Carbon Taxes and Tariffs, Financial Frictions, and International Spillovers*

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Abstract

Financial frictions are a key element of our economies. Climate change is too. Ambitious climate policy, coupled with financial frictions, has the potential to create macrofinancial stability risk. Such stability risk may expand beyond the economy implementing climate policy, potentially catching other countries off guard. International spillovers may occur because of trade and financial channels. Further, climate policy may also cover imports, such as with carbon tariffs. Hence, we study the design and effects of climate policies in the world economy with international trade and financial flows and frictions. We develop a multi-sector, multi-country, dynamic general equilibrium model with financial frictions, climate policies, including carbon tariffs, and macroprudential policies. Using the calibrated model, we evaluate spillovers from unilateral domestic carbon pricing to foreign economies and back. We also examine more ambitious climate architectures involving carbon tariffs or a global carbon price. We find that accounting for cross-border financial flows and frictions in credit markets is crucial to understand the effects of climate policies and to guide the implementation of macroprudential policies at the global scale aimed at minimizing transition risk and paving the way to much-needed ambitious climate action.

JEL Classifications: E44; E58; F38; F42; G18; Q58

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1 Introduction

Financial stability is one of the most important topics that economists can tackle as scholars or practitioners. In recognition of the importance of this topic, in 2022 the Nobel Memorial Prize in Economic Sciences was awarded to Ben Bernanke, Douglas Diamond, and Philip Dybvig for their research on banks and financial crises. The crucial role of financial stability re-emerged over the last decade in the economics literature, following the Great Recession. More recently, another concern for financial stability has been receiving increasing attention from both academics and financial regulators: transition risk.

Transition risk refers to the potential systemic risk that could follow from a necessary, yet abrupt transition to a low-carbon economy. Despite climate change being a major issue since the early 1990s, the private sector, including financial companies, is still misaligned with the goal of the Paris Agreement to maintain global temperature increases within 1.5°C above pre-industrial levels (e.g., ECB 2021). Stringent climate policy measures are therefore required at the global level. However, such policies may pose a threat to financial stability, especially if implemented abruptly, which may be necessary after decades of policy delays. Financial assets may become "stranded," leading to important losses for the financial institutions owning them. For instance, McGlade and Ekins (2015) stress that estimates of global fossil fuel reserves vastly exceed the amount of carbon that can still be emitted without exceeding the goals of the Paris Agreement, leading to one of two outcomes: either to more severe climate change or to such carbon staying in the ground and thus to a reevaluation of those assets. To use the words of the former governor of the Bank of England Mark Carney's (Carney 2015), "a wholesale reassessment of prospects, especially if it were to occur suddenly, could potentially destabilize markets, spark a pro-cyclical crystallization of losses and a persistent tightening of financial conditions. In other words, an abrupt resolution of the tragedy of horizons is in itself a financial stability risk".

Several recent papers analyze transition risk using quantitative macro models with climate externality and financial frictions in the banking sector. In particular, Carattini, Heutel, and Melkadze (2021) show that significant climate policy-driven financial instability risk is indeed possible: An abrupt implementation of ambitious climate policy can trigger asset losses in the banking sector that causes a tightening of credit supply and, as a result, an economy-wide recession. However, macroprudential financial regulation can mitigate the transition risk. Diluiso et al. (2021) instead consider a gradual ramp-up approach to climate policy, which they show would not be conducive to transition risk, at the cost, however, of delaying climate action. These papers focus on closed economies in which domestic climate policies interact with domestic financial sector's stability.

In this paper we study international aspects of climate policies and the resulting cross-country spillovers through financial and trade linkages. Understanding cross-border implications of climate policies is important for several reasons. First, the presence of vast cross-border flows in trade and financial markets implies that the effects of national climate policies are not limited only to the home countries. The realization of transition risk following the implementation of ambitious climate policy, even when originated only in one group of countries, can thus have implications for other economies in the world. It follows that countries may need to implement macroprudential policy in anticipation not only of their own policies, but also of other countries'. Second, some climate policy measures that are being considered by policymakers, for instance in the European Union, directly target international trade flows with the stated goal of mitigating carbon leakage and ensuring a level playing field for domestic industries that are subject to climate policy at home. Carbon border adjustment mechanisms, in particular, would tax imports based on their carbon emissions in the same way that domestic production would be taxed. Therefore, a proper quantification of the effects of climate policies requires accounting for these cross-border spillovers.

To explore these questions, we develop a multi-sector, multi-country, dynamic stochastic general equilibrium (DSGE) model with a climate externality, climate and macroprudential policies, and cross-border financial and trade flows. The model builds on the seminal papers by

Backus, Kehoe, and Kydland (1992) and Corsetti, Dedola, and Leduc (2008) on international Real Business Cycles (RBC). We extend the two-sector, two-country RBC model in several important dimensions: (i) We introduce the climate externality and corresponding climate policies, including carbon border adjustment mechanisms; (ii) Each country has financial intermediaries which finance domestic as well as foreign investment projects subject to funding constraints that arise endogenously due to financial frictions as in Gertler and Kiyotaki (2010) and Gertler and Karadi (2011). The global nature of financial intermediaries captures a well-established fact that financial markets across countries are interlinked through large cross-border banking flows; (iii) A financial regulator in each country can implement macroprudential policies targeting the domestic financial sector.

Using the calibrated model, we simulate several climate policy scenarios that are very relevant for policymakers around the world, and infer which policy packages achieve the transition from high to a low carbon economy with the lowest transition cost, which in our novel framework accounts for the probability of financial contagion and possible policy-induced recessions, domestic or global. To be clear, our goal is to identify any obstacles related to financial frictions that could hamper a quick transition towards a cleaner economy as urged by climate scientists. The objective is to pave the way for ambitious climate policy as highly needed at this time by identifying potential sources of transition risk and providing policy recommendations to address them, so that if the opportunity for ambitious climate policy arises, transition risk would not be a reason not to go ahead with such ambitious plans.

In detail, we proceed as follows. First, we evaluate spillovers from domestic carbon taxes to foreign economies through cross-border financial linkages and international trade flows. An ambitious domestic carbon tax can affect foreign economies through financial linkages because stringent climate regulations at home might tighten domestic banks' funding constraints, thereby forcing them to pull back lending to foreign firms pushing foreign economic activity down. On the other hand, the negative impact of the ambitious carbon tax on the domestic carbon-intensive industries may drive foreign production up as global demand shifts toward cheaper foreign-produced goods, a mechanism known as carbon leakage. The model allows us to quantify all these forces.

Second, we study a novel trade-off faced by a country when imposing a carbon border adjustment mechanism on goods imported from the foreign country, where the latter is assumed not to have any domestic carbon tax in place. While the carbon border adjustment mechanism may bring several key benefits - leveling the playing field and to some extent preventing carbon leakage - it may also trigger "asset stranding" in the carbon-intensive foreign economy. Asset stranding in the foreign economy, in turn, may have destabilizing effects on the domestic economy through cross-border exposure of domestic financial sector to foreign assets. Our model allows us to quantify this unexplored trade-off and to assess the effectiveness of macroprudential policies, in the domestic as well as in the foreign country, in avoiding financial contagion and a potential policy-driven recession.

In short, the policy experiments that we study are as follows. First, we examine the consequences of the unilateral implementation of a carbon tax in the home country. We do so assuming that no country has macroprudential policy in place at the time of the policy shock, only the home country does, or both country do. Second, we assess the implications of adding a carbon border adjustment mechanism in the home country, on top of the carbon tax. Again, we study them in absence or presence of macruprudential policy in either country. Third, we turn to our last policy experiment, which involves a global carbon price obtained through harmonized carbon taxes with revenues redistributed domestically. This scenario implies that both countries implement a carbon tax simultaneously, again in presence or absence of macroprudential policy in either country. These simulations allow us to examine a very timely and policy-relevant question, how to best proceed with both climate policy and macroprudential policy in a highly connected world.

In the current version of the paper we look at the United States and the European Union which take turns as the home and foreign country. The European Union, for instance, recently announced a plan to trial a carbon border adjustment mechanism on certain imports to the bloc. In our setting, we simulate the case where the jurisdiction's entire economy is covered by a carbon price and, where relevant, a carbon border adjustment mechanism applies on top.

We find that financial frictions and cross-border banking flows are very important for understanding the effects of ambitious climate policies. In particular, in our baseline model, the abrupt implementation of an ambitious carbon tax in the domestic economy generates a global recession. At the core of this result is financially constrained domestic banks that operate globally through their cross-border lending activities. The domestic carbon tax lowers the return on carbon-intensive capital that banks are exposed to, thereby lowering banks' net worth. Banks with lower net worth face tighter funding constraints due to financial frictions and, thus, are forced to cut back on lending to domestic green sectors, as in Carattini, Heutel, and Melkadze (2021), but also to firms in the foreign economy, in both the green and carbon-intensive sectors. In addition, since foreign banks are also exposed to assets in home emissions-intensive industries, their net worth falls too, putting funding pressures on foreign banking sector. These two effects reinforce each other and a global recession follows. When we shut down financial frictions, a domestic carbon tax results in an expansion of the green sectors both at home and abroad, and also an increase in foreign dirty production, i.e., some carbon leakage.

Next, we explore the scenario in which the domestic economy implements a more ambitious climate policy package: a domestic carbon tax plus carbon border adjustment mechanism, which we model as a tariff on carbon-intensive imports from the foreign country. In the baseline model with financial frictions, the carbon border adjustment mechanism does mitigate carbon leakage in the short to medium term. However, this benefit comes at the cost of jeopardizing the stability of the financial system leading to a more severe recession including in the green sectors (compared to the case with only the domestic carbon tax). Hence, we identify a novel important trade-off, in the absence of macroprudential policy, between transition risk and the mitigation of carbon leakage.

