# Emission trading, financial frictions, and transition risks[1]

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**Abstract**

I examine how a carbon permit market affects financial stability by using a two-sector Environmental Dynamic General Equilibrium model with emission intensity target and financial frictions. The Ramsey-optimal environmental target and macroprudential policy (taxes or subsidies on bank assets) are contingent on initial permit allocation method and financial frictions. I find that the asymmetric effect of permit trading between firms due to their differing policy compliance propagates from firms' profit maximization to banks' portfolio composition. Permit trading and macroprudential policy shift lending toward permit sellers. When policy is implemented without prior announcement, bank net worth falls. Auctioning generates larger losses and a recession, while free allocation entails smaller losses and avoids recession under optimal targets but can be recessionary under stringent targets. However, macroprudential policy limits these losses. Advance policy announcements mitigate transition risk by reducing net worth losses under auctioning and increasing bank net worth under free allocation.

***JEL Codes:*** E44, E32, G18, Q58, D47

**Keywords:** Financial frictions, macroprudential policy, transition risk, permit trading, intensity target

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# 1 Introduction

After 10 years of the Paris Agreement, nations have repeatedly fallen short of their environmental targets, leading to a rise in global GHG emissions by 2.3% in 2024 from 2023 levels (UNEP, 2025). To address the challenge of increasing emissions, nations require urgent and ambitious climate actions (Stern, 2006; Nordhaus, 2007). Carbon pricing tools have been increasingly used to reduce emissions (Stavins, 2022). However, a sudden implementation can lead to transition risk[2] (Carney, 2015) and can be recessionary (Le, 2025), thus impacting the financial stability (NGFS, 2023). Hence, the regulator now has to solve two problems simultaneously: How could it reduce the financial sector's exposure to carbon-intensive assets in an orderly way? Could a climate policy achieve environmental goals, i.e., emission reductions, without causing recessions?

The first problem concerns financial stability of the economy. A financial sector is deemed crucial for the green transition, serving as a source of external finance (Campiglio, 2016), aligning investment to sustainability (Dunz et al., 2021; Monasterolo, 2020), determining the cost of capital (Schuldt and Lessmann, 2023) and as a transmission channel for macroeconomic shocks and environmental policies (Annicchiarico et al., 2026). The second problem is to reduce emissions without unduly constraining economic activity. Carbon pricing reduces emissions but increases the marginal cost of production (Annicchiarico and Di Dio, 2015). This creates a trade-off between emissions reductions and economic activity (Känzig, 2025). In addition, recessionary effects of carbon taxes persist despite macroprudential policies (Carattini et al., 2023). Hence, there is a need to study alternative environmental policies such as emission trading scheme (ETS) and their interactions with financial frictions.

Existing studies typically model ETS as a pure cap system[3], which does not fully cap-

[2] Carney (2015) defines transition risk as the risk that assets become stranded in emissions-intensive sectors arising from the financial sector's exposure to carbon-intensive assets

[3] See Fischer and Springborn (2011); Heutel (2012); Annicchiarico and Di Dio (2015); Annicchiarico et al. (2026); Benmir et al. (2024).

ture the nature of trading (Annicchiarico et al., 2026). Hence, how permit trading affects firms' balance sheets and, in turn, bank lending and financial stability remains largely unexplored. This paper fills this gap and studies the interaction between the financial sector and a permit market where firms trade permit among each other. Specifically, I ask: (i) How do financial frictions shape the macro-finance transmission of permit trading over the long run and business cycles? (ii) Can macroprudential policy that targets banks' sectoral asset exposure mitigate transition risks? (iii) What factors determine the optimal design of emission-intensity targets and macroprudential policies?

I develop an environmental dynamic general equilibrium model with a permit market and financial frictions featuring two distortions: a pollution externality and financial frictions. I consider an emission-intensity-based ETS to address the environmental externality and macroprudential policies that tax or subsidize banks' assets to address financial frictions and transition risks[4]. While a cap-and-trade can mitigate the output–emission tradeoff, as in Känzig (2025), through gains from permit trading (Lanz and Rausch, 2016; Dardati and Saygili, 2020), evidence suggests that these policies remain contractionary (Känzig and Konradt, 2024; Degasperi et al., 2026). An intensity-based ETS instead links the environmental target to economic activity, allowing the target to adjust with the business cycle (Jotzo and Pezzey, 2007). Permits are initially allocated either for free or sold by the regulator at a competitive price, after which firms trade them in the permit market. Hence, it inherently creates winners and losers in the permit market by implicitly subsidizing winners output and taxing losers output (Quan et al., 2026). Firms with emission intensity below the target become permit sellers (see Burgold et al., 2025).

At the core of the model are banks with financial frictions in the spirit of Gertler and Karadi (2011) and the asymmetric financial implications of a permit market due to

[4] A Basel framework introduces a positive risk-weights on the brown assets and thus discourage firms from lending to carbon-intensive firms. The macroprudential policy proposed by Carattini et al. (2023) also introduces this carbon-penalizing factor, facilitating a direct comparison with this aspect of the Basel framework. The paper can be extended to other macroprudential policies as well. While the framework can be extended to incorporate alternative macroprudential policies, I focus on this relatively simple specification to isolate the interaction between permit markets and financial frictions. The analysis of alternative macroprudential instruments is left for future research.

the differing compliance positions of firms. Banks raise deposits from households and extend loans to non-financial firms to finance their capital purchases. Financial frictions constrain this lending channel. Revenue from selling permits strengthens firms' balance sheets and attracts credit through appreciation in asset valuations. This channel gets undermined and may get impaired under auction. These are newly identified channels through which the permit market can impact the economy.

The model is calibrated to the U.S. and follows Carattini et al. (2023) for the real business cycle parameters and Burgold et al. (2025) for the carbon market parameters. I conduct a series of simulations to examine the long-run results and the short-run transition dynamics. These experiments quantify transition risks, credit conditions, and macroeconomic adjustment during the transition to a low-emissions economy.

An unanticipated permanent introduction of environmental policy triggers financial instability and transition risks. The macroprudential policy partially mitigates the risk. Without financial frictions, the economy transitions toward the sellers under free allocation, mildly increasing aggregate activity. Auction contracts activity in both sectors, i.e., recession. Financial frictions slow the transition and deepen the contraction. Under free allocation, gains from permit trading raise seller asset values (after an initial fall), increasing lending and preventing a recession. Under auction, lower asset values generate equity losses and constrain lending to both sectors. Thus, free allocation alleviates financial frictions by raising low-intensity asset values, whereas auctioning strengthens them by lowering asset values and constraining external finance.

The long-run results show that emissions and environmental damage are high when pollution is not internalized. Financial frictions achieve both by dampening economic activity. However, the planner seeks to stimulate activity while reducing emissions. An intensity target with free allocation achieves both through the implicit output subsidy. This subsidy differs from Lanz and Rausch (2016), where free allocations lower regulated

output prices, and from Dardati and Saygili (2020), where output-based allocation lowers firms' effective emissions cost. In our setting, free permits create an incentive to increase production relative to emissions, thereby generating additional permit allocations. The increase in seller lending counters the fall in buyer lending and raises bank net worth. Auctioning weakens the subsidy and leads to a more visible output-environment tradeoff. I quantitatively show that macroprudential policy alone shifts lending towards sellers, which gets further reinforced under free allocation. However, auction dampens the effect of tax/subsidy policy.

The above results are contingent on Ramsey policy response that is jointly determined by financial frictions and initial allocation method. Financial frictions and initial permit allocation jointly shape the Ramsey-policy. Financial frictions reduce economic activity, relaxing the intensity target. This resonates with the findings of Döttling and Rola-Janicka (2025) who finds that optimal Pigouvian carbon tax is lower than in the absence of financial frictions. A free method relaxes the target through its implicit output subsidy. Auction through dampening activity, induces a relaxation of tax/subsidy. Under auction, the equilibrium permit price falls within the carbon-price range estimated by Stiglitz et al. (2017) and IMF (2019), whereas free allocation yields a lower permit price. This indicates that auctioning places a greater share of the carbon-pricing burden on firms, whereas free allocation transfers part of the permit rents to firms (MacDonald and Parry, 2024).

The results depend on policy timing, target stringency, and the size of the environmental-friendly sector. Pre-announcement allows firms to adjust production and banks to rebalance portfolios before implementation, improving bank net worth under free allocation and limiting its decline under auctioning. Stricter targets improve portfolio allocation toward sellers, but excessively strict or relaxed targets weaken the effectiveness of environmental policy and reduce net worth. Finally, a larger seller sector reduces the need for environmental policy and permit-market activity. In addition, a decrease in the carbon-

intensive sector abatement cost significantly improves asset prices, leading to increased investment.

This paper contributes to several strands of literature. I contribute to a growing theoretical literature on environmental policy and stranded assets. Van der Ploeg and Rezai (2020) and Rozenberg et al. (2020) show that unanticipated tightening of environmental policy threatens stranding of carbon-intensive capital, thus affecting the financial stability. Sen and Von Schickfus (2020) find that investors take these risks into consideration. Hence, asset stranding may undermine the effectiveness of environmental policy (Von Dulong et al., 2023).

I also contribute to the literature on interactions between financial frictions and environmental policy in a quantitative E-DSGE model. Diluiso et al. (2021) study the transition risk originating from delayed and disorderly environmental policies and show that transition costs can be moderate if policies are timely and orderly. However, they do not study the first-best or second-best efficient policy design via the Ramsey problem. Carattini et al. (2023) show that macroprudential policy along with emission tax is the first-best policy and can limit the risk of recessions. The environmental policy in these papers is carbon tax. Benmir et al. (2024) and Annicchiarico et al. (2026) extend the literature to cap-and-trade policy. Annicchiarico et al. (2026) show higher economic stability in cap-and-trade policy than a carbon tax while a macroprudential policy aligns the performance of both policies. Benmir et al. (2024) find that a macroprudential policy that includes climate risks on loans improves the substitution effect between clean and dirty sectors. However, these papers do not consider permit trading among firms.

Given the gap, I extend Carattini et al. (2018) framework by incorporating an endogenous permit market following Burgold et al. (2025). Dardati and Saygili (2020) and Lanz and Rausch (2016) also develop a permit market framework. However, it does not interact with financial agents. To the best of our knowledge, this is the first attempt to

study the transition risk in the presence of financial frictions and permit trading between firms.

Overall, this paper adds to the rapidly growing E-DSGE literature that includes initial contributions by Angelopoulos et al. (2010), Heutel (2012), Fischer and Springborn (2011), and Annicchiarico and Di Dio (2015) to the multi-sector models by Golosov et al. (2014) and Dissou and Karnizova (2016). In addition, this paper is related to a model with environmental policy implications on the financial sector such as Chan et al. (2024), Frankovic and Kolb (2024), and Ferrari and Landi (2024), to name a few.

The paper proceeds as follows. Section 2 presents the model, Section 3 presents the calibration, Section 4 presents steady state results and transition dynamics in the presence of exogenous shocks, and Section 5 concludes the paper.

# 2 Model

I build an Environment Dynamic General Equilibrium model augmented with environmental externality, financial friction, and a carbon permit market framework. The economy consists of (i) a continuum of infinitely lived households, who consume, provide labor services, and saves in form of deposits (ii) perfectly competitive producers divided into two sectors based on their compliance position, each of which produces homogeneous goods by using labor and capital as factor inputs, takes abatement efforts to reduce their emissions, and trades carbon permits, (iii) a financial intermediary that collects deposits from households and lends to production sector, and (iv) a government that implements environmental policy and targets. The compliance position divides the production sector into a permit seller and a buyer. The economy features two sources of inefficiency. The first inefficiency is environmental externality, where firms do not internalize the effect of production decisions on the pollution stock. The second inefficiency is the moral hazard problem between banks and households that constrains credit supply in the economy, called financial frictions. To address these inefficiencies, this paper introduces an intensity

target with permit trading and macroprudential policy as taxes or subsidies on banks' assets. The prices are in real terms unless stated.

## 2.1 Household

There is a continuum of identical households $i \in [0,1]$ of measure unity in the economy. As in Gertler and Karadi (2011), each household has a continuum of family members of measure unity. A fraction $(1-o)$ of the members are workers, and the rest are bankers who manage the banks. Each household provides labor to seller ($S$) and buyer ($B$) production sectors, i.e., non-financial firms. It saves in the form of deposits $D_t$ in the bank. A representative household $i$ chooses consumption, labor, and deposit to maximize its lifetime utility ($\mathbb{U}_0$):

$$\mathbb{U}_0 = \max \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left( \log(C_{i,t} - hC_{t-1}) - \mu_S \frac{(L^S_{i,t})^{1+\eta}}{1+\eta} - \mu_B \frac{(L^B_{i,t})^{1+\eta}}{1+\eta} \right) \tag{1}$$

where $\beta \in (0,1)$ is the subjective discount factor, $C_t$ is the consumption of the final good, $L^j_t$ are labor hours where $j \in \{B,S\}$, $\eta$ is the inverse of Frisch elasticity of labor, $\mu_j$ is labor disutility parameter, and $h$ is the habit formation parameter. The utility is maximized subject to the budget constraint:

$$C_{i,t} + D_{i,t} = R_{t-1} D_{i,t-1} + w^S_t L^S_{i,t} + w^B_t L^B_{i,t} + \mathcal{T}_{i,t} + \Pi_{i,t} \tag{2}$$

where $R_t$ is the interest rate earned in deposits, $w^j_t$ is the real wage rate, $\mathcal{T}_t$ is the lump-sum tax or transfer and $\Pi_t$ is the profit from the ownership of the production and banking sector.

