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Abstract

How should bank capital requirements be set to deal with climate-related transition risks? We build a general equilibrium macro banking model where production requires fossil and low-carbon energy intermediate inputs, and the banking sector is subject to volatility risk linked to changes in energy prices. Introducing carbon taxes to reduce carbon emissions from fossil energy induces risk spillovers into the banking sector. Sectoral capital requirements can effectively address risks from energy-related exposures, benefiting household welfare and indirectly facilitating capital reallocation. Absent carbon taxes, implementing fossil penalizing capital requirements does not reduce emissions significantly and may threaten financial stability. During the transition, capital requirements can complement carbon tax policies, safeguarding financial stability and trading off long-run welfare gains against lower investment and credit supply in the short run.

Keywords: climate risk, financial intermediation, macroprudential policy, bank capital requirements.

JEL classification: Q43, D58, G21, E44.

Resumen

¿Cómo deberían diseñarse los requerimientos de capital bancarios para hacer frente a los riesgos financieros derivados de la transición climática? Para responder a esta pregunta, primero, desarrollamos un modelo macroeconómico bancario de equilibrio general en el cual el sector productivo requiere como insumos energía fósil contaminante y energía verde y en el que la volatilidad de los retornos de los préstamos bancarios responde a las fluctuaciones de los precios de la energía. Segundo, evaluamos la implementación de impuestos sobre la emisión de carbono y cuantificamos los riesgos financieros derivados de dicha política. Nuestros resultados indican lo siguiente: 1) introducir requerimientos de capital a exposiciones en sectores económicos más expuestos a riesgos energéticos aumenta el bienestar de los hogares y facilita, de forma indirecta, la reasignación de capital entre sectores; 2) en ausencia de impuestos sobre el carbono, incrementar requerimientos de capital a las exposiciones de energía contaminante tiene un efecto muy limitado en la reducción de emisiones y podría generar inestabilidad financiera, y 3) durante la transición climática, los requerimientos de capital desempeñan un papel complementario al de las políticas fiscales (impositivas) para reducir emisiones de carbono, contribuyendo positivamente a la estabilidad financiera del sector bancario. Aunque a corto plazo los requerimientos de capital pueden generar menor inversión y oferta de crédito, a largo plazo la robustez del sector bancario produce ganancias de bienestar para la economía.

Palabras clave: riesgo climático, intermediación financiera, política macroprudencial, requerimientos de capital bancario.

Códigos JEL: Q43, D58, G21, E44.

1 Introduction

As climate change and the transition to net-zero carbon emissions evolve, the financial sector is expected to face spillovers from fast and intense climate policy action.[1] This concerns policymakers since a healthy banking system is fundamental to finance the carbon transition. In this context, it is crucial to understand the macro-financial effects of carbon emission reduction policies and the trade-offs macroprudential policy faces when addressing risk spillovers into the banking sector.[2] Our work investigates three key questions: (i) How may bank capital regulation —specifically capital requirements— address the financial risks derived from implementing carbon taxes? (ii) In the absence of climate policy action, how far can this type of capital-based macroprudential policies go as a sole climate policy tool? (iii) How do bank capital requirements interact with carbon tax policies along the equilibrium transition path to achieve climate goals?

To investigate these questions, we embed climate transition risk in a standard dynamic stochastic general equilibrium (DSGE) model with financial frictions and bank failure risk (Clerc et al., 2015; Mendicino et al., 2018, 2020). The model features two distinct production sectors: a non-energy sector and an energy sector that bundles low-carbon and fossil energy —that emits carbon due to the use of fossil resources as in (Diluiso et al., 2021; Coenen et al., 2023). Importantly, each economic sector requires unique capital intermediated by sector-specific banks. Banks' portfolio returns are subject to two sources of risk: exogenous idiosyncratic risk and endogenous aggregate volatility risk linked to changes in energy prices.[3] These sources of risk, together with limited liability, may lead to costly bank failures and credit disruption. We calibrate the model to match salient features of macroeconomic aggregates in the Euro Area during the last two decades.

As in the real world, in our model, carbon mitigation policies affect energy prices and have implications for households, firms, and the financial sector. Introducing a carbon tax on fossil fuels increases energy prices and sparks a reallocation of capital across economic sectors. Real sector dynamics propagate to the financial system through the effect of energy prices on the return volatility of banks' energy-linked assets —we call this the energy price risk channel. In this scenario, the macroprudential authority finds it optimal to increase sectoral capital requirements (asymmetrically) in proportion to the risk borne by each sectoral exposure as opposed to applying the same capital surcharge to all bank exposures. Such pol-

[1] The introduction of swift and stricter policies aimed at reducing carbon emissions may expose banks to financial risks not captured by the current regulatory framework, see Mark Carney's, ex-governor of the Bank of England, influential speech (Carney, 2015). See also European Central Bank (2022); Financial Stability Board (2022).

[2] Our work concentrates on bank capital requirements rather than all possible forms of macroprudential policies. See Coelho and Restoy (2023) and Hiebert and Monnin (2023) for detailed policy discussion on the limitations of the current Basel III macroprudential framework and trade-offs faced when ensuring the stability of the financial system while not hindering credit provision.

[3] We focus on the spillovers from energy price shocks. Transitioning from current carbon prices to the ones required in the net-zero transition would likely result in a significant increase in energy prices as predicted by the International Energy Agency (2023). Although there are other potential sources of risk –such as a collapse in productivity, or devaluation of banks' legacy assets–, energy price risks have been widely acknowledged and predicted to materialize as the transition intensifies.

icy increases households' welfare as it contains financial risks arising from banks' exposures to energy production.

Although not within its primary objective, this optimal policy indirectly supports a *green credit transition* —credit flowing out of the fossil energy sector and into the low-carbon energy sector. Importantly, we show that the level of optimal capital requirements and the implied effects on the magnitude of the *green credit transition* depend on the structural characteristics of an economy's production and energy sectors. Given the heterogeneity in structural features across European economies, this result has relevant implications for the conduct of macroprudential policy in the Euro Area.

A current debate in the academic and policy arenas is whether macroprudential policies could not only address climate-related financial risks —a goal within their macroprudential mandate, but also actively promote a transition to a green economy through the credit market.[4] We find that under the latter policy goal and absent carbon taxes, fossil penalizing capital requirements have a limited impact in generating an investment transition from the fossil to the low-carbon energy sector. While a carbon tax lowers the return on fossil assets, fossil penalizing capital requirements can only reduce the return on equity for banks' fossil assets — which induces a disintermediation towards the non-banking sector, with low impact on the capital accumulation across the low-carbon and fossil energy sectors. Moreover, the associated effects on output and financial stability —due to higher non-bank financial intermediation (NBFI)— are unambiguously adverse.

Finally, we investigate the complementarities between macroprudential policies and carbon taxes along a plausible carbon transition aligned with European emission reduction targets. Our findings reveal that increasing sectoral capital requirements to their optimal level —as a precautionary tool to mitigate the impacts of carbon taxes—delivers lower bank failure rates and long-run welfare gains at the expense of lower investment and credit supply in the short-run.

Related Literature. Our work relates to several strands of the literature on the interaction of climate risk and financial stability.[5] We relate to the theoretical literature studying the role of central banks and macroprudential authorities in the presence of climate change; while Campiglio (2016) explore the role of reserve requirements, and Böser and Colesanti Senni (2021) study climate-risk adjusted refinancing operations, our work focuses on adapting bank capital requirements.