Finally, we consider the scenario wherein climate policy is implemented at the global stage, with both countries introducing a domestic carbon tax with the same level of stringency, thus leading to a global carbon price through harmonized carbon taxes. Such policy coordination successfully reduces global emissions, but results in stronger transition risk, which particularly hurts the green sector. Yet, we show that macroprudential policy, implemented by both countries before they coordinate on a carbon tax, can mitigate transition risk. Macroprudential policy penalizes banks' carbon exposures encouraging them to decarbonize their balance sheets. At the time of the abrupt implementation of globally coordinated climate policy, banks are thus more resilient to the risk of asset stranding and can withstand the climate policy shock without cutting back on green lending too much.

Our paper contributes to several strands of literature. First, it speaks to an established literature examining the role of financial instability, its drivers, and the possible ways to minimize it, preemptively or in reaction to a financial crisis (Bernanke 1983, Diamond and Dybvig 1983, Bernanke and Gertler 1989, Kiyotaki and Moore 1997, Gertler and Kiyotaki 2010, Mendoza 2010, Meh and Moran 2010, Bianchi 2011, Gertler and Karadi 2011, Christiano and Ikeda 2013, Brunnermeer and Sannikov 2014, Gete and Melkadze 2020, Gertler, Kiyotaki, and Prestipino 2021, among others). This strand of research also includes a growing body of work, that emerged largely in response to the Great Recession, on international financial flows, the cross-border transmission of shocks and the role of global banks in international spillovers (Devereux and Yetman 2010, Mendoza and Quadrini 2010, Milesi-Ferretti and Tille 2011, Dedola and Lombardo 2012, Cetorelli and Goldberg 2012, Ueda 2012, Dedola, Lombardo, and Karadi 2013, Kollman 2013, Kalemli-Ozcan, Papaioannou, and Perri 2013, Bruno and Shin 2015, De Haas and Van Horen 2013, Cerutti et al. 2015, Miranda-Agrippino and Rey 2020, Hale et al. 2020), as well as the potential of macroprudential policies in the international context, in particular through capital controls, to address such shocks and the related cross-border transmission (Ostry et al. 2010, Bianchi 2011, Costinot, Lorenzoni, and Werning 2014, Kara 2016, Korinek and Sandri 2016, Jean and Korinek 2020). We contribute to these strands of literature by studying the international spillovers of climate-policy driven transition risk through financial frictions and cross-border financial flows, and the role of macroprudential policies in managing such spillovers.

Second, we contribute to a strand of literature analyzing transition risk, in particular using DSGE models so far only in a closed economy, and assessing the role of macroprudential policies, but also green quantitative easing, in addressing them (Carattini, Heutel, and Melkadze 2021, Dilusio et al. 2021, Giovanardi et al. 2021, Comerford and Spiganti 2022, Ferrari and Nespi Landi 2020). Related work also assesses the potential for and implications of asset stranding in various contexts (Rozenberg et al. 2018, Campiglio et al. 2020, Van der Ploeg and Rezai 2020), the exposure of financial institutions to carbon-intensive assets, including as measured with the first generation of climate-stress tests (Battiston et al. 2018, Alogoskoufis et al. 2021), as well as the behavior of investors with respect to transition risk (Carattini and Sen 2019, Bolton and Kacperczyk 2021a,b, Ramelli et al. 2021). The existing literature confirms that concerns about transition risks are justified as financial institutions are largely exposed to carbon-intensive assets and investors are not really aligned with long-term climate goals, even if they increasingly demand a risk premium for holding carbon-intensive assets. By moving to an open economy, our study highlights the potential for a global recession driven by transition risk, as well as the potential for macroprudential measures, even in just one country, to mitigate it, thus paving the way for ambitious climate policy.

Third, we contribute to a set of studies at the crossroad of trade and environmental economics, examining the design and assessing the potential impact of carbon border adjustment mechanisms (Elliott et al. 2010, Fischer and Fox 2012, Kortum and Weisbach 2017, Larch and Wanner 2017, Lyubich et al. 2018, Bohringer et al. 2021, 2022, Weisbach et al. 2022). The literature generally identifies a set of main channels through which carbon border adjustment mechanisms affect the economy, including competitiveness effects potentially addressing leakage, a general equilibrium effect through the price of fossil fuels, and a terms of trade channel. In this paper, we highlight the importance of financial spillovers, in particular in presence of financial frictions. Our paper also speaks to a related scholarship on the economics of global carbon pricing (Hoel 1992, Weitzman 2014, Nordhaus 2015, Cramton et al. 2017, Stiglitz et al. 2017, Weitzman 2017, Carattini et al. 2019, IMF 2019, Nordhaus 2019, Parry et al. 2021). In both cases, we examine the impacts through both international trade and finance while accounting for the important real-world feature that financial frictions represent. Our model confirms the powerfulness of harmonizing carbon taxes at the global level, and to a lesser extent of carbon border adjustment mechanisms, in tackling carbon emissions, but also the importance of accounting for international finance and trade links as well as financial frictions when designing relevant policy packages, which need accompanying macroprudential measures.

Fourth and finally, we also add to a body of work that uses DSGE models in presence of an environmental externality, to which the literature generally refers to as E-DSGE models (see the original contributions of Fischer and Springborn 2011, and Heutel 2012, as well as Annicchiarico et al. 2021 for a review). This literature has generally largely evolved in the context of a closed economy. Two recent studies do extend their framework to open economies, Ferrari and Pagliari (2021) and Ernst et al. (2022), but, unlike our paper, these studies do not consider climate-policy-related financial stability risks and international contagion of such risks through financial frictions.

The remainder of the paper is organized as follows. Section 2 introduces our theoretical model. Section 3 describes the calibration. Section 4 provides our main results. Section 5 concludes.

2 Model

We consider a two-country, two-sector, model with financial frictions and climate externality. We refer to the two countries as Home and Foreign. Both countries are assumed to be of similar size. Each country's economy consists of households, financial intermediaries, the government and two types of non-financial firms: goods producers and capital producers. Goods producing firms in turn operate in two types of sectors: emissions-intensive tradable sector (T) and 'green' non-tradable sector (N). We describe Home country's economy. Foreign country is similar. Foreign variables are denoted by asterisk (*).

2.1 Households

In each country there is a continuum of identical households of measure unity. There is a constant fraction of bankers and workers in each household. Bankers manage financial intermediaries (or banks) and pay dividends to their households. Workers supply labor to non-financial firms in tradable and non-tradable sectors and earn wage income, which they bring to their household. There is a perfect consumption sharing among the household members. Households consume tradable and non-tradable goods, save in the form of domestic bank deposits and supply labor to non-financial firms at home. That is, we assume labor to be immobile across countries. Households' preferences are defined over domestic consumption C_t and labor hours L_t,

$$U\left(C_t, L_t\right) = \frac{C_t^{1-\gamma}}{1-\gamma} - \varpi \frac{L_t^{1+\xi}}{1+\xi}, \tag{1}$$

where C_t is the constant elasticity of substitution (CES) aggregate of tradable ($C_{T,t}$) and non-tradable ($C_{N,t}$) consumption,

$$C_t \equiv \left[a_T^{1-\phi} C_{T,t}^{\phi} + a_N^{1-\phi} C_{N,t}^{\phi}\right]^{\frac{1}{\phi}}, \ \phi < 1, \tag{2}$$

and $C_{T,t}$ denotes the CES composite of Home ($C_{H,t}$) and Foreign-produced ($C_{F,t}$) tradable goods

$$C_{T,t} \equiv \left[a_H^{1-\rho} C_{H,t}^{\rho} + a_F^{1-\rho} C_{F,t}^{\rho}\right]^{\frac{1}{\rho}}, \ \rho < 1. \tag{3}$$

Here $a_N = 1 - a_T$, $a_F = 1 - a_H$, are shares of respective consumption goods, $\frac{1}{1-\phi}$ is the elasticity of substitution between the composite of tradables consumption $C_{T,t}$ and non-tradable consumption $C_{N,t}$. Similarly, $\frac{1}{1-\rho}$ is the elasticity of substitution between domestic and foreign produced tradable goods. L_t denotes aggregate labor hours supplied by the domestic households to Home tradable and non-tradable sectors, $L_t \equiv \left[L_{T,t}^{\eta} + L_{N,t}^{\eta}\right]^{\frac{1}{\eta}}$, $\eta < 1$. The formulation of labor in the utility function allows for less than perfect mobility of labor between the two sectors with η governing the degree of substitutability. The parameter ξ controls the elasticity of composite labor hours with respect to wages, and ϖ is the labor disutility parameter.

The domestic household chooses state-contingent sequences $\{C_{H,t}, C_{N,t}, C_{F,t}, L_{T,t}, L_{N,t}, D_t\}_{t=0}^{\infty}$ to maximize the lifetime utility,

$$\mathbb{E}_0 \left\{ \sum_{t=0}^{\infty} \beta^t U(C_t, L_t) \right\}, \tag{4}$$

subject to the budget constraint,

$$\begin{aligned} &P_{H,t}C_{H,t} + P_{N,t}C_{N,t} + (P_{F,t} + \tau_{cba,t})\, C_{F,t} + D_t \\ &= W_{T,t}L_{T,t} + W_{N,t}L_{N,t} + R_{t-1}D_{t-1} + \Pi_t + div_t + \Xi_t, \end{aligned} \tag{5}$$

where $P_{H,t}$, $P_{F,t}$, and $P_{N,t}$ are prices (in abstract units) of Home and Foreign tradable goods, and Home non-tradable good, respectively. D_t denotes deposits and R_t is the interest rate on deposits. Imports of foreign goods $C_{F,t}$ can be subject to the carbon border adjustment mechanism $\tau_{cba,t}$. Π_t denotes profits from Home firms and Ξ_t is lump-sum transfers and div_t are net dividends obtained from Home banks.

