel through which climate policy can impact the economy.

We calibrate the model to U.S. data and run two sets of simulations. First, we consider the response of the economy to an exogenous abrupt introduction of ambitious climate policy, and we study how this response can be mitigated using macroprudential policies. These simulations address the threat of transition risk induced by climate policy. Second, we solve for the efficient policy responses (the Ramsey problem) both in the long run (the steady state) and in response to business cycles generated by exogenous productivity shocks (as in the real business cycle literature). These simulations address how the pollution externality and the financial friction externality interact in the design of efficient policies. We consider both the first-best case, where both a carbon tax and macroprudential policies are available, and second-best cases where some policies are constrained. To assess the role of financial stability risk, we compare economies both with and without financial frictions.

Our first set of simulations shows that transition risk is possible – ambitious climate action can trigger instability in the banking sector – and that macroprudential policy can alleviate this risk. Without financial frictions, an unanticipated introduction of a permanent carbon tax triggers a transition away from brown production and towards green production. But, with financial frictions, the same carbon tax can lead to a contraction in both the green and brown sector – a recession. Due to financial instability in the banking sector, climate policy has a negative spillover effect on the green sector. The hike in the carbon tax lowers the market value of carbon-intensive assets (asset stranding). Because of their exposure to these assets, banks experience equity losses and are forced to cut lending to both brown and green producers. Investment in green capital and green output fall.

The extent of transition risk depends on banks' exposure to carbon-intensive assets at the time of climate action. Therefore, we consider macroprudential policy tools to mitigate the transition risk – taxes or subsidies on banks' assets – that shift banks' portfolio composition away from brown assets.[2] Our results suggest that financial regulators, acting within their financial stability mandates, can reduce banks' exposure to climate-sensitive industries that would mitigate the risk of a disorderly transition to a low carbon economy. That is, central banks and financial regulators can limit transition risk now to prevent the need to delay, on financial stability grounds, ambitious climate policy, when the opportunity for more stringent policy would present itself.

In our second set of simulations, we solve for the Ramsey-optimal carbon tax and macroprudential policy under financial frictions. That is, a regulator can set either policy to maximize economic efficiency given the market failures. In these simulations we focus on both the long run (the steady state) and on business cycles driven by productivity shocks.

[2]Although we focus on one type of macroprudential instrument (taxes) our modelling approach captures a broader set of proposed prudential tools, including climate risk stress-tests, whose main goal is to explicitly or implicitly 'penalize' banks' exposure to carbon-intensive sectors. See Campiglio et al. (2018) and Krogstrup and Oman (2019) for surveys of proposed tools including climate stress-tests and risk disclosure, brown penalizing and green subsidizing factors in bank capital requirements. For instance, a recent policy being discussed by the European Central Bank consists in requiring banks to provide a climate risk assessment, following which banks with excessive exposure to climate risk could see their collateral valuations affected, potentially limiting their access to central bank's funding.

The steady state results demonstrate the importance of the interaction of the two market failures. Without financial frictions, the carbon tax brings about the first best by reducing emissions. With financial frictions, and when the only available policy instrument is the carbon tax, the second-best carbon tax is lower than its first-best level. This is because the financial friction externality works in the opposite direction as the climate externality – the financial frictions lead to underproduction, and the pollution externality leads to overproduction. When the only available policy instrument is a uniform macroprudential policy – a tax or subsidy on banks' assets that is the same for brown and green assets – then output is higher than in the unregulated equilibrium, but pollution is also higher. The regulator uses macroprudential policy to primarily tackle financial frictions and pays very little attention (in a quantitative sense) to fixing the climate externality. Using financial regulation alone as a substitute for climate policy is not very efficient. This is even true when the regulator can use a differentiated macroprudential policy – a tax or subsidy on banks' assets that can be different for brown and green assets. Under the second-best differentiated macroprudential policy, pollution is not much lower than it is under the second-best uniform macroprudential policy. When both a carbon tax and macroprudential policy are available, then the first-best outcome can be achieved. Hence, the implementation of macroprudential policy is not only useful in dealing with transition risk, but also later on, to complement climate policy with the goal of leading to an efficient level of economic activity and emissions.

The business cycle results also demonstrate the importance of accounting for both market failures. In response to a negative total factor productivity shock, when financial frictions are present the efficient carbon tax falls by more than when those frictions are absent. As a result, emissions are less procyclical when financial frictions are present. When macroprudential policies are available, emissions are more procylical than when the carbon tax is the only available instrument. In the absence of a carbon tax, macroprudential policies (both uniform and differentiated) yield more procyclical emissions than the first best.

Our paper contributes to several strands of literature. Our paper contributes to a growing theoretical literature on climate policy and stranded assets. For example, van der Ploeg and Rezai (2020) and Rozenberg, Vogt-Schilb and Hallegatte (2020) show that unanticipated changes in climate policy may result in stranding of carbon-intensive capital.[3] We also contribute to an emerging literature analyzing the role, if any, of central banks and macroprudential authorities in tackling climate change, including Campiglio (2016), Böser and Senni (2020), and McConnell et al. (2020).

Methodologically, our paper combines two strands of the DSGE literature. The first is the literature that adds an environmental component to a DSGE model (which has been called an E-DSGE model) to study climate and other environmental policies under business cycles, including Fischer and Springborn (2011), Heutel (2012), and Dissou and Karnizova (2016).[4] Second, our paper relates to the literature addressing the role of financial frictions in driving macroeconomic dynamics, using a banking sector model from Gertler and Kiyotaki (2010) and Gertler and Karadi (2011). Our model combines a standard DSGE real business cycle model with an environmental component (as in the E-DSGE literature) and with banking financial frictions (as in Gertler and Kiyotaki 2010 and Gertler and Karadi 2011).

Several other E-DSGE papers also consider macroeconomic policies and the interaction between macroeconomic and environmental policies. Annicchiarico and Di Dio (2015, 2017) and Economides and Xepapadeas (2018) add a new-Keynesian specification of price rigidities to an E-DSGE model to study monetary policy. Chan (2020) compares fiscal and monetary policies to climate policies.

Two concurrent working papers are most closely-related to our paper: Diluisi et al. (2020) and Benmir and Roman (2020). Both of these papers also combine an E-DSGE model with a model of banking sector financial frictions based on Gertler and Kiyotaki (2010) and Gertler

[3] There is also growing empirical literature studying climate policy and stranded assets, such as Ramelli et al. (2019), Carattini and Sen (2019), Sen and von Schickfus (2020). This literature generally shows that stock market valuations tend to react immediately to climate policy shocks, as modeled in our paper. If the threat of immediate climate policy disappears, stock valuations rebound, even if climate change has not disappeared (see also van der Ploeg 2020 for a review of the inability of financial markets to fully price climate risks).

[4] See Fischer and Heutel (2013) for an early survey of this literature.

and Karadi (2011), and both of these papers also consider both a carbon tax as well as various macroprudential policies.[5] In contrast to our paper, neither of these two papers considers the first-best or second-best efficient policy design via a Ramsey optimization problem.[6] While Diluiso et al. (2020) studies the transition risk in response to climate policy, our modeling approaches differ. They focus on a pre-announced, gradually increasing emissions tax. Because of anticipation effects driven by the pre-announced path, they find that transition risk is limited. Instead, in line with the concerns raised by central banks and financial regulators, our focus is on an unanticipated introduction of ambitious climate policy. We find that transition risk can be important with negative spillovers on the green sector.

The paper proceeds as follows. Section 2 presents the model, and Section 3 describes the calibration. Sections 4 and 5 present our simulation results. In Section 4, we assess the transition risk of climate-policy-induced recession by presenting the response to an unanticipated exogenous emissions tax shock, both with and without financial frictions, and with and without macroprudential policies. Section 5 presents results from the Ramsey problems of efficiency-maximizing emissions tax and/or macroprudential policies in the deterministic steady state and in response to exogenous productivity shocks. Section 6 concludes.

2 Model

We consider a closed economy consisting of households, a government, and four types of firms – financial intermediaries (banks), capital producers, and non-financial final-goods-producing 'green' and 'brown' firms. Our economy features two sources of inefficiency. The first is a standard environmental externality: brown firms do not internalize how their individual production decisions affect the pollution stock and thus aggregate output. The second source of inefficiency comes from financial market frictions: total capital in the economy is limited

[5] Böser et al. (2020) also model financial frictions, but not in a DSGE context.

[6] Benmir and Roman (2020) consider a Ramsey problem, but only for the second-best carbon tax.

by banks' net worth, and bankers do not internalize how their net worth affects the economy. To address these inefficiencies we model two types of policies: climate policy, in the form of a carbon tax, and macroprudential policies, in the form of taxes or subsidies on banks' assets, which could be assessed at different rates for brown and green assets.

2.1 Households

We follow Gertler and Karadi (2011) in formulating the household sector. There is a continuum of identical households of measure unity. Each household has a continuum of a unit measure of family members. A fraction $(1-\iota)$ of members are workers and a fraction ι are bankers. Workers supply labor hours to non-financial firms in brown and green production sectors and return wage income to the household. Each banker manages a financial intermediary (a bank) and transfers dividends to the household. There is perfect consumption insurance within the household. The household consumes and saves. Households cannot save by directly lending to productive firms. Rather, they can only save through depositing funds in banks.

A representative household chooses consumption C_t, savings in the form of bank deposits D_t, and sector-specific labor hours, L_t^b and L_t^g, to maximize

$$\mathbb{E}_0 \left\{ \sum_{t=0}^{\infty} \beta^t \frac{1}{1-\eta} \left(C_t - \varpi \frac{\left[\left(L_t^b\right)^{1+\rho_L} + \left(L_t^g\right)^{1+\rho_L} \right]^{\frac{1+\xi}{1+\rho_L}}}{1+\xi} \right)^{1-\eta} \right\}, \tag{1}$$

subject to the budget constraint,

$$C_t + D_t = w_t^b L_t^b + w_t^g L_t^g + R_{t-1} D_{t-1} + \Xi_t + \Pi_t + T_t, \tag{2}$$

where w_t^b and w_t^g are wage rates in brown and green sectors; R_{t-1} is a non-contingent interest rate on bank deposits; Ξ_t are net dividends from banks; Π_t denotes profits from the ownership of non-financial firms; and T_t is a lump-sum transfer from the government. The parameter

$\beta \in (0,1)$ is the household's subjective discount factor, $\varpi > 0$ is a labor disutility parameter, and $\eta > 0$ controls the curvature of the utility function.

The specification of labor hours in the utility function follows Horvath (2000) and allows for imperfect labor substitutability between the sectors. In every period the representative household is endowed with one unit of time. Denote by $L_t \equiv \left[\left(L_t^b\right)^{1+\rho_L} + \left(L_t^g\right)^{1+\rho_L}\right]^{\frac{1}{1+\rho_L}}$ total (composite) hours worked in period t. When $\rho_L = 0$ labor hours in brown and green sectors are perfect substitutes. When $\rho_L > 0$, labor hours are imperfect substitutes across the sectors. The parameter ξ is the inverse of the Frisch elasticity of the labor hours aggregator.