We combine two strands of the DSGE literature. To our knowledge, this paper is the first to study the complementarities between carbon policies affecting the energy sector and bank capital regulation in the presence of bank failure risk. First, by incorporating bank failure risk (Clerc et al., 2015; Mendicino et al., 2018, 2020)

[4]Several works analyze the feasibility of fossil (brown) penalizing and low-carbon (green) supporting factors. On the policy front, see European Commission (2018b), European Commission (2018a). On the academic front, see Dafermos et al. (2018); Dankert et al. (2018); Oehmke and Opp (2022).

[5]See Monasterolo (2020); Giglio et al. (2021); Daumas (2023) for an extensive survey of the current state of the literature on financial stability, stranded assets, and low-carbon transition policies. Also, Annicchiarico et al. (2021) review the literature on business cycles and environmental policy.

and its consequences on financial stability and the real economy, our model can help identify optimal levels of capital requirements along the climate transition, assess the economy's responsiveness to climate policies, and evaluate the effectiveness of regulatory adjustments to capital ratios in general equilibrium. Second, by adding a rich production sector that features differentiated energy inputs in final goods production (Aboumahboub et al., 2020; Coenen et al., 2023) we investigate how climate policy affecting the energy sector propagates to the financial system.[6] We leverage recent work, such as Nasim et al. (2023); Nasim and Downing (2023); Lee and Lee (2019) —showing that energy price shocks have a significant negative direct impact on banks' performance and bank efficiency— to quantitatively assess the role of this energy price risk channel in a general equilibrium environment.

Most related to our work is the branch of the literature studying the role of the financial frictions in DSGE models that incorporate climate risk (Diluiso et al., 2021; Carattini et al., 2023; Benmir and Roman, 2020). We depart from their work in the way we model financial frictions and the banking system. While they assume banks face market-financing constraints a la Gertler and Kiyotaki (2010) due to depositor's moral hazard concerns, we introduce banks' limited liability and deposit insurance (Kareken and Wallace, 1978) as the fundamental distortions motivating the presence of capital requirements to limit banks' leverage.[7] This approach has two advantages: first, capital requirements easily map to Basel III capital regulatory policies and have a straightforward interpretation; second, we can derive direct implications of carbon policies for bank failure and its consequences for financial stability.

Similar to Diluiso et al. (2021) and Carattini et al. (2023), our findings support the introduction of macroprudential policies in anticipation of uncertain or ambitious carbon policies, as they can lessen welfare losses. In addition, we find significant complementarities between capital requirements and carbon taxes in accelerating a green credit transition; and our general equilibrium approach highlights the limits of capital requirements as a sole tool to achieve carbon emission targets, complementing other partial equilibrium works in the literature (Oehmke and Opp, 2022; Dankert et al., 2018).[8] Lastly, we also contribute to the literature studying the importance of the economy's structural characteristics for optimal policy design, for instance, an economy's elasticity of substitution between fossil and clean energy inputs.[9] Our work shows that this, and other structural parameters, also play a key role in informing the magnitude of the optimal macroprudential intervention.

[6] Although Computational General Equilibrium (CGE) models, such as those developed by Varga et al. (2022) and Aguilar et al. (2023), offer a higher degree of disaggregation with explicit input-output sectoral interlinkages, they exclude the financial sector.

[7] We follow the long tradition in the banking literature (Kareken and Wallace, 1978; Bhattacharya et al., 1998) that emphasizes banks' limited liability and deposit insurance give rise to banks' over-leverage (or excessive risk-taking).

[8] A key insight arising from our and these works is that capital requirements can be an effective tool to deal with climate-related financial risks but are rather ineffective as a climate policy tool to reduce greenhouse emissions.

[9] The elasticity substitution between fossil and low-carbon production inputs plays a central role in the design of optimal fiscal environmental policies (Acemoglu et al., 2012; Golosov et al., 2014; Mattauch et al., 2015; Jo and Miftakhova, 2022), as it determines the economy's potential to achieve long-term growth sustained by low-carbon technologies.

Outline. The paper is structured as follows: Section 2 describes the model; Section 3 explains the calibration of our quantitative experiments; Section 4 presents results on optimal capital requirements and its interactions with climate policies in steady state; Section 5 analyses the joint transitional dynamics of carbon taxes and optimal capital requirements; Section 6 concludes.

2 The Model

The model is a real business cycle version of the standard macro-models of banking developed in Clerc et al. (2015); Mendicino et al. (2018, 2020) extended to include differentiated energy sectors in production as in Diluiso et al. (2021). The economy is composed of a household with a continuum of members of mass one that, at each period, can be either workers or bankers. The household provides perfect consumption insurance to each member. The worker members supply labor to the non-energy production sector and return the wages to the household. The banker members manage financial firms called *banks*. Bankers receive an equity endowment from the household, which they use to finance the banks' operations.[10] Banks combine the banker's equity and household deposits to provide credit to firms in the production sector. Their portfolio returns are subject to two sources of risk: exogenous idiosyncratic risk and endogenous aggregate volatility risk linked to changes in energy prices, which may lead to banks defaulting on their deposit obligations whenever shocks on their returns are adverse enough. As it is standard, bankers are protected by limited liability in the event of bank failure — see Section 2.3.1 for more details. By the end of the period, bankers transfer banks' dividends to the household, plus their accumulated earnings whenever they retire and become workers.

There are two layers in the production sector; final goods are produced by a firm that combines an intermediate non-energy bundle Y with an energy bundle E —representing the energy sector's intermediate output. The energy bundle is produced using intermediate energy inputs produced from low-carbon L and fossil F energy producers, respectively. Fossil energy producers differ from low-carbon energy producers in that they require fossil resources as an additional input for energy production, hence, generating carbon emissions. We assume that the non-energy bundle, as well as each type of energy, requires sector-specific capital as production input. Sector-specific capital is produced by firms that repair the depreciated capital, build new capital, and sell it to the energy and non-energy producing firms. To finance capital purchases, these firms take on credit from a banking sector that invests sector-specific assets.[11] The public sector consists of a fiscal authority and a macroprudential authority. The fiscal authority manages a deposit

[10] As in Gertler and Kiyotaki (2010); Clerc et al. (2015); Mendicino et al. (2018), this assumption links banks' equity financing to the limited resources available to bankers. It is a reduced form to capture other frictions faced by intermediaries to raise outside equity.

[11] Modeling a banking sector that invests in sector-specific assets allows us to test the role of general and sectoral capital requirements along the climate transition and their interaction with climate policy actions.

insurance scheme (DIS), levies taxes on carbon-emitting fossil firms, and balances its budget by levying lump-sum taxes to the household. The macroprudential authority sets minimum capital requirements for each banking sector.