Given perfect risk sharing across households, the index $i$ can be omitted. The FOCs

for the household problem are:

$$\frac{1}{C_t - hC_{t-1}} = \lambda_t \tag{3}$$

$$\mu_S (L_t^S)^\eta = \lambda_t w_t^S \tag{4}$$

$$\mu_B (L_t^B)^\eta = \lambda_t w_t^B \tag{5}$$

$$\tag{6}$$

$$\frac{1}{R_t} = \beta \mathbb{E}_t \left( \frac{\lambda_{t+1}}{\lambda_t} \right) \tag{7}$$

where $\lambda_t$ is the lagrange multiplier of the household problem. The Euler equation that characterizes the intertemporal tradeoff in consumption can be derived by substituting $\lambda_t$ in eq. (7) with eq. (3).

## 2.2 Good producer

The aggregate production is a composite function of seller and buyer good bundles $Y_t^S$ and $Y_t^B$:

$$Y_t = \left[ \omega^{\frac{1}{\epsilon}} (Y_t^S)^{\frac{\epsilon-1}{\epsilon}} + (1-\omega)^{\frac{1}{\epsilon}} (Y_t^B)^{\frac{\epsilon-1}{\epsilon}} \right]^{\frac{\epsilon}{\epsilon-1}} \tag{8}$$

where $\omega$ and $\epsilon$ determine the weight and elasticity of substitution between different goods. The demand functions for two consumption goods are:

$$Y_t^S = \frac{\omega Y_t}{(p_t^S)^\epsilon} \tag{9}$$

$$Y_t^B = \frac{(1-\omega) Y_t}{(p_t^B)^\epsilon} \tag{10}$$

where $p_t^j$ is the price of sectoral goods. The final consumption good is a numeraire. Hence, I can normalize its price to 1.

In each sector $j \in \{B, S\}$, a firm produces output $Y_t^j$ using labor $(L_t^j)$ and capital

$(K^j_{t-1})$. The production function is a standard Cobb-Douglas function:

$$Y^j_t = (1 - \Lambda(M_t))A^j_t(K^j_{t-1})^\alpha(L^j_t)^{1-\alpha} \tag{11}$$

where $\Lambda(\cdot) \in (0, 1)$ is an increasing damage function that represents the damage due to the accumulated pollution stock $(M_t)$, $\alpha$ is the factor intensity, and $A^j_t$ is the total factor productivity given by an AR(1) function:

$$log(A^j_t) = \rho_{A^j} log(A^j_{t-1}) + \varepsilon_{A^j,t} \tag{12}$$

I model the damage function $(\Lambda_t)$ as

$$\Lambda_t = (d_0 + d_1 M_t + d_2 M^2_t) \tag{13}$$

where $M_t$ is the pollution stock. The accumulated pollution stock $(M_t)$ evolves according to

$$M_t = Z_t + Z^{\text{row}} + (1 - \delta_M)M_{t-1} \tag{14}$$

where $\delta_M$ is the decay rate of emissions, $Z_t$ is emissions produced during the production process and $Z^{\text{row}}$ is the emission of the rest of the world.

Each firm in both sectors takes abatement efforts $U_t$ to reduce emissions. Hence, emission is given by

$$Z^j_t = \phi_j(1 - U^j_t)Y^j_t \tag{15}$$

where $\phi_j$ is the emission intensity of sector $j$. The abatement is costly with cost function

$$\mathcal{C}^j_t = \phi_1(U^j_t)^{\phi_2} Y^j_t \tag{16}$$

where $\phi_1 > 0$ and $\phi_2 > 1$ are technological parameters.

The environmental policy is an emission intensity target with permit trading among

firms in the permit market. The regulator either allocates permits at no cost (free allocation) or through auctions. Each producer is subject to an emission intensity target ($\phi_T$) imposed by the government and receives permits based on the corresponding target emissions, i.e., $\phi_T Y_t^j$. Following Burgold et al. (2025), the policy target is non-sector specific. Hence, a firm with lower emission intensity than the target sells their unused permits to the firm with higher emission intensity. This leads to trading. The number of permits ($\mathcal{N}_t^j$) being traded by a producer $j$ in the carbon market is given by

$$\mathcal{N}_t^j = \phi_T Y_t^j - \phi_j (1 - U_t^j) Y_t^j \tag{17}$$

where $\mathcal{N}_t^j > 0$ means the producer is selling surplus permits and $\mathcal{N}_t^j < 0$ means the producer is buying deficit permits. The profit maximization problem of each producer is:

$$p_t^j Y_t^j - w_t^j L_t^j - r_{k,t}^j q_{t-1}^j K_{t-1}^j - [\mathcal{S}_t \phi_{1,t} (U_t^j)^{\phi_2} Y_t^j - p_t^C \mathcal{N}_t^j - \mathcal{A}_t \phi_T Y_t^j p_t^c] + (1 - \delta_k) q_t^j K_{t-1}^j \tag{18}$$

where $r_{k,t}^j$ is capital rent, $\mathcal{S}_t = 1$ when there exists a functioning permit market and $\mathcal{S}_t = 0$ otherwise, and $\mathcal{A}_t = 1$ if the initial permit allocation is auction-based and $\mathcal{A}_t = 0$ if it is free allocation based. The FOCs are given by

$$w_t^j = (1 - \alpha) \frac{Y_t^j}{L_t^j} mc_t^j \tag{19}$$

$$r_{k,t}^j = \frac{\alpha \frac{Y_t^j}{K_{t-1}^j} mc_t^j + (1 - \delta_k) q_t^j}{q_{t-1}^j} \tag{20}$$

$$\phi_{1,t} \phi_2 (U_t^j)^{\phi_2 - 1} = p_t^C \phi_j \tag{21}$$

where $mc_t^j = \left( p_t^j - \left[ \mathcal{S}_t \phi_{1,t} (U_t^j)^{\phi_2} - p_t^C \frac{\mathcal{N}_t^j}{Y_t^j} - \mathcal{A}_t \phi_T p_t^c \right] \right)$ is the marginal cost of input of sector $j$. Eq. (19) and eq. (20) are sectoral labor and capital demand equations. Eq. (21) determines optimal abatement efforts. Similarly to Annicchiarico and Di Dio (2015), the total marginal cost of input is:

$$mc_t^j = \left( p_t^j + \left[ \mathcal{S}_t \phi_{1,t} (U_t^j)^{\phi_2} - p_t^C \frac{\mathcal{N}_t^j}{Y_t^j} - \mathcal{A}_t \phi_T p_t^c \right] \right) \tag{22}$$

## 2.3 Financial Intermediaries

A financial intermediary lends to the production sector by combining net worth ($N_t$) and deposits ($D_t$) raised from households. It purchases claims $S_t^j$ issued by good producing firms at sector-specific unit price $q_t^j$. The government levies macroprudential tax $\tau_t^j > 0$ or subsidy $\tau_t^j < 0$ on banks' assets[5].

I follow Gertler and Karadi (2011) to model the moral hazard problem of the financial intermediaries. The financial friction occurs because banks face borrowing constrains. In each period, banks raise deposits from households and lend to producers. The $k^{th}$ individual bank's balance sheet at time $t$ is:

$$\sum_{j=\{B,S\}} q_t^j S_{k,t}^j = D_{k,t} + N_{k,t} \tag{23}$$

The bank's net worth evolves according to:

$$N_{k,t+1} = \sum_{j=\{B,S\}} r_{k,t+1}^j q_t^j S_{k,t}^j - R_t D_{k,t} \tag{24}$$

The bank $k$ can choose to divert an exogenous fraction $\kappa$ of total assets for personal use of the respective owner household. However, the cost associated with diverting funds is that depositors can shut down the bank after recovering the remaining $(1-\kappa)$ assets. A bank can only continue operations if the value of the bank is not lower than the fraction of divertible funds. Hence, the incentive constraint must satisfy;

$$\underbrace{V_{k,t}}_{\text{Loss when diverting a fraction of assets}} \geq \underbrace{\kappa \sum_{j=\{B,S\}} q_t^j S_{k,t}^j}_{\text{Gains from diverting the fund}} \tag{25}$$

where $V_{k,t}$ represents continuation value of the bank and measures the present discounted value of its terminal wealth.

[5] See Carattini et al. (2023) for the discussion on these taxes and subsidies.

A banker can exit from the market with exogenous probability $(1-\gamma_B)$ and surviving bankers continue business by reinvesting all their net worth. The maximization problem of the bank is to maximize their terminal wealth, given by

$$V_{k,t} = \max \mathbb{E}_t \sum_{m=0}^{\infty} (1-\gamma_B)\gamma_B^m \Lambda_{t,t+1+m} N_{k,t+1+m} \tag{26}$$

subject to eq. (23), (24), and (25). Value function is linear in net worth

$$V_{k,t} = \varphi_t N_{k,t} \tag{27}$$

where $\varphi_t \geq 1$ is the shadow value of the bank's net worth. Rewriting the incentive constraint in terms of $\varphi_t$ and $N_{k,t}$ and aggregating for the banking sector leads to

$$\sum_{j=\{B,S\}} q_t^j S_{k,t}^j = \frac{\varphi_t}{\kappa} N_t \tag{28}$$

The above equation implies that when banks are financially constrained, demand of capital is constrained by banks' net worth. This constraint amplifies the effects of shocks hitting the economy through banks' equity capital.

Following the portfolio choice problem, the expected discounted excess return on two assets should equal, i.e.,

$$\mathbb{E}_t r_{k,t+1}^S - (1+\tau_t^S)R_t = \mathbb{E}_t r_{k,t+1}^B - (1+\tau_t^B)R_t \tag{29}$$

This is the no-arbitrage condition between two types of assets.

Each exiting bank is replaced by an equal number of new banks. These new entering banks receive an initial transfer $\frac{\zeta}{1-\gamma_B} \sum_{j=\{B,S\}} q_t^j S_t^j$ from the household. Hence, the

aggregate banking sector's net worth evolution is given by

$$N_{t+1} = \gamma_B \left[ \sum_{j=\{B,S\}} r^j_{k,t+1} q^j_t S^j_t - R_t D_t \right] + \zeta \sum_{j=\{B,S\}} q^j_t S^j_t \tag{30}$$

Hence, net dividend payouts to the household is given by

$$\Xi_{t+1} = (1-\gamma_B) \left[ \sum_{j=\{B,S\}} r^j_{k,t+1} q^j_t S^j_t - R_t D_t \right] - \zeta \sum_{i=\{B,S\}} q^j_t S^j_t \tag{31}$$

Similar to the financial friction literature, credit spread is given by the difference between the expected rate of return on an asset and the risk-free rate. Hence, the sectoral credit spread is:

$$\text{spread}^B_t = \mathbb{E}_t(r^B_{k,t+1}) - R_t \tag{32}$$

$$\text{spread}^S_t = \mathbb{E}_t(r^S_{k,t+1}) - R_t \tag{33}$$

The leverage ratio is given by:

$$\text{lev}_t = \frac{q^B_t S^B_t + q^S_t S^S_t}{N_t} \tag{34}$$

## 2.4 Capital sector

Capital producer provides sector-specific and immobile capital to the production sector in competitive manner. It builds both type of capital goods subject to a convex investment adjustment cost $\frac{\gamma_I}{2}\left(\frac{I^j_t}{I^j_{t-1}} - 1\right)^2 I^j_t$, where $\gamma_I \geq 0$ is the size of adjustment cost parameter. Hence, the profit maximization problem is:

$$\max \mathbb{E}_0 \sum_{t=0}^{\infty} \Lambda_{0,t} \sum_{j\in\{B,S\}} \left[ q^j_t I^j_t - \left(1 + \frac{\gamma_I}{2}\left(\frac{I^j_t}{I^j_{t-1}} - 1\right)^2\right) I^j_t \right] \tag{35}$$

where $\Lambda_{t,t+1} = \beta^t \frac{\lambda_{t+1}}{\lambda_t}$ is the stochastic discount factor. The optimality condition gives

$$q_t^j = 1 + \frac{\gamma_I}{2}\left(\frac{I_t^j}{I_{t-1}^j} - 1\right)^2 + \gamma_I\left(\frac{I_t^j}{I_{t-1}^j} - 1\right)\frac{I_t^j}{I_{t-1}^j} - \mathbb{E}_t\left[\Lambda_{t,t+1}\gamma_I\left(\frac{I_{t+1}^j}{I_t^j} - 1\right)^2\left(\frac{I_{t+1}^j}{I_t^j}\right)^2\right] \tag{36}$$

The capital evolution equation is given by:

$$K_t^j = (1 - \delta_k)K_{t-1}^j + I_t^j \tag{37}$$

### 2.5 Government

The government announces the intensity target ($\phi_{T,t}$) and transfers net revenues from macroprudential policies and permit auction (if applicable) to households in a lump-sum manner

$$\mathcal{T}_t = p_t^c \phi_T \mathcal{A}_t(Y_t^S + Y_t^B) + \sum_{i=\{B,S\}} \tau_t^j q_t^j S_t^j \tag{38}$$

## 3 Calibration

Table 1 presents the parameter calibration for the model with an active permit market and financial frictions without macroprudential policy, i.e. $\tau_t^S = \tau_t^B = 0$. Each period in the model corresponds to a quarter. The parameters can be divided into three categories: standard RBC, banking, and environmental parameters.