Let $M_{t,t+1} \equiv \beta \frac{U_{c,t+1}}{U_{c,t}}$ be the household's stochastic discount factor, where $U_{c,t} = \left(C_t - \varpi \frac{L_t^{1+\xi}}{1+\xi}\right)^{-\eta}$ is the marginal utility of consumption in period t. Then households' optimal consumption and sector-specific labor supply decisions are characterized by the standard first order conditions:

$$\mathbb{E}_t \left(M_{t,t+1} R_t\right) = 1, \tag{3}$$

$$\varpi L_t^{\xi-\rho_L} \left(L_t^i\right)^{\rho_L} = w_t^i, \quad \text{for } i = \{g, b\}. \tag{4}$$

2.2 Bankers

Each banker manages a financial intermediary (a bank). The banker offers loans to non-financial firms by combining her own net worth with external funds raised from households in the form of deposits. In particular, at time t, an individual banker j purchases securities $S_{j,t}^i$, at unit price Q_t^i, issued by final good producing firms in sector $i = \{g, b\}$.[7] We assume that the government can levy macroprudential taxes (or subsidies if negative) τ_t^i, $i = \{g, b\}$, on banks' assets. We allow these taxes to potentially differ across brown and green assets, which would capture the scenario in which a supervisory authority takes into account environmental aspects

[7] These securities are claims on the gross rate of return on sector-specific capital.

in bank capital regulation.[8] In addition, banks are subject to small asset management costs, described below in detail. The banker finances the expenditure side of her balance sheet with net worth $N_{j,t}$ and newly issued deposits $D_{j,t}$.

The individual bank's balance sheet or flow-of-funds constraint is

$$(1+\tau_t^b)Q_t^b S_{j,t}^b + (1+\tau_t^g)Q_t^g S_{j,t}^g + \Psi(Q_t^g S_{j,t}^g, \mathcal{W}_{j,t}) = D_{j,t} + N_{j,t}, \tag{5}$$

where Ψ is a quadratic cost function, $\Psi(Q_t^g S_{j,t}^g, \mathcal{W}_{j,t}) = \frac{\psi}{2}\left(\frac{Q_t^g S_{j,t}^g}{\mathcal{W}_{j,t}} - \overline{s}^g\right)^2 \mathcal{W}_{j,t}$. Here $\mathcal{W}_{j,t} \equiv Q_t^b S_{j,t}^b + Q_t^g S_{j,t}^g$ is the total value of assets held by banker j at time t. The parameter $\overline{s}^g$ is a measure of banks' long-run (steady state) green-to-total assets ratio, and $\psi > 0$ is the adjustment cost parameter. In our calibration these costs are very small and their sole purpose is to make banks' steady-state portfolio choice determinate.[9]

Denote by $R_{k,t}^b$ and $R_{k,t}^g$ the time t realized gross rate of returns on banks' brown and green assets, respectively. Then over time the individual bank's net worth evolves according to

$$N_{j,t+1} = R_{k,t+1}^b Q_t^b S_{j,t}^b + R_{k,t+1}^g Q_t^g S_{j,t}^g - R_t D_{j,t}. \tag{6}$$

As in Gertler and Kiyotaki (2010) and Gertler and Karadi (2011), we introduce the following moral hazard problem to limit banks' ability to obtain external funds: After raising deposits and purchasing assets at time t a banker managing the bank can choose to divert an exogenous

[8] These taxes/subsidies capture some of the proposed policies - e.g., brown penalizing and green supporting factors - in bank regulatory frameworks. They can also implicitly capture other types of macroprudential policy tools that could make brown assets less attractive for banks not necessarily through direct cost. While bank regulation is more frequently implemented via capital requirements that impose banks to hold a certain fraction of equity against their assets, many countries also widely use a tax on banks' balance sheets as a macroprudential policy tool. See Cerutti et al. (2017) for a survey. Further, as mentioned earlier, central banks are starting to consider implicit taxes on banks depending on the carbon intensity of their assets.

[9] This is a common technical tool to make portfolio choice determinate in models solved around deterministic steady state (see, for example, Gertler et al. 2012, Aoki et al. 2018). Intuitively, in our model asset management costs capture the idea that moving assets between sectors may be costly. For example, banks may have branches that specialize in specific type of loans or sectors. Changing the structure of asset portfolios may thus require costly allocation of resources (human and physical) between the branches.

fraction κ of total assets for personal use (i.e., transfer the funds to his/her own household).[10] The cost to the banker from diverting the funds is that the depositors can shut down the bank after recovering the remaining $(1-\kappa)$ fraction of assets. Recognizing the possibility of bankers 'running away', depositors will thus lend to banker j only if she has incentives to operate honestly.

Let $V_{j,t}$ denote the franchise (or continuation) value of the bank at the end of period t. Then for the depositors (households) to be willing to deposit money with banker j, the following incentive constraint must be satisfied,

$$V_{j,t} \geq \kappa \underbrace{\left(Q_t^b S_{j,t}^b + Q_t^g S_{j,t}^g\right)}_{\mathcal{W}_{j,t}}. \tag{7}$$

That is, households are willing to lend to a bank as long as the bank's franchise value $V_{j,t}$, which measures the present discounted value of future profits from operating honestly, is larger than the gains from diverting funds. Because this inequality always holds, in equilibrium bankers never actually 'run away' or divert funds.

At the end of each period a banker may exit the business with an exogenous i.i.d. probability $1-\gamma$.[11] Upon exit, a banker transfers its retained earnings to her family in the form of dividends, and becomes a worker.[12] Surviving bankers reinvest all their net worth. Since bankers are members of households, they maximize the expected present value of their terminal wealth (or future dividend payouts to households). A banker chooses asset holdings in green and brown

[10] Households deposit funds in banks other than the ones they own.

[11] This assumption is common in the financial frictions literature (see, for example, Gertler and Kiyotaki 2010, Gertler and Karadi 2011) and guarantees that banks never accumulate enough internal funds to avoid the need for external finance.

[12] The number of bankers that become workers in every period is thus $(1-\gamma)\,\iota$. To keep the relative proportion of each group fixed over time, we assume that the same number of workers randomly become bankers in every period.

production sectors $S^i_{j,t}$, $i = \{g, b\}$, and deposits $D_{j,t}$ to maximize

$$V_{j,t} = \mathbb{E}_t \left\{ \sum_{\widetilde{\tau}=t+1}^{\infty} (1-\gamma)\, \gamma^{\widetilde{\tau}-t-1} M_{t,\widetilde{\tau}} N_{j,\widetilde{\tau}} \right\}, \tag{8}$$

subject to (5), (6) and (7), where $M_{t,\widetilde{\tau}}$ is the households' stochastic discount factor $M_{t,\widetilde{\tau}} \equiv \beta^{\widetilde{\tau}-t} \frac{U'_{c,\widetilde{\tau}}}{U'_{c,t}}$.

Denote by $s^g_t = \frac{Q^g_t S^g_{j,t}}{\mathcal{W}_{j,t}}$ the portfolio share of green assets.[13] It is convenient to reformulate the banker's problem in which the banker decides on holdings of total assets ($\mathcal{W}_{j,t}$) and the portfolio share of green assets (s^g_t). Appendix A contains a detailed characterization of the bank's problem and associated optimality conditions. Here we discuss key equations.

In the Appendix we show that the bank's value function is linear in individual net worth,

$$V_{j,t} = \varphi_t N_{j,t}, \tag{9}$$

where $\varphi_t \geq 1$ is the time-varying shadow value of bank's net worth, common across banks.[14] Combining (9) with (7) we can express the incentive constraint as

$$Q^b_{j,t} S^b_{j,t} + Q^g_{j,t} S^g_{j,t} \leq \frac{\varphi_t}{\kappa} N_{j,t}. \tag{10}$$

That is, bank's assets cannot exceed a fraction $\frac{\varphi_t}{\kappa}$ of its equity capital. In our calibrated model, this constraint will always bind in the proximity of the steady state. Aggregating (10) at equality over the entire banking sector yields

$$Q^b_t S^b_t + Q^g_t S^g_t = \frac{\varphi_t}{\kappa} N_t. \tag{11}$$

[13] We dropped the bank-specific index j from s^g_t, because as we show later the portfolio shares are the same across banks.

[14] The marginal shadow value of net worth positively depends on the expected average excess return on bank's assets over deposits.

This is the key equation capturing the negative financial accelerator and the inefficiency arising from the financial sector. When banks are financially constrained, the demand for capital in the economy $\left(Q_t^b S_t^b + Q_t^g S_t^g\right)$ is restricted by the amount of financial intermediaries' net worth (N_t). Shocks to the economy get amplified through fluctuations in the banking sector's equity capital. Bankers do not internalize this effect that their net worth has on the economy, and thus the equilibrium fails to reach the efficient level of production.

Equation (11) determines the total amount of brown and green capital intermediated by banks. The demand for sector-specific assets is then pinned down by the optimal portfolio share of green assets,

$$s_t^g = \frac{\mathbb{E}_t \left\{\Omega_{t+1} \left[\left(R_{k,t+1}^g - R_{k,t+1}^b\right) - \left(\tau_t^g - \tau_t^b\right) R_t\right]\right\}}{\psi \mathbb{E}_t \left[\Omega_{t+1} R_t\right]} + \overline{s}^g, \tag{12}$$

where $\Omega_{t+1} \equiv M_{t,t+1} \left(1 - \gamma + \gamma \varphi_{t+1}\right)$ is the banker's effective stochastic discount factor. The numerator on the right hand side of equation (12) is the expected discounted excess return on green assets over brown assets. It takes into account tax (dis)advantage of each type of asset. For example, other things equal, higher τ_t^b (or lower τ_t^g) increases the optimal share of green assets in bank's portfolio. Therefore, through macroprudential taxes a regulator can affect relative attractiveness of brown versus green assets in banks' portfolios.

Banks that exit the business are replaced by an equal number of new banks with each of them receiving a small initial start-up transfer $\frac{\zeta}{1-\gamma} \sum_{i=\{g,b\}} Q_t^i S_t^i$ from the households. Thus, the aggregate banking sector's net worth evolves according to

$$N_{t+1} = \gamma \left[\sum_{i=\{g,b\}} R_{k,t+1}^i Q_t^i S_t^i - R_t D_t\right] + \zeta \sum_{i=\{g,b\}} Q_t^i S_t^i, \tag{13}$$

and the net dividend payouts to households are

$$\Xi_{t+1} = (1-\gamma)\left[\sum_{i=\{g,b\}} R^i_{k,t+1} Q^i_t S^i_t - R_t D_t\right] - \zeta \sum_{i=\{g,b\}} Q^i_t S^i_t. \tag{14}$$

As is common in the financial frictions literature, we define aggregate banking sector leverage ratio as the value of banks' total assets over net worth, $\text{lev}_t \equiv \frac{Q^b_t S^b_t + Q^g_t S^g_t}{N_t}$. Similarly, credit spread is a difference between the expected rate of return on a given type of asset and the risk free rate, $\text{spread}^i_t \equiv \mathbb{E}_t\left(R^i_{k,t+1} - R_t\right), \ \ i \in \{b, g\}$.

2.3 Firms producing goods

There are two types of representative goods-producing firms: green and brown. Brown production entails emissions as a by-product, while green production does not. Both production sectors rely on the banking sector in obtaining external funds to purchase capital for production.