Main financial frictions. In our environment, the justification for implementing bank capital regulation stems from two primary frictions related to banks' reliance on external debt financing. Due to these frictions, banks fail to internalize the aggregate effects of their leverage choice and expose themselves to elevated levels of risk. The first friction arises from the combination of banks' limited liability and the presence of deposit insurance, which encourages banks to increase leverage, as the potential costs of banks' failure are partially borne by the deposit insurance scheme. This may result in a scenario where bank loans are more easily accessible and come at a lower cost than what a social planner —considering the full consequences of bank failure— would deem optimal. The second friction comes from the assumption that depositors charge a common deposit risk premium —on the fraction of uninsured deposits— that is a function of the average risk of bank failure in the economy.[12] As a result of these distortions, banks choose to lever up to the regulatory limit. In this context, bank capital requirements play a central role in mitigating banks' excessive leverage. The focus of our model is on studying how spillovers from exogenous carbon policies interact with these frictions in the banking sector.[13]

Next, we detail the problems of households, firms, banks, and the public sector. The description of capital-producing firms, capital management firms, and market clearing conditions is left for Appendix A as they are standard in this type of model.

2.1 Households

The representative household maximizes:

$$\mathbb{E}_t \sum_{i=0}^{\infty} \beta^{t+i} \left[\frac{(C_{t+i})^{1-\varsigma} - 1}{1-\varsigma} - \frac{\eta}{1+\nu} L_{t+i}^{1+\nu} \right] \tag{1}$$

subject to:

$$\begin{aligned} C_t + B_t + D_t + \sum_j (Q_{j,t} + z_{j,t}) S_{j,t}^H = W_t L_t + \Pi_t + R_{t-1} B_{t-1} \\ + \widetilde{R}_t^D D_{t-1} + \sum_j R_{j,t} S_{j,t-1}^H - T_t, \end{aligned} \tag{2}$$

[12]The assumption that depositors can only observe the average risk in the banking system (Clerc et al., 2015) encourages riskier behavior from individual banks as well as the possibility of contagion of financial risk from one banking sector to another through the increase in the cost of overall deposit funding.

[13]To keep consistency with our approach in modeling exogenous carbon policies, we abstract from including climate externalities affecting the real sector through physical damages. Furthermore, given our focus on the Euro Area, modeling climate externalities would require a different setup to properly account for the effects of European carbon policies on the global stock of CO2. See Diluiso et al. (2021) for a similar approach to ours and see Acemoglu et al. (2012); Golosov et al. (2014); Carattini et al. (2023) among others, for models with climate externalities.

where C_t is consumption and L_t is labor. $\beta \in (0,1)$ is the discount factor, $\varsigma > 0$ is the coefficient of risk aversion, $\nu > 0$ is the inverse of the Frisch elasticity of labor supply and $\eta > 0$ measures the relative disutility of labor.

The sources of income to the household are wages $W_t L_t$ from workers; combined profits Π_t from bankers, capital management firms, capital producing firms, and fossil resources firms; plus interest-rate bearing assets; minus lump-sum taxes T_t. Government bonds B_t pay the risk-free real interest rate R_t.[14] We assume households can purchase shares of capital $S^H_{j,t}$ from firms in each intermediate sector $j \in \{Y, F, L\}$ through capital management firms. For each unit, households pay the price of capital $Q_{j,t}$ plus a management fee $z_{j,t}$ and by the end of the next period receive a return $R_{j,t+1}$ on their holdings.[15] In contrast, bank deposits pay a gross return $\widetilde{R}^D_t = R^D_{t-1} - (1-\kappa)\Omega_t$, where R^D_{t-1} represents the *promised* gross deposit rate. Following the macro-banking literature, we assume that a fraction κ of deposits are insured by the DIS and paid back in full in the event of bank failure. Ω_t represents household's average loss—per unit of bank debt—on the fraction of uninsured deposits $(1-\kappa)$. This loss introduces a key friction since the cost of deposit funding is not a function of the risk taken by an individual bank but of the average risk of the banking system.

2.2 Production

Final goods are produced by profit-maximizing perfectly competitive firms using a non-energy input Y_t and an energy composite E_t according to the following technology function:[16]

$$\widetilde{Y}_t = \left[(1-\alpha_E)^{1/\varphi_Y} Y_t^{\frac{(\varphi_Y - 1)}{\varphi_Y}} + \alpha_E^{1/\varphi_Y} E_t^{\frac{(\varphi_Y - 1)}{\varphi_Y}} \right]^{\frac{\varphi_Y}{(\varphi_Y - 1)}}, \tag{3}$$

where $\varphi_Y > 0$ is the elasticity of intratemporal substitution between the inputs, while α_E is the weight of the energy bundle in production.

The non-energy input $Y_t = A_Y (K_{Y,t})^{\alpha_Y} (L_t)^{1-\alpha_Y}$ is a standard capital and labor composite where A_Y is the sector specific productivity, $K_{Y,t}$ is the sector specific capital used in production and L_t is the labor input.

The energy composite E_t is produced through a CES aggregator of two different energy inputs: low-carbon energy, $E_{L,t}$, and fossil energy $E_{F,t}$

$$E_t = \left[(1-\alpha_F)^{1/\varphi_E} E_{L,t}^{\frac{(\varphi_E - 1)}{\varphi_E}} + \alpha_F^{1/\varphi_E} E_{F,t}^{\frac{(\varphi_E - 1)}{\varphi_E}} \right]^{\frac{\varphi_E}{(\varphi_E - 1)}}, \tag{4}$$

[14] Government bonds are assumed to be in zero net supply. However, their interest rate serves as a referential rate for the pricing of other interest-bearing assets.

[15] This arrangement allows the household to invest directly in the firm's capital without channeling its savings through banks. It also serves as a proxy for non-bank financial intermediation (NBFI) in the model. However, this investment option is costly; management fees aim to capture inefficiencies in the NBFI sector.

[16] Such a nested constant elasticity of substitution formulation is used in Integrated Assessment Models (IAM), see for instance, Aboumahboub et al. (2020).

where $\varphi_E > 0$ is the elasticity of substitution between the low-carbon and the fossil input, while α_F represents the weight of fossil energy in the bundle.

Hence, profit maximization delivers the following demands for labor and energy inputs $W_t = P_t \widetilde{Y}_t^{\frac{1}{\varphi_Y}} (1-\alpha_E)^{\frac{1}{\varphi_Y}} Y_t^{(\varphi_Y-1)/\varphi_Y} (1-\alpha_Y) \frac{1}{L_t}$, $E_t = \alpha_E \left(P_{E_Y,t}/P_t\right)^{-\varphi_Y} \widetilde{Y}_t$ respectively, where W_t is the wage, P_t is the price of final goods (normalized to 1) and $P_{E_Y,t}$ is the price of the energy composite.

Similarly, profit maximization of the energy composite producers delivers the following demands for each type of energy input: $E_{L,t} = (1-\alpha_F)\left(P_{E_L,t}/P_{E_Y,t}\right)^{-\varphi_E}$, and $E_{F,t} = \alpha_F \left(P_{E_F,t}/P_{E_Y,t}\right)^{-\varphi_E}$, where $P_{E_L,t}$ and $P_{E_F,t}$ is the price of each energy input. By the end of period $t+1$, the ex-post return on the capital units used in the non-energy sector $R_{Y,t+1}$ is given by:

$$R_{Y,t+1} = \frac{(Q_{Y,t+1} - \delta_Y) + \frac{W_t L_t \frac{\alpha_Y}{1-\alpha_Y}}{K_{Y,t+1}}}{Q_{Y,t}}, \tag{5}$$

where $Q_{Y,t}$ is the real price of a $K_{Y,t}$ unit of physical capital installed in the non-energy sector, and δ_Y is the capital depreciation rate.