The household's consumption-savings decision problem implies that the household has to optimally decide on aggregate consumption C_t and the optimal allocation of expenditures over different types of consumption goods, $C_{H,t}, C_{N,t}$ and $C_{F,t}$, taking their prices as given. The solution to this problem leads to standard demand functions for each type of consumption and welfare-based price indexes. Denoting by P_t the price (i.e., consumer price index, CPI) of domestic aggregate consumption basket (C_t) and by $P_{T,t}$ the price of domestic consumption of

Home and Foreign tradables ($C_{T,t}$), the standard demand functions are given by:

$$C_{H,t} = a_H \left(\frac{P_{T,t}}{P_{H,t}} \right)^{\frac{1}{1-\rho}} C_{T,t}, \tag{6}$$

$$C_{F,t} = a_F \left(\frac{P_{T,t}}{P_{F,t} + \tau_{cba,t}} \right)^{\frac{1}{1-\rho}} C_{T,t}, \tag{7}$$

$$C_{T,t} = a_T \left(\frac{P_t}{P_{T,t}} \right)^{\frac{1}{1-\phi}} C_t, \tag{8}$$

$$C_{N,t} = a_N \left(\frac{P_t}{P_{N,t}} \right)^{\frac{1}{1-\phi}} C_t. \tag{9}$$

where the associated welfare based Home aggregate price index is given by

$$P_t = \left[a_T P_{T,t}^{\frac{\phi}{\phi-1}} + a_N P_{N,t}^{\frac{\phi}{\phi-1}} \right]^{\frac{\phi-1}{\phi}}, \tag{10}$$

and the price of Home composite of tradable goods is

$$P_{T,t} = \left[a_H P_{H,t}^{\frac{\rho}{\rho-1}} + a_F \left(P_{F,t} + \tau_{cba,t} \right)^{\frac{\rho}{\rho-1}} \right]^{\frac{\rho-1}{\rho}}. \tag{11}$$

We take the price P_t as the numeraire and normalize its value to 1 so that all prices are in terms of Home aggregate consumption composite.

The household's optimality conditions with respect to sector-specific labor hours imply

$$\varpi L_t^{1-\eta+\xi} L_{T,t}^{\eta-1} = \lambda_t^h W_{T,t}, \tag{12}$$

$$\varpi L_t^{1-\eta+\xi} L_{N,t}^{\eta-1} = \lambda_t^h W_{N,t}. \tag{13}$$

The optimality condition with respect to deposits gives the standard Euler equation $E_t \left(M_{t,t+1} R_t \right) = 1$, where $M_{t,t+1}$ denotes the household's stochastic discount factor $M_{t,t+1} = \beta \frac{\lambda_{t+1}^h}{\lambda_t^h}$, with the Lagrange multiplier on the budget constraint given by $\lambda_t^h = C_t^{\gamma}$.

2.2 Bankers

Each banker manages a financial intermediary. An individual bank i combines its net worth ($NW_{i,t}$) with the funds raised from depositors, ($D_{i,t}$) to fund loans ($S_{j,i,t}, S^F_{j,i,t}, j \in \{T, N\}$) to goods producing firms in Home and Foreign economies plus small portfolio management costs ($\Psi_{i,t}$). We assume that the government can levy macroprudential taxes ($\tau_j, \tau^F_j, j \in \{T, N\}$) on banks' assets, which could be differentiated across types of assets. These macroprudential taxes essentially mimic the effect of differentiated capital requirements. An important assumption that we make here, and that other studies in the literature implicitly make as well, is that the government is able to observe banks' exposure to green and brown assets. We consider this assumption as very plausible in a context where mandated disclosure of climate risks and the use of climate stress tests are rapidly expanding.[1]

The bank's flow-of-funds constraint in time period t is

$$\sum_{j\in\{T,N\}} \left[(1+\tau_{j,t})Q_{j,t}S_{j,i,t} + (1+\tau^F_{j,t})Q^*_{j,t}S^F_{j,i,t}\right] + \Psi_{i,t} = NW_{i,t} + D_{i,t}, \tag{14}$$

where $Q_{j,t}$ ($Q^F_{j,t}$) denotes a unit price of loans to Home (Foreign) firms in sector $j \in \{T, N\}$. The quadratic portfolio adjustment cost $\Psi_{i,t}$ helps us pin down the steady-state portfolio shares. We provide the detailed description of these adjustment costs in Appendix A.[2]

The law of motion of bank's net worth is given by

$$NW_{i,t+1} = \sum_{j\in\{T,N\}} \left[R_{j,t+1}Q_{j,t}S_{j,i,t} + R^*_{j,t+1}Q^*_{j,t}S^F_{j,i,t}\right] - R_tD_{i,t}. \tag{15}$$

Following Gertler and Kiyotaki (2010) and Gertler and Karadi (2011), we assume that there is an agency problem between bankers and depositors in order to limit banks' ability to obtain

[1]See, for example, Carattini et al. (2022) for an extensive discussion on climate-related disclosures.

[2]Intuitively, we want to capture the idea that it might be costly for a bank to move financial assets across sectors or countries (e.g., due to transactions costs). We calibrate these adjustment costs to be extremely small so that quantitatively they do not affect model dynamics.

external funds: After raising deposits and purchasing assets at time t, a banker managing the bank can divert funds for personal benefit. If the banker diverts funds, households force the bank into bankruptcy. We assume that upon the bank's bankruptcy, the households can only recover an exogenous fraction $(1-\kappa)$ of assets. A representative banker thus faces an incentive constraint which states that the depositors will lend to the bank only if the banker has no incentives to run away with depositors' money,

$$V_{i,t} \geq \kappa \sum_{j \in \{T,N\}} \left(Q_{j,t} S_{j,i,t} + Q^*_{j,t} S^F_{j,i,t} \right), \tag{16}$$

where $V_{i,t}$ is the franchise (or continuation value) for the bank at the end of period t.

At the end of each period, bankers may exit the market with exogenous probability $(1-\pi)$. Upon exit, a banker transfers her retained earnings to her household in the form of dividends and becomes a worker. The banker chooses the composition of assets portfolio and the amount of deposits to maximize the expected present discounted value of terminal equity (or dividend payouts). Since bankers are members of households, they discount future profits using the household's stochastic discount factor. The problem recursively is

$$V_{i,t} = \max_{D_{i,t}, (S_{j,i,t}, S^F_{j,i,t})_{j \in \{T,N\}}} \mathbb{E}_t \left\{ (1-\pi) M_{t,t+1} NW_{i,t+1} + \pi M_{t,t+1} V_{i,t+1} \right\}, \tag{17}$$

subject to the balance sheet constraint (14), the net worth accumulation equation (15) and the incentive constraint (16). Appendix A contains a detailed characterization of the bank's problem and associated optimality conditions. Here we discuss key equations.

We guess and verify that a bank's value function is linear in individual net worth,

$$V_{i,t} = \varphi_t NW_{i,t}, \tag{18}$$

where $\varphi_t \geq 1$ is the time-varying shadow value of a bank's net worth, common across banks.

Combining (18) with (16), we can express the incentive constraint as

$$\sum_{j\in\{T,N\}} \left(Q_{j,t}S_{j,i,t} + Q^*_{j,t}S^F_{j,i,t}\right) \leq \frac{\varphi_t}{\kappa}NW_{i,t}. \tag{19}$$

In our calibrated model, this constraint will always bind in the proximity of the steady state and thus, aggregating (19) at equality over the entire domestic banking sector yields

$$\sum_{j\in\{T,N\}} \left(Q_{j,t}S_{j,t} + Q^*_{j,t}S^F_{j,t}\right) = \frac{\varphi_t}{\kappa}NW_t. \tag{20}$$

Equation (20) determines Home banks' supply of credit, which is constrained by the amount of their aggregate net worth.

Bankers who exit the business are replaced by an equal number of new bankers who receive small initial startup funds from the households, $\Lambda_t = \varsigma \sum_{j=T,N}\left[Q_{j,t}S_{j,t} + Q^*_{j,t}S^F_{j,t}\right]$. The aggregate banking sector net worth thus evolves according to

$$NW_{t+1} = \pi\left[\sum_{j=T,N}\left(R_{j,t+1}Q_{j,t}S_{j,t} + R^*_{j,t+1}Q^*_{j,t}S^F_{j,t}\right) - R_tD_t\right] + \Lambda_t. \tag{21}$$

The aggregate net dividend payouts to households is given by

$$div_{t+1} = (1-\pi)\left[\sum_{j=T,N}(R_{j,t+1}Q_{j,t}S_{j,t} + R^*_{j,t+1}Q^*_{j,t}S^F_{j,t}) - R_tD_t\right] - \Lambda_t. \tag{22}$$

We define the Home banking sector leverage as the ratio of the value of the Home banks' total assets to their aggregate net worth, $\frac{\sum_{j=T,N}(Q_{j,t}S_{j,t}+Q^*_{j,t}S^F_{j,t})}{NW_t}$, and credit spreads as the difference between expected return on capital and the risk-free rate, $\mathbb{E}_t(R_{j,t+1} - R_t)$ for $j \in \{T, N\}$.