Production technology — Pollution negatively affects productivity in both green and brown sectors. Both types of firms operate a standard Cobb-Douglas production technology with capital $\left(K^i_{t-1}\right)$ and labor (L^i_t) inputs,

$$Y^i_t = \left[1 - d\left(X_t\right)\right] A_t \left(K^i_{t-1}\right)^{\alpha^i} \left(L^i_t\right)^{1-\alpha^i}, \ 0 < \alpha^i < 1,$$

where X_t is the pollution stock in the economy, $d(\cdot) \in (0, 1)$ is an increasing damage function; A_t is the aggregate economy-wide total factor productivity (TFP) shock

$$\log A_t = \rho_A \log A_{t-1} + \sigma_A \varepsilon_{A,t}, \quad \varepsilon_{A,t} \sim \mathcal{N}(0,1). \tag{15}$$

We assume that goods produced using green and brown technologies are imperfect substitutes. The final consumption good Y_t is a constant elasticity of substitution aggregate of sectoral outputs,

$$Y_t = \left[\left(\pi^b\right)^{\frac{1}{\rho_Y}} \left(Y_t^b\right)^{\frac{\rho_Y - 1}{\rho_Y}} + \left(1 - \pi^b\right)^{\frac{1}{\rho_Y}} \left(Y_t^g\right)^{\frac{\rho_Y - 1}{\rho_Y}} \right]^{\frac{\rho_Y}{\rho_Y - 1}}, \tag{16}$$

where $\rho_Y > 0$ is the elasticity of substitution parameter, and π^b is the weight on brown input in the final good production. The standard demand functions for the two types of output are

$$Y_t^b = \pi^b \frac{Y_t}{\left(p_t^b\right)^{\rho_Y}},\ Y_t^g = \left(1 - \pi^b\right) \frac{Y_t}{\left(p_t^g\right)^{\rho_Y}}, \tag{17}$$

where p_t^b and p_t^g denote relative prices of brown and green goods.[15]

Brown sector — Production in the brown sector entails emissions as a by-product. The pollution stock X_t evolves according to

$$X_t = \delta_X X_{t-1} + e_t + e_t^{\text{row}}, \tag{18}$$

where e_t denotes current-period domestic emissions and e_t^{row} is emissions imposed from the rest of the world. Domestic emissions depend on production level in the brown sector $\left(Y_t^b\right)$ and fraction of emissions abated (μ_t),

$$e_t = (1 - \mu_t)\, h\left(Y_t^b\right). \tag{19}$$

Abateting fraction μ_t of emissions costs Z_t units of final good,

$$Z_t = f\left(\mu_t\right) Y_t^b, \tag{20}$$

We follow Heutel (2012) and Nordhaus (2008) in specifying the functional forms for emissions elasticity with respect to output, $h\left(Y_t^b\right) = \left(Y_t^b\right)^{\epsilon}$, and the abatement cost function, $f\left(\mu_t\right) = \theta_1 \mu_t^{\theta_2}$. An environmental externality arises from the fact that a representative carbon-intensive firm does not internalize how its production decisions affect both green and brown output

[15] We use the price of the final consumption good as a numeraire and normalize its value to 1.

through the pollution stock X_t and associated damages $d(X_t)$.

At the end of period t final goods firms in the brown sector purchase capital K_t^b from capital producers at market price Q_t^b. Following Gertler and Karadi (2011) the firms finance their capital purchases by issuing financial claims S_t^b to banks. Each claim is priced at the same price $\left(Q_t^b\right)$ as capital so that $Q_t^b K_t^b = Q_t^b S_t^b$.[16] After production takes place in time $t+1$, the firm can sell the undepreciated capital $\left(1-\delta^b\right) K_t^b$ on the market at price Q_{t+1}^b. We assume that there are no financing frictions between firms and banks, and thus, the firms offer a state-contingent payoff $R_{k,t+1}^b$ on securities owned by the financial intermediaries.

Brown firms are subject to emissions tax τ_t^e imposed by the government. Their time t realized profits are

$$\Pi_t^b = p_t^b Y_t^b - \tau_t^e e_t - Z_t - w_t^b L_t^b - R_{k,t}^b Q_{t-1}^b K_{t-1}^b + \left(1-\delta^b\right) Q_t^b K_{t-1}^b, \tag{21}$$

The optimality conditions with respect to labor $\left(L_t^b\right)$ and abatement (μ_t) are:

$$w_t^b = \left(1-\alpha^b\right) \frac{Y_t^b}{L_t^b} \left[p_t^b - f(\mu_t) - \tau_t^e (1-\mu_t) h'\left(Y_t^b\right)\right], \tag{22}$$

$$\tau_t^e h\left(Y_t^b\right) = Y_t^b f'(\mu_t). \tag{23}$$

A state-contingent return on brown assets, satisfying the first order optimality condition, is given by

$$R_{k,t}^b = \frac{\alpha^b \frac{Y_t^b}{K_{t-1}^b} \left[p_t^b - f(\mu_t) - \tau_t^e (1-\mu_t) h'\left(Y_t^b\right)\right] + \left(1-\delta^b\right) Q_t^b}{Q_{t-1}^b}. \tag{24}$$

Green sector — Similar to brown firms, green firms rely on bank credit to purchase sector-specific capital K_t^g at price Q_t^g. They also hire labor L_t^g from households at wage rate w_t^g. The

[16]By arbitrage the price of claims issued by firms must be the same as a price of new capital goods.

green firms' optimality conditions imply

$$w_t^g = (1 - \alpha^g) \frac{p_t^g Y_t^g}{L_t^g}, \tag{25}$$

and

$$R_{k,t}^g = \frac{\alpha^g \frac{p_t^g Y_t^g}{K_{t-1}^g} + (1 - \delta^g) Q_t^g}{Q_{t-1}^g}. \tag{26}$$

2.4 Capital goods producers

Capital is sector-specific and immobile across sectors. At the end of period t, competitive capital-producing firms build new capital for the green and brown sectors. Producing capital goods is subject to quadratic adjustment costs. Producing I_t^i, $i = \{g, b\}$, units of sector-specific new capital goods requires $\left(1 + \frac{\phi^i}{2}\left(\frac{I_t^i}{I_{t-1}^i} - 1\right)^2\right) I_t^i$ units of the final good, where $\frac{\phi^i}{2}\left(\frac{I_t^i}{I_{t-1}^i} - 1\right)^2 I_t^i$ is the investment adjustment cost.[17] The parameter $\phi^i \geq 0$ controls the size of the adjustment cost. These adjustment costs ensure that the equilibrium prices of brown and green assets vary endogenously, affecting the banking sector's net worth.

Denote by Q_t^i the price of new sector-specific capital goods. The capital producers solve

$$\max_{\{I_t^i\}_{i=\{g,b\}}} \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t M_{0,t} \left[\sum_{i=\{g,b\}} Q_t^i I_t^i - \left(1 + \frac{\phi^i}{2}\left(\frac{I_t^i}{I_{t-1}^i} - 1\right)^2\right) I_t^i\right]. \tag{27}$$

The first order optimality condition associated with this problem is

$$Q_t^i = 1 + \frac{\phi^i}{2}\left(\frac{I_t^i}{I_{t-1}^i} - 1\right)^2 + \phi^i \left(\frac{I_t^i}{I_{t-1}^i} - 1\right) \frac{I_t^i}{I_{t-1}^i} - \mathbb{E}_t \left\{M_{t,t+1} \phi^i \left(\frac{I_{t+1}^i}{I_t^i} - 1\right)\left(\frac{I_{t+1}^i}{I_t^i}\right)^2\right\}, \quad i = \{g, b\}. \tag{28}$$

[17] The quadratic adjustment cost function is based on Christiano, Eichenbaum, and Evans (2005) and is standard in the literature.

Sector-specific capital stock evolves according to

$$K_t^i = \left(1 - \delta^i\right) K_{t-1}^i + I_t^i, \text{ for } i = \{g, b\}, \tag{29}$$

where δ^i is the depreciation rate of capital.

2.5 Government

The government simply transfers revenues to households in a lump-sum manner,

$$T_t = \tau_t^e e_t + \tau_t^b Q_t^b S_t^b + \tau_t^g Q_t^g S_t^g. \tag{30}$$

3 Calibration

In this section we describe the calibration of the model. A period in the model corresponds to one quarter. The model parameters can be divided into three categories: standard real business cycle (RBC) parameters, parameters related to financial frictions, and parameters related to climate externalities. Table 1 summarizes the calibrated values. The calibration is done for the baseline scenario when all policy instruments are set at zero (i.e., $\tau_t^e = \tau_t^b = \tau_t^g = 0$).

We choose standard values for the subjective discount factor $\beta = 0.995$ (which implies annualized risk-free rate of 2% in the steady state), the risk aversion parameter, $\eta = 2$, the Frisch elasticity of labor supply, $\frac{1}{\xi} = 1$, and the capital depreciation rate $\delta^b = \delta^g = 0.025$. We set the capital share in green production α^g to 0.33. We allow the brown sector to be slightly more capital intensive, $\alpha^g = 0.35$.[18] Both of these values are commonly used in the RBC literature. The parameter controlling for inter-sectoral elasticity of substitution between labor hours (ρ_L) is set to 1. This is the estimate found by Horvath (2000) using sectoral labor

[18]For instance, Antweiler et al. (2001) and Fullerton and Heutel (2007) find that the dirty sector is slightly more capital intensive than the clean sector.

hours data from the U.S.[19] As is common in the RBC literature, we set the labor disutility parameter ϖ so that the fraction of time spent working in the steady state is $\frac{1}{3}$.

For the elasticity of substitution between green and brown output we rely on empirical estimates in Papageorgiou et al. (2013) and set $\rho_Y = 2$. We choose the share of brown output in the production of final consumption good $\left(\pi^b\right)$ to target the steady state ratio of green-to-total capital stock of 0.60. The implied value, $\pi^b = 0.3326$, is also consistent with the fact that income share of green sector to total output is about 70%.

The persistence and standard deviation of the aggregate TFP shock are set at the standard RBC values, $\rho_A = 0.95$, $\sigma_A = 0.007$. The investment adjustment cost parameter for both sectors (ϕ^i) is 10. These values are in line with the parameter values also used in the environmental DSGE literature (e.g., Heutel 2012, Annicchiarico and Di Dio 2015).

We calibrate the environmental part of the model based on the most recent version of the DICE model (Nordhaus 2018). While DICE models damage as a function of temperature, where temperature is affected by the carbon stock through a dynamic climate model, here we simplify and model damages directly as a function of carbon $d\left(X_t\right)$. The climate damage function takes a quadratic form $d\left(X_t\right) = d_0 + d_1 X_t + d_2 X_t^2$. We use the parameter estimates $d_0 = -0.0076$, $d_1 = 8.10e-6$, and $d_2 = 1.05e-8$ from Gibson and Heutel (2020). In the parameterized damage function, pollution stock (X_t) is measured in gigatons, while in our model the units are abstract. To map the empirical estimates into the model, we set the steady-state pollution level to 2030 GtC, which is the mean value of the carbon stock over the first 250 years of the simulation in the DICE business-as-usual scenario.[20] This implies that at the steady state, damages are of 5.2% of output (i.e., $d(X_{ss,\text{model}}) = 0.052$). It also implies (as we will show in the results) that the steady-state level of the efficient carbon tax is about \$ 30 per ton of carbon

[19] Horvath (2000) estimates inter-sectoral constant elasticity of substitution parameter, restricted to be the same across sectors, of labor hours using a multi-sector RBC model parametrized to the 2-digit SIC level of disaggregation.