2.2.1 Energy Producers

Low-carbon energy sector. Perfectly competitive low-carbon energy firms use sector-specific capital $K_{L,t}$ as the only input to produce low-carbon energy.[17]

$$E_{L,t} = A_L K_{L,t}, \tag{6}$$

where A_L is the sector-specific productivity.[18] The ex-post return on low-carbon capital is:

$$R_{L,t+1} = \frac{(Q_{L,t+1} - \delta_L) + \frac{P_{E_{L,t+1}}}{P_{t+1}} \frac{E_{L,t+1}}{K_{L,t+1}}}{Q_{L,t}}, \tag{7}$$

where $Q_{L,t}$ is the price of the physical capital installed in the low-carbon energy sector, and δ_L is the capital depreciation rate.

Fossil Energy Sector. Perfectly competitive fossil energy firms use sector-specific capital $K_{F,t}$ and fossil resources X_t as inputs to produce fossil energy through a CES aggregate:

$$E_{F,t} = \left[(1-\alpha_X)^{1/\varphi_F} (A_F K_{F,t})^{\frac{(\varphi_F-1)}{\varphi_F}} + \alpha_X^{1/\varphi_F} X_t^{\frac{(\varphi_F-1)}{\varphi_F}}\right]^{\frac{\varphi_F}{(\varphi_F-1)}}, \tag{8}$$

[17] We follow the E-DSGE literature (Diluiso et al., 2021; Coenen et al., 2023)) in modeling the clean-energy sector as a one-input sector dependent on sector-specific capital only. Although stylized, this approach captures the observation that clean energy generates substantially less or zero carbon emissions compared to the fossil energy sector. The model can be easily extended to include other resources as input to the low-carbon energy sector. However, it will not make a difference to our results as long as carbon taxes do not affect the price of these resources.

[18] We abstract from labor inputs in energy production since it is not our purpose to study labor reallocation across sectors. Moreover, energy sectors tend to be capital intensive.

where $\varphi_F > 0$ is the elasticity of substitution between fossil capital and fossil resources, while α_X represents the weight of fossil resources. We let A_F represent the sector-specific productivity. The ex-post return on fossil energy capital is:

$$R_{F,t+1} = \frac{(Q_{F,t+1} - \delta_F) + \frac{P_{E_F,t+1}}{P_{t+1}} \frac{E_{F,t+1}^{1/\varphi_F} \alpha_X^{1/\varphi_F} \widetilde{K}_{F,t}^{(\varphi_F - 1)/\varphi_F}}{K_{F,t+1}}}{Q_{F,t}}, \tag{9}$$

where $Q_{F,t}$ is the price of the physical capital installed in the low-carbon energy sector, and δ_F is the capital depreciation rate.

We assume the household owns the fossil resource, and it is elastically supplied at an exogenously given price $P_{X,t}$, which captures the exogenous dynamics of the international price of commodities like gas and oil used as inputs in the fossil energy producing sector.

Carbon policy. For tractability, we simply assume that the level of carbon emissions in the fossil energy sector is given by its use of fossil resources $X_{F,t}$.[19] The fiscal authority may implement a carbon tax $\tau_{X_F,t}$ for each unit of $X_{F,t}$ used in fossil energy production —paid by the fossil energy producers. Since a firm optimizes such that the marginal product of fossil resources equals its price, we obtain:

$$P_{X_F,t} + \tau_{X_F,t} = P_{E_F,t} E_{F,t}^{1/\varphi_F} \alpha_X^{1/\varphi_F} X_{F,t}^{-1/\varphi_F}. \tag{10}$$

2.3 Bank Credit Market Structure

By the end of the period, firms in each sector $j \in \{Y, L, F\}$ must purchase next-period capital $K_{j,t+1}$ at a price $Q_{j,t}$. To finance these purchases, firms issue state-contingent claims to their future earnings; $S_{j,t}^B$ denotes claims purchased by sector-specific banks —such arrangement represents bank credit provision as $S_{j,t}^B$ is registered on the asset side of banks' balance sheets; $S_{j,t}^H$ denotes claims purchased by households through the capital management firms, which represent non-banking financial intermediation. Then, the market value of the next period capital equals the market value of claims issued by each firm:

$$Q_{j,t} K_{j,t+1} = Q_{j,t}(S_{j,t}^B + S_{j,t}^H), \quad j \in \{Y, L, F\}. \tag{11}$$

Recall from the household's problem (2) that non-banking financial intermediation entails additional management costs for households which restrict firms access to credit as in Mendicino et al. (2018, 2020). In contrast, firms' access to bank credit is frictionless.

2.3.1 Individual Bankers

The structure of our banking sector closely follows Mendicino et al. (2018, 2020), extended to include three types of intermediated capital. In each period, individ-

[19] For more comprehensive approaches see Nordhaus (2017); Golosov et al. (2014); Acemoglu et al. (2012).

ual bankers may remain active with independent probability θ or become inactive and switch to be workers with probability $1-\theta$.[20] By the end of the period, exiting bankers transfer their accumulated earnings to the household, and an equal mass of new bankers enters —such that the mass of bankers and workers remains constant over time. Entering bankers are endowed with an initial equity, which we assume to be a fixed proportion $\chi \in (0,1]$ of exiting banks' net worth.

Individual bankers can invest their net worth NW_t into three classes j of competitive specialized banks. Bank specialization is an efficient equilibrium outcome product of the limited liability (Repullo and Suarez, 2004).[21] Intuitively, the optimal strategy of a banker is to invest in specialized banks to maximize the benefits of limited liability, i.e., bankers don't want the losses from a portfolio with one type of risk profile to subtract from the profits of another portfolio with a different risk profile. The problem of a representative banker is

$$V_t = \max_{\{NW_{j,t},\ \mathrm{div}_t \geq 0\}} \mathrm{div}_t + \mathbb{E}_t \left[\Lambda_{t+1} \left[(1-\theta)\, NW_{t+1} + \theta V_{t+1}\right]\right] \tag{12}$$

subject to

$$\sum_j NW_{j,t} + \mathrm{div}_t = NW_t, \tag{13}$$

$$NW_{t+1} = \sum_j \left[\int_0^\infty \rho_{j,t+1}(\omega) dF_{j,t+1}(\omega)\right] NW_{j,t}, \tag{14}$$

where $\Lambda_{t+1} = \beta(\frac{C_t}{C_{t+1}})^{-\varsigma}$ is the household stochastic discount factor; $NW_{j,t}$ in the bankers' balance sheet (13) represents the diversified equity investment in the continuum of banks of class j, and div_t is the dividend paid to the household; (14) is the law of motion of an individual banker's net worth, $\rho_{j,t+1}(\omega)$ is the return from investing equity in a bank of class j that experiences idiosyncratic shocks ω to the returns of its asset portfolio (explained below, see subsection 2.3.2). Additionally, we define $\rho_{j,t+1} = \int_0^\infty \rho_{j,t+1}(\omega) dF_{j,t+1}(\omega)$ as the per unit return of a diversified portfolio of equity shares of banks class $j \in \{Y, L, F\}$.

As it is standard in these type of models (Gertler and Kiyotaki, 2010), it can be shown that the bankers' value function is linear in their net worth $V_t = v_t NW_t$, where v_t is the shadow value of a unit of the banker's wealth.[22] Then, the objective function in (12) can be rewritten as

$$v_t NW_t = \max_{\{NW_{j,t},\ \mathrm{div}_t \geq 0\}} \mathrm{div}_t + \mathbb{E}_t \left[\Lambda_{t+1} \left(1 - \theta + \theta v_{t+1}\right) NW_{t+1}\right], \tag{15}$$

[20] This arrangement ensures that the aggregate accumulated net worth across all active bankers remains limited and does not grow excessively over time.