The subjective discount factor $\beta = 0.9975$ corresponds to an annualized risk-free rate ($R$) of 1% in the steady state. The labor disutility parameters are calibrated as $\mu_S = 9$ and $\mu_B = 13$ such that $L^B = L^S = \frac{1}{3}$ in the steady state. The parameter values of inverse of Frisch elasticity of labor $\rho_L = 1$, the share of capital in production $\alpha = 0.35$ and capital depreciation rate $\delta_K = 0.025$ are standard in the RBC literature. The habit persistence parameter comes from the Bayesian estimates of Diluiso et al. (2021). The TFP persistence parameter $\rho_A = 0.95$, standard deviation of TFP $\sigma_A = 0.007$, and in-

| Parameters | Description | Value | Source |
|---|---|---|---|
| *RBC parameters* | | | |
| $h$ | Internal habit parameter | 0.6326 | Diluiso et al. (2021) |
| $\beta$ | Discount factor | 0.9975 | Carattini et al. (2023) |
| $\mu_S$ | Labour disutility (low-intensity) | 9 | Author's calculation |
| $\mu_B$ | Labour disutility (high-intensity) | 13 | Author's calculation |
| $\rho_L$ | Frisch elasticity of labor hours | 1 | Carattini et al. (2023) |
| $\omega$ | Share of low-intensity output | 0.332 | |
| $\varepsilon$ | CES between two types of output | 2 | Carattini et al. (2023) |
| $\alpha$ | Capital share in output production | 0.35 | Carattini et al. (2023) |
| $\delta_k$ | Depreciation rate | 0.025 | Standard value |
| $\gamma_I$ | Investment adjustment parameter | 10 | Carattini et al. (2023) |
| $\rho_A$ | Technology persistence parameter | 0.95 | Standard value |
| *Banking parameters* | | | |
| $\gamma$ | Bank's survival rate | 0.972 | Carattini et al. (2023) |
| $\zeta$ | Proportional transfer to new bankers | 0.0029 | Carattini et al. (2023) |
| $\kappa$ | Fraction of divertable assets | 0.3313 | Carattini et al. (2023) |
| *Environmental parameters* | | | |
| $\phi_H$ | Emission intensity of high-intensity sector | 0.7 | Burgold et al. (2025) |
| $\phi_L$ | Emission intensity of low-intensity sector | 0.157 | Burgold et al. (2025) |
| $\bar{\phi_1}$ | Abatement cost parameter | 0.0334 | Carattini et al. (2023) |
| $\phi_2$ | Abatement cost parameter | 2.6 | Carattini et al. (2023) |
| $d_0$ | Damage function parameters | -0.26 | Carattini et al. (2023) |
| $d_1$ | | 3.6613e-5 | Carattini et al. (2023) |
| $d_2$ | | 1.4812e-8 | Carattini et al. (2023) |
| $\bar{Z}^{\text{row}}$ | Rest of the world emissions | 3.3705 | Carattini et al. (2023) |

Table 1: Calibrated parameters for model with financial frictions and permit market

vestment adjustment parameter $\gamma_I = 10$ are set in line with Annicchiarico and Di Dio (2015). I calibrate the share of the seller sector $\omega = 0.332$[6]. The elasticity of substitution between seller and buyer outputs $\varepsilon = 2$ is calibrated from Carattini et al. (2023). The banking parameters, bank's survival rate $\gamma = 0.972$, household transfer to new bankers in the market $\zeta = 0.0029$, and fraction of divertable assets $\kappa = 0.3313$ are calibrated from Carattini et al. (2023), Gertler and Karadi (2011), and Gertler and Kiyotaki (2010).

The abatement cost parameters $\phi_1 = 0.185$ and $\phi_2 = 2.8$ are taken from Diluiso et al. (2021) and Annicchiarico and Di Dio (2015). Burgold et al. (2025) calculates the sectoral emission intensities of 11 sectors using World Input Output Database and environmental accounts from 2014. The two sectors with highest emission intensities are electricity sector and transportation with values 0.73 and 0.699 respectively. Given the absence of disaggregated data on permit buyers and sellers, I calibrate emission intensities, $\phi_H = 0.7$, the intensity of manufacturing [7] and $\phi_L = 0.157$. The calibration of $\phi_L$ represents a conservative lower bound for the seller intensity since sectors that are covered under the EU-ETS have higher emission intensities. Hence, it implies an upper bound on the volume of permit supply and correspondingly, a lower bound on the equilibrium permit price.

# 4 Results and Discussions

In this section, I study the long-run impact and transition dynamics of introducing an intensity target policy with permit trading [8] to assess the macro-finance implications of a permit market on the economic stability and transition. Further, I introduce a macro-prudential policy that either taxes each asset or taxes buyer assets and subsidizes seller assets[9]. The deterministic steady states reflect long-run impacts. I then consider a surprise introduction of a permanent intensity target $\phi_T = 0.291$. The intensity target comes

[6] Carattini et al. (2023) calibrate it to be 0.668. However, their distinction is between brown and clean sector. I perform sensitivity analysis to a range of weights to understand the implications of sectoral size on the environmental policy.

[7] The literature, for example, see Goulder et al. (2022), Pizer and Zhang (2018) etc., find that energy sector, energy-intensive sector and manufacturing sector are generally permit buyer in the permit market. Hence, I set $\phi_L = 0.157$, equivalent to the sector that precedes manufacturing sector in EU28 as given by Burgold et al. (2025).

[8] To obtain the transition dynamics, I introduce a small perturbation of order $10^{-5}$ in $\tau^S$ and $\tau^B$. It does not introduce an economically meaningful distortion to the steady state (see Table H.1). It is done to numerically solve the model.

[9] A similar macroprudential policy is modeled in Aoki et al. (2016) and Carattini et al. (2023).

with free or auction-based allocation of permits to firms.

The economy starts in the baseline deterministic steady state with no policy. In period 1, the economy is surprised by the introduction of a target with free and auction-based allocations.

## 4.1 Transition dynamics

This section presents the transition dynamics for 20 periods when an intensity target is introduced. I assess the risk associated with policy and the potential for macroprudential policy to address it. I begin with a surprise introduction of the policy, followed by the assessment of dynamics when the policy is pre-announced. The target is set at 0.291 (or approximately 35% fall in emissions) and macroprudential policy at -0.00131 and 0.00131. The calibration is consistent with column 12 of Table 2.

The economy is subjected to a permanent emission intensity target. The agents have perfect foresight about their future path after the target has been introduced. I compare results from the baseline model (without financial frictions) to a model with financial frictions and macroprudential policy. Blue dashed lines show the dynamics of the model without financial frictions, red dashed-dotted lines show the dynamics of the model with financial frictions, and green solid lines represent macroprudential policies, unless stated otherwise.

### 4.1.1 No policy to free allocation

Fig. 1 plots the transition dynamics of the main variables in response to an exogenous introduction of a target with an initial free allocation of permits. Fig. C.1 presents the rest of the variables required to explain the dynamics. The economy begins in the baseline deterministic state without permit market.

Following the introduction of the intensity target, the aggregate output shows a

modest growth. The economies without financial friction, with financial frictions and macroprudential policies show an initial growth of 0.084%, 0.077% and 0.072%. The aggregate investment and capital persistently decline, mainly driven by the buyer sector. Firms begin to abate emissions where firms with higher emission intensity take a higher abatement than those of firms with lower emission intensity.

The revenue and cost channels of the permits, inherent in permit market, affect the prices of sectors of the assets differently. With financial frictions, the introduction of permit market leads to a fall in investment in both sectors. The revenue from permits strengthens the seller's balance sheet, making the investment rebounds by 6th period. Hence, asset prices increase after an initial fall by 0.22%. In contrast, investment in the buyer sector does not recover, leading to an initial fall in asset prices of 1.2%. Hence, undercapitalized bank is forced to cut lending in the buyer sector and channel it to the seller sector. The resulting transition risk leads to equity losses due to a higher fall in the asset prices of the buyer sector. It translates into a quick fall of banks' net worth by 3.8% before rebounding. Without financial frictions, the transition is more efficient as the seller asset price increases in the first period itself.

A macroprudential policy that taxes buyer assets and subsidizes seller assets mitigates the severity of the transition risk as the bank is less exposed to buyer sector, equity losses are milder and credit issued to the firms fall by less. Hence, the aggregate investment and capital fall by less and aggregate output increases by more. The increase is still lower (and fall is higher) than without financial frictions because the bank is undercapitalized. The fall in emissions is greater by 0.9%.

The free permit allocation only prices emissions that are beyond the target. As a result, the cost of emissions are not as severe as a carbon tax. In addition, it incentivizes a sector through revenue. Hence, unlike the carbon tax (see Carattini et al., 2023), the economy does not experience a recession. The bank net worth and investment fall by less.

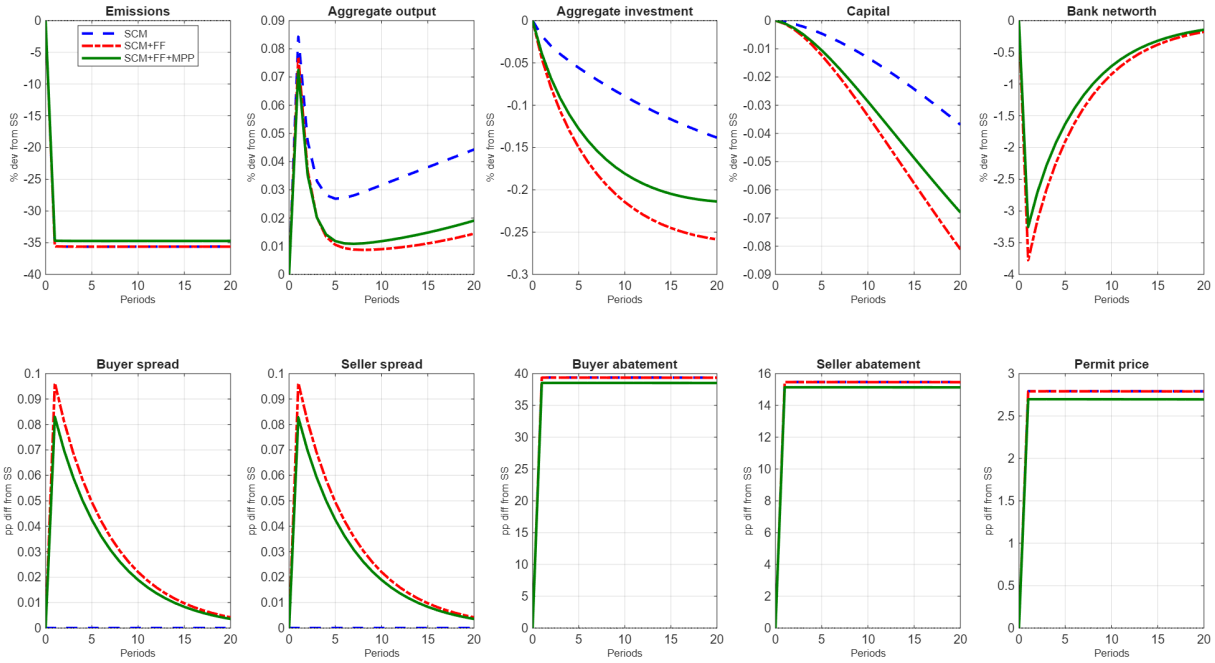



Figure 1: Transition dynamics in the response to an introduction of permit market in the three economies. Each economy begins with no environmental policy steady states and achieve new steady states after the introduction of policy in period 1.

### 4.1.2 Free allocation to auction

Fig. 2 presents the transition dynamics of the main variables when the regulators move from free allocation to auction-based allocation of permits. Fig. C.2 presents the rest of the variables required to explain the dynamics. The permit market still operates as in section 4.1.1.

When the economy moves from a free allocation to an auction mechanism, each unit of emissions is priced, thus increasing the marginal cost of production in both sectors. Although the seller can partially offset the cost by selling excess permits, the buyer has no way to do that. Since the cost of emissions has increased, emissions, output, investment, and capital further decline, abatement increases and economy suffers a recession. The economy suffers a deeper recession in the presence of financial friction as the net worth of banks falls by approx. 15% before rebounding. The macroprudential policy modestly mitigates the transition risks, but is insufficient in completely internalizing the risk. Asset

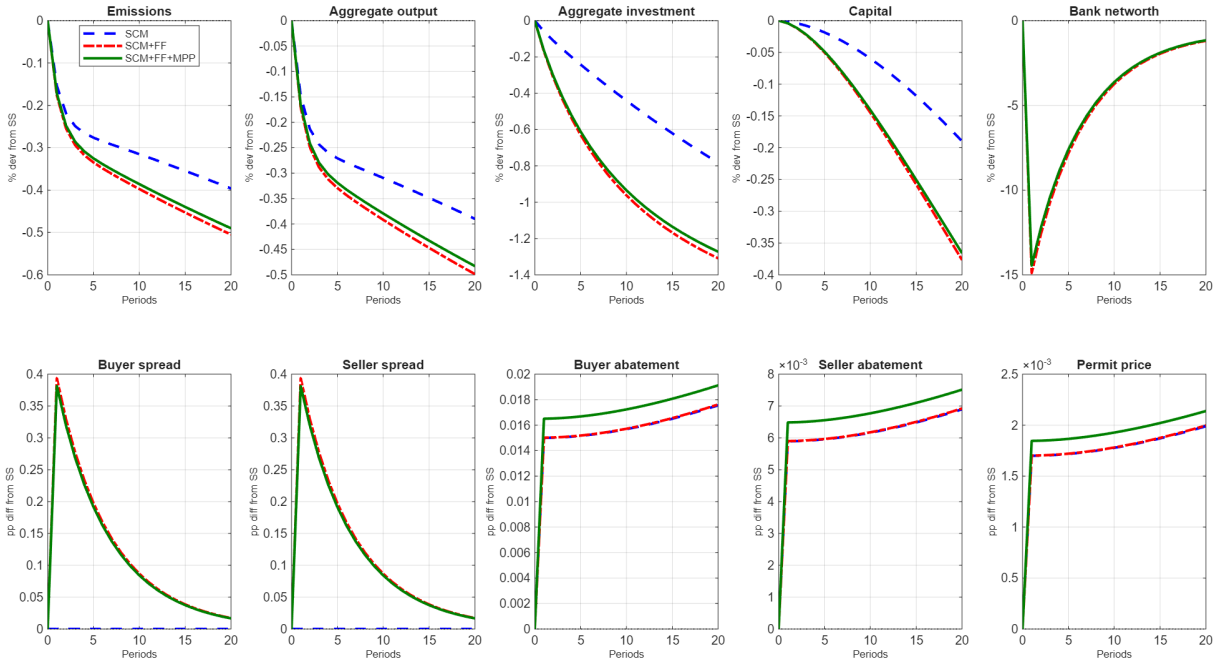



Figure 2: Transition dynamics in the response to auctioning permit in primary carbon market in the three economies. Each economy begins with free permit allocation steady states and achieve new steady states after the introduction of auction mechanism in period 1.

prices fall by 3.2% in the seller sector and 3.1% in the buyer sector in the presence of financial frictions and by 1.2% and 1% without financial frictions.