[20] That is, we compute $d_{\text{scale}} = \frac{X_{ss,\text{model}}}{2030 \text{ GtC}}$ and rescale the empirical estimates accordingly: $\widehat{d_1} = \frac{d_1}{d_{\text{scale}}}$ and $\widehat{d_2} = \frac{d_2}{d_{\text{scale}}^2}$.

dioxide, which is approximately equal to the social cost of carbon found in IAMs like DICE (Nordhaus 2017).[21]

The abatement cost function is also parameterized following Nordhaus (2018). We set the exponent θ_2 to 2.6 – the same value as in Nordhaus (2018). To calibrate the coefficient θ_1, we take into account two considerations: First, the abatement cost coefficient is a decreasing function of time in DICE, representing growth in abatement technology, though it is constant in our model. Second, in our model the abatement cost applies only to the brown sector, while in DICE it is calibrated as a share of total GDP. As in our strategy for the steady-state pollution stock calibration, we take the mean value of the abatement coefficient from DICE over the first 250 years of the simulation, and then we rescale it to account for the fact that it applies just to the brown sector.[22] The resulting value of θ_1 is 0.0335.

Since in our model emissions depend on brown production, we assume the unit elasticity of emissions with respect to brown output, $\epsilon = 1$. This value is consistent with the estimates in the existing one-sector environmental RBC literature.[23] The pollution decay parameter δ_X is 0.9965. Emissions from the rest of the world are assumed to be constant over time $e_t^{\text{row}} = e^{\text{row}}$. Consistent with the fact that the U.S. emits about one-sixth of global carbon dioxide, we set e^{row} to equal five times the steady state value of domestic emissions.

We set the bank survival rate γ to 0.972 as in Gertler and Karadi (2011), implying that on average bankers survive for about 9 years. We choose the values for the fraction of funds that can be diverted (κ) and transfer parameter (ζ) to match the steady state leverage ratio of the banking sector of 4.5 and annualized credit spreads (both on brown and green assets) of 90 basis points. This implies the parameter values $\kappa = 0.3409$, $\zeta = 0.003$, which are in

[21]However, other studies using other IAMs or other methodologies argue for higher social costs of carbon (e.g. Ricke et al. 2018, Pindyck 2019).

[22]The mean value of the abatement cost coefficient for the first 250 years of DICE simulation is 0.015. We multiply this value by the ratio $\frac{Y_{ss}}{Y_{ss}^b}$ to obtain the adjusted θ_1.

[23]Heutel (2012) estimates the elasticity of CO_2 emissions with respect to GDP using the monthly data from the U.S. and finds this elasticity to be within the range of $0.55 - 0.88$. Doda (2014) finds this elascticity to be 1.01 using annual data.

line with the ones used in Gertler and Karadi (2011) and Gertler and Kiyotaki (2010). We set the banks' portfolio adjustment cost parameter to a very small number, $\psi = 10^{-4}$, as its sole purpose is to make banks' steady state portfolio determinate. The parameter $\overline{s}^g$ is set at 0.60 to be consistent with the share of green capital of 60%.

4 Climate action and transition risk

In this section we study transition dynamics to a low-carbon economy, and we assess the risk of policy-induced recession and the potential for macroprudential policy to address it.[24] We consider a surprise introduction of a permanent emissions tax of 30.5 dollars per ton of CO_2, which corresponds to the efficient steady-state carbon price in our model. We can think of this scenario as one in which, after decades of delayed and insufficient action, there is a sudden shift in the global political environment resulting in the implementation of ambitious climate policy. The carbon tax that we consider is the same order of magnitude as those recommended by Stiglitz and Stern (2017) and the IMF (2019), which argue that a global carbon tax within the $40-$80 range by 2020 would be necessary to achieve the temperature trajectory consistent with the Paris Agreement. The economy starts in the baseline deterministic steady state (with no policies of either type, climate or macroprudential). In time period 5, the economy is surprised by an introduction of the permanent emissions tax.[25] We focus on the transition dynamics in which, after the tax has been introduced, the economy has perfect foresight about its future path. In this section we ignore productivity shocks. We compare results from our baseline model (described above) to a model that does not have a financial sector and thus does not have financial frictions.[26] This allows us to gauge the importance of financial frictions in the

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[24] We solve the model numerically using Dynare package developed by Adjemian et al. (2011).

[25] The $30.5 per ton tax corresponds to an increase in τ_t^e from 0 to 0.017. To obtain dollar amounts we perform a back-of-the-envelope calculation in which we set the steady state level of aggregate output in the baseline model to be equal to the U.S. GDP ($20 trillion) and the steady state emissions to total U.S. emissions (5 billion tons CO_2).

[26] The model without financial frictions is a two-sector Environmental-DSGE in which households directly intermediate capital to non-financial firms and there is no agency problem between households and firms.

macroeconomic effects of a carbon price shock.

Figures 1 and 2 plot the transition dynamics in response to the emissions tax. Solid lines show the dynamics of our baseline model with financial frictions presented in Section 2. Dashed lines show the dynamics of the model without financial frictions. In response to the exogenous introduction of the permanent tax on carbon, emissions fall by about 36% (Figure 1, Panel (b)). The magnitudes of emissions reduction are very similar in the two models. However, the economy with financial frictions experiences a deeper recession: investment and output fall by more (Figure 1, Panels (c) and (d)).[27]

Figure 2 plots the transition dynamics of financial and sectoral variables to illustrate the mechanisms behind climate-policy-induced financial crisis. Panel (a) shows that the banking sector's net worth falls by about 10% in response to the climate policy shock. The reason for these equity losses in the banking sector is falling asset prices (particularly on brown assets) due to the introduction of the emissions tax. The undercapitalized banks are forced to cut lending both to brown and green sectors. As a result, both brown and green capital fall (Panels (b) and (c)). Importantly, when financial markets are frictionless, the economy moves away from brown and towards green investment, and green capital expands as a result. Thus, the green sector experiences a deeper and more prolonged recession in the economy with financial frictions.

We next ask whether financial regulation can mitigate this transition risk by reducing banks' exposure to brown assets. Suppose that prior to the introduction of the emissions tax, the regulator enacts a tax-and-subsidy scheme on brown and green assets to shift banks' steady-state portfolio composition away from brown assets. We set $\tau^b = 0.006$ and $\tau^g = -0.00316$ so that the policy reduces the share of brown assets in banks' portfolios from 40% (baseline

[27]In these transition simulations our focus is on relatively short to medium term economic dynamics (e.g., during the first 5 years after the carbon tax has been put in place). After the economy fully transitions to a new steady state, in both versions of the model, output and investment increase and efficiency improves due to lower pollution and lower damages from climate change. Early in the transition, however, output falls even in the economy without financial frictions, because the emissions tax lowers equilibrium labor hours, and even though damages also fall, initially the former effect dominates.

calibration) to 32%, and at the same time leaves the steady state output level unchanged.[28]

Figure 3 shows that the macroprudential policy can mitigate the severity of climate policy-induced transition risk. Aggregate investment and output fall by less with the macroprudential policy. At the core of this result is the dynamics of banks' net worth. Since the banking sector is now less exposed to the brown sector, bank equity losses are milder and credit intermediated to the non-financial firms falls by less. In addition, with the macroprudential policy, green economic activity experiences a milder slowdown and faster recovery.[29]

5 Ramsey-optimal climate and macroprudential policies

In Section 4 we studied the role of the financial sector for transition risk induced by an abrupt implementation of climate policy. In those simulations we focused on exogenous policies. This section explores the interactions between financial frictions and environmental externalities and their implications for Ramsey-optimal policies. When both a carbon tax τ_t^e and a common macroprudential tax $\tau_t^b = \tau_t^g$ (subsidy if negative) on banks' assets are available, a Ramsey policymaker can fully undo both types of distortions. We refer to this Ramsey-efficient policy mix and the associated allocations as 'first-best'. Using this first-best scenario as a benchmark, we consider the second-best Ramsey-optimal policies, that is, when one of the instruments is absent from a policy toolbox, and compare outcomes across different scenarios. We also consider the case when, in the absence of an emissions tax, the Ramsey policymaker can set separate taxes on different types of assets (green or brown) in banks' portfolio ($\tau_t^b \neq \tau_t^g$). While

[28]Gertler et al. (2012) and Aoki et al. (2018) also use this type of tax-subsidy scheme on banks' balance sheets to model macroprudential policies. While macroprudential policy can take different forms, the goal of this exercise is not to study optimal policies. Rather, we want to illustrate that macroprudential tools can be potentially used to mitigate the transition risk. Further, tax-subsidy schemes on bank assets mimic well potential capital requirements limiting the amount of brown capital that prudential authorities would allow banks to hold, or limits to central bank's money for banks highly exposed to carbon-intensive sectors.

[29]With macroprudential policy, brown capital and the price of brown assets still fall by almost the same magnitude as in the case with no macroprudential policy (Figure A1 in Appendix). In other words, carbon-intensive assets lose almost as much of their value as before, but the consequences for the aggregate economy, and for the green sector, are not as severe because macroprudential policy makes the banking sector more resilient to brown-asset stranding.

Diluioso et al. (2020) also studied transition risk, as we did in Section 4, they do not address the Ramsey-optimal policy design that we consider here.

5.1 Steady state

Table 2 reports the deterministic steady-state outcomes of key variables in the models with and without financial frictions across different policy scenarios. The first two columns report steady-state outcomes in the model without financial frictions under no-policy scenario and with the Ramsey-optimal emissions tax policy. Columns 3 and 4 consider similar policy scenarios in the model with financial frictions, and the remaining columns also consider macroprudential policies.

In the absence of an emissions tax, firms do not internalize the negative pollution externality, pushing emissions up to inefficiently high levels in both economies. In the model with financial frictions, this effect is counteracted by the inefficiently low production from the banks' externality. That is to say, the two sources of market failure work in opposite directions. As a result, in the unregulated steady-state equilibrium emissions are lower in our baseline model with financial frictions than without them.

In the absence of financial frictions the Ramsey-optimal steady-state emissions tax is 0.0017 in abstract DSGE units, which corresponds to 30.5 dollars per ton of CO_2. In the economy with financial frictions, the optimal carbon tax is 24.2 dollars per ton of CO_2. Because the financial frictions work in the opposite direction of the climate externality, the presence of the financial frictions implies that the carbon tax can be lower. The steady state emissions are thus higher in the model with financial frictions, although this difference is very small in magnitude (i.e., 0.23%). Note that the second column represents a first-best outcome, since in the model without financial frictions the only externality is pollution, and it is corrected through the Pigouvian tax. The fourth column is a second-best outcome; there are two sources of market inefficiencies (pollution externality and financial frictions) but only one instrument (the emissions tax) to address them.

The last three columns report deterministic steady-state outcomes in the baseline model (with both a pollution externalty and financial frictions) when macroprudential policy instruments are available. The fifth column is the case where only a uniform macroprudential policy (i.e., $\tau_t^b = \tau_t^g$) is available,[30] and the sixth column allows for differentiated macroprudential policies. The last column is the 'first-best' scenario, where both the climate and macroprudential instruments available.

When only a uniform macroprudential policy is available, since financial frictions limit the level of economic activity to inefficiently low levels, the Ramsey policymaker subsidizes banks to increase credit supply to the economy. That is, the Ramsey-optimal policy recapitalizes the banking sector by setting $\tau_{ss}^b = \tau_{ss}^g =$ -0.0018. As a result, banks' net worth, aggregate investment and output are all brought closer to their first-best levels. The second-best macroprudential policy, however, implies much higher emissions than the first best due to increased economic activity. The steady-state emissions are about 50% higher than their first-best level, implying more future climate damages.