2.3 Goods producing firms

In each country there are two sectors – non-tradable (N) and emission-intensive-trade-exposed sectors (T). Goods produced in the latter sector are tradable across countries. There is a continuum of identical firms operating in each sector. Inputs in both productions are capital and labor. The production technologies in the two sector are of Cobb-Douglas form,

$$Y_{j,t} = A_{j,t} K_{j,t-1}^{\alpha_j} L_{j,t}^{1-\alpha_j}, \ \ j \in \{T, N\}, \tag{23}$$

where $K_{j,t}$ and $L_{j,t}$ denote capital and labor inputs and $A_{j,t}$ is the exogenous sector-specific productivity that follows a standard AR(1) process

$$\log A_{j,t} = \varrho_j \log A_{j,t-1} + \sigma_j \epsilon_{j,t}, \ \epsilon_{j,t} \sim \mathcal{N}(0,1).$$

Sector-specific carbon emissions are given by

$$e_{j,t} = g_j Y_{j,t}, \ \ j \in \{T, N\}, \tag{24}$$

where the emissions intensity parameters satisfy $g_T > g_N > 0$.

For carbon tax rate, we use \$80 per ton of CO_2, the central estimate in the cost-effectiveness study by Stiglitz et al. (2017), which identifies the range of carbon prices necessary to reach the temperature targets of the Paris Agreement. Similar estimates are provided in IMF (2019). Recent estimates of the social cost of carbon are also well aligned with the figures in our paper. If anything, the carbon tax shock to which we subject the Home and Foreign economies is on the low end, making our approach rather conservative with respect to recent estimates of the social cost of carbon (see Rennert et al. 2022) or the scenarios considered by the Network for Greening the Financial System.

Firms in each sector borrow from domestic and foreign banks to purchase capital which they then combine with labor to produce output in the next period. Specifically, in time t a representative firm has to purchase capital to be used in production in the next period. Given the unit price of capital $Q_{T,t}$ the firm in the tradable sector finances capital purchases $Q_{T,t}K_{T,t}$ by issuing claims of the same amount to the banking sector. The firm offers a state-contingent return $R_{T,t+1}$ to the banks to be payed in $t+1$. The firm's time t realized profits are:

$$\Pi_{T,t} = P_{H,t}Y_{T,t} - W_{T,t}L_{T,t} - \tau_{e,t}e_{T,t} - R_{T,t}Q_{T,t-1}K_{T,t-1} + (1-\delta_k)\,Q_{T,t}K_{T,t-1}. \tag{25}$$

The optimality condition with respect to labor is:

$$W_{T,t} = (1-\alpha_T)\,(P_{H,t} - \tau_{e,t}g_T)\,\frac{Y_{T,t}}{L_{T,t}}, \tag{26}$$

and the state-contingent return on capital consistent with the firm's state-by-state zero profit condition is

$$R_{T,t} = \frac{\alpha_T\,[P_{H,t} - \tau_{e,t}g_T]\,\frac{Y_{T,t}}{K_{T,t-1}} + (1-\delta_k)\,Q_{T,t}}{Q_{T,t-1}}. \tag{27}$$

A representative firm in the non-tradable sector faces a similar problem as the tradable sector firms, and the associated optimality conditions are thus similar:

$$W_{N,t} = (1-\alpha_N)\,(P_{N,t} - \tau_{e,t}g_N)\,\frac{Y_{N,t}}{L_{N,t}}, \tag{28}$$

$$R_{N,t} = \frac{\alpha_N\,[P_{N,t} - \tau_{e,t}g_N]\,\frac{Y_{N,t}}{K_{N,t-1}} + (1-\delta_k)\,Q_{N,t}}{Q_{N,t-1}}. \tag{29}$$

2.4 Capital producers

Capital is sector-specific and immobile across sectors. Competitive capital-producing firms build sector-specific capital subject to convex capital adjustment costs. The sector-specific capital accumulates according to

$$K_{j,t} = (1 - \delta_j) K_{j,t-1} + I_{j,t} - \frac{\psi_j}{2} \left(\frac{I_{j,t}}{K_{j,t-1}} - \delta_j \right)^2 K_{j,t-1}, for\ j = \{T, N\}, \tag{30}$$

where the parameter $\psi_i \geq 0$ controls the size of the adjustment cost.

Denote by $Q_{j,t}$ the price of new sector-specific capital goods in units of Home composite consumption. The capital producers solve

$$\max_{\{I_{j,t}\}_{j=\{T,N\}}} \mathbb{E}_0 \sum_{t=0}^{\infty} M_{0,t} \left[\sum_{j=\{T,N\}} [Q_{j,t} K_{j,t} - Q_{j,t} (1 - \delta_j) K_{j,t-1}] - P_{H,t} I_{T,t} - P_{N,t} I_{N,t} \right] \tag{31}$$

subject to the capital accumulation equation (30). The first order optimality conditions with respect to sector-specific investments are,

$$Q_{T,t} = P_{H,t} \left[1 - \psi_T \left(\frac{I_{T,t}}{K_{T,t-1}} - \delta_T \right) \right]^{-1}, \tag{32}$$

$$Q_{N,t} = P_{N,t} \left[1 - \psi_N \left(\frac{I_{N,t}}{K_{N,t-1}} - \delta_N \right) \right]^{-1}. \tag{33}$$

2.5 Government

The government can impose a carbon tax on the carbon-intensive sector, either unilaterally or in coordination with the Foreign country. In the latter case, coordination between the two countries leads to a uniform global carbon price, obtained through harmonized carbon taxes. When only the Home country imposes a carbon tax, the government in the Home country can decide to also levy a carbon tariff, or carbon motivated adjustment mechanism, on carbon-intensive imports from the Foreign country. The government does so to level the playing field, applying the exact same tax rate to domestic and foreign production.

The government transfers the revenues from carbon and border adjustment taxes to the domestic households in a lump-sum manner,

$$\Xi_t = \tau_{e,t}\left(e_{T,t} + e_{N,t}\right) + \tau_{cba,t} C_{F,t} + \sum_{j \in T,N} \left[\tau_{j,t} Q_{j,t} S_{j,t} + \tau_{j,t}^F Q_{j,t}^* S_{j,t}^F\right]. \tag{34}$$

2.6 Market Clearing

Foreign country's economy has a symmetric structure to the Home country. Market clearing conditions for tradables are given by

$$Y_{T,t} = C_{H,t} + C_{H,t}^* + I_{T,t},\ \ Y_{T,t}^* = C_{F,t}^* + C_{F,t} + I_{T,t}^*, \tag{35}$$

and for non-tradables,

$$Y_{N,t} = C_{N,t} + I_{N,t} + \frac{\Psi_t}{P_{N,t}},\ \ Y_{N,t}^* = C_{N,t}^* + I_{N,t}^* + \frac{\Psi_t^*}{P_{N,t}^*}. \tag{36}$$

Financial markets' clearing implies:

$$S_{T,t} + S_{T,t}^{H*} = K_{T,t},\ \ S_{N,t} + S_{N,t}^{H*} = K_{N,t}, \tag{37}$$

$$S_{T,t}^* + S_{T,t}^F = K_{T,t}^*,\ \ S_{N,t}^* + S_{N,t}^F = K_{N,t}^*. \tag{38}$$

3 Calibration

The model is calibrated at quarterly frequency. Table 1 summarizes the parameter values.

We choose standard values for the subjective discount factor $\beta = 0.99$, the risk aversion parameter $\gamma = 2$, the labor supply elasticity parameter $\xi = 1.1$, the capital share in both tradable and non-tradable sectors $\alpha_T = \alpha_N = 0.33$, the capital depreciation rate $\delta_k = 0.025$

and adjustment cost parameter $\psi_T = \psi_N = 20$. The parameter controlling the elasticity of substitution of labor hours between two sectors, η, is set to 2 following Carattini, Heutel, and Melkadze (2021). We set the labor disutility parameter ϖ to match the steady-state labor hours of 0.3. We follow Corsetti et al. (2008) in parameterizing CES consumption composites. We choose the elasticity of substitution between tradable and non-tradable goods $\frac{1}{1-\phi} = 0.74$, between Home- and Foreign-produced tradable goods $\frac{1}{1-\rho} = 0.85$, the share of tradable goods $a_T = 0.55$, and the share of Home-produced tradables $a_H = 0.72$. The persistence and standard deviation of the TFP shocks are 0.95 and 0.007 in line with standard RBC models.

We set the bank survival rate π 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 (ς) to match the steady-state leverage ratio of the banking sector of 5.4 and annualized credit spreads (both on brown and green assets) of about 100 basis points. This implies the parameter values $\kappa = 0.3309$, $\zeta = 0.001$, which are in line with the ones used in Gertler and Karadi (2011) and Gertler and Kiyotaki (2010). We set banks' steady state exposure to domestic assets to 80%, a value in line with the empirical estimates of home bias in equities and banking assets (see, e.g., Coeurdacier and Rey 2013). In the steady state, banks hold about half of their portfolio in carbon intensive assets (Battiston et al. 2017, ECB 2021). The portfolio adjustment cost parameters are set to a very small value so that these costs do not affect the dynamics quantitatively.