Note that $\phi_T = 0.291$ is a relaxed target for model with auction. E.3 remains robust to $\phi_T = 0.227$.

### 4.1.3 Announced Environmental Policy

Fig. C.4 presents the transition dynamics when a free allocation based intensity target is announced in the 1st period and gets implemented in the 5th period. The economy begins in no policy steady state. I compare the dynamics with Section 4.1.1.

When an environmental policy is pre-announced, economic agents, essentially banks, begin to internalize the effects of the policy prior to its implementation. Hence, the mid-term growth in output (20th period) is higher than exogenous and sudden implementation. It is mainly driven by the higher (lower) growth (fall) in the seller (buyer) output. Similarly, the investment also falls less. In contrast to un-announced policy, the bank net worth increases initially since the seller asset prices appreciate and dominate the fall in

buyer asset prices, signifying effective transition to low carbon economy.

The macroprudential policy internalizes the effects of policy better than those of financial friction. In the presence of macroprudential policy, aggregate investment and bank net worth begin to decline only after the 9th and 15th periods, respectively, where the decline in bank net worth is negligible. In contrast, in the absence of macroprudential policy (i.e., only financial friction), these variables begin to decline in the 7th and 12th periods. Thus, macroprudential policy delays the contraction in investment and bank net worth in comparison to the case with financial frictions alone.

Fig. C.5 presents the transition dynamics when an auction-based allocation is announced in the 1st period and gets implemented in the 5th period. The economy begins at free allocation steady states. Similarly to Fig. C.4, macrovariables like output, investment, and capital fall lesser than those of unannounced and suddenly implemented policy. Emissions also decline less. While bank net worth still falls before rebounding, compared to 15% in Fig. 2, it only falls by 6.65%.

Overall, announcement of a policy before implementation provides time to economic agents to adjust for future, especially banks begin to adjust their portfolio before the policy is implemented, leading to a reduction in the extent of risk due to the transition to a low carbon economy.

## 4.2 Efficient environmental policies

This section studies the interaction between environmental externalities and financial frictions and their effects on efficient policy design. Table 2 presents the deterministic steady state values in arbitrary model units for selected variables in six models with free and auction-based permit allocation. The first three columns report the steady states of the models without financial friction, under the no-policy, and with the permit market based on free and auction-based allocation. Column 4 to 6 augment previous models

with financial frictions and the remaining columns include macroprudential policies. The macroprudential taxes/subsidy, damages and credit spreads are in percentages. The welfare losses are in terms of compensating variation in consumption that equates steady state welfare of the economy with auction allocation and tax on assets as it generates highest welfare values. The Ramsey planner chooses an emission intensity target and macroprudential policy to be implemented.

Carattini et al. (2023) characterizes the first best policy, i.e., a carbon tax and a uniform macroprudential policy can fully undo both types of distortion. I study the corresponding policy problem through permit trading with an emission intensity framework. The results generate a characterization for the second-best policies, as permit price and a uniform macroprudential policy do not fully achieve environmental ambitions. This is because ETS regulates emissions through a binding constraint and the permit price reflects the market clearance of allowances.

In the absence of any environmental policy, producers do not internalize the negative emission externality. As a result, emissions are abruptly high. Financial frictions constrain efficient bank lending, limiting firms' access to external finance. Hence, investment, production and emissions are lower by 12.82%, 5.6% and 9.06%, respectively. Hence, the two sources of market failure have opposite effects on the economy, so emissions are lower with financial frictions than without them.

Without financial frictions, the Ramsey targets are 0.283 and 0.222 under free and auction, respectively. With financial frictions, they are 0.29 and 0.228, signifying that the target depends on whether the policy is with or without financial frictions and is free- or auction-based. Financial frictions already reduce output and emissions. Hence, a tighter target is not necessary to reduce the emissions, leading to a relaxed target. A free method effectively acts as an implicit output subsidy, since increasing production at a higher rate than emissions results in a higher permit allocation and effectively decreasing

the cost of production. Hence, firms have incentive to increase production. Unlike Lanz and Rausch (2016) where free allocations lower regulated output prices, and Dardati and Saygili (2020), where output-based allocation lowers firms' effective emissions cost, free permits create an incentive to increase production relative to emissions, thereby generating additional permit allocations.This subsidy vanishes under auction. As a result, the Ramsey planner does not have any obligations towards output, firms must purchase the permits they require as production does not itself generate additional permits, the target is more stringent in auction than in free. However, the auction also reduces economic activity meaning the lending is reduced. Hence, there is no requirement of stringent tax/subsidies, leading to a relaxed macroprudential policy.

The stringency of the target translates to higher abatement and a higher permit demand, thereby higher permit prices. Without financial frictions, the permit prices are \$26.88 and \$43.9 per ton of CO2 under free and auction, respectively. With financial frictions, the prices are \$25.08 and \$42.1. The carbon price determined in the auction method corresponds to the recommended value of \$40-\$80 in the literature (see Stiglitz et al., 2017; IMF, 2019), while it is lower under the free method. The carbon price in the presence of financial frictions is lower by 19.77% than without financial frictions in Carattini et al. (2023). In comparison, my results only show a drop of 6.7% in free and 4.1% in auction method. This limited response suggests that the permit market remains partially resilient to the effects of financial friction and primarily reflects the market clearing condition. However, the allocation method has an impact on different firms' FOCs through marginal costs. It reduces economic activity in auction method than in free method. The emission is lesser, producing lesser demand and thus lesser permit price.

Compared to the no permit market case, the implicit output subsidy under the free allocation method increases aggregate production by 1.19% and 1.32%, with and without financial friction, respectively. The auction method generates heterogeneous output responses among firms. While seller output increases by 0.84% and 0.97% since the net

payoff from the permit market is positive, buyer output falls by 0.4% and 0.3% due to an increase in the marginal cost of emissions. However, aggregate production increases modestly by 0.17% and 0.3%.

The increase in aggregate output under free allocation translates into 1.17% and 1.15% higher investment, with and without financial friction, respectively. Thus, the bank net worth also improves by 0.96%. Under auctioning, investment in the seller sector remains close to the no-policy benchmark, while the higher marginal cost of emissions in the buyer sector reduces bank lending. The resulting decline in aggregate bank assets reduces bank net worth by 2.34%.

I consider two alternative macroprudential policy designs. In the first (uniform macroprudential policy), the Ramsey planner imposes a tax on bank assets in both sectors to limit bank lending to reduce environmental damage. In the second (differentiated macroprudential policy), the Ramsey planner imposes a tax on high carbon assets and a subsidy on low carbon assets to incentivize lending to the seller sector. As a result of different motives, the first policy leads to a tax of 1.05% while the second policy imposes a tax/subsidy of 0.15%. However, a tax (even with a subsidy) is a cost on the balance sheet of banks. Hence, a pure tax policy reduces bank net worth by 40%. The tax and subsidy policy limits the reduction to 1.36% and improves economic activity. The second policy results in higher environmental damage, at 4.35%, compared to 3.98% under the first policy. I repeat this experiment with different permit allocation methods.

As the auction method has better environmental outcomes than free allocation, the tax or tax/subsidy is lower. The remaining variables display qualitatively similar responses to those in the corresponding economies discussed above. It indicates that macroprudential regulation primarily modifies the financial channel and does not alter broader transmission of the permit market.

| | No financial friction | | | Financial friction | | | Macroprudential policies | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | No PM | Free | Auction | No PM | Free | Auction | Only MPP | | Free | | Auction | |
| | | | | | | | Tax | Tax & Subsidy | Tax | Tax & Subsidy | Tax | Tax & Subsidy |
| Variables | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) | (12) |
| Target | - | 0.283 | 0.222 | - | 0.29 | 0.228 | - | - | 0.311 | 0.291 | 0.25 | 0.227 |
| Tax on assets (in %) | - | - | - | - | - | - | 1.053 | 0.15 | 1.035 | 0.131 | 0.968 | 0.121 |
| Seller output | 1.126 | 1.148 | 1.137 | 1.063 | 1.082 | 1.072 | 0.863 | 1.091 | 0.877 | 1.106 | 0.88 | 1.095 |
| Buyer output | 1.342 | 1.353 | 1.338 | 1.267 | 1.276 | 1.262 | 1.029 | 1.233 | 1.036 | 1.245 | 1.037 | 1.235 |
| Consumption | 1.656 | 1.674 | 1.661 | 1.618 | 1.634 | 1.621 | 1.457 | 1.614 | 1.469 | 1.629 | 1.467 | 1.617 |
| Seller investment | 0.303 | 0.31 | 0.302 | 0.264 | 0.27 | 0.264 | 0.158 | 0.281 | 0.162 | 0.284 | 0.163 | 0.277 |
| Buyer investment | 0.469 | 0.471 | 0.46 | 0.409 | 0.411 | 0.4 | 0.245 | 0.383 | 0.247 | 0.388 | 0.249 | 0.38 |
| Seller spread (in %) | 0 | 0 | 0 | 0.225 | 0.225 | 0.225 | 1.28 | 0.075 | 1.26 | 0.094 | 1.2 | 0.104 |
| Buyer spread (in %) | 0 | 0 | 0 | 0.225 | 0.225 | 0.225 | 1.28 | 0.376 | 1.26 | 0.357 | 1.2 | 0.347 |
| Bank net worth | - | - | - | 5.369 | 5.421 | 5.294 | 3.217 | 5.296 | 3.263 | 5.354 | 3.285 | 5.234 |
| Seller abatement | - | 0.162 | 0.221 | - | 0.155 | 0.215 | - | - | 0.135 | 0.151 | 0.194 | 0.214 |
| Buyer abatement | - | 0.411 | 0.562 | - | 0.395 | 0.547 | - | - | 0.344 | 0.384 | 0.493 | 0.545 |
| Permit price | - | 26.88 | 43.9 | - | 25.08 | 42.10 | - | - | 20.07 | 24.19 | 35.83 | 42.1 |
| Emissions | 1.116 | 0.708 | 0.55 | 1.054 | 0.684 | 0.532 | 0.855 | 1.035 | 0.595 | 0.684 | 0.479 | 0.529 |
| damage (in %) | 4.53 | 3.68 | 3.36 | 4.4 | 3.63 | 3.32 | 3.98 | 4.35 | 3.45 | 3.63 | 3.22 | 3.32 |
| welfare loss (in %) | 5.56 | 4.45 | 3.06 | 3.33 | 2.35 | 1.18 | 1.47 | 3.2 | 0.77 | 2.28 | 0 | 1.13 |

Table 2: Steady state values of selected variables in the economies with and without financial frictions under different policy scenarios. No permit market means no intensity target, hence no permit market scenario. Free represents an economy with an initial free allocation of permits. Auction represents an initial auction-based allocation. Tax represents when both buyer and seller assets are taxed. Tax & Subsidy represents when buyer assets are taxed while seller assets are subsidized. Permit price is in $ per ton of CO2. Welfare loss is in terms of compensating consumption variation relative to the first best allocation. All other variables are in arbitrary model units. Here PM is abbreviation of Permit market.

## 4.3 Sensitivity analysis

### 4.3.1 Different target

Section E.1 presents steady states for different intensity targets under free allocation. The intensities considered are $\phi_T = \{0.13, 0.22, 0.27, 0.3, 0.35\}$. The tables show that target tightening is associated with higher output in both sectors. The abatement and permit price increases, signifying an increase in permit demand. Higher investment is allocated towards seller sector and it declines in the buyer sector. While a tighter target improves bank net worth, a target below emission intensities of both sectors reduces bank net worth due to lower aggregate investment.

Section E.2 presents steady states for different intensity targets under auction. Seller (buyer) output decreases (increases) as the target is relaxed, signifying that the payoff (cost) from permit trading declines with relaxation in the target. The bank net worth improves as the bank is less exposed to buyer assets. Note that when $\phi_T = 0.13$, the buyer output is higher than that of $\phi_T = 0.2$. Increasing output with higher abatement when permit price is higher can lead to lower permit need.

Section 4.1.1 shows that the introduction of a permit market with free allocation promotes modest growth. I recheck this hypothesis by tightening the target. Fig. E.1 shows that recession is possible if the target is below 0.25 and 0.24 for financial frictions and macroprudential policies. A model without financial frictions does not face recession even when I set the target to as low as 0.05. Fig. E.2 shows that economies face deeper recession at $\phi_T = 0.05$, i.e., if the target is made too stringent. The results imply that it is undercapitalized banks that cause recessions.

### 4.3.2 Abatement cost fall in buyer sector

This paper calibrates the abatement cost parameter $\phi_1$ to be identical across sectors. However, high emitting firms face higher abatement cost (Martinsson et al., 2024). Con-

sistent with this, I set $\phi_1$ in the buyer sector to be higher than in the seller sector. Fig. D.1 presents the transition dynamics in the presence of free permit allocation. $\phi_1$ changes from 0.0415 to 0.0375.

A reduction in the abatement cost parameter in the buyer sector counteracts the effects of environmental policy as the marginal cost of production falls. Hence, permit price falls. In addition, output, abatement, capital, investment, and asset prices increase. In the seller sector, these variables fall. Hence, aggregate output and emissions initially fall until the environmental policy effect takes over. In the presence of financial frictions, environmental policy leads to an increase in seller asset prices, but the decline in abatement costs increases buyer asset prices by more. Banks therefore reallocate their portfolios towards the buyer sector. Hence, the increases in aggregate output and investment are larger, and emissions begin to rise earlier than in the frictionless case.

#### 4.3.3 Sectoral size

Table F presents the steady states under different weights (or sizes) of the seller for the model with free allocation. The weights I consider are $\omega = \{0.332, 0.5, 0.668\}$.