[21] Although, in practice, no bank is completely specialized in a given industry, some banks have a significantly high concentration of their lending portfolio in specific industries due to industry-specific knowledge (about default risk, business models, or collateral of loans, to name a few examples), see Blickle et al. (2023). Our model aims to capture this feature as it is relevant to address climate-related risks in banking; for instance, the European Systemic Risk Board (2023) identifies a bank's climate-related concentration risk as a key determinant for predicted losses along the climate transition. Also, notice that in our model, the effects of sectoral lending diversification are captured through the allocation of bankers' net worth (or bank equity) into different sectors. Hence, at the aggregate level, the banking sector is realistically diversified.

[22] As in Gertler and Kiyotaki (2010), we guess and then verify that is the case in equilibrium.

and bankers will find it optimal not to pay dividends before exiting $(\text{div}_t = 0)$ insofar as $v_t > 1$. From (15), bankers' stochastic discount factor can be defined as $\Lambda^B_{t+1} = \Lambda_{t+1}(1 - \theta + \theta v_{t+1})$.

An interior equilibrium in which all classes of banks receive strictly positive equity from bankers $(NW_{j,t} > 0)$ requires the discounted gross expected return on equity at each class of bank to be equal to v_t. Which obtains the following non-arbitrage equilibrium conditions across classes of banks:

$$\mathbb{E}_t \left[\Lambda^B_{t+1}\rho_{Y,t+1}\right] = \mathbb{E}_t \left[\Lambda^B_{t+1}\rho_{F,t+1}\right] = v_t, \tag{16}$$

$$\mathbb{E}_t \left[\Lambda^B_{t+1}\rho_{F,t+1}\right] = \mathbb{E}_t \left[\Lambda^B_{t+1}\rho_{L,t+1}\right] = v_t. \tag{17}$$

The evolution of the aggregate net worth across all active bankers is described by:

$$\widetilde{NW}_{t+1} = \theta NW_t + \chi(1-\theta)NW_t, \tag{18}$$

where the first term represents the aggregate net worth of bankers that remain active, and the second term denotes the aggregate net worth endowment of entering bankers provided by the household, which we assume to be a proportion χ of the net worth of exiting bankers.

2.3.2 Banks

Banks are one-period limited liability ventures that finance credit investments by combining equity and deposits. A representative bank of each class $j \in \{Y, F, L\}$ issues equity $NW_{j,t}$ among bankers and debt among households in the form of deposits $D_{j,t}$ that pay a promised gross interest rate R^D_t. Each class of bank uses these funds to invest an amount $Q_{j,t}S^B_{j,t}$ in the production firms of sector j, which has the interpretation of a diversified credit portfolio. By the end of the period, such a portfolio yields a gross return $R_{j,t+1}$ that is subject to an exogenous idiosyncratic shock $\omega_{j,t+1}$ such that the portfolio's terminal return is $\omega_{j,t+1}R_{j,t+1}$.[23] The idiosyncratic asset return shock is assumed to be i.i.d across time and banks of class j, and follows a log-normal distribution with a mean of one, a time-varying standard deviation $\widetilde{\sigma_{j,t}}$, and a cumulative distribution function $F_j(\omega_{j,t})$.

The objective function of the representative bank of class j is to maximize the net present value of their shareholders' stake at the bank

$$NPV_{j,t} = \mathbb{E}_t \left[\Lambda^B_{t+1} \max\left[\omega_{j,t+1}R_{j,t+1}Q_{j,t}S^B_{j,t} - R^D_t D_{j,t}, 0\right] - v_t NW_{j,t}\right], \tag{19}$$

where the bankers' equity investment $NW_{j,t}$ is valued at its equilibrium opportunity cost v_t, and the max operator captures the possibility of banks defaulting on their deposit obligations whenever the end-of-period net worth becomes negative. Bank failures are costly to the economy because resources are lost in the dissolution process; after seizing and liquidating a bank's assets, the DIS obtains

[23] As argued by Mendicino et al. (2018) bank idiosyncratic return risk is an important originator of bank default and is intended to capture the limitations that a bank faces when diversifying borrowers' risk stemming from regional or sectoral specialization or granular (large) exposures.

$(1-\mu)\,\omega_{j,t+1}R_{j,t+1}Q_{j,t}S^B_{j,t}$, where $\mu \in (0,1)$ represents the asset liquidation costs. The bank's balance sheet is given by:

$$Q_{j,t}S^B_{j,t} = NW_{j,t} + D_{j,t}. \tag{20}$$

Additionally, banks face a regulatory capital constraint

$$NW_{j,t} \geq \phi_{j,t}Q_{j,t}S^B_{j,t}, \tag{21}$$

where $\phi_{j,t}$ is the capital requirement on assets of bank class j.

Due to the existence of limited liability and deposit insurance, the model features binding capital requirements in equilibrium —partially insured debt financing is always cheaper than equity financing. Based on this, we can express bank's assets as $Q_{j,t}S^B_{j,t} = NW_{j,t}/\phi_{j,t}$, its deposits as $D_{j,t} = (1-\phi_{j,t})\,NW_{j,t}/\phi_{j,t}$, and derive the threshold $\overline{\omega}_{j,t+1}$ below which realizations of the idiosyncratic shock to bank's returns induce bank failures:

$$\overline{\omega}_{j,t+1} = (1-\phi_{j,t})\,\frac{R^D_t}{R_{j,t+1}}. \tag{22}$$

Notice that the probability of failure of a bank $F_{j,t+1}\left(\overline{\omega}_{j,t+1}\right)$ will be driven by fluctuations in the aggregate return on loans $R_{j,t+1}$, as well as fluctuations in the volatility of the distribution of the bank returns $\widetilde{\sigma}_{j,t}$.

As in Bernanke et al. (1999), in the appendix A.4, we derive the expected gross share of terminal asset value $\Gamma_{j,t+1}(\overline{\omega}_{j,t+1})$ that goes to the bankers after factoring in defaults from all banks of class j with shock realizations below $\overline{\omega}_{j,t+1}$. This object is useful to rewrite the objective function of a representative bank in (19) as:

$$NPV_{j,t} = \left\{\mathbb{E}_t\left[\Lambda^B_{t+1}\left[1-\Gamma_{j,t+1}\left(\overline{\omega}_{j,t+1}\right)\right]\frac{R_{j,t+1}}{\phi_{j,t}} - v_t\right]\right\}NW_{j,t} \tag{23}$$

which is linear in the bankers' net worth, $NW_{j,t}$. An intuitive condition governing banks' incentives to invest in the assets of each productive sector j arises:

$$\mathbb{E}_t\left[\Lambda^B_{t+1}\left[1-\Gamma_{j,t+1}\left(\overline{\omega}_{j,t+1}\right)\right]R_{j,t+1}\right] \geq \phi_{j,t}v_t \tag{24}$$

In equilibrium, (24) holds with equality as banks provide credit to firms until the net risk-adjusted return of productive assets equates to the regulatory-weighted opportunity cost of banker's equity.