Emissions intensity parameters are calibrated to $g_T = 0.5$ and $g_N = 0$ for both countries.[3] Tradable sectors are defined as goods-producing sectors (sectors A, B, and C in NACE rev. 2), and other sectors are considered non-tradable except for "Electricity; gas, steam and air conditioning supply" (sector D), whose emissions we attribute to the other sectors as scope 2 emissions. We use data for the years 2015 and 2016 on gross value added from the OECD and emissions and electricity use from the World Input-Output Database Environmental Accounts (WIOD EA) to compute sectoral emissions intensities. Sector-level emissions intensity is defined

[3]Note that we treat the 27 European member states plus the United Kingdom as one country (i.e. Europe).

as the average across 2015 and 2016 of scope 1 plus scope 2 emissions (in a kilogram of CO_2) divided by the value added of each sector (in USD constant prices).[4] That is,

$$g_j = \frac{1}{2} \sum_{t=2015}^{2016} \frac{\text{Scope 1 plus scope 2 emissions, sector } j \text{ in year } t \text{ (kg of CO}_2\text{)}}{\text{Gross value added, sector } j \text{ in year } t \text{ (real \$)}}.$$

We calculate sector j's scope 2 emissions by attributing scope 1 emissions from sector D to sector j in proportion to a sectoral share in total electricity use in each country.[5] Table 2 reports the resulting estimates of sectoral emissions intensities at the disaggregated level. The respective weighted average estimates for tradable and non-tradable sectors in Europe (United States) are 0.53 and 0.096 (0.50 and 0.14). Consistent with these estimates, in our current symmetric calibration of the model, we set $g_T = 0.50$ for both countries. Since non-tradables are on average much less emissions intensive, we set $g_N = 0$, which allows us for cleaner assessment of the main transmission channels of climate policies across sectors.

4 Results

4.1 Transition risk and cross-border spillovers

4.1.1 Domestic carbon tax in the Home country

In this section we study the international spillovers of transition risk that originates in the Home country. Specifically, we consider a surprise introduction of a permanent economywide carbon tax of 80 dollars per ton of CO_2 in Home country. Prior to the introduction of the carbon tax, both countries start in the baseline symmetric deterministic steady state without any policy in place. In period 5, we hit the Home country with the permanent carbon tax shock. We

[4] Currency units are converted using annual exchange rates

[5] We use 2011 sectoral electricity use since we observe anomalous trends in 2012-2016 for some sectors in the data we use.

focus on perfect foresight transition dynamics. Figures 1 and 2 present transition dynamics in response to such shock. Figure 1 displays the endogenous transition dynamics of output and capital, while Figure 2 focuses on financial variables. Blue solid lines show the dynamics of the baseline model with financial frictions. To assess the role of financial frictions, we also display the transition dynamics, in response to the same climate policy shock, from the model with frictionless credit markets, as highlighted by the red dashed lines.[6]

Figure 1 illustrates key implications of financial frictions for the transmission of domestic carbon tax shock internationally and across sectors. Specifically, several results stand out. First, the carbon tax lowers production in the Home carbon-intensive sector (i.e., sector T) and consequently reduces domestic CO_2 emissions. This emissions reduction is similar across the two versions of the model (i.e., with and without financial frictions). Second, financial frictions imply that the domestic climate policy shock has a negative effect on output and capital in the Home and Foreign green sectors (i.e., sector N) as well, while in the model with frictionless credit markets, green sectors expand both at home and abroad. That is, in the absence of financial frictions, capital flows into sectors and countries with relatively high return on capital. Therefore, a third result is that dirty production and hence, emissions, migrate to the Foreign country, so that there is some carbon leakage with frictionless financial markets. In our baseline model, this leakage is limited in the short to medium term as financial frictions constrain the expansion of Foreign tradable output.

Figure 2 shows the dynamics of banks' net worth and credit spreads to illustrate the key mechanisms underlying the sectoral and international contagion of the climate policy shock discussed above for the baseline model with financial frictions. The domestic carbon tax lowers the realized return on domestic dirty capital, pushing both domestic banks' and foreign banks' net worth down. Banks with lower net worth face tighter financing constraints and are forced to cut the supply of credit both to domestic as well as to foreign non-financial firms including

[6]In the model without financial frictions, households directly hold equity claims in non-financial firms at home and abroad and there are no frictions between households and firms.

the green firms. This deleveraging by banks leads to an increase in credit spreads and fall in asset prices, which further tightens their funding constraint.[7] Overall, an unanticipated implementation of the domestic carbon tax causes a contraction in the supply of bank credit and a global economic slowdown ensues.

4.1.2 Domestic carbon tax and carbon border adjustment mechanism in the Home country

Next, we consider the scenario in which the Home country simultaneously implements domestic carbon tax and a carbon border adjustment mechanism (CBAM) as modelled in Section 2 (equation 5). The purpose of the carbon border adjustment mechanism is to level the playing field between Home and Foreign industries and, ideally, to mitigate carbon leakage. Figure 3 compares the transition dynamics in response to only a domestic carbon tax in the Home country to the dynamics with the Home carbon tax plus the carbon border adjustment mechanism in our baseline model with financial frictions. The carbon border adjustment mechanism has a negative effect on economic activity abroad: Foreign output falls by more both in the dirty and green sectors compared to the case with only a domestic carbon tax in the Home country. The carbon border adjustment mechanism thus mitigates carbon leakage to some extent, as, for example, foreign production in the carbon-intensive sector temporary falls more with the carbon border adjustment mechanism. But adding the carbon border adjustment mechanism on top of the domestic carbon tax also makes the recession in the domestic economy more severe, in presence of financial frictions and in the absence of macroprudential policy. The intuition behind this results is that the carbon border adjustment mechanism imposes a lower return on foreign dirty capital and hence equity losses for banks, which in turn cut the supply of credit to non-financial firms, including in the Home economy. This effect lowers Home investment and

[7] Note that in the model without financial frictions credit spreads are always zero. That is, the expected return on capital is equalized with the risk-free rate of return in every period. Financial frictions constrain banks to fully arbitrage out the return differential, which moves inversely with the amount of banks' net worth, reflecting the fact that financial stress (e.g., low bank equity) is associated with the widening of credit spreads.

asset prices and consequently further reduces banks' net worth. Note that the carbon border adjustment mechanism still has stronger effects on the Foreign economy and financial sector than the domestic ones.

4.1.3 Uniform global carbon price

Next we consider the scenario in which both Home and Foreign countries implement a carbon tax of the same magnitude ($80 dollars per ton) in a coordinated effort to tackle climate change. In this case, we obtain a uniform global carbon price, through harmonized carbon taxes. Since the two countries are symmetric, the global carbon price generates symmetric dynamics across the two countries. As intended by the policy, production in emissions intensive sectors falls, which leads to the reduction in global emissions. In the model without financial frictions, green capital and output expand globally. However, the presence of financial frictions implies that global climate policy has a negative unintended consequence for green sectors, with green capital and production declining in the medium term. The recessionary forces brought about by financial frictions can, however, be mitigated through macroprudential policy.

Hence, we consider a scenario in which financial regulators in each country implement a symmetric macroprudential policy in the form of a tax on banks' brown asset holdings, both foreign and domestic. The policy can be thought of as a stand in for a "brown penalizing factor" in Basel-type capital requirements that would impose a higher risk weight on brown asset holdings in banks portfolio. Specifically, we assume that prior to the implementation of the global carbon price, financial regulators impose a tax on banks' brown asset purchases, which lowers banks' carbon-intensive exposures from 52% (in the baseline calibration) to about 40%.

Figure 5 compares the transition dynamics in response to the global carbon price with and without macroprudential policy. Since macroprudential policy lowers banks' exposure to carbon-intensive sectors, equity losses that banks experience are milder and so is the contraction in credit supply. As a result, green capital declines less in response to the climate policy shock. Hence, macroprudential policy can limit the negative effect on banks' net worth and, thus, contribute to a smoother transition to a low carbon economy.

5 Conclusions

Transition risk is currently one of the main obstacles to ambitious climate policy and one of the main issues for financial regulators. In a financially and trade integrated world, transition risk should not only be a concern for those countries planning to implement such policies, but for all others as well. The situation is even more acute when also considering the use of carbon border adjustment mechanisms in climate policymaking.

In this paper, we develop a multi-sector, multi-country, dynamic stochastic general equilibrium model, with climate and macroprudential policies, and cross-border financial and trade flows. With it, we examine the impact of the following three policy experiments: the unilateral implementation of a carbon tax in either country, the unilateral implementation of a carbon tax and carbon border adjustment mechanism in either country, and the coordinated implementation of carbon taxes in both countries, leading to a global carbon price through harmonized carbon taxes.

We find that financial frictions and cross-border banking flows can play a key role in the realization and contagion of transition risk, a result that carries important policy implications for financial regulators. In particular, our main policy experiment shows that the abrupt implementation of an ambitious carbon tax in the domestic economy generates a global recession. The global recession is driven by domestic and foreign banks suffering from asset stranding in the carbon-intensive sector and adjusting lending downward to the clean sector as well. The economic slowdown is even more pronounced following the implementation of carbon border adjustment mechanisms, even if the latter contributes to reduce carbon leakage, as intended, or following the coordinated implementation of domestic carbon taxes, leading to a uniform global carbon price through harmonized carbon taxes. However, macroprudential policy can mitigate such recessionary forces, by addressing transition risk. Hence, macroprudential policy can pave the way to the most ambitious climate policy, including a global carbon price.