With increasing seller size, the exposure to seller assets increases. An environmental policy further increases lending towards seller and bank net worth improves, reflecting that the climate-induced financial risks are mitigated. The increase in size also reduces the need for an environmental policy. Hence, permit demand and consequently their prices fall. The result reinforces the need of increasing the size of the sector with low emission intensity if the economy wants to experience reduced effects of climate externality and financial frictions.

#### 4.3.4 Varying seller emission intensity

I calibrate $\phi_S = 0.157$ which happens to be the emission intensity of the sector not covered under the EU-ETS. To check the robustness of transition dynamics, I vary this

intensity and set to 0.4, 0.5, and 0.6. First, I determine the Ramsey policy, i.e., intensity target and macroprudential policy. The corresponding targets are 0.36, 0.383, and 0.402, respectively. Note that each of these targets are lower than the emission intensities of sellers. The corresponding taxes/subsidies are 0.134%, 0.135%, and 0.136%. Next, I use these values to plot transition dynamics, as shown in Fig. G.1, Fig. G.2, and Fig. G.3. I find that previous results are robust to varying emission intensity of the sellers.

# 5 Conclusion

Emission Trading Systems are gaining popularity as a preferred environmental policy worldwide, yet how does asymmetric effects of permit market transmit from firm's balance sheet to bank's portfolio composition is largely unexplored. I develop a Environment Dynamic General Equilibrium model to study macro-finance and environmental implications of a permit market. The model features two sources of inefficiency, an environmental externality and financial frictions. The two externalities are addressed by the ETS and a macroprudential policy that taxes and subsidizes banks' assets, respectively. I consider two alternative initial permit-allocation mechanisms: free allocation and competitive auctioning.

Our results show that transition risks and financial instability are possible due to banks' portfolio restructuring towards low-intensity sectors. This restructuring leads to mild economic growth under free allocation (though a recession is possible in the presence of stringent intensity targets). An auction method impairs overall economic activity due to the increased cost of production, leading to a recession. Financial frictions slow the transition due to reduced lending efficiency. While a free method improves the lending, thus alleviate financial frictions, by improving low intensity asset value, auction method strengthens financial frictions by lowering asset valuation. The macroprudential policy partially mitigates the transition risk and financial instability by reinforcing lending towards the low intensity sector.

The long-run results show that free allocation achieves environmental goals and improved economic activity through an implicit output subsidy. This subsidy incentivizes production increase relative to emissions by generating higher permit allocations and lowering the marginal cost of production. This also leads to an increased lending towards low intensity sector. An auction method weakens this subsidy and leads to a relatively reduced economic activity. Financial frictions, through lending inefficiency, reduces economic activity. Finally, financial frictions and initial permit allocation jointly shape the Ramsey-optimal intensity target and tax/subsidy on banks' assets. I see a lower intensity target when economy is subject to a financial frictions as lower economic activity also produces lower emissions. A free method through implicit output subsidy relaxes the target while auction relaxes the macroprudential policy.

The timing of policy implementation matters considerably. Pre-announced transitions reduce stranded asset risk, improve bank net worth, and sustain higher aggregate output relative to unanticipated transitions. A stricter target improves portfolio allocation towards the low intensity sector but may reduce net worth. A larger environmentally friendly sector reduces the need for environmental policy intervention and permit-market activity. Lower abatement costs in the carbon-intensive sector, in contrast, raise asset prices and stimulate investment.


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# Declaration of competing interest

I have nothing to declare.

## Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work, the author used ChatGPT to assist with language editing, including improving conciseness and refining phrasing. The author reviewed and edited the content as needed and takes full responsibility for the content of the published article.

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# A Model description

| Model | permit market | Financial friction | Macroprudential Policy | Nomenclature |
|---|---|---|---|---|
| Model 1 | No | No | No | No policy |
| Model 2 | Yes | No | No | permit market |
| Model 3 | No | Yes | No | FF |
| Model 4 | Yes | Yes | No | FF+permit market |
| Model 5 | No | Yes | Yes | FF+MPP |
| Model 6 | Yes | Yes | Yes | FF+MPP+permit market |

Table A.1: Summary of description of different models.

# B Competitive Equilibrium

This section presents the competitive equilibrium of a DGSE framework augmented with financial frictions, macroprudential policies, and a permit market framework with free permit allocation.

**Household**

$$\frac{1}{C_t - hC_{t-1}} = \lambda_t \tag{B.1}$$

$$\mu_S (L_t^S)^\eta = \lambda_t w_t^S \tag{B.2}$$

$$\mu_B (L_t^B)^\eta = \lambda_t w_t^B \tag{B.3}$$

$$\frac{1}{R_t} = \beta \mathbb{E}_t \left( \frac{\lambda_{t+1}}{\lambda_t} \right) \tag{B.4}$$

**Banks**

$$\chi_t^S = \mathbb{E}_t \Omega_{t+1}(r_{k,t+1}^S - (1+\tau^S)R_t) \tag{B.5}$$

$$\chi_t^B = \mathbb{E}_t \Omega_{t+1}(r_{k,t+1}^B - (1+\tau^B)R_t) \tag{B.6}$$

$$\nu_t = \mathbb{E}_t \Omega_{t+1} R_t \tag{B.7}$$

$$\Omega_{t+1} = \frac{1}{R_t}(1-\gamma+\gamma\varphi_{t+1}) \tag{B.8}$$

$$\chi_t^S = \chi_t^B \tag{B.9}$$

$$\varphi_t = \frac{\kappa\nu_t}{\kappa - \chi_t^B} \tag{B.10}$$

$$q_t^B S_t^B + q_t^S S_t^S = \frac{\nu_t}{\kappa - \chi_t^B} N_t \tag{B.11}$$

$$N_{t+1} = \gamma \left[ \sum_{i=\{B,S\}} r_{k,t+1}^j q_t^j S_t^j - R_t D_t \right] + \zeta \sum_{i=\{B,S\}} q_t^j S_t^j \tag{B.12}$$

$$D_t = \sum_{i=\{B,S\}} (1+\tau^j) q_t^j S_t^j - N_t \tag{B.13}$$

**Good producer**

$$Y_t = \left[ \omega^{\frac{1}{\epsilon}} (Y_t^S)^{\frac{\epsilon-1}{\epsilon}} + (1-\omega)^{\frac{1}{\epsilon}} (Y_t^B)^{\frac{\epsilon-1}{\epsilon}} \right]^{\frac{\epsilon}{\epsilon-1}} \tag{B.14}$$

$$Y_t^S = \frac{\omega Y_t}{(p_t^S)^\epsilon} \tag{B.15}$$

$$Y_t^B = \frac{(1-\omega) Y_t}{(p_t^B)^\epsilon} \tag{B.16}$$

$$Y_t^j = A_t^j (K_{t-1}^j)^\alpha (L_t^j)^{1-\alpha} \quad i = \{S, B\} \tag{B.17}$$

$$Z_t^j = \phi_j (1 - U_t^j) Y_t^j \tag{B.18}$$

$$w_t^j = (1-\alpha) \frac{Y_t^j}{L_t^j} mc_t^j \tag{B.19}$$

$$r_{k,t}^j = \frac{\alpha \frac{Y_t^j}{K_{t-1}^j} mc_t^j + (1-\delta_k) q_t^j}{q_{t-1}^j} \tag{B.20}$$

$$\phi_{1,t} \phi_2 (U_t^j)^{\phi_2 - 1} = p_t^C \phi_j \tag{B.21}$$

$$mc_t^j = \left( p_t^j - \left[ \mathcal{S}_t \phi_{1,t} (U_t^j)^{\phi_2} - p_t^C \frac{\mathcal{N}_t^j}{Y_t^j} - \mathcal{A}_t \phi_T p_t^c \right] \right) \tag{B.22}$$

$$\mathcal{N}_t^j = \phi_1 (U_t^j)^{\phi_2} Y_t^j - p_t^c (\phi_T - (1 - U_t^j)\phi_j) Y_t^j \tag{B.23}$$

**Capital Producer**

$$q_t^j = 1 + \frac{\gamma_I}{2}\left(\frac{I_t^j}{I_{t-1}^j} - 1\right)^2 + \gamma_I\left(\frac{I_t^j}{I_{t-1}^j} - 1\right)\frac{I_t^j}{I_{t-1}^j} - \mathbb{E}_t\left[\frac{\lambda_{t+1}}{\lambda_t}\gamma_I\left(\frac{I_{t+1}^j}{I_t^j} - 1\right)^2\left(\frac{I_{t+1}^j}{I_t^j}\right)^2\right] \tag{B.24}$$

$$K_t^j = (1 - \delta_K)K_{t-1}^j + I_t^j \tag{B.25}$$

**Environmental externality**

$$\Lambda_t = d_0 + d_1 M_t + d_2 M_t^2 \tag{B.26}$$

$$M_t = Z_t + Z^{\text{row}} + (1 - \delta_M)M_{t-1} \tag{B.27}$$

$$Z_t = Z_t^B + Z_t^S \tag{B.28}$$

**Market clearance**

$$S_t^j = K_t^j \tag{B.29}$$

$$Y_t = C_t + \sum_{i=\{B,S\}}\left(I_t^j + \phi_{1,t}(U_t^j)^{\phi_2}Y_t^j + \frac{\gamma}{2}\left(\frac{I_t^j}{I_{t-1}^j} - 1\right)^2 I_t^j\right) \tag{B.30}$$

$$\phi_T(Y_t^S + Y_t^B) = \sum_{i=\{B,S\}}\phi^j(1 - U_t^j)Y_t^j \tag{B.31}$$

$$\mathcal{T}_t = p_t^c\phi_T\mathcal{A}_t(Y_t^S + Y_t^B) + \sum_{i=\{B,S\}}\tau_t^j q_t^j S_t^j \tag{B.32}$$

# C Transition dynamics: Unanticipated implementation

## C.1 No policy to free allocation

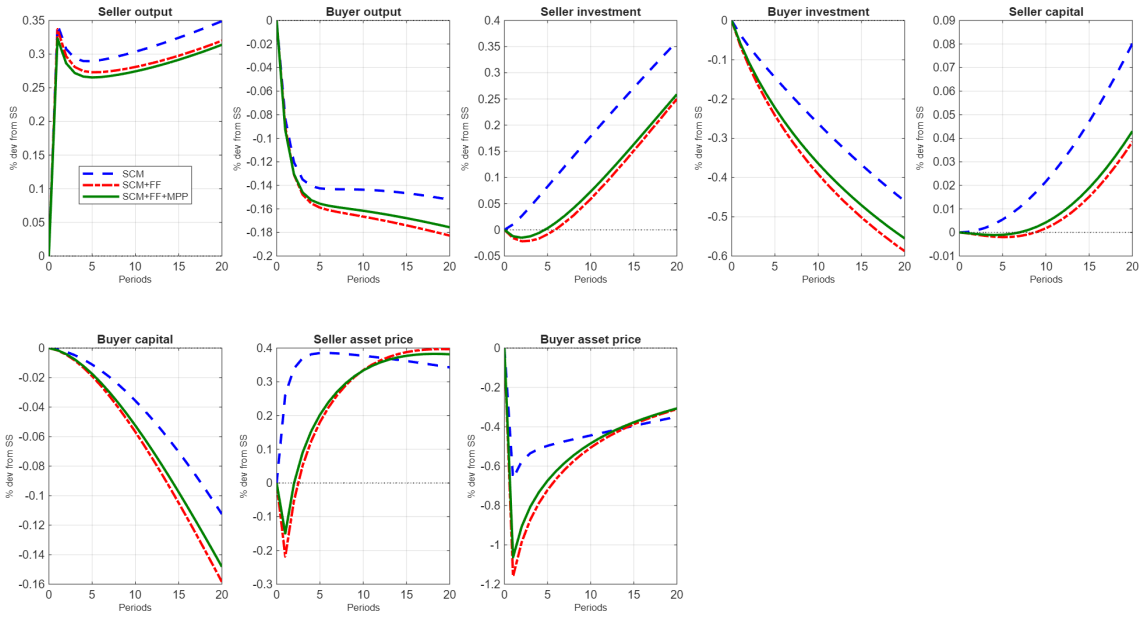



Figure C.1: Transition dynamics of rest of variables in the response to an introduction of permit market in the three economies. The economy begins at no policy steady states.

## C.2 Free allocation to auction

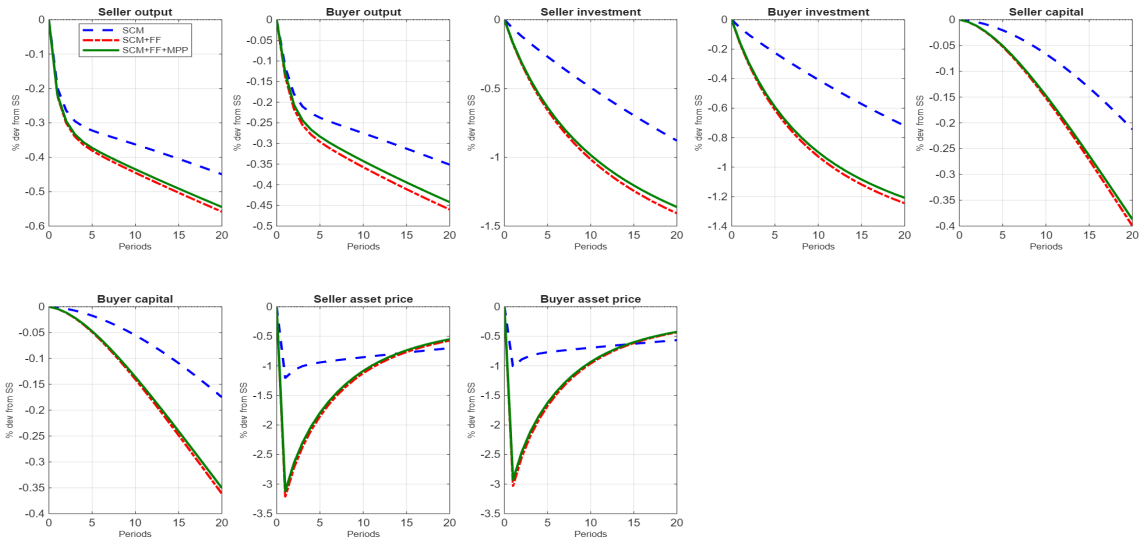



Figure C.2: Transition dynamics of rest of variables in the response to auction of permits. The economy begins at free allocation steady states.