Climate risk spillovers to the banking sector. In the real world, as in our model, energy is a fundamental input for the production process. Its importance in the economy implies that energy prices have essential implications for households, firms, and the financial sector. In the context of climate change, transitioning from current carbon prices to ones consistent with the EU net-zero targets would significantly increase energy prices (International Energy Agency (2023)) —these observations make energy price risks a recognized and significant risk predicted to materialize as the transition intensifies. Furthermore, this a relevant concern

for the banking sector given the empirically documented strong relationship between energy prices and bank performance.[24] Our approach stresses this channel as a relevant source of risk for the banking sector, we capture the relationship between banks' performance and energy price dynamics by assuming that the cross-sectional volatility of banks' sectoral idiosyncratic risk evolves according to:

$$\widetilde{\sigma}_{j,t}(\tau_{X,t}) = \sigma_j [P_{E_j,t}(\tau_{X,t})]^{\beta_j}, \quad j \in \{Y, F, L\}, \tag{25}$$

where σ_j represents the time-invariant level of the volatility, and β_j is a parameter determining how sectoral energy prices affect the volatility of banks' returns. When $\beta_j > 0$, an endogenous *energy price risk channel* becomes active. Energy price dynamics from the production side of the economy affect the volatility of assets' returns of banks exposed to that sector.[25]

2.4 Public Sector

Macroprudential authority. Consistent with the risk-based approach under Basel II and Basel III, the macroprudential authority sets capital requirements that differ across types of exposure: $\phi_{j,t} \in \{\phi_{Y,t}, \phi_{F,t}, \phi_{L,t}\}$ through regulatory constraints in (21).[26]

Fiscal authority. The fiscal authority manages the deposit insurance scheme, implements the carbon tax policy, and levies lump-sum taxes or transfers T_t on households to balance its budget every period. The total costs incurred by the deposit insurance scheme are

$$T_t^{DIS} = \kappa \Omega_t D_{t-1}, \tag{26}$$

where Ω_t is the average default loss per unit of bank debt, which is the properly weighted average of the losses realized at each class of bank and explicitly defined in Appendix A.4. Additionally, balancing the budget requires financing exogenous government expenditure G_t. The government's budget constraint is:

$$B_t + T_t = T_t^{DIS} + G_t - \tau_{X,t} X_t - R_t B_{t-1}. \tag{27}$$

3 Calibration

In this section, we outline our calibration strategy. The model is calibrated at a quarterly frequency.

[24] Nasim et al. (2023); Nasim and Downing (2023) show that energy price shocks have a significant negative direct impact on banks' performance and bank efficiency, even after controlling for all the relevant macroeconomic variables. Also, Lee and Lee (2019) show that increases in oil prices trigger a reduction in bank capitalization, earnings, and liquidity in Chinese banks.

[25] When $\beta_j = 0$ shocks in the production side of the economy do not affect the financial sector in steady-state since all the adjustment takes place via quantities. Returns on different types of capital —the variables linking the production and the financial sides of the economy— remain unaffected.

[26] This is equivalent to set a minimum level of capital requirements for all types of exposures and to adjust differential risk weights for each sectoral exposure —a standard interpretation (Mendicino et al., 2020; Bahaj and Malherbe, 2020).

Households. Household parameters are set following standard values in the literature: the discount factor, β, is set to match an annualized risk-free rate of 2% in the steady state; the parameter governing the degree of risk-aversion ς is set equal to 2; the labor disutility parameter η, which has a purely scaling role, is normalized to 1; the Frisch elasticity of labor supply ν is set equal to 1.

Production sector. The parameter determining the share of capital in the non-energy sector, α_Y, is set to 0.3 as standard in the literature. The weight of the energy composite in the final output α_E is set equal to 0.1.[27] The elasticity of substitution between the non-energy capital and labor inputs and the energy composite φ_Y, is set to 0.5 implying imperfect complementarity. In the energy sector, the weight of fossil energy into the energy composite α_F is set to 0.8 to match a share of 20% renewable energy in total energy in the Euro Area. We set φ_E to 3 which implies that fossil energy and low-carbon energy are strong substitutes in the CES aggregation function for the energy composite (Papageorgiou et al., 2017). The elasticity between fossil energy inputs φ_F is set to 0.3 indicating a high degree of complementarity between fossil capital and fossil resources.[28] Following Diluiso et al. (2021) we assume there is no price differential between low-carbon and fossil energy in the benchmark economy and both prices are normalized to one. We use the steady state price of fossil resources to target a value of fossil resources expenditure over GDP equal to 1.8%, in line with the energy import bill of EU countries reported by the European Commission (2020). We set the annualized depreciation rate in the non-energy sector equal to 10% (Fagan et al., 2005). We set annualized depreciation rates of 8%, and 5% for the low-carbon and fossil energy sectors respectively capturing heterogeneous infrastructure across energy producing sectors (Baldwin et al., 2020). Capital adjustment costs ϱ_j are set in line with the values used in models with bank default (Mendicino et al., 2018, 2020).[29] Finally, government expenditure G is calibrated to match the share of private consumption in total output equal to 0.56 (Fagan et al., 2005).

Banking sector. Turning to the banking side of the economy, we follow the calibration strategy in Mendicino et al. (2020). The survival rate of bankers θ is set to match the median return on average equity in the systemically significant Euro Area banks. The endowment of new bankers χ is used so that the shadow value of bank equity ν_t matches the average price-to-book ratio of EA banks. The share of insured deposits κ is set to 0.54 following Demirgüç-Kunt et al. (2015) for EA countries.

To isolate the risk spillovers from carbon policy and the optimal response of capital requirements—see the following section, we assume that our banking sec-

[27] From 2013 to 2020, the energy share in intermediate input production across economic industries averaged 7% for the European Union. Nonetheless, this share varies significantly among European countries. In view of this, we set our benchmark to $\alpha_E = 0.1$ consistent with other E-DSGE models (Diluiso et al. (2021)). See, Appendix C.4 for further robustness.

[28] In Appendix C, we perform a sensitivity analysis for different elasticities of substitution.

[29] Moreover, the E-DSGE literature does not differentiate adjustment costs across energy sectors (Annicchiarico and Di Dio, 2015; Carattini et al., 2023).