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Tables and Figures

Table 1: **Calibration**

Parameter	Value	Description	Source/Target
β	0.99	Discount factor	Standard value
ϖ	10.47	Labor disutility	SS hours worked
ξ	1.1	Labor elasticity	Standard
γ	2	Risk aversion	Standard
η	2	Intersectoral substitutability of labor	Carattini et al. (2021)
$\frac{1}{1-\phi}$	0.74	EoS between tradable & non-tradables	Corsetti et al. (2008)
$\frac{1}{1-\rho}$	0.85	EoS between home & foreign tradables	Corsetti et al.
a_T	0.55	Share of tradables in consumption	Corsetti et al.
a_H	0.72	Share of domestic tradables	Corsetti et al.
α_j	0.33	Capital share	Standard
g_T, g_T^*	0.50	Emissions intensity in sector T	Emissions intensity
g_N, g_N^*	0.0	Emissions intensity in sector N	Emissions intensity
δ_k	0.025	Capital depreciation rate	Standard
ϱ_j	0.95	Persistence of TFP in sector j	Standard
σ_j	0.007	Std. dev. of TFP innov. in sector j	Standard
κ	0.3409	Fraction of divertable assets	SS leverage, spreads
π	0.972	Bankers' survival rate	Gertler and Karadi (2012)
ς	0.001	Transfer to new bankers	SS leverage, spreads
$\phi_{p1}, \phi_{p2}, \phi_{p3}$	10^{-4}	Portfolio adjustment cost	Small value
ψ_T, ψ_N	20	Capital adjustment cost	Relative $\sigma(I)$

Table 2: **Emissions intensity by sector**

Sector (NACE rev. 2)	US		Europe	
	Scope 1	+Scope 2	Scope 1	+Scope 2
A. Agriculture; forestry and fishing	0.27	0.34	0.43	0.49
B. Mining and quarrying	0.53	0.66	0.65	1.26
C. Manufacturing	0.32	0.50	0.36	0.51
D. Electricity; gas, steam and air conditioning supply	7.05	.	3.91	.
E. Water supply; sewerage, waste management and remediation activities	0.44	0.59	0.27	0.39
F. Construction	0.06	0.10	0.07	0.08
G. Wholesale and retail trade; repair of motor vehicles and motorcycles	0.03	0.06	0.05	0.08
H. Transportation and storage	1.56	1.58	0.72	0.76
I. Accommodation and food service activities	0.08	0.14	0.04	0.09
J. Information and communication	0.01	0.02	0.01	0.04
K. Financial and insurance activities	0.01	0.02	0.01	0.02
L. Real estate activities	0.00	0.12	0.00	0.02
M. Professional, scientific and technical activities	0.02	0.04	0.02	0.03
N. Administrative and support service activities	0.05	0.06	0.03	0.04
O. Public administration and defence; compulsory social security	0.12	0.18	0.03	0.05
P. Education	0.02	0.06	0.02	0.04
Q. Human health and social work activities	0.04	0.07	0.03	0.05
R_S. Arts, entertainment and recreation; Other service activties	0.04	0.09	0.04	0.07

Sources: 2015 and 2016 OECD National Account, and 2011,2015, and 2016 World Input-Output Database Environmental Accounts (WIOD EA) (Corsatea et al., 2016).

Note: This table presents sectoral emissions intensities at a more disaggregated level than in the main text, where we provide average estimates for tradable (sectors A, B, and C) and non-tradable (the others except sector D) sectors. Sectoral emissions intensity is expressed as kilos of CO_2 per real gross value added in dollar. Only scope 1 emissions count as numerators in columns labeled "Scope 1", while scope 2 emissions are added to numerators in columns labeled "+Scope 2." We calculated scope 2 emissions by attributing scope 1 emissions from sector D to the other sectors in proportion to electricity consumption. We use data for 2015 and 2016 on scope 1 emissions from CO_2 Emissions Account of WIOD EA. For electricity consumption, we use only the 2011 Gross Energy Accounts of WIOD EA since we observe anomalous trends in 2012-2016 for some sectors in the data.