## C.3 No policy to auction mechanism

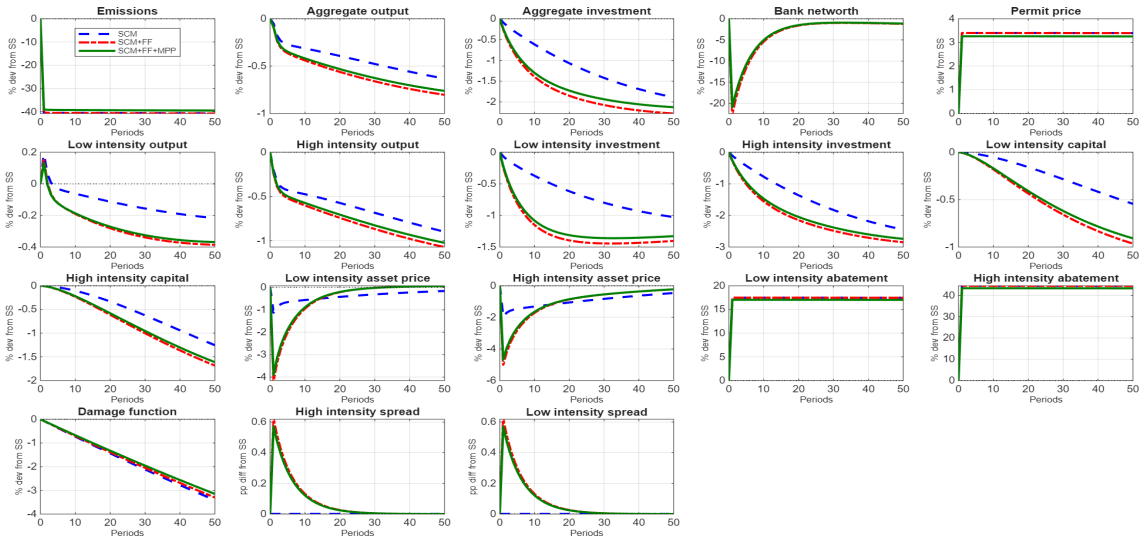



Figure C.3: Transition dynamics in the response to an introduction of permit market directly with permit auction mechanism in the primary carbon market in the three economies. The economy begins at no policy steady states.

## C.4 Anticipated policy dynamics

(a) No policy to free allocation

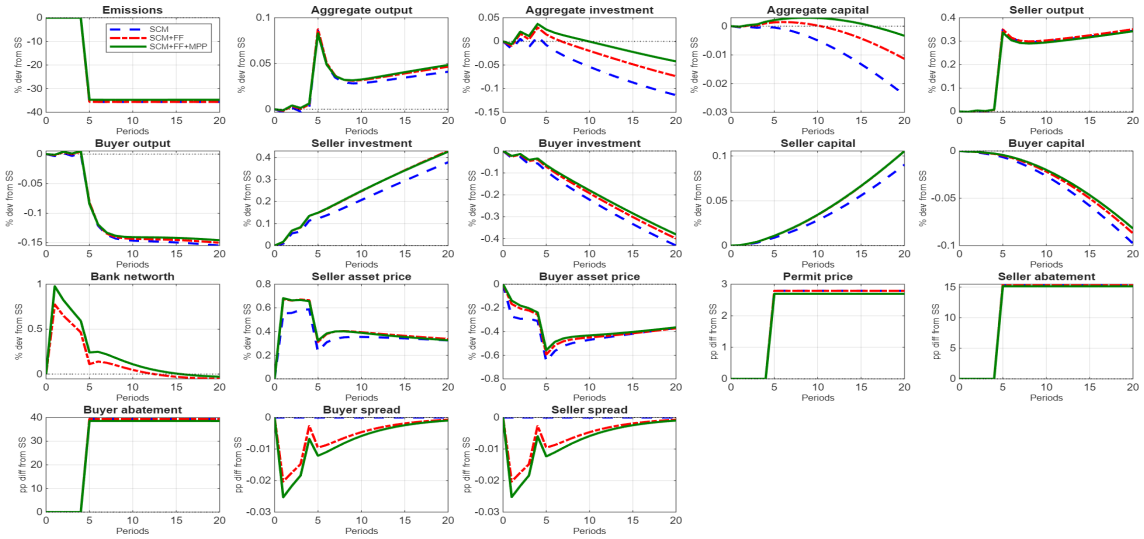



Figure C.4: Transition dynamics in the response to a pre-announced free allocation based permit market. The economy begins at no policy steady states.

(b) Free allocation to auction

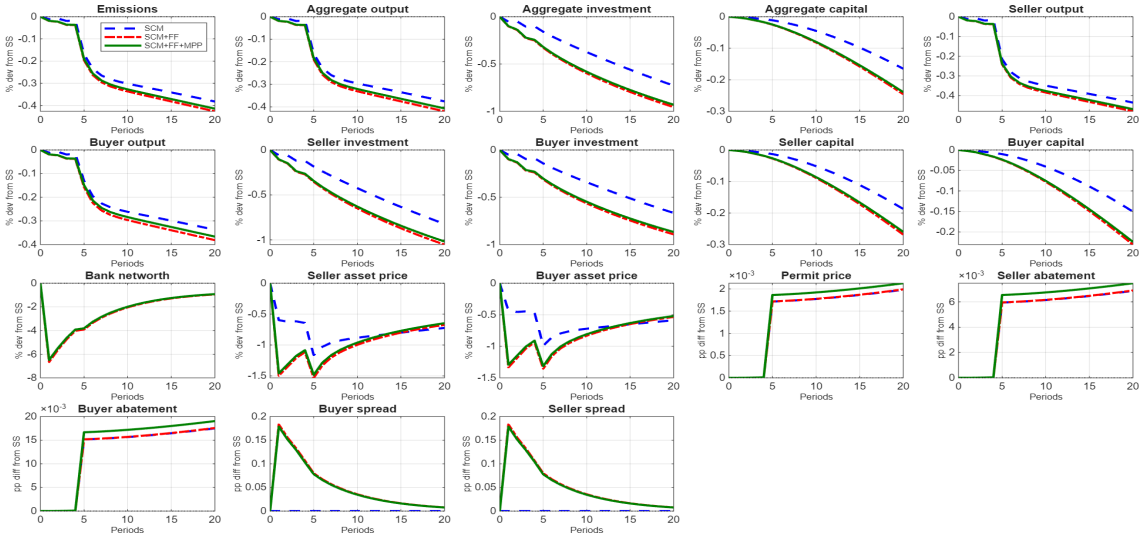



Figure C.5: Transition dynamics in the response to a pre-announced free allocation based permit market. The economy begins at free allocation steady states.

# D Abatement cost as permanent shock

The economy begins at $\phi_1^B = 0.0417$ and $\phi_1^S = 0.0334$. I consider two cases for the end value of $\phi_1^B$: (a) $\phi_1^B > \phi_1^S$ (b) $\phi_1^B = \phi_1^S$. I do not consider $\phi_1^B < \phi_1^S$ as it is unlikely that high intensity firms will have lower cost of abatement scale than low intensity firms.

## D.1 Transition dynamics: Free allocation

(a) $\phi_1^B > \phi_1^S$

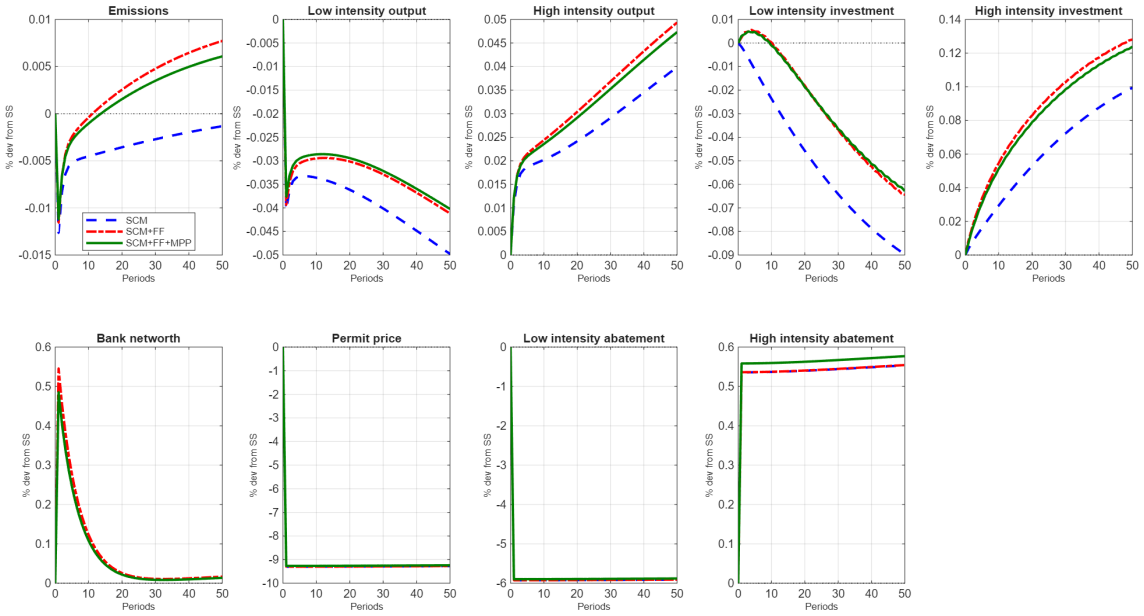



Figure D.1

(b) $\phi_1^B = \phi_1^S$

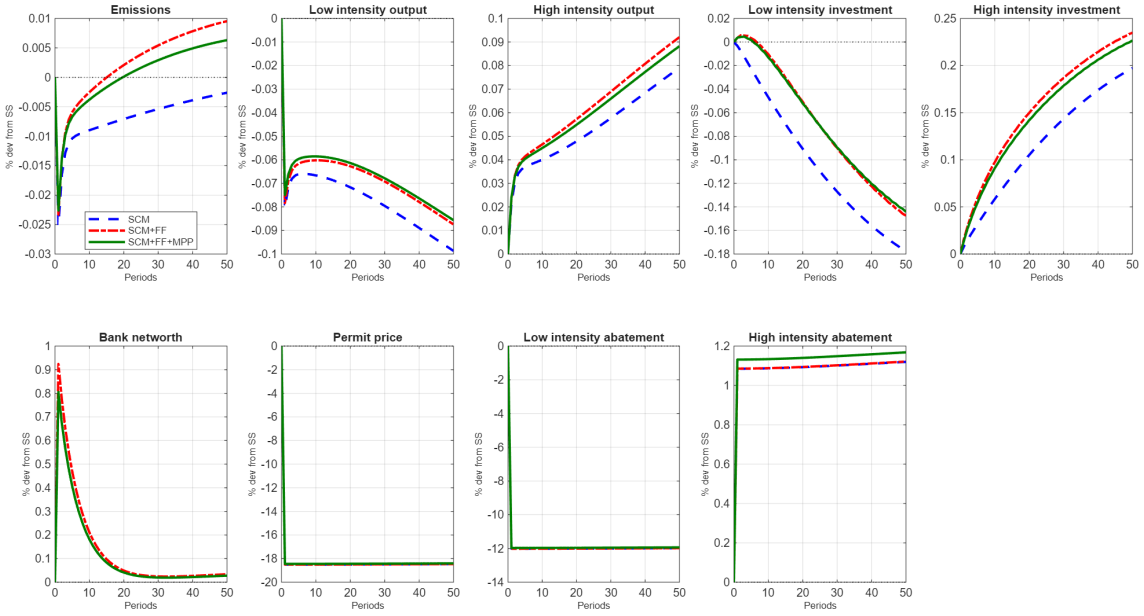



Figure D.2

## D.2 Steady states: Free allocation

| | No bank | | | Bank | | | Macroprudential policy | | |
|---|---|---|---|---|---|---|---|---|---|
| Variable | Baseline | a | b | Baseline | a | b | Baseline | a | b |
| $Y^S$ | 1.149 | 1.148 | 1.147 | 1.084 | 1.083 | 1.085 | 1.108 | 1.107 | 1.106 |
| $Y^B$ | 1.351 | 1.352 | 1.353 | 1.274 | 1.274 | 1.275 | 1.244 | 1.245 | 1.245 |
| $I^S$ | 0.31 | 0.31 | 0.31 | 0.27 | 0.27 | 0.27 | 0.285 | 0.285 | 0.284 |
| $I^B$ | 0.47 | 0.471 | 0.471 | 0.409 | 0.41 | 0.41 | 0.387 | 0.387 | 0.388 |
| $N$ | - | - | - | 5.416 | 5.418 | 5.42 | 5.351 | 5.353 | 5.354 |
| $U^S$ | 0.175 | 0.165 | 0.154 | 0.175 | 0.165 | 0.154 | 0.171 | 0.161 | 0.151 |
| $U^B$ | 0.388 | 0.39 | 0.393 | 0.388 | 0.39 | 0.392 | 0.379 | 0.382 | 0.384 |
| $p^C$ | 0.034 | 0.031 | 0.028 | 0.034 | 0.031 | 0.028 | 0.033 | 0.03 | 0.027 |
| $Z$ | 0.727 | 0.728 | 0.728 | 0.686 | 0.686 | 0.686 | 0.684 | 0.684 | 0.684 |

Table D.1: Steady states for two cases mentioned above. A free allocation based permit market is functioning. Columns withing no bank do not have any financial intermediaries. Columns within Bank represent the economy with financial frictions. Columns within Macroprudential policy represent the economy with financial frictions and macroprudential policies.