In column 6, the regulator can take environmental factors into account when setting macroprudential policy by setting separate tax instruments targeted at brown and green assets held by banks. Without an emissions tax, the Ramsey planner subsidizes green assets more than brown assets. The second-best optimal steady-state taxes on brown and green assets are $\tau_{ss}^b = -0.0014$ and $\tau_{ss}^g = -0.0021$, respectively. As a result emissions are lower relative to the case with the uniform macroprudential policy. However, the difference is negligible in magnitude. This happens because when only financial regulatory tools are available, the gains from pushing economic activity closer to its first-best level largely outweigh the costs from increased climate damages.

[30]This policy captures the existing bank regulatory frameworks worldwide, which do not incorporate climate considerations in setting capital requirements.

5.2 Dynamics

Next we study the implications of pollution externalities and financial frictions for Ramsey-optimal dynamic policies in response to productivity shocks. We consider impulse responses to a one-standard deviation negative shock to aggregate productivity A_t.[31]

Figure 4 shows the impulse responses of key variables in the economies with and without credit market frictions, under the Ramsey-optimal emissions tax policy.[32] Similar to the standard RBC model, a negative TFP shock has a familiar contractionary effect on the economy: aggregate investment, output, and labor hours fall. In addition, in our two-sector model all sectoral variables get depressed as the shock symmetrically impacts both sectors.

Consistent with the previous findings in the environmental RBC literature, we find that the optimal emissions tax and emissions are both procyclical. Credit market frictions affect the dynamics of the efficient carbon tax. In the economy with credit market frictions, the optimal emissions tax falls by much more in response to the negative shock, so that emissions actually increase on impact (Figure 4, Panels (b) and (c)). Procyclicality of emissions is thus dampened.

The second-best emissions tax falls more because the credit market frictions inefficiently amplify the responses of the macro aggregates to the negative TFP shock via banks' net worth. A decline in productivity reduces banks' net worth by lowering the return on assets. Given the lower level of equity, the banking sector becomes more constrained in its ability to raise deposits and lend to firms. The lower credit supply further amplifies the decline in investment and output. Since the Ramsey policymaker is equipped with only one instrument – the emissions tax – she uses this instrument to address both the pollution externality and the financial frictions. In response to the negative productivity shock, the Ramsey planner cuts the emissions tax more aggressively to mitigate the fall in bank net worth and credit supply.[33]

[31] The reaction of our economy to negative and positive shocks is symmetric.

[32] Figure A2 in the Appendix reports the responses of labor hours, consumption and sectoral variables to the same shock.

[33] In the unregulated equilibrium, banks' net worth and capital investment decline by more in response to the negative TFP shock.

Figure 5 plots impulse responses of our baseline economy when macroprudential instruments are available to a Ramsey planner. We consider the second-best policies when only a uniform tax on banks' assets are available (i.e., $\tau_t^b = \tau_t^g$) and when these taxes can be differentiated across asset classes. We compare these scenarios to the first-best dynamic responses when both a carbon tax and macroprudential instrument are available.

In the first-best scenario, the Ramsey planner uses the emissions tax to solely address the climate externality and the macroprudential policy to stabilize the banking sector. The Ramsey-optimal tax on banks' assets is procyclical. When the economy is in a recession, the policymaker subsidizes banks' asset purchases, thereby propping up asset prices and bank equity.[34] On impact, the optimal subsidy increases from its steady state level of -0.22% to about -1.7%. As a result, banks' net worth is greatly stabilized falling by only 9% versus 17% in the absence of the prudential policy.

In Figure 5, the solid lines plot the dynamic responses under a second-best uniform tax on banks' asset, and the dotted lines show the responses when these taxes are allowed to differ across assets. The two sets of dynamic responses implied by these policy scenarios are barely distinguishable from each other. In both cases, emissions fall by more than optimal, while investment and net worth dynamics closely replicate the first-best responses. This suggests that from the Ramsey-efficiency perspective, second-best macroprudential taxes (i.e., in the absence of emissions tax) do not address negative pollution externalities over the business cycle. The intuition behind this result is that climate damages, which affect net output, are driven by pollution stock – a very slow-moving variable over the business cycle. Therefore, the Ramsey planner with only macroprudential taxes can let emissions fluctuate more than optimally in response to mean-reverting productivity shocks without incurring much efficiency losses in investment and output.

[34] The procyclical nature of macroprudential tax levied on banks' assets is similar in nature to countercyclical bank capital buffers advocated by the Basel III framework and adopted by financial regulators in many countries. Basel III - developed by the Basel Committee on Banking Supervision - is an international regulatory framework that requires tightening capital requirements in times of excessive credit growth and relaxing them during recessions.

6 Conclusion

The Paris Agreement reflects the goal of keeping global warming to within 1.5 to 2 degrees above the pre-industrial level, but policies in signatory countries and beyond are not yet aligned with it. Additional efforts will be required to close this gap. Central banks and financial regulators have recently expressed the concern that if, after decades of delayed action, policymaking in the climate realm would experience a sudden acceleration, systemic risk could materialize, possibly leading to a policy-driven recession. Preventing such recession is as important as preventing the risk that ambitious climate action is not implemented when the opportunity finally presents itself, because of potential systemic risk.

Systemic risk from transitioning to a low-carbon economy, known as transition risk, arises from the fact that meeting the abovementioned climate goals would imply leaving most fossil fuel reserves in the ground as well as reevaluating carbon-intensive assets across the board. Further, it would imply revaluating the assets of all financial firms holding carbon-intensive assets. To minimize transition risk, central banks and financial regulators have started expanding their set of tools to include new macroprudential policies, specifically tailored to green and brown assets.

To shed light on the functioning of these macroprudential policies, and their interaction with climate policy, we develop a model of an economy with two key market failures, a climate externality and financial frictions. In this model, banks lend to firms, and the amount of lending depends on the financial sector's stability. There are two types of firms, and production from one type creates emissions as a byproduct, which negatively affect production.

Our results show that macroprudential policies can be successful in reducing the risk of a severe recession following a major climate policy shock. Further, by addressing financial frictions, macroprudential policies can also support economic growth once climate policy is in place. Macroprudential policies, however, perform relatively poorly when used to steer the economy towards lower emissions in lieu of climate policy.

Important policy implications follow from our study. First, introducing macroprudential policy today can prevent a potential recession tomorrow, or the need to forgo the opportunity to implement ambitious climate policy because of financial stability risks. Second, climate and macroprudential policies work best when used as complements, rather than substitutes. Hence, our paper supports, and can potentially guide, current efforts by central banks and financial regulators to minimize transition risk.

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Tables and Figures

Table 1: Calibration

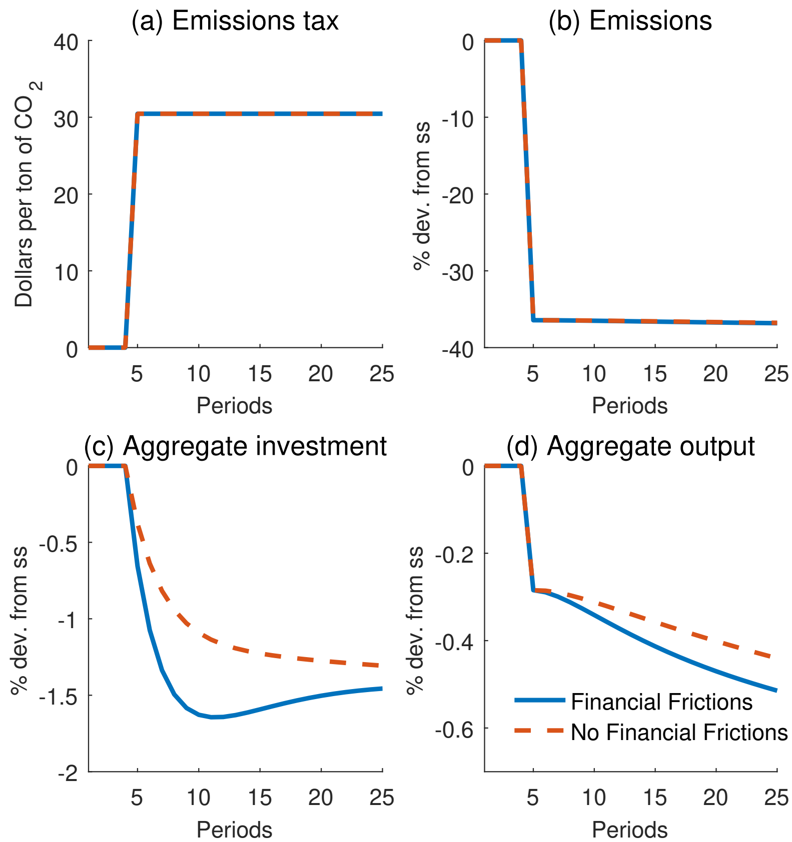
Parameter	Value	Description
RBC parameters		
β	0.995	Discount factor
η	2	Risk aversion
ξ	1	Frisch elasticity of labor hours
ϖ	8.3849	Labor disutility
ρ_L	1	Intrasectoral CES of labor hours
α^b	0.35	Capital share in 'brown' production
α^g	0.33	Capital share in 'green' production
δ^b, δ^g	0.025	Capital depreciation rate
ϕ^b, ϕ^g	10	Investment adjustment cost
ρ_A	0.95	Persistence of aggregate TFP shocks
σ_A	0.007	Std. dev. of innovations to TFP
Environmental parameters		
θ_1	0.0335	Abatement cost function parameters
θ_2	2.6	
d_0	-0.0076	Damage function parameters
d_1	$8.10e-6$	
d_2	$1.05e-8$	
δ_X	0.9965	Pollution decay
ϵ	1	Emissions elasticity parameter
e^{row}	3.1499	Emissions in the ROW
ρ_Y	2	CES between 'green' and 'brown' outputs
π^b	0.3326	Share of 'brown' output
Banking sector parameters		
κ	0.3409	Fraction of divertable assets
γ	0.972	Bankers' survival rate
ζ	0.003	Proportional transfer to new bankers
ψ	10^{-4}	Banks' portfolio management cost
$\overline{s}^g$	0.60	Portfolio share of green assets

Table 2: Deterministic steady state

	No financial frictions		Financial frictions				
	No policy	τ^e	No policy	τ^e	$\tau^b = \tau^g$	τ^b& τ^g	τ^e& $\tau^b = \tau^g$
Emissions tax ($ per ton)	0	30.5	0	24.2	0	0	30.5
Tax on brown assets (%)	–	–	0	0	-0.18	-0.14	-0.22
Tax on green assets (%)	–	–	0	0	-0.18	-0.21	-0.22
Emissions	0.676	0.432	0.630	0.433	0.668	0.663	0.432
Aggregate output	1.506	1.519	1.407	1.416	1.488	1.489	1.519
Banks' net worth	–	–	3.276	3.281	3.675	3.677	3.773
Welfare (% CE)	0.84	0	1.97	1.30	1.00	0.98	0