Table 1: Benchmark Calibration

Description	Parameter	Value	Source/Target
Households			
Discount factor	β	0.995	2% risk-free rate
Disutility of labor	η	1	Normalization
Frisch elasticity of labor	ν	1	Carattini et al. (2023)
Risk aversion	ς	2	Carattini et al. (2023)
Government expenditure	G	0.19	$C/Y = 0.56$ (Fagan et al., 2005)
Final output			
Weight of energy sector	α_E	0.1	Eurostat (2013-2020)
ES between energy and non-energy	φ_Y	0.5	Diluiso et al. (2021)
Weight of capital	α_Y	0.36	Carattini et al. (2023)
Non-Energy Factors Efficiency	A_Y	0.26	$Y = 1$
Energy production			
Weight of fossil energy	α_F	0.8	Coenen et al. (2023)
Weight of fossil natural resources	α_X	0.3	Coenen et al. (2023)
ES between energy inputs	φ_E	3	Papageorgiou et al. (2017)
ES between capital and resources	φ_F	0.3	Coenen et al. (2023)
Energy Capital Efficiency	A_F, A_L	$\{0.010, 0.016\}$	$P_{E_F} = P_{E_L} = 1$
Capital producers			
Capital adjustment cost	$\varrho_Y, \varrho_F, \varrho_L$	$\{4.57, 4.57, 4.57\}$	Mendicino et al. (2020)
Depreciation rate (annualized)	$\delta_Y, \delta_F, \delta_L$	$\{10\%, 5\%, 8\%\}$	Fagan et al. (2005); Diluiso et al. (2021)
Financial sector			
Share of insured deposits	κ	0.54	Demirgüç-Kunt et al. (2015)
Survival rate of banks	θ	0.9126	Bank price-to-book ratio of 1.1
Transfers from HH to bankers	χ	0.8032	Bank return on equity of 7.9%
STD iid bank risk	$\sigma_Y, \sigma_F, \sigma_L$	$\{0.03, 0.03, 0.03\}$	0.67% bank failure rate
Energy price-risk elasticity	$\beta_Y, \beta_F, \beta_L$	$\{1, 1, 1\}$	2.9% stressed bank failure rate
Bankruptcy cost	μ	0.1	$\phi = 9.4\%$ optimal
Capital management cost	$\zeta_Y, \zeta_F, \zeta_L$	$\{0.4, 1.58, 2.33\}$	22% NBFI and $R_F = R_L$

tors start with the same level of risk and no return premium between sectors in the benchmark economy. Hence, the time-invariant volatility of the idiosyncratic shock to banks' returns σ_j is set to make the probability of bank default equal to an annual bank failure rate of 0.67% for all banks. In the same line, bank resolution costs μ are set such that the benchmark level of capital requirements is also the optimal one; we assume these costs are the same across sectors as it is standard in the literature. For the parameter measuring the intensity of the energy price risk channel β_j, we assume a value of one in all sectors.[30] Hence, the volatility of banks' returns in each sector has two components: a constant and symmetrical volatility risk and a variable volatility component capturing the spillover effects of the energy price risk channel. This approach allows us to isolate the effects of the energy price risk channel, and it is useful to quantify how the optimal capital requirement policy should optimally adjust to address spillovers from carbon taxes into the financial sector.

We set bank capital requirements ϕ_j to the same level for all sectors at 9.4% — labeled *general* capital requirement, which is the level that maximizes household

[30] As shown in Section 4, upon the introduction of the carbon tax, our assumption on β_j's delivers an increase in the average bank failure rate in line with market-expected default frequencies for European financial institutions before the implementation of Basel III. In Appendix C.1, we do sensitivity analysis over β_j.

welfare in our benchmark economy.[31] This approach captures the fact that the current prudential regulation does not distinguish between non-energy, fossil, and low-carbon assets. We interpret this optimum capital requirement as the relevant starting point for the policy analysis performed in the next sections. This choice facilitates the identification of welfare gains or losses resulting from prudential interventions related to the climate transition rather than capturing differences in inherent sectoral risk from the calibration. Moreover, since the model is calibrated to capture the characteristics of systemically significant banks in the Euro Area, our benchmark capital requirement level can be interpreted as an aggregated measure combining additional regulatory requirements, which were gradually incorporated starting in 2016 following Basel III guidelines. Our capital requirements align with the reported combined regulatory requirements on total core capital for banks in the Euro Area, which averaged 9.4% in 2020 (Behn et al., 2020) and with the optimal values found in macroeconomic models studying the role of macroprudential policy (Mendicino et al., 2018, 2020).

Non-Banking sector. The capital management cost parameter ζ_Y is set to target an average NBFI market share of 20% in the economy (Mendicino et al., 2020). ζ_F and ζ_L are used to equalize returns across sectors following recent evidence showing zero greenium in bond markets (European Securities and Markets Authority, 2023).[32]

In the following sections, we analyze the impact of introducing a carbon tax to curb fossil emissions and its interaction with capital requirements; we first perform a steady-state analysis (Section 4) and then a transitional dynamics analysis (Section 5).

4 Climate Transition Risk and Bank Capital Requirements in the Medium-Run

We start by tackling two relevant questions for economies implementing carbon taxes as a carbon emission mitigation policy: (i) What are the real and financial effects of introducing a carbon tax?; (ii) How should macroprudential policy react in this context? To answer these questions, this section presents a set of steady-state comparative static exercises.[33] The central insight from the following analysis is that adjusting bank capital requirements based on sectoral risk exposure —arising

[31] See Appendix B.1 for a detailed explanation of the optimal level of capital requirements in our benchmark economy. We focus on a utilitarian welfare measure. See Aguilar et al. (2019) for an extended assessment of welfare measures in models with bank failure.

[32] Our calibration delivers a benchmark NBFI market share of 12% and 32% for fossil and low-carbon technologies, respectively. This captures evidence that bank intermediation is relatively stronger in the traditional fossil sector and relatively low in the more innovative low-carbon sector (Buchner et al., 2023). Banks might hesitate to finance innovation due to a lack of expertise in evaluating high-risk projects that cannot be used as collateral or harm the value of the underlying collateral for existing loans (Ueda, 2004; Hall and Lerner, 2010).

[33] Any long-run analysis should consider the effects of technological change (see Airaudo et al., 2023). Since our model lacks this feature, our results should be interpreted as *medium-run*.

from spillovers in the implementation of carbon taxes through the energy price risk channel— may generate welfare gains and support financial stability. Furthermore, such a policy indirectly favors a green credit transition, pointing to the complementarity between capital-based macroprudential policy and (fiscal) carbon tax policies in reducing carbon emissions.

4.1 Introducing a Carbon Tax

We start by introducing a carbon tax τ_X that delivers a 35% reduction in carbon emissions with respect to the level of the benchmark economy. This magnitude of emissions reduction is in line with the European Commission's 2030 Target Plan, which sets climate goals for the period 2020-2030.[34] The main effects of introducing a carbon tax in our benchmark economy are summarized in the column (CT) in Table 2.

Through a marked increase in the price of energy, the carbon tax policy entails sizable real economic costs in the medium run.[35] The direct impact of introducing a carbon tax is an increase in the price of fossil energy (+25%), which translates into an increase in the final price of energy (+19%) due to the high share of fossil energy in the energy composite. The price of low-carbon energy also experiences a small increase mainly due to general equilibrium effects arising from higher demand for low-carbon energy. As the economy substitutes —fossil for low-carbon— energy inputs, the demand for fossil energy falls, bringing its share down from 80% to 68% in the new steady state. The total production of energy contracts, and so does GDP due to the strong complementarity between energy and other intermediate inputs.

On the financial stability side, the *energy price risk channel* in (25) plays a central role: changes in energy prices spill over to the volatility of banks' net returns to investments in each economic sector. Such heightened volatility translates into a heterogeneous increase in bank failure rates across banking sectors, pushing the average bank failure rate in the economy close to 3%.[36] At the same time, the economy experiences a sizable reallocation of capital from the fossil to the low-carbon energy sector. As the carbon tax affects the relative prices of fossil and low-carbon energy, it directly impacts returns to capital investments across these sectors, which leads to a change in banks' portfolio composition.[37]

Overall, our model predictions are consistent with other quantitative studies establishing that the carbon transition entails output losses; for instance, the Eu-

[34]The 2023 European Commission's proposal sets a goal of cutting greenhouse emissions by at least 55% by 2030 with respect to the 1990 emission levels. As of 2020, EU greenhouse emissions have already been reduced by 33.8%. The remaining change in emissions needed is roughly 35% with respect to the 2020 levels. See European Commission (2023) for more details.