Figure 1: **Home carbon tax shock: Output and capital**

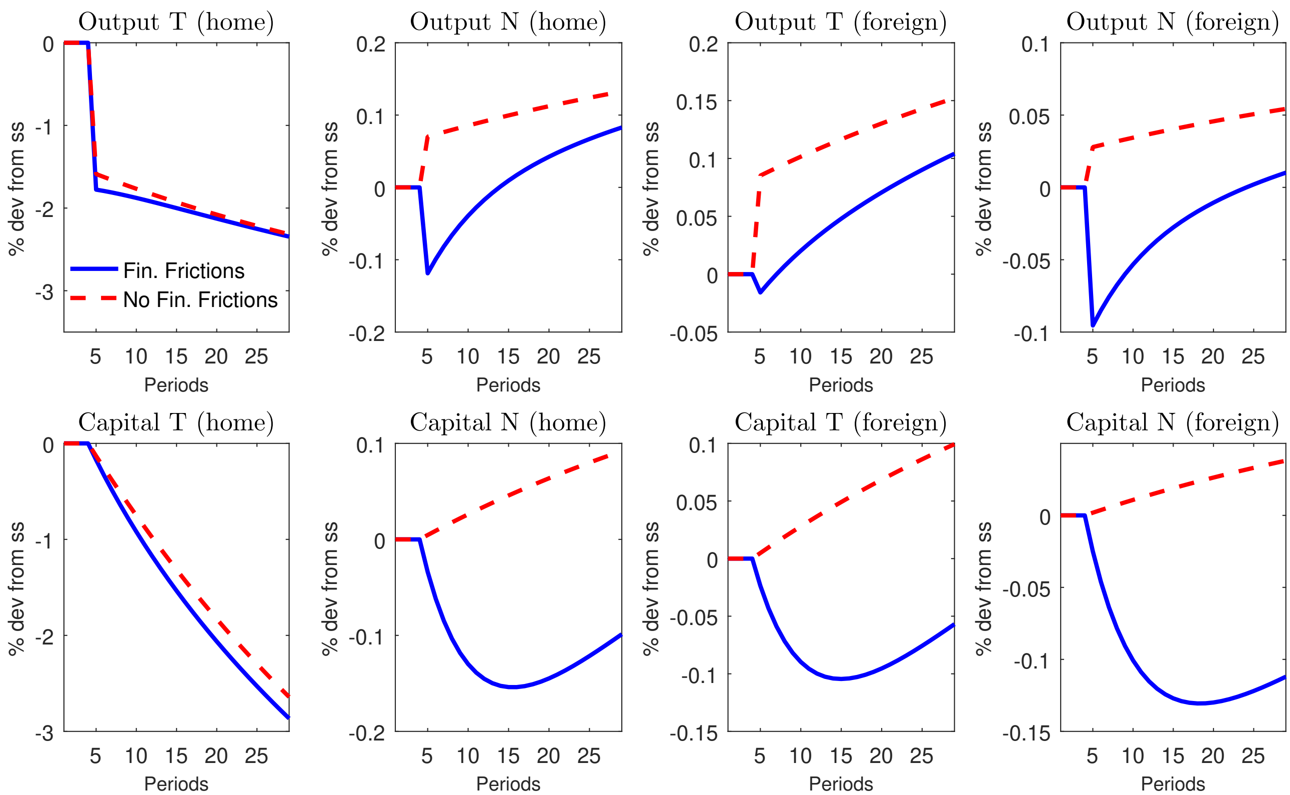


Figure 2: **Home carbon tax shock: Banks' net worth and credit spreads**

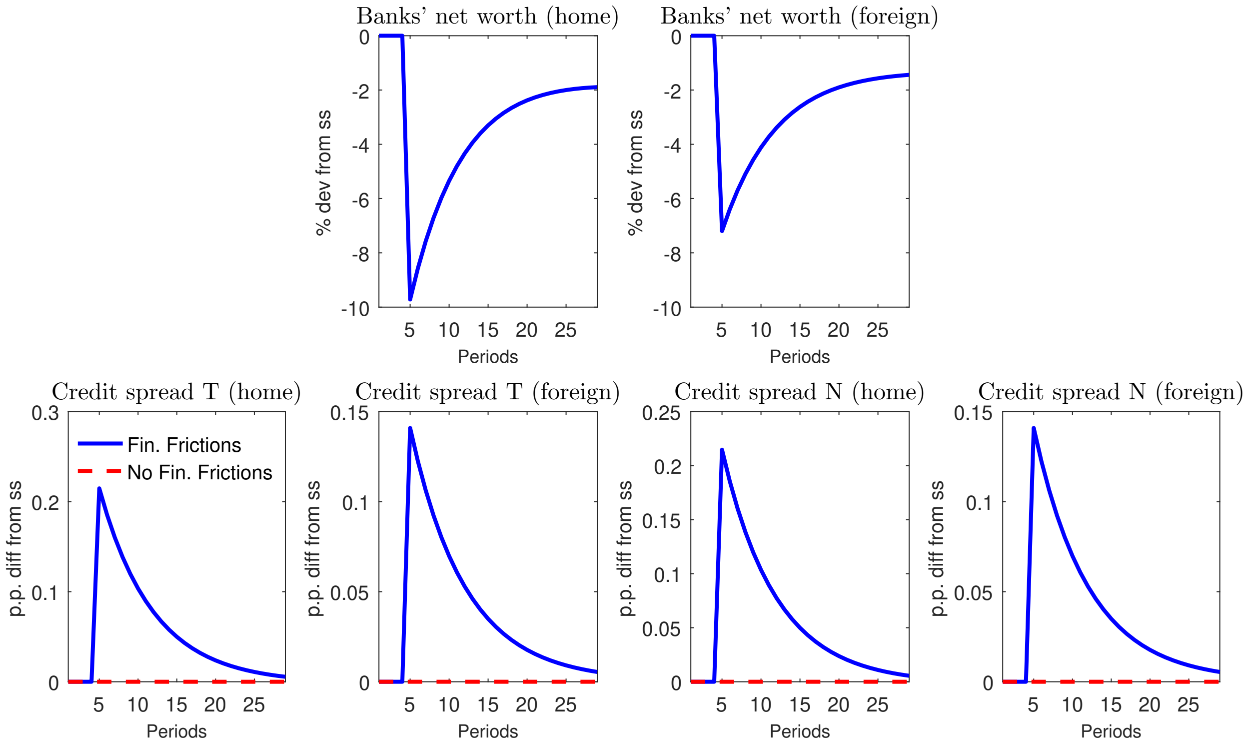


Figure 3: **Home carbon tax plus carbon border adjustment mechanism**

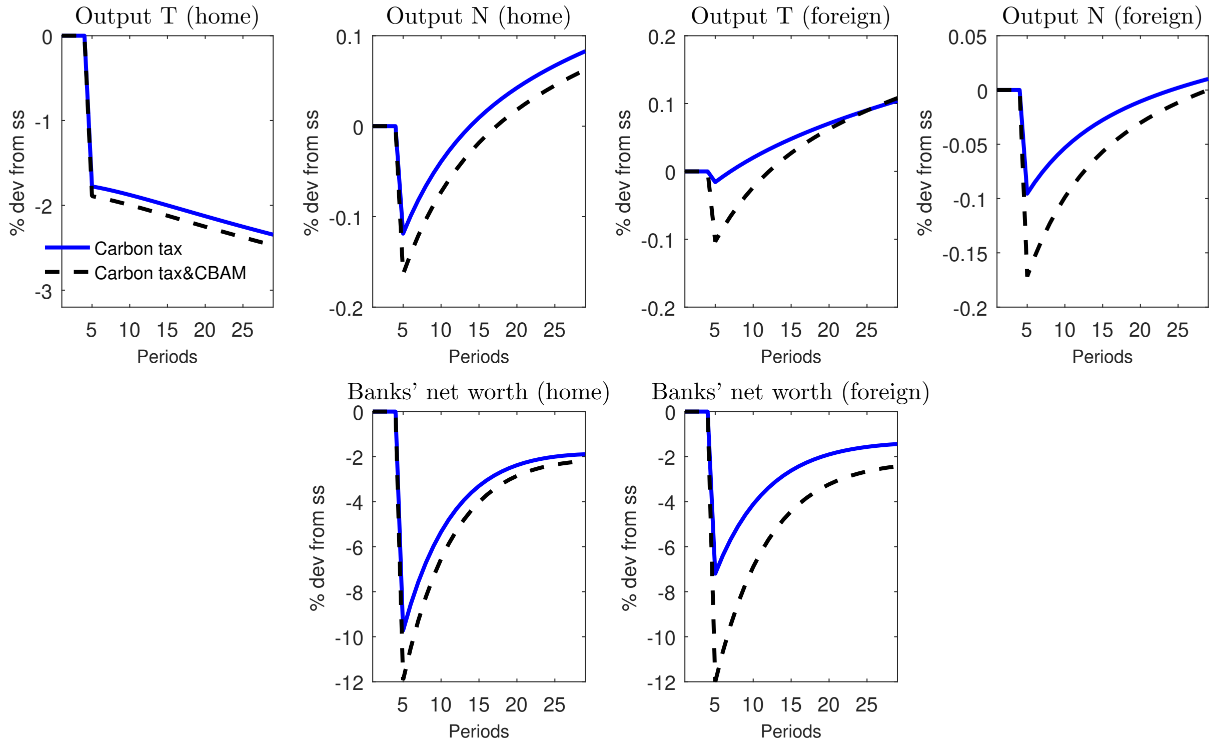


Figure 4: **Carbon tax shock in both countries**

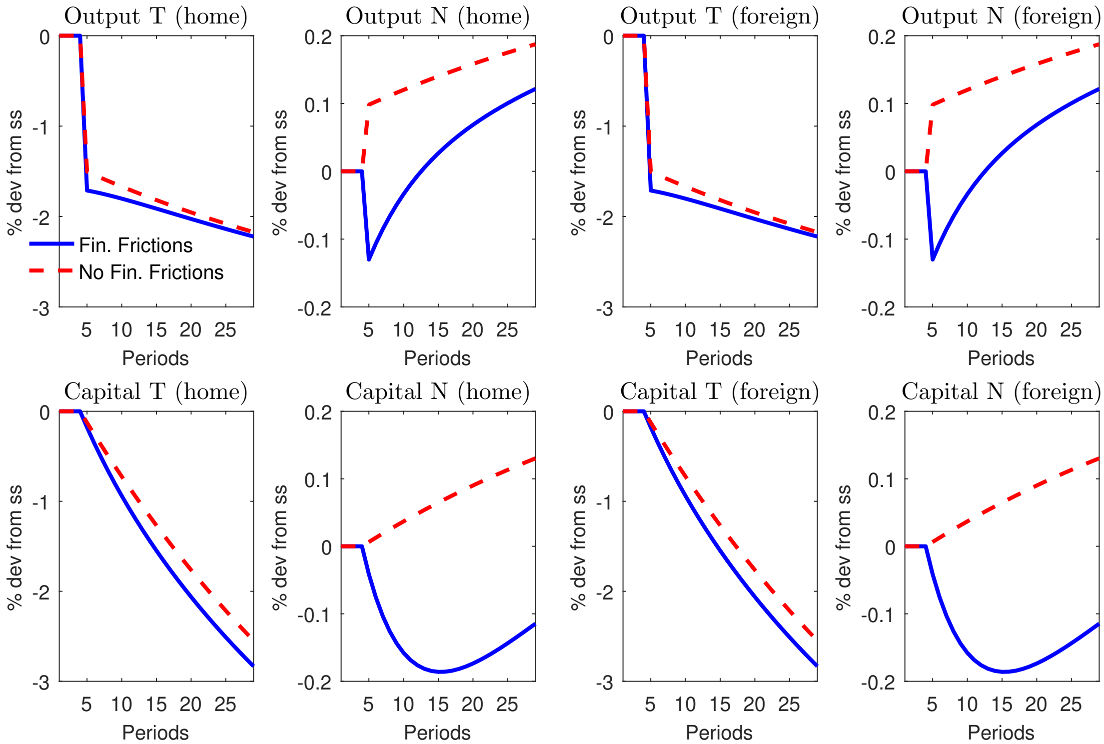
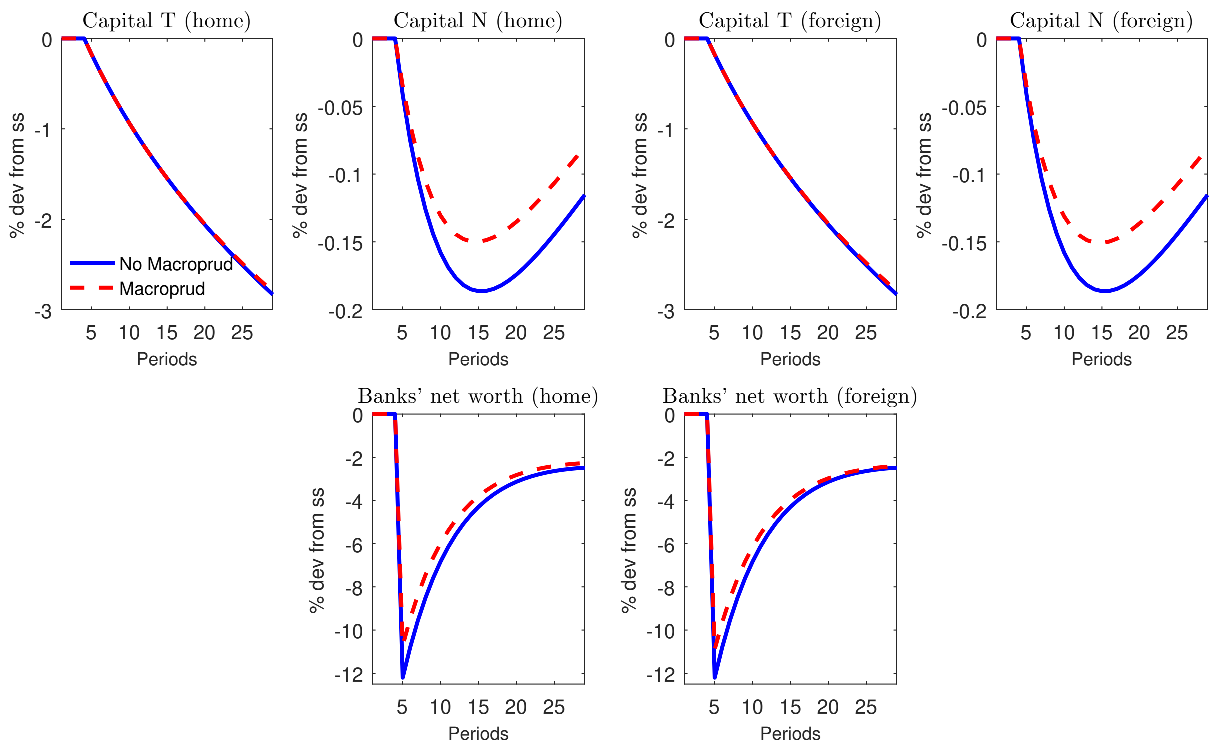