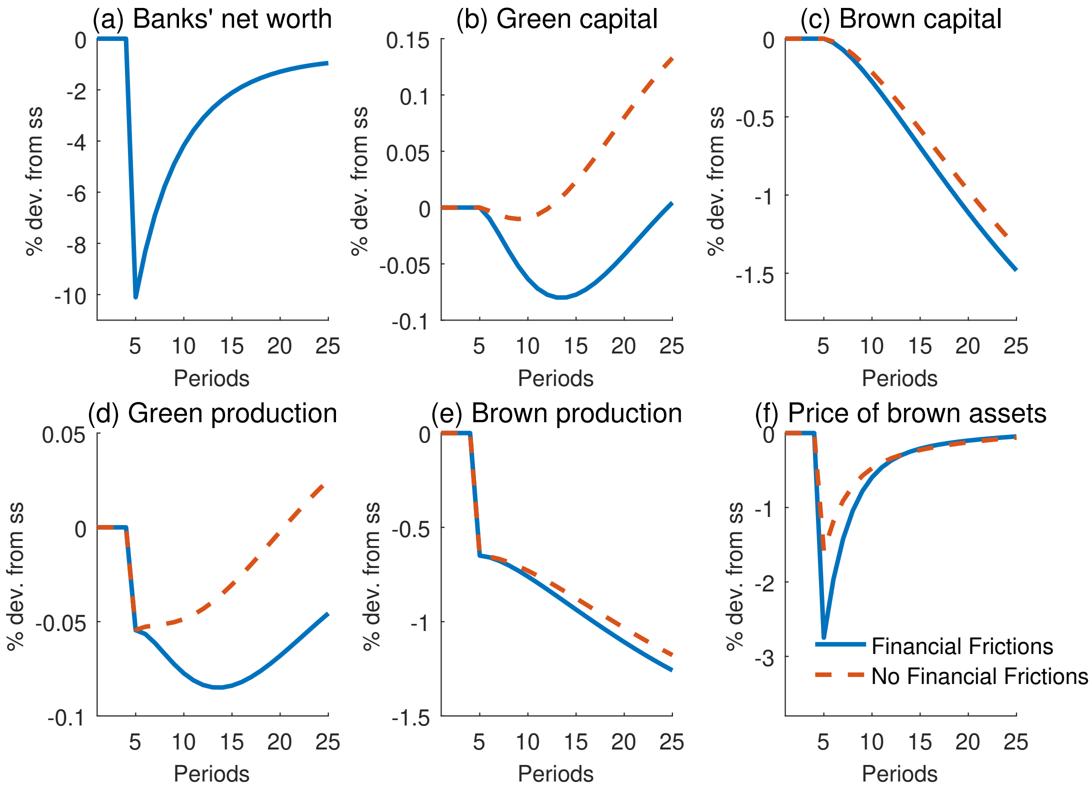
Note: This table shows the steady state values of selected variables in the economies with and without financial frictions under different policy scenarios. Emissions tax is in terms of dollars per ton of CO_2. Tax rates on banks' assets are in percentages. Steady-state welfare is in terms of compensating consumption variation relative to the 'first-best' allocations. All other variables are in arbitrary model units.

Figure 1: Transition dynamics to a low carbon economy



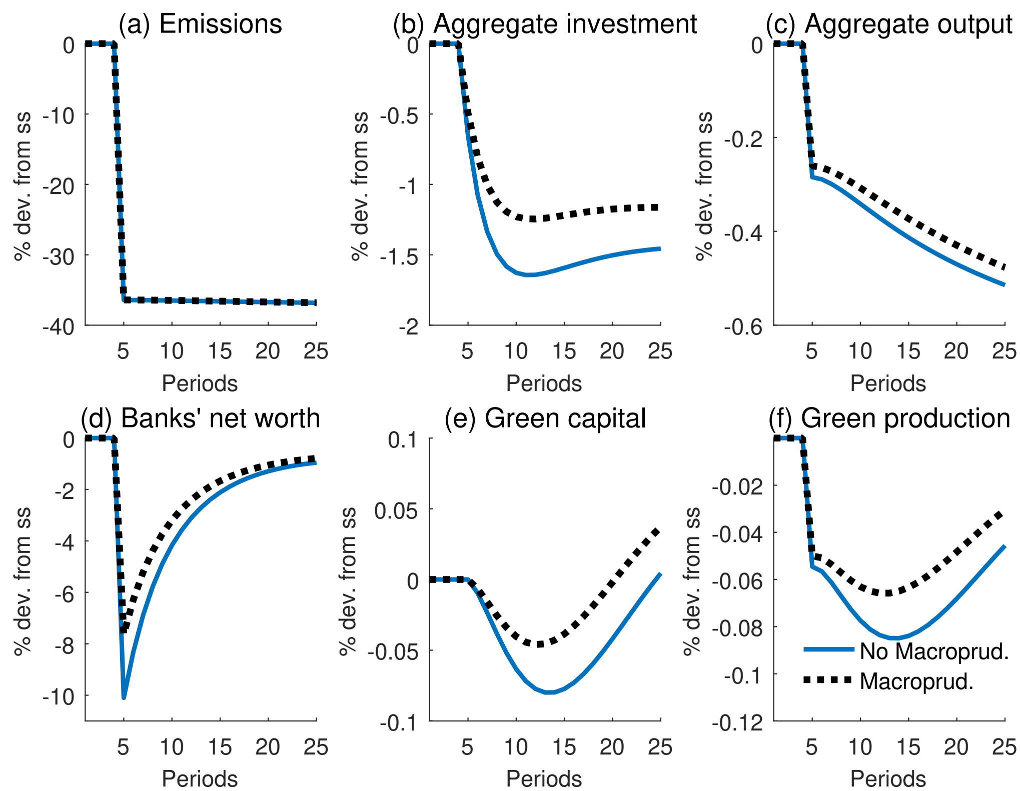
Note: This figure plots the transition dynamics of emissions, aggregate investment and output in response to an unanticipated introduction of the permanent emissions tax of about 30 dollars per ton of CO_2 in the economies with and without financial frictions.

Figure 2: Transition to a low carbon economy: Financial and sectoral variables



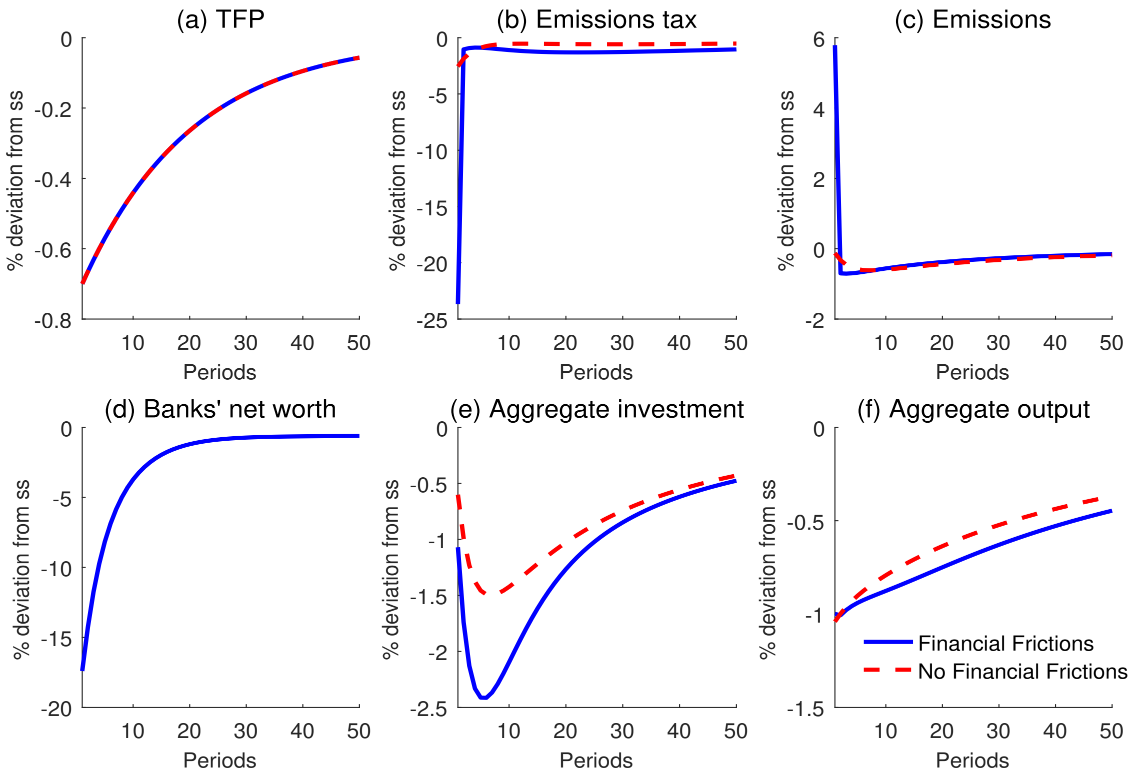
Note: This figure plots the transition dynamics of financial and sectoral variables in response to the same path of the emissions tax as in Figure 1.

Figure 3: Transition to a low carbon economy with macroprudential policy



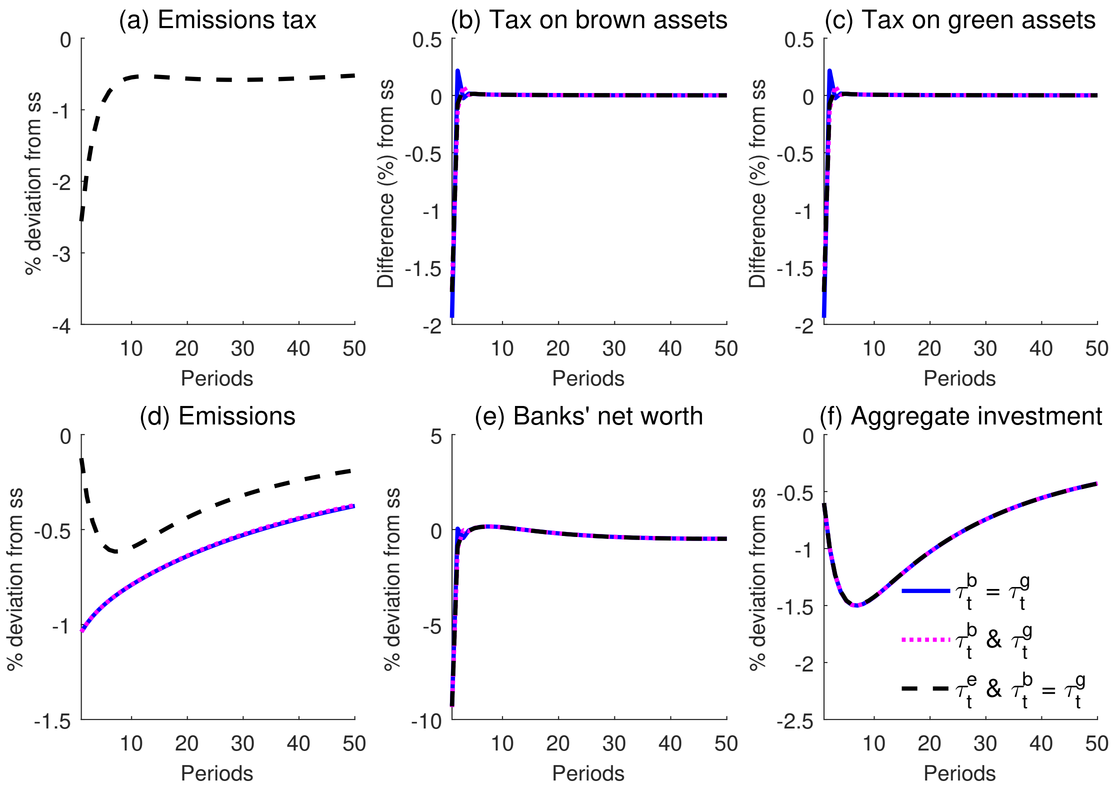
Note: This figure plots the transition dynamics in the model with financial frictions to the same emissions tax shock as in Figure 2 under two scenarios: (i) No macroprudential policy (solid lines); (ii) with macroprudential policy (dashed lines). Macroprudential policy is such that it lowers banks' steady state exposure to the brown sector from 40% (baseline calibration) to 32%. Deviations are calculated relative to the respective initial steady states.