## D.3 Transition dynamics: Auction based allocation

(a) $\phi_1^B > \phi_1^S$

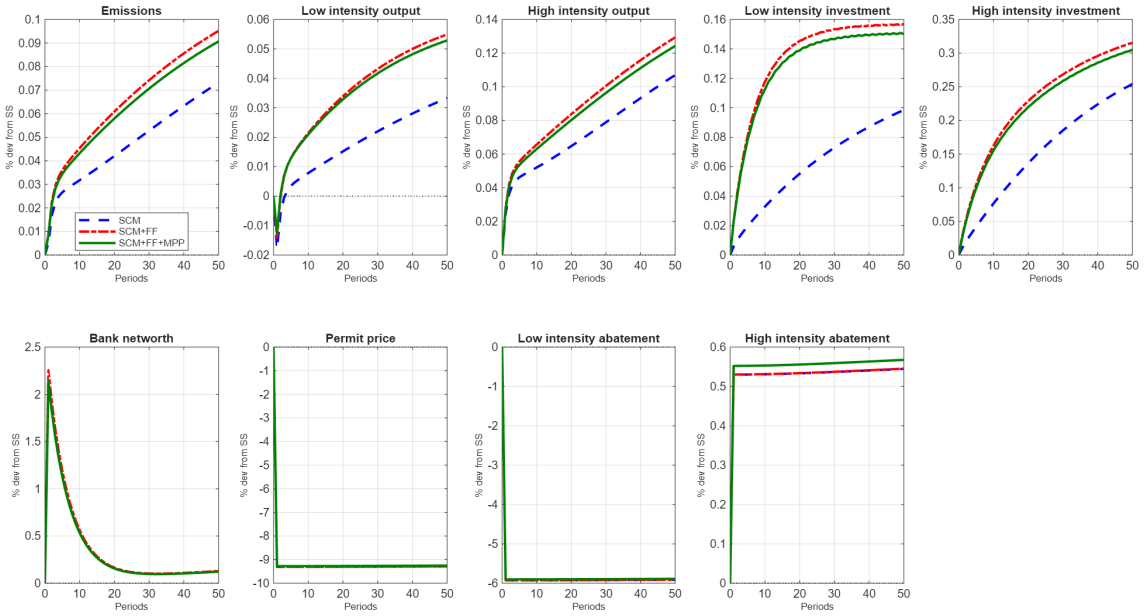



Figure D.3

(b) $\phi_1^B = \phi_1^S$

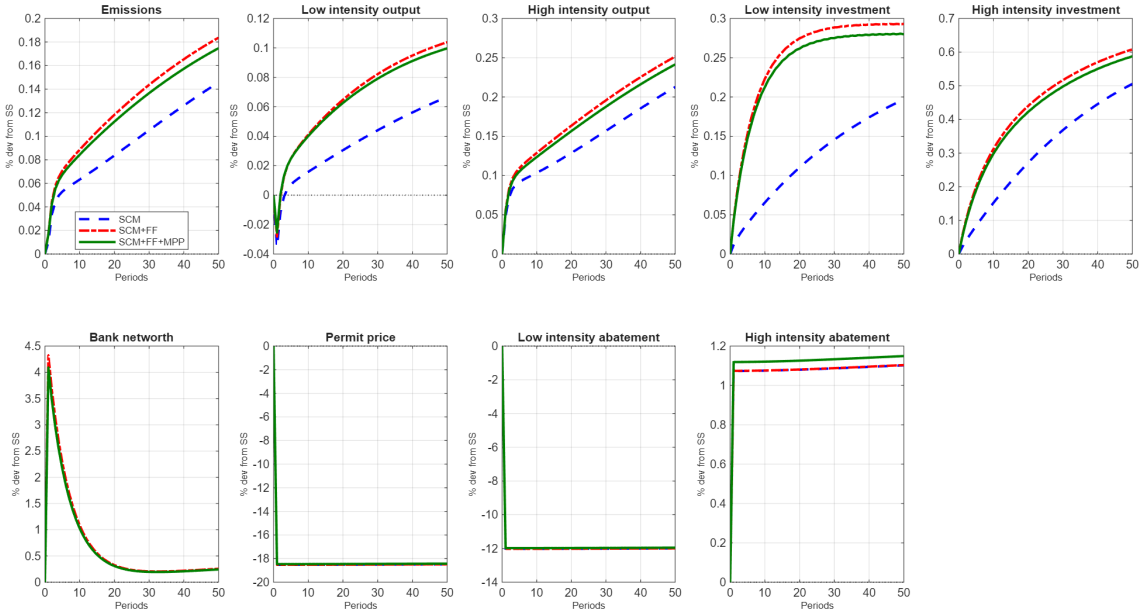



Figure D.4

## D.4 Steady states: Auction based allocation

| | No bank | | | Bank | | | Macroprudential policy | | |
|---|---|---|---|---|---|---|---|---|---|
| Variable | Baseline | a | b | Baseline | a | b | Baseline | a | b |
| $Y^S$ | 1.133 | 1.133 | 1.134 | 1.069 | 1.07 | 1.07 | 1.093 | 1.094 | 1.094 |
| $Y^B$ | 1.335 | 1.338 | 1.34 | 1.259 | 1.261 | 1.263 | 1.23 | 1.232 | 1.234 |
| $I^S$ | 0.302 | 0.303 | 0.303 | 0.264 | 0.264 | 0.264 | 0.278 | 0.278 | 0.279 |
| $I^B$ | 0.46 | 0.462 | 0.463 | 0.401 | 0.402 | 0.403 | 0.379 | 0.38 | 0.381 |
| $N$ | - | - | - | 5.295 | 5.308 | 5.321 | 5.235 | 5.247 | 5.256 |
| $U^S$ | 0.175 | 0.165 | 0.154 | 0.175 | 0.165 | 0.154 | 0.172 | 0.161 | 0.151 |
| $U^B$ | 0.389 | 0.391 | 0.393 | 0.388 | 0.391 | 0.393 | 0.38 | 0.382 | 0.385 |
| $p^C$ | 0.034 | 0.031 | 0.028 | 0.034 | 0.031 | 0.028 | 0.033 | 0.03 | 0.027 |
| $Z$ | 0.718 | 0.719 | 0.72 | 0.678 | 0.678 | 0.679 | 0.676 | 0.677 | 0.678 |

Table D.2: Steady states for three cases mentioned above. An auction allocation based permit market is functioning. Columns within no bank do not have any financial intermediaries. Columns within Bank represent the economy with financial frictions. Columns within Macroprudential policy represent the economy with financial frictions and macroprudential policies.

# E Different Target

## E.1 Steady states: Free allocation

(a) Model without bank

| Variable | Description | $\phi_T = 0.13$ | $\phi_T = 0.22$ | $\phi_T = 0.27$ | $\phi_T = 0.3$ | $\phi_T = 0.35$ |
|---|---|---|---|---|---|---|
| $Y^S$ | Seller output | 1.162 | 1.156 | 1.150 | 1.146 | 1.139 |
| $Y^B$ | Buyer output | 1.359 | 1.356 | 1.354 | 1.352 | 1.350 |
| $I^S$ | Seller investment | 0.311 | 0.311 | 0.310 | 0.309 | 0.307 |
| $I^B$ | Buyer investment | 0.469 | 0.470 | 0.471 | 0.471 | 0.471 |
| $U^S$ | Seller abatement | 0.310 | 0.223 | 0.174 | 0.146 | 0.098 |
| $U^B$ | Buyer abatement | 0.788 | 0.566 | 0.444 | 0.371 | 0.249 |
| $p^C$ | Permit price | 0.085 | 0.050 | 0.034 | 0.025 | 0.013 |
| $Z$ | Emissions | 0.328 | 0.552 | 0.676 | 0.750 | 0.871 |

Table E.1: Steady states of models without banks for different targets.

(b) Model with financial frictions

| Variable | Description | $\phi_T = 0.13$ | $\phi_T = 0.22$ | $\phi_T = 0.27$ | $\phi_T = 0.3$ | $\phi_T = 0.35$ |
|---|---|---|---|---|---|---|
| $Y^S$ | Seller output | 1.095 | 1.09 | 1.085 | 1.081 | 1.075 |
| $Y^B$ | Buyer output | 1.281 | 1.278 | 1.276 | 1.275 | 1.273 |
| $I^S$ | Seller investment | 0.271 | 0.271 | 0.27 | 0.269 | 0.268 |
| $I^B$ | Buyer investment | 0.408 | 0.41 | 0.41 | 0.41 | 0.41 |
| $N$ | Bank's net worth | 5.409 | 5.425 | 5.424 | 5.418 | 5.405 |
| $U^S$ | Seller abatement | 0.309 | 0.222 | 0.174 | 0.146 | 0.098 |
| $U^B$ | Buyer abatement | 0.788 | 0.566 | 0.444 | 0.37 | 0.249 |
| $p^C$ | Permit price | 0.085 | 0.05 | 0.0338 | 0.0253 | 0.0134 |
| $Z$ | Emissions | 0.309 | 0.521 | 0.637 | 0.707 | 0.822 |

Table E.2: Steady states of models with financial frictions for different targets.

(c) Model with financial frictions and macroprudential policies

| Variable | Description | $\phi_T = 0.13$ | $\phi_T = 0.22$ | $\phi_T = 0.27$ | $\phi_T = 0.3$ | $\phi_T = 0.35$ |
|---|---|---|---|---|---|---|
| $Y^S$ | Seller output | 1.119 | 1.114 | 1.109 | 1.105 | 1.1 |
| $Y^B$ | Buyer output | 1.251 | 1.248 | 1.246 | 1.245 | 1.243 |
| $I^S$ | Seller investment | 0.286 | 0.286 | 0.285 | 0.284 | 0.282 |
| $I^B$ | Buyer investment | 0.385 | 0.387 | 0.387 | 0.388 | 0.388 |
| $N$ | Bank's net worth | 5.346 | 5.361 | 5.357 | 5.352 | 5.339 |
| $U^S$ | Seller abatement | 0.309 | 0.22 | 0.171 | 0.142 | 0.093 |
| $U^B$ | Buyer abatement | 0.787 | 0.561 | 0.436 | 0.362 | 0.238 |
| $p^C$ | Permit price | 0.084 | 0.049 | 0.033 | 0.024 | 0.012 |
| $Z$ | Emissions | 0.308 | 0.52 | 0.636 | 0.705 | 0.82 |

Table E.3: Steady states of models with financial frictions and macroprudential policies for different targets.

## E.2 Steady states: Auction

(a) Model without bank

| Variable | Description | $\phi_T = 0.13$ | $\phi_T = 0.2$ | $\phi_T = 0.27$ | $\phi_T = 0.3$ | $\phi_T = 0.35$ |
|---|---|---|---|---|---|---|
| $Y^S$ | Seller output | 1.143 | 1.138 | 1.135 | 1.134 | 1.132 |
| $Y^B$ | Buyer output | 1.342 | 1.338 | 1.339 | 1.340 | 1.343 |
| $I^S$ | Seller investment | 0.302 | 0.302 | 0.303 | 0.303 | 0.303 |
| $I^B$ | Buyer investment | 0.458 | 0.459 | 0.462 | 0.464 | 0.467 |
| $U^S$ | Seller abatement | 0.310 | 0.242 | 0.175 | 0.146 | 0.098 |
| $U^B$ | Buyer abatement | 0.788 | 0.616 | 0.444 | 0.371 | 0.249 |
| $p^C$ | Permit price | 0.085 | 0.057 | 0.034 | 0.025 | 0.013 |
| $Z$ | Emissions | 0.323 | 0.495 | 0.668 | 0.742 | 0.866 |

Table E.4: Steady states of models without financial frictions for different targets.

(b) Model with bank

| Variable | Description | $\phi_T = 0.13$ | $\phi_T = 0.2$ | $\phi_T = 0.27$ | $\phi_T = 0.3$ | $\phi_T = 0.35$ |
|---|---|---|---|---|---|---|
| $Y^S$ | Seller output | 1.078 | 1.074 | 1.071 | 1.07 | 1.068 |
| $Y^B$ | Buyer output | 1.264 | 1.262 | 1.263 | 1.264 | 1.266 |
| $I^S$ | Seller investment | 0.263 | 0.264 | 0.264 | 0.264 | 0.265 |
| $I^B$ | Buyer investment | 0.398 | 0.399 | 0.402 | 0.404 | 0.406 |
| $N$ | Bank's net worth | 5.273 | 5.283 | 5.311 | 5.325 | 5.348 |
| $U^S$ | Seller abatement | 0.31 | 0.242 | 0.175 | 0.146 | 0.098 |
| $U^B$ | Buyer abatement | 0.788 | 0.616 | 0.444 | 0.371 | 0.249 |
| $p^C$ | Permit price | 0.085 | 0.057 | 0.034 | 0.025 | 0.013 |
| $Z$ | Emissions | 0.304 | 0.467 | 0.63 | 0.7 | 0.817 |

Table E.5: Steady states of models with financial frictions for different targets.

(b) Model with bank and macroprudential policies

| Variable | Description | $\phi_T = 0.13$ | $\phi_T = 0.2$ | $\phi_T = 0.27$ | $\phi_T = 0.3$ | $\phi_T = 0.35$ |
|---|---|---|---|---|---|---|
| $Y^S$ | Seller output | 1.102 | 1.1 | 1.095 | 1.094 | 1.092 |
| $Y^B$ | Buyer output | 1.235 | 1.232 | 1.234 | 1.235 | 1.237 |
| $I^S$ | Seller investment | 0.278 | 0.278 | 0.278 | 0.279 | 0.279 |
| $I^B$ | Buyer investment | 0.376 | 0.377 | 0.38 | 0.382 | 0.384 |
| $N$ | Bank's net worth | 5.211 | 5.222 | 5.249 | 5.263 | 5.286 |
| $U^S$ | Seller abatement | 0.309 | 0.24 | 0.172 | 0.142 | 0.093 |
| $U^B$ | Buyer abatement | 0.787 | 0.611 | 0.434 | 0.362 | 0.238 |
| $p^C$ | Permit price | 0.085 | 0.056 | 0.033 | 0.024 | 0.012 |
| $Z$ | Emissions | 0.304 | 0.466 | 0.629 | 0.699 | 0.815 |

Table E.6: Steady states of models with financial frictions and macroprudential policies for different targets.