Figure 5: **Global carbon tax: The role of macroprudential policy**



Appendices

A Details on banks' optimization problem

Home bank j's flow-of-funds constraint in time period t is

$$\sum_{j\in\{T,N\}} \left[(1+\tau_{j,t})Q_{j,t}S_{j,i,t} + (1+\tau^F_{j,t})Q^*_{j,t}S^F_{j,i,t}\right] + \Psi_{i,t} = NW_{i,t} + D_{i,t}, \tag{A1}$$

where $\Psi_{i,t}$ denotes the quadratic portfolio adjustment costs,

$$\Psi_{i,t} = \left[\frac{\phi_{p_1}}{2}\left(\Upsilon_t - \overline{\Upsilon}\right)^2 + \frac{\phi_{p_2}}{2}\left(\Upsilon_{T,t} - \overline{\Upsilon}_T\right)^2 + \frac{\phi_{p_3}}{2}\left(\Upsilon^F_{T,t} - \overline{\Upsilon}^F_T\right)^2\right]\Gamma_{i,t} \tag{A2}$$

with $\Gamma_{i,t}$ denoting the value of the bank's total asset portfolio,

$$\Gamma_{i,t} \equiv \sum_{j\in\{T,N\}} \left(Q_{j,t}S_{j,i,t} + Q^*_{j,t}S^F_{j,i,t}\right). \tag{A3}$$

We define the Home bank's exposure to foreign assets as the ratio

$$\Upsilon_t \equiv \frac{Q^*_{T,t}S^F_{T,i,t} + Q^*_{N,t}S^F_{N,i,t}}{\Gamma_{i,t}}, \tag{A4}$$

and the exposures to domestic and foreign dirty sectors as

$$\Upsilon_{T,t} \equiv \frac{Q_{T,t}S_{T,i,t}}{Q_{T,t}S_{T,i,t} + Q_{N,t}S_{N,i,t}}, \Upsilon^F_{T,t} \equiv \frac{Q^*_{T,t}S^F_{T,i,t}}{Q^*_{T,t}S^F_{T,i,t} + Q^*_{N,t}S^F_{N,i,t}}. \tag{A5}$$

Using the flow-of-funds constraint (eq. 14) and the definitions above, we can rewrite the law of motion of bank's net worth (eq. 15) as follows,

$$NW_{i,t+1} = \left\{\begin{array}{c} \left[R_{T,t+1} - (1+\tau_{T,t})R_t\right]\Upsilon_{T,t}(1-\Upsilon_t) + \left[R_{N,t+1} - (1+\tau_{N,t})R_t\right](1-\Upsilon_{T,t})(1-\Upsilon_t) \\ + \left[R^*_{N,t+1} - \left(1+\tau^F_{N,t}\right)R_t\right]\Upsilon^F_{T,t}\Upsilon_t + \left[R^*_{N,t+1} - \left(1+\tau^F_{N,t}\right)R_t\right]\left(1-\Upsilon^F_{T,t}\right)\Upsilon_t - R_t ac_t \end{array}\right\}\Gamma_{i,t}$$
$$+ R_t NW_{i,t}, \tag{A6}$$

where $ac_t = \frac{\Psi_{i,t}}{\Gamma_{i,t}} = \frac{\phi_{p_1}}{2}\left(\Upsilon_t - \overline{\Upsilon}\right)^2 + \frac{\phi_{p_2}}{2}\left(\Upsilon_{T,t} - \overline{\Upsilon}_T\right)^2 + \frac{\phi_{p_3}}{2}\left(\Upsilon^F_{T,t} - \overline{\Upsilon}^F_T\right)^2$.

We guess and later verify that a bank's value function is linear in its individual net worth,

$$V_{i,t} = \varphi_t NW_{i,t}, \tag{A7}$$

where φ_t is time-varying but common across banks. For convenience, we define the following variables:

$$\chi_{j,t} \equiv E_t \left[\Omega_{t+1} \left(R_{j,t+1} - \left(1 + \tau_{j,t}\right) R_t\right)\right] \quad j \in \{T, N\}, \tag{A8}$$

$$\chi^F_{j,t} \equiv E_t \left[\Omega_{t+1} \left(R^*_{j,t+1} - \left(1 + \tau^F_{j,t}\right) R_t\right)\right] \quad j \in \{T, N\}, \tag{A9}$$

$$\nu_t \equiv E_t \left[\Omega_{t+1} R_t\right], \tag{A10}$$

where $\Omega_{t+1} \equiv M_{t,t+1} \left(1 - \pi + \pi\varphi_{t+1}\right)$ denotes the bank's stochastic discount factor.

The banker's optimization problem can then be rewritten as:

$$V_{i,t} = \max_{\Gamma_{i,t}, \Upsilon_{T,t}, \Upsilon^F_{T,t}, \Upsilon_t} \left[\begin{array}{c} \chi_{T,t}\Upsilon_{T,t}\left(1 - \Upsilon_t\right) + \chi_{N,t}\left(1 - \Upsilon_{T,t}\right)\left(1 - \Upsilon_t\right) + \\ +\chi^F_{T,t}\Upsilon^F_{T,t}\Upsilon_t + \chi^F_{N,t}\left(1 - \Upsilon^F_{T,t}\right)\Upsilon_t - \nu_t ac_t \end{array} \right] \Gamma_{i,t} + \nu_t NW_{i,t}, \tag{A11}$$

subject to the incentive constraint,

$$\left[\begin{array}{c} \chi_{T,t}\Upsilon_{T,t}\left(1 - \Upsilon_t\right) + \chi_{N,t}\left(1 - \Upsilon_{T,t}\right)\left(1 - \Upsilon_t\right) + \\ +\chi^F_{T,t}\Upsilon^F_{T,t}\Upsilon_t + \chi^F_{N,t}\left(1 - \Upsilon^F_{T,t}\right)\Upsilon_t - \nu_t ac_t \end{array} \right] \Gamma_{i,t} + \nu_t NW_{i,t} \geq \kappa\Gamma_{i,t}. \tag{A12}$$

The Lagrangian for this problem is

$$\pounds_{i,t} = \left\{ \left[\begin{array}{c} \chi_{T,t}\Upsilon_{T,t}\left(1 - \Upsilon_t\right) + \chi_{N,t}\left(1 - \Upsilon_{T,t}\right)\left(1 - \Upsilon_t\right) \\ +\chi^F_{T,t}\Upsilon^F_{T,t}\Upsilon_t + \chi^F_{N,t}\left(1 - \Upsilon^F_{T,t}\right)\Upsilon_t - \nu_t ac_t \end{array} \right] \Gamma_{i,t} + \nu_t NW_{i,t} \right\} \left(1 + \lambda^b_t\right) - \lambda^b_t \kappa \Gamma_{i,t}.$$

The first order optimality conditions with respect to $\Gamma_{i,t}$, $\Upsilon_{T,t}$, $\Upsilon^F_{T,t}$, Υ_t, respectively, are:

$$\left[\begin{array}{c} \chi_{T,t}\Upsilon_{T,t}\left(1 - \Upsilon_t\right) + \chi_{N,t}\left(1 - \Upsilon_{T,t}\right)\left(1 - \Upsilon_t\right) \\ +\chi^F_{T,t}\Upsilon^F_{T,t}\Upsilon_t + \chi^F_{N,t}\left(1 - \Upsilon^F_{T,t}\right)\Upsilon_t - \nu_t ac_t \end{array} \right] = \frac{\lambda^b_t}{1 + \lambda^b_t}\kappa, \tag{A13}$$

$$\Upsilon_{T,t} = \frac{\left(\chi_{T,t} - \chi_{N,t}\right)\left(1 - \Upsilon_t\right)}{\nu_t \phi_{p_2}} + \overline{\Upsilon}_T, \tag{A14}$$

$$\Upsilon^F_{T,t} = \frac{\left(\chi^F_{T,t} - \chi^F_{N,t}\right)\Upsilon_t}{\nu_t \phi_{p_3}} + \overline{\Upsilon}^F_T, \tag{A15}$$

$$\Upsilon_t = \frac{\chi^F_{T,t}\Upsilon^F_{T,t} + \chi^F_{N,t}\left(1-\Upsilon^F_{T,t}\right) - \chi_{T,t}\Upsilon_{T,t} - \chi_{N,t}\left(1-\Upsilon_{T,t}\right)}{\nu_t\phi_{p_1}} + \overline{\Upsilon}. \tag{A16}$$

In our calibrated model, the incentive constraint (eq. 16) always binds. Using the optimality conditions together with the binding incentive constraint, we have

$$\Gamma_{i,t} = \frac{\nu_t}{\kappa - z_t} NW_{i,t}, \tag{A17}$$

where $z_t \equiv \chi_{T,t}\Upsilon_{T,t}\left(1-\Upsilon_t\right) + \chi_{N,t}\left(1-\Upsilon_{T,t}\right)\left(1-\Upsilon_t\right) + + \chi^F_{T,t}\Upsilon_{T,t}\Upsilon_t + \chi^F_{N,t}\left(1-\Upsilon^F_{T,t}\right)\Upsilon_t - \nu_t ac_t$. To verify the conjecture notice that the value function is linear in net worth, note that

$$V_{i,t} = \frac{\kappa\nu_t}{\kappa - z_t} NW_{i,t}, \tag{A18}$$

which implies $\varphi_t = \frac{\kappa\nu_t}{\kappa - z_t}$ verifying out initial conjecture. Thus, aggregating equation (A17) across banks yields equation (20) in the main text:

$$\sum_{j\in\{T,N\}} \left(Q_{j,t}S_{j,t} + Q^*_{j,t}S^F_{j,t}\right) = \frac{\varphi_t}{\kappa} NW_t.$$