Figure 4: The Ramsey-optimal dynamic emissions tax



Note: This figure plots the impulse responses to a one-standard deviation negative TFP shock under the Ramsey-optimal emissions tax policy in the economies (i) with financial frictions (solid lines) and (ii) without financial frictions (dashed lines).

Figure 5: Ramsey-optimal dynamic policies under different sets of instruments



Note: This figure plots the impulse responses to a one-standard deviation negative TFP shock in the baseline model with Ramsey-optimal policies when (i) only uniform tax on banks' assets (τ_t^b=τ_t^g) is available (solid lines); (ii) only differentiated taxes on banks' brown (τ_t^b) and green (τ_t^g) assets are available (dotted lines); (iii) emissions tax (τ_t^e) and a uniform tax on banks' assets (τ_t^b=τ_t^g) are available (dashed lines).

Online Appendices

A Details on banks' optimization problem

We formulate banker's optimization problem in terms of choosing the value of total portfolio, $\mathcal{W}_{j,t} \equiv Q_t^g S_{j,t}^g + Q_t^b S_{j,t}^b$, and the portfolio share of green assets, $s_t^g \equiv \frac{Q_t^g S_{j,t}^g}{\mathcal{W}_{j,t}}$. Using these definitions, and the flow of funds constraint (5) to replace deposits $D_{j,t}$, we can express the evolution of bank's net worth (6) as

$$N_{j,t+1} = \left\{ \begin{array}{c} \left[R_{k,t+1}^b - \left(1+\tau_t^b\right) R_t\right] + \\ + \left[\left(R_{k,t+1}^g - R_{k,t+1}^b\right) - \left(\tau_t^g - \tau_t^b\right) R_t\right] s_t^g + \\ -\frac{\psi}{2} \left(s_t^g - \overline{s}^g\right)^2 R_t \end{array} \right\} \mathcal{W}_{j,t} + R_t N_{j,t}. \tag{A1}$$

The banker's optimization problem in recursive form then becomes:

$$V_{j,t} = \max_{\mathcal{W}_{j,t}, s_t^g} \mathbb{E}_t \left\{ \left[(1-\gamma) M_{t,t+1} N_{j,t+1} + \gamma M_{t,t+1} V_{j,t+1} \right] \right\}, \tag{A2}$$

subject to the incentive constraint (7) and the evolution of net worth $(A1)$.

We guess and later verify that the value function is linear in net worth $N_{j,t}$,

$$V_{j,t} = \varphi_t N_{j,t}, \tag{A3}$$

where φ_t is the time-varying coefficient common across banks. It is convenient to define the variables:

$$\chi_t^b \equiv \mathbb{E}_t \left[\Omega_{t+1} \left(R_{k,t+1}^b - \left(1+\tau_t^b\right) R_t \right) \right], \tag{A4}$$

$$\chi_t^g \equiv \mathbb{E}_t \left\{ \Omega_{t+1} \left[\left(R_{k,t+1}^g - R_{k,t+1}^b \right) - \left(\tau_t^g - \tau_t^b \right) R_t \right] \right\}, \tag{A5}$$

$$\nu_t \equiv \mathbb{E}_t \left[\Omega_{t+1} R_t \right], \tag{A6}$$

where $\Omega_{t+1} \equiv M_{t,t+1} \left(1 - \gamma + \gamma \varphi_{t+1}\right)$ can be interpreted as the banker's effective stochastic discount factor. χ_t^b is the expected discounted (tax adjusted) excess return on brown assets relative to deposits, and χ_t^g is the expected excess return on green assets relative to brown assets. ν_t is the expected discounted cost of raising an additional unit of deposits.

Using the definitions $(A4)$-$(A6)$, the conjecture $(A3)$, and $(A1)$, we can rewrite the Bellman equation $(A2)$ as

$$V_{j,t} = \max_{\mathcal{W}_{j,t}, s_t^g} \left\{ \left[\chi_t^b + \chi_t^g s_t^g - \frac{\nu_t \psi}{2} \left(s_t^g - \overline{s}^g \right)^2 \right] \mathcal{W}_{j,t} + \nu_t N_{j,t} \right\}. \tag{A7}$$

The incentive constraint (7) then becomes,

$$\left[\chi_t^b + \chi_t^g s_t^g - \frac{\nu_t \psi}{2} \left(s_t^g - \overline{s}^g \right)^2 \right] \mathcal{W}_{j,t} + \nu_t N_{j,t} \geq \kappa \mathcal{W}_{j,t}. \tag{A8}$$

The Lagrangian function for this problem is

$$\mathcal{L}_t = \left(\left[\chi_t^b + \chi_t^g s_t^g - \frac{\nu_t \psi}{2} \left(s_t^g - \overline{s}^g \right)^2 \right] \mathcal{W}_{j,t} + \nu_t N_{j,t} \right) (1 + \lambda_t) - \lambda_t \kappa \mathcal{W}_{j,t}, \tag{A9}$$

where λ_t is the Lagrange multiplier on the incentive constraint $(A8)$. The first order optimality conditions with respect to $\mathcal{W}_{j,t}$ and s_t^g are:

$$(1 + \lambda_t) \left[\chi_t^b + \chi_t^g s_t^g - \frac{\nu_t \psi}{2} \left(s_t^g - \overline{s}^g \right)^2 \right] = \lambda_t \kappa, \tag{A10}$$

$$(1 + \lambda_t) \left[\chi_t^g - \nu_t \psi \left(s_t^g - \overline{s}^g \right) \right] \mathcal{W}_{j,t} = 0, \tag{A11}$$

$$\lambda_t \left(\left[\chi_t^b + \chi_t^g s_t^g - \frac{\nu_t \psi}{2} \left(s_t^g - \overline{s}^g \right)^2 \right] \mathcal{W}_{j,t} + \nu_t N_{j,t} - \kappa \mathcal{W}_{j,t} \right) = 0, \text{ with } \lambda_t \geq 0. \tag{A12}$$

Denote by $\Upsilon_t \equiv \chi_t^b + \chi_t^g s_t^g - \frac{\nu_t \psi}{2} \left(s_t^g - \overline{s}^g \right)^2$ the average excess return on bank's portfolio net of asset management costs. From $(A10)$ we have $\lambda_t = \frac{\Upsilon_t}{\kappa - \Upsilon_t}$. The incentive constraint $(A8)$ binds whenever $\lambda_t > 0$, or when $0 < \Upsilon_t < \kappa$. In our realistic parametrization of the model, the incentive constraint always binds in a local region of the steady state. Therefore, the amount of assets intermediated is limited by bank's equity capital,

$$\mathcal{W}_{j,t} = \frac{\nu_t}{\kappa - \Upsilon_t} N_{j,t}. \tag{A13}$$

The first order optimality condition with respect to s_t^g determines the portfolio composition,

$$s_t^g = \frac{\chi_t^g}{\nu_t \psi} + \overline{s}^g. \tag{A14}$$

Equation $(A14)$ is the same as equation (12) in Section 2 of the main text. Note that since both χ_t^g and ν_t depend on aggregate variables, s_t^g is common across all banks; therefore, Υ_t does not depend on individual bank-specific characteristics either. Using $(A13)$ we can then verify our conjecture that

$$V_{j,t} = \varphi_t N_{j,t} = \Upsilon_t \frac{\nu_t}{\kappa - \Upsilon_t} N_{j,t} + \nu_t N_{j,t} = \frac{\kappa \nu_t}{\kappa - \Upsilon_t} N_{j,t}, \tag{A15}$$

$$\Rightarrow \varphi_t = \frac{\kappa \nu_t}{\kappa - \Upsilon_t}. \tag{A16}$$

Imposing ($A16$) in ($A13$) and aggregating over all banks yields equation (11) in the main text.

B Full set of equilibrium conditions

$$L_t = \left[\left(L_t^b\right)^{1+\rho_L} + \left(L_t^g\right)^{1+\rho_L} \right]^{\frac{1}{1+\rho_L}}, \tag{B1}$$

$$M_{t,t+1} = \beta \frac{\left(C_{t+1} - \varpi \frac{L_{t+1}^{1+\xi}}{1+\xi}\right)^{-\eta}}{\left(C_t - \varpi \frac{L_t^{1+\xi}}{1+\xi}\right)^{-\eta}}, \tag{B2}$$

$$1 = \mathbb{E}_t \left(M_{t,t+1} R_t\right), \tag{B3}$$

$$w_t^i = \varpi L_t^{\xi - \rho_L} \left(L_t^i\right)^{\rho_L}, \quad \text{for } i = \{g, b\}, \tag{B4}$$

$$\mathcal{W}_t = Q_t^b S_t^b + Q_t^g S_t^g, \tag{B5}$$

$$s_t^g = \frac{Q_t^b S_t^b}{\mathcal{W}_t}, \tag{B6}$$

$$\chi_t^b = \mathbb{E}_t \left[\Omega_{t+1} \left(R_{k,t+1}^b - \left(1 + \tau_t^b\right) R_t\right)\right], \tag{B7}$$

$$\chi_t^g = \mathbb{E}_t \left\{\Omega_{t+1} \left[\left(R_{k,t+1}^g - R_{k,t+1}^b\right) - \left(\tau_t^g - \tau_t^b\right) R_t\right]\right\}, \tag{B8}$$

$$\nu_t = \mathbb{E}_t \left[\Omega_{t+1} R_t\right], \tag{B9}$$

$$\Omega_{t+1} = M_{t,t+1} \left(1 - \gamma + \gamma \varphi_{t+1}\right), \tag{B10}$$

$$\Upsilon_t = \chi_t^b + \chi_t^g s_t^g - \frac{\nu_t \psi}{2} \left(s_t^g - \overline{s}^g\right)^2, \tag{B11}$$

$$\varphi_t = \frac{\kappa \nu_t}{\kappa - \Upsilon_t}, \tag{B12}$$

$$\mathcal{W}_t = \frac{\nu_t}{\kappa - \Upsilon_t} N_t, \tag{B13}$$

$$s_t^g = \frac{\chi_t^g}{\nu_t \psi} + \overline{s}^g, \tag{B14}$$

$$N_{t+1} = \gamma \left[\sum_{i=\{g,b\}} R_{k,t+1}^i Q_t^i S_t^i - R_t D_t \right] + \zeta \sum_{i=\{g,b\}} Q_t^i S_t^i, \tag{B15}$$

$$D_t = (1 + \tau_t^b) Q_t^b S_t^b + (1 + \tau_t^g) Q_t^g S_t^g + \frac{\psi}{2} \left(s_t^g - \overline{s}^g\right)^2 \mathcal{W}_t - N_t, \tag{B16}$$

$$Y_t = \left[\left(\pi^b\right)^{\frac{1}{\rho_Y}} \left(Y_t^b\right)^{\frac{\rho_Y - 1}{\rho_Y}} + \left(1-\pi^b\right)^{\frac{1}{\rho_Y}} \left(Y_t^g\right)^{\frac{\rho_Y-1}{\rho_Y}} \right]^{\frac{\rho_Y}{\rho_Y-1}}, \tag{B17}$$

$$Y_t^i = \left[1 - d\left(X_t\right)\right] A_t \left(K_{t-1}^i\right)^{\alpha^i} \left(L_t^i\right)^{1-\alpha^i}, \text{ for } i = \{g, b\}, \tag{B18}$$