## E.3 Transition dynamics: Free allocation

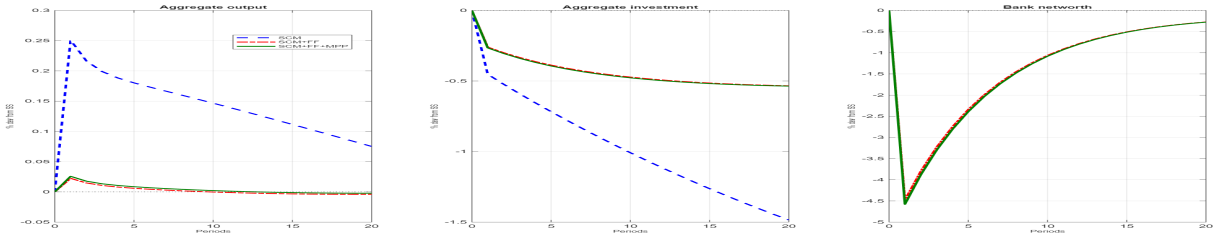



Figure E.1: The emission intensities at which recession happens in different models. For permit market, $\phi_T = 0.05$, for financial friction model, $\phi_T = 0.24$, and for macroprudential policy model, $\phi_T = 0.23$.

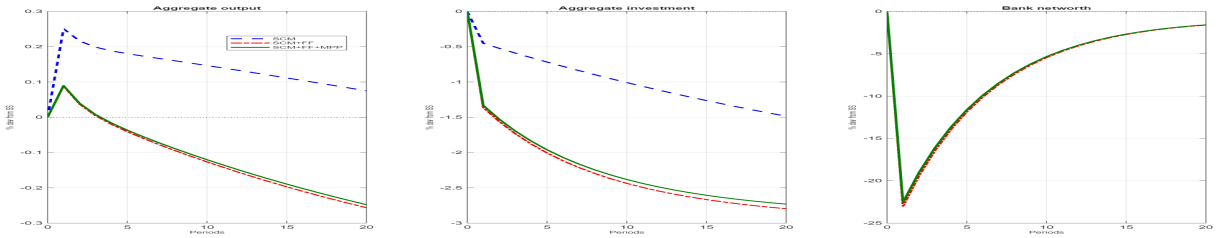



Figure E.2: The plot shows extent of recession when $\phi_T = 0.05$ in each model.

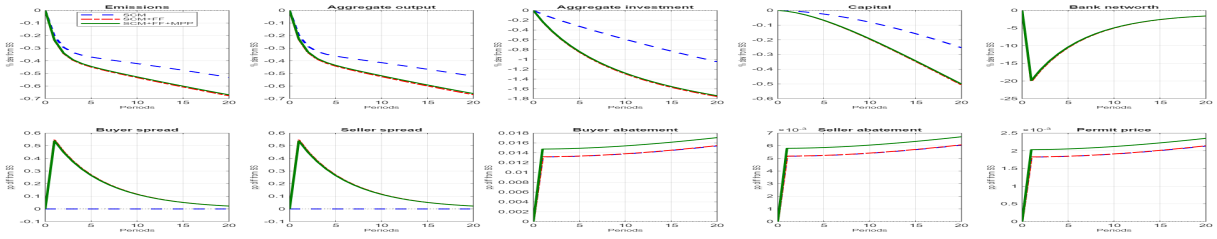



Figure E.3: The transition dynamics of auction models with $\phi_T = 0.227$.

# F Different weights

| | No bank | | | Bank | | | Macroprudential policy | | |
|---|---|---|---|---|---|---|---|---|---|
| Variable | $\omega = 0.332$ | $\omega = 0.5$ | $\omega = 0.668$ | $\omega = 0.332$ | $\omega = 0.5$ | $\omega = 0.668$ | $\omega = 0.332$ | $\omega = 0.5$ | $\omega = 0.668$ |
| $Y^S$ | 1.147 | 1.41 | 1.632 | 1.082 | 1.331 | 1.534 | 1.106 | 1.363 | 1.581 |
| $Y^B$ | 1.353 | 1.168 | 0.949 | 1.275 | 1.101 | 0.895 | 1.245 | 1.078 | 0.878 |
| $I^S$ | 0.309 | 0.43 | 0.534 | 0.27 | 0.375 | 0.466 | 0.284 | 0.397 | 0.496 |
| $I^B$ | 0.471 | 0.388 | 0.286 | 0.41 | 0.338 | 0.249 | 0.388 | 0.321 | 0.238 |
| $N$ | - | - | - | 5.419 | 5.679 | 5.694 | 5.354 | 5.721 | 5.846 |
| $U^S$ | 0.154 | 0.125 | 0.087 | 0.154 | 0.125 | 0.087 | 0.151 | 0.121 | 0.081 |
| $U^B$ | 0.393 | 0.319 | 0.222 | 0.392 | 0.319 | 0.221 | 0.384 | 0.308 | 0.207 |
| $p^C$ | 0.028 | 0.02 | 0.011 | 0.028 | 0.02 | 0.011 | 0.027 | 0.019 | 0.01 |
| $Z$ | 0.728 | 0.75 | 0.751 | 0.686 | 0.708 | 0.708 | 0.684 | 0.71 | 0.716 |

Table F.1: Steady states for different weights under free allocation.

# G Different emission intensities

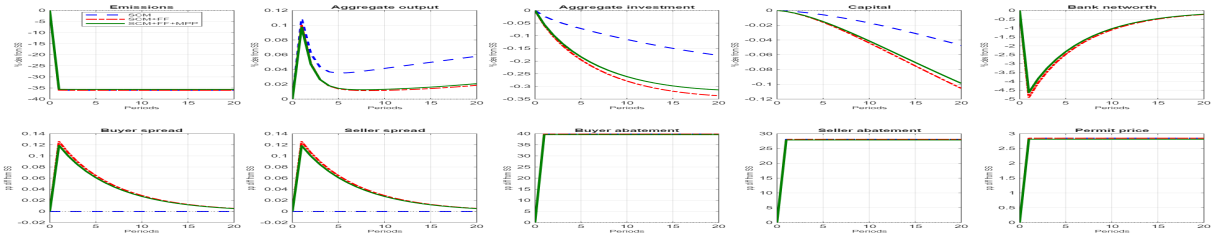



Figure G.1: Transition dynamics when $\phi_T = 0.4$.

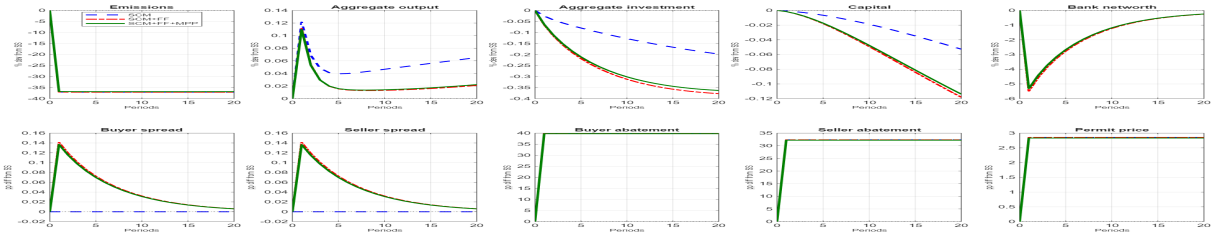



Figure G.2: Transition dynamics when $\phi_T = 0.5$.

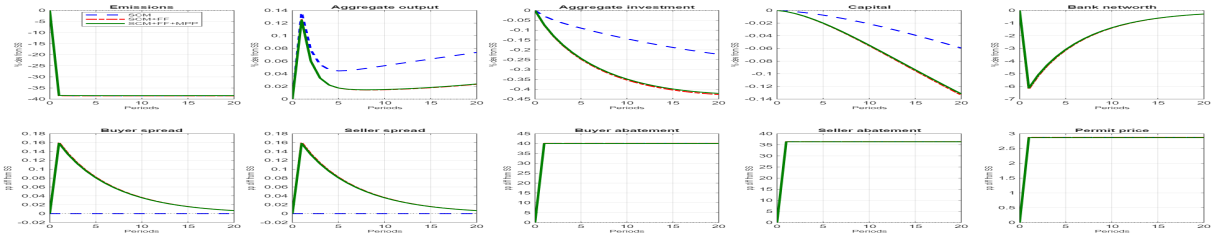



Figure G.3: Transition dynamics when $\phi_T = 0.6$.

# H Pertubation for dynare

| **Variable** | $\tau_l = \tau_h = 0$ | $\tau_l = -2$**e-**$5,\ \tau_h = +2$**e-**$5$ | **Abs. diff.** | **% diff.** |
|---|---|---|---|---|
| $Y^S$ | 1.08452 | 1.08487 | $3.5e{-4}$ | +0.0323 |
| $Y^B$ | 1.27650 | 1.27602 | $4.8e{-4}$ | −0.0376 |
| $I^B$ | 0.41053 | 0.41016 | $3.7e{-4}$ | −0.0901 |
| $I^S$ | 0.270138 | 0.270349 | $2.1e{-4}$ | +0.0781 |
| $I$ | 0.680668 | 0.680504 | $1.6e{-4}$ | −0.0241 |
| spread$^B$ | 0.00225473 | 0.00227478 | $2e{-5}$ | +0.8894 |
| spread$^S$ | 0.00225473 | 0.00223468 | $2e{-5}$ | −0.8894 |
| $N$ | 5.42355 | 5.42224 | $1.3e{-3}$ | −0.0242 |
| $U^B$ | 0.443904 | 0.443792 | $1.1e{-4}$ | −0.0252 |
| $U^S$ | 0.174397 | 0.174353 | $4.4e{-5}$ | −0.0252 |
| $p^c$ | 0.0338286 | 0.0338149 | $1.4e{-5}$ | −0.0405 |
| permit | 0.152245 | 0.152287 | $4.2e{-5}$ | +0.0276 |
| $Z$ | 0.637477 | 0.637440 | $3.7e{-5}$ | −0.0058 |
| $Z^B$ | 0.496901 | 0.496811 | $9e{-5}$ | −0.0181 |
| $Z^S$ | 0.140575 | 0.140628 | $5.3e{-5}$ | +0.0377 |
| $\lambda$ | 1.66498 | 1.66506 | $8e{-5}$ | +0.0048 |
| $C$ | 1.63475 | 1.63468 | $7e{-5}$ | −0.0043 |
| $R$ | 1.00251 | 1.00251 | 0 | 0.0000 |
| $L^S$ | 0.332415 | 0.332440 | $2.5e{-5}$ | +0.0075 |
| $L^B$ | 0.340965 | 0.340931 | $3.4e{-5}$ | −0.0100 |
| $w^S$ | 1.79685 | 1.79691 | $6e{-5}$ | +0.0033 |
| $w^B$ | 2.66221 | 2.66183 | $3.8e{-4}$ | −0.0143 |
| $\chi^S$ | 0.00369881 | 0.00369881 | $0e0$ | 0.0000 |
| $\chi^B$ | 0.00369881 | 0.00369881 | $0e0$ | 0.0000 |
| $\omega$ | 1.64047 | 1.64047 | $0e0$ | 0.0000 |
| $r_k^S$ | 1.00476 | 1.00474 | $2e{-5}$ | −0.0020 |
| $r_k^B$ | 1.00476 | 1.00478 | $2e{-5}$ | +0.0020 |
| $\nu$ | 1.64459 | 1.64459 | 0 | 0.0000 |
| $\varphi$ | 1.66316 | 1.66316 | 0 | 0.0000 |
| $q^S$ | 1.00000 | 1.00000 | 0 | 0.0000 |
| $q^B$ | 1.00000 | 1.00000 | 0 | 0.0000 |
| $S^S$ | 10.8055 | 10.8140 | $8.5e{-3}$ | +0.0787 |
| $S^B$ | 16.4212 | 16.4062 | $1.5e{-2}$ | −0.0914 |
| $D$ | 21.8032 | 21.7980 | $5.2e{-3}$ | −0.0238 |
| $Y$ | 2.32096 | 2.32072 | $2.4e{-4}$ | −0.0103 |
| $K^B$ | 16.4212 | 16.4062 | $1.5e{-2}$ | −0.0914 |
| $K^S$ | 10.8055 | 10.8140 | $8.5e{-3}$ | +0.0787 |
| $p^B$ | 1.10208 | 1.10223 | $1.5e{-4}$ | +0.0136 |
| $p^S$ | 0.842916 | 0.842735 | $1.8e{-4}$ | −0.0215 |
| $\Lambda$ | 0.0353504 | 0.0353496 | $8e{-7}$ | −0.0023 |
| $M$ | 1145.14 | 1145.13 | $1e{-2}$ | −0.0009 |
| lev | 5.02009 | 5.02009 | 0 | 0.0000 |

**Note:** The largest discrepancy is in the sector-specific spreads (spread$^B$ and spread$^S$, $\approx 0.89\%$), which follows mechanically from the asymmetric subsidy/tax perturbation. For spread the absolute dfference matters and not the percentage. All other variables differ by less than 0.10%. The perturbation $(\tau_l, \tau_h) = (-2 \times 10^{-5}, +2 \times 10^{-5})$ serves purely as a numerical regularisation device to break the degeneracy of equations (5), (6), and (9) when $\tau^S = \tau^B = 0$; it introduces no economically meaningful distortion to the steady state.

Table H.1: Steady State Comparison: $\tau_l = \tau_h = 0$ vs. $\tau_l = -2 \times 10^{-5},\ \tau_h = +2 \times 10^{-5}$