$$p_t^b = \left(\frac{\pi^b Y_t}{Y_t^b}\right)^{\frac{1}{\rho_Y}}, \tag{B19}$$

$$p_t^g = \left(\frac{\left(1-\pi^b\right) Y_t}{Y_t^g}\right)^{\frac{1}{\rho_Y}}, \tag{B20}$$

$$X_t = \delta_X X_{t-1} + e_t + e_t^{\text{row}}, \tag{B21}$$

$$e_t = \left(1 - \mu_t\right) \left(Y_t^b\right)^{\epsilon}, \tag{B22}$$

$$Z_t = \theta_1 \mu_t^{\theta_2} Y_t^b, \tag{B23}$$

$$w_t^b = \left(1 - \alpha^b\right) \frac{Y_t^b}{L_t^b} \left[p_t^b - \theta_1 \mu_t^{\theta_2} - \tau_t^e \left(1 - \mu_t\right) \epsilon \left(Y_t^b\right)^{\epsilon - 1}\right], \tag{B24}$$

$$\tau_t^e = \left(Y_t^b\right)^{1-\epsilon} \theta_1 \theta_2 \mu_t^{\theta_2 - 1}, \tag{B25}$$

$$R_{k,t}^b = \frac{\alpha^b \frac{Y_t^b}{K_{t-1}^b} \left[p_t^b - \theta_1 \mu_t^{\theta_2} - \tau_t^e \left(1 - \mu_t\right) \epsilon \left(Y_t^b\right)^{\epsilon-1}\right] + \left(1 - \delta^b\right) Q_t^b}{Q_{t-1}^b}, \tag{B26}$$

$$w_t^g = \left(1 - \alpha^g\right) \frac{p_t^g Y_t^g}{L_t^g}, \tag{B27}$$

$$R_{k,t}^g = \frac{\alpha^g \frac{p_t^g Y_t^g}{K_{t-1}^g} + \left(1 - \delta^g\right) Q_t^g}{Q_{t-1}^g}, \tag{B28}$$

$$\begin{aligned} Q_t^i = {} & 1 + \frac{\phi^i}{2} \left(\frac{I_t^i}{I_{t-1}^i} - 1\right)^2 + \phi^i \left(\frac{I_t^i}{I_{t-1}^i} - 1\right) \frac{I_t^i}{I_{t-1}^i} + \\ & - \mathbb{E}_t \left\{ M_{t,t+1} \phi^i \left(\frac{I_{t+1}^i}{I_t^i} - 1\right) \left(\frac{I_{t+1}^i}{I_t^i}\right)^2 \right\}, \text{for } i = \{g, b\}, \end{aligned} \tag{B29}$$

$$K_t^i = \left(1 - \delta^i\right) K_{t-1}^i + I_t^i, \text{ for } i = \{g, b\}, \tag{B30}$$

$$Q_t^i S_t^i = Q_t^i K_t^i, \quad \text{for } i = \{g, b\}, \tag{B31}$$

$$Y_t = C_t + \sum_{i=\{g,b\}} I_t^i + Z_t + \sum_{i=\{g,b\}} \frac{\phi^i}{2} \left(\frac{I_t^i}{I_{t-1}^i} - 1\right)^2 I_t^i + \frac{\psi}{2} \left(s_t^g - \overline{s}^g\right)^2 \mathcal{W}_t. \tag{B32}$$

Given government policies $(\tau_t^e, \tau_t^b, \tau_t^g)$ and exogenous total factor productivity (A_t), a competitive equilibrium is described by the stochastic sequences of endogenous variables $\mathbf{J}_t \equiv [\left\{L_t^i, K_t^i, I_t^i, Y_t^i, S_t^i, w_t^i, R_{k,t}^i, Q_t^i, p_t^i\right\}_{i=g,b}, C_t, M_{t,t+1}, L_t, Y_t, Z_t, \mu_t, e_t, X_t, N_t, \mathcal{W}_t, s_t^g, D_t, R_t, \chi_t^b, \chi_t^g,$ $\nu_t, \varphi_t, \Upsilon_t, \Omega_{t+1}]$ that satisfy the system of equations B1-B32.

C The Ramsey-efficient policy problem

For a given set of available instruments (e.g., only τ_t^e; only $\tau_t^b = \tau_t^g$; τ_t^b and τ_t^g; τ_t^e and $\tau_t^b = \tau_t^g$) the Ramsey planner solves:

$$\max_{\{\mathbf{J}_t,\text{ and a given set of instruments}\}_{t=0}^{\infty}} \mathbb{E}_0 \left\{ \sum_{t=0}^{\infty} \beta^t \frac{1}{1-\eta} \left(C_t - \varpi \frac{\left[\left(L_t^b\right)^{1+\rho_L} + \left(L_t^g\right)^{1+\rho_L} \right]^{\frac{1+\xi}{1+\rho_L}}}{1+\xi} \right)^{1-\eta} \right\}, \tag{C1}$$

subject to the constraints of the competitive equilibrium (i.e., equations B1-B32). As is common in the literature, we take the 'timeless perspective' approach to implement the solution to the Ramsey problem; The policymaker is able to commit to a state-contingent dynamic policy announced in time 0.

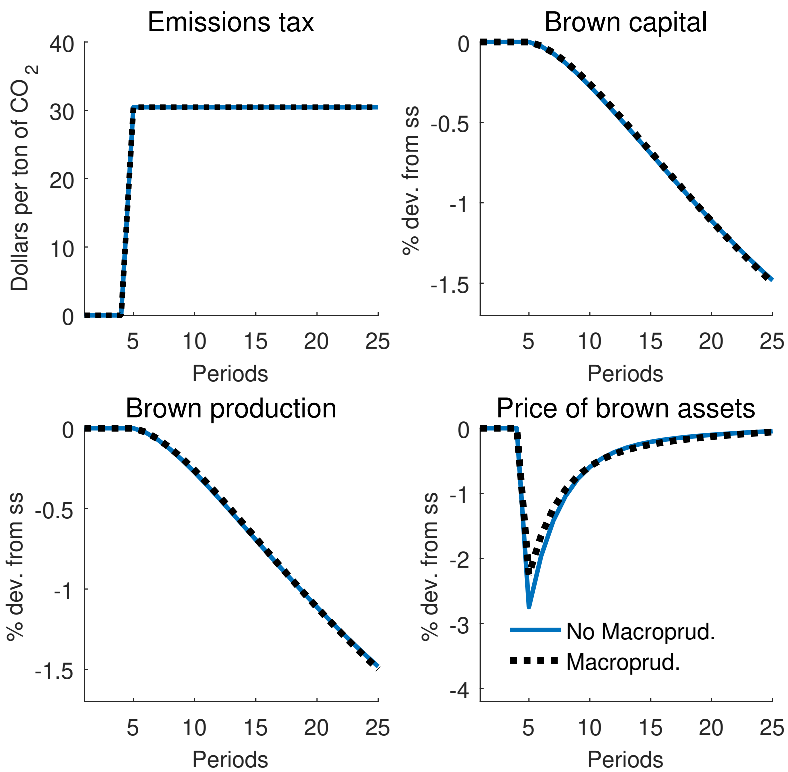
Additional Tables and Figures

Table A1: Deterministic steady state: additional variables

	No financial frictions		Financial frictions				
	No policy	τ^e	No policy	τ^e	$\tau^b = \tau^g$	τ^b & τ^g	τ^e & $\tau^b = \tau^g$
Consumption	1.082	1.093	1.038	1.046	1.075	1.075	1.093
Green output	0.850	0.862	0.795	0.804	0.840	0.845	0.862
Brown output	0.676	0.675	0.630	0.629	0.668	0.663	0.675
Green investment	0.254	0.257	0.221	0.223	0.248	0.251	0.257
Brown investment	0.170	0.168	0.147	0.146	0.166	0.163	0.168
Labor in green prod.	0.272	0.273	0.263	0.264	0.270	0.271	0.273
Labor in brown prod.	0.212	0.211	0.205	0.204	0.211	0.211	0.211
Climate damages	0.053	0.047	0.052	0.047	0.053	0.053	0.047

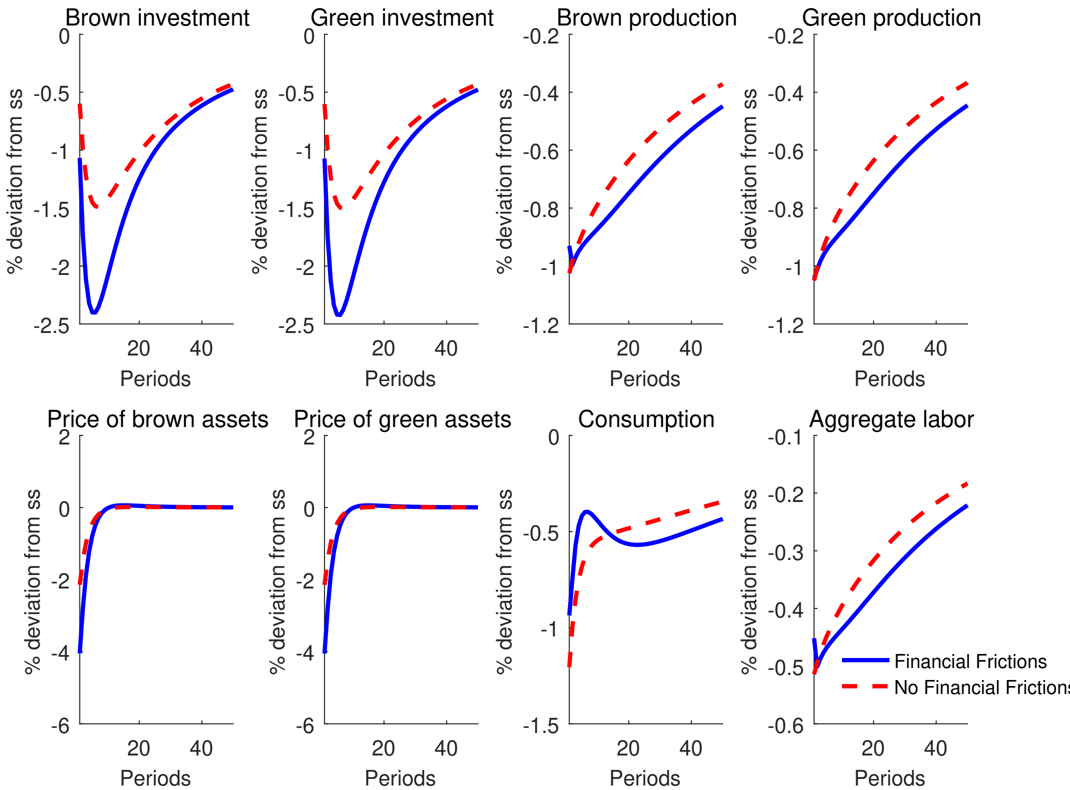
Note: This table shows the steady state values of selected variables in the economies with and without financial frictions under different policy scenarios. All variables are in arbitrary model units, expect climate damages are a fraction of output.

Figure A1: Transition to a low carbon economy with macroprudential policy: Additional variables



Note: This figure plots the transition dynamics of additional variables in response to the emissions tax introduction in the economies with and without macroprudential policy.

Figure A2: The Ramsey-optimal emissions tax: Sectoral and other variables



Note: This figure plots the impulse responses of additional variables to the same TFP shock as in Figure 4 under the Ramsey-optimal emissions tax policy in the economies (i) with financial frictions (solid lines) and (ii) without financial frictions (dashed lines).