[35]In Appendix C.5 we quantitatively validate our model by checking that the reaction of GDP to a permanent increase in the price of fossil resources aligns with the empirical evidence (Peersman and Van Robays, 2009, 2012).

[36]The implied failure rate aligns with the market expected default frequencies for European financial institutions, which ranged between 3% and 5% before the implementation of Basel III, as documented by Mendicino et al. (2020).

[37]Such predictions align with central banks and financial supervisors' medium-run expectations (European Systemic Risk Board, 2023; Hiebert and Monnin, 2023), i.e., implementing carbon emission reduction policies will lead to substantial portfolio reallocation across economic activities.

ropean Central Bank (2023) predicts an interval of output losses across scenarios ranging from 0 to -1.2% fall in GDP in 10 years —in Appendix C.6, we show that our model delivers a fall of around 1%. Our analysis further illustrates that the green transition may entail substantial risks for banks' performance through the energy price risk channel, especially for those banks with higher exposure to carbon-intensive economic sectors.[38]

4.2 Optimal Capital Requirements with Carbon Tax

What is the role of bank capital regulation in addressing spillovers from implementing a carbon tax policy? Here, we present the results from numerical simulations addressing this question. In an economy with the same carbon tax policy as in the previous subsection 4.1, we consider two possible capital-based macroprudential policies: (i) a *general* capital requirements (CT+GCR), where capital requirements are optimally adjusted symmetrically in all banking sectors and (ii) *sectoral* capital requirements (CT+SCR), where capital requirements are optimally adjusted asymetrically in each banking sector.

Our main finding is that optimally adjusting sectoral capital requirements is welfare superior to adjusting general capital requirements in addressing heightened risks arising from carbon tax spillovers to the banking sector. Intuitively, the heterogeneous spillover of risks across banking sectors —measured by banks' failure rates— calls for heterogeneous capital requirements, in line with an asset risk-based approach.[39] Figure 1 shows changes in household welfare associated with changes in sectoral capital requirements; in particular, household welfare is maximized when capital requirements for non-energy, fossil, and low-carbon energy assets are increased to $\phi_Y = 10.8$, $\phi_F = 11.1$, $\phi_L = 9.7$, respectively. This implies that the spillovers from higher energy prices mainly require higher capital requirements in the loan exposures of the fossil energy (+183 bp) and the non-energy (+142 bp) sectors, see Table 2.[40]

The impact on the production sector. The economy with optimal sectoral capital requirements features an additional reduction in carbon emissions and lower welfare losses compared to other policies. Reducing carbon emissions is costly to the economy; despite this, when such a policy is coupled with SCRs, the economy experiences small positive gains on aggregate household consumption due to

[38] Dankert et al. (2018) review the empirical literature measuring the financial performance of green and non-green assets. Based on the documented risk-based evidence, the authors find that the current supervisory framework may understate the underlying risk behind asset exposures in climate-sensitive economic sectors.

[39] There is real-world evidence of differentiated levels of capital requirements for different economic sectors, although not applied to address climate-related risks; for instance, corporate and housing loans have different treatment in Basel regulations. See Section 4.3 for a discussion on how our simulation exercises could inform adapting the current capital-based macroprudential tools to address climate-related risks.

[40] Our model's predictions for sectoral capital requirements are in the same direction that the projections of the European Systemic Risk Board (2023)'s calibration exercise, where the use of bank-specific SyRB for climate risk is evaluated using stress test techniques. However, the magnitudes in our model tend to be higher due to second-round general equilibrium effects.

Table 2: Carbon Tax and Optimal Capital Requirements

	B	CT	CT + GCR	CT + SCR
Non-Energy CR, ϕ_Y. Δbp.	-	-	145	142
Fossil CR, ϕ_F. Δbp.	-	-	145	183
Low-Carbon CR, ϕ_L. Δbp.	-	-	145	29
Carbon Emissions, $\%\Delta$.	-	-35.3	-35.7	-36.0
Price of Fossil Energy, $\%\Delta$.	-	25.7	25.8	26.0
Price of Low-Carbon Energy, $\%\Delta$.	-	0.87	0.80	0.23
Price of Energy Bundle, $\%\Delta$.	-	19.2	19.3	19.3
Fossil Energy, ratio $(\%)$.	80.0	68.3	68.2	67.8
GDP, $\%\Delta$.	-	-2.12	-2.19	-2.16
Welfare, cons. equivalent $\%\Delta$.	-	-2.22	-2.03	-2.02
Fossil Bank Credit, $\%\Delta$.	-	-21.2	-22.4	-23.5
Low-Carbon Bank Credit, $\%\Delta$.	-	62.4	62.9	72.0
NBFI, ratio $(\%)$.	20.3	23.9	24.5	24.2
Bank Failure, annual rate $(\%)$.	0.67	2.90	0.88	0.86

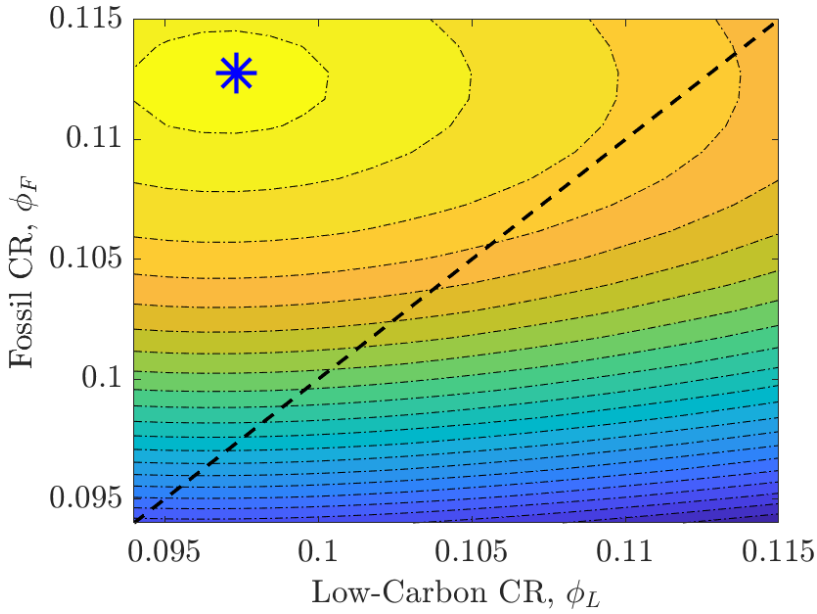
Note: the column *B* represents the benchmark economy. *CT* compares an economy with carbon taxes to the benchmark. *CT + GCR* compares an economy with carbon taxes and the level of general capital requirements that maximizes welfare to the benchmark. *CT + SCR* compares an economy with carbon taxes and the level of sectoral capital requirements that maximizes welfare to the benchmark. Δbp: denotes differences in basis points with respect to the benchmark economy steady state with ϕ_F equal to 9.4%. $\%\Delta$: represents the percentage change with respect to the benchmark. Ratio $(\%)$: reports the ratio in the new steady state.

a more resilient banking sector —the sources of the welfare gains shown in Figure 1. In contrast, implementing general capital requirements would induce a stronger contraction in GDP, leading to further welfare losses, as shown in Column *CT+GCR* in Table 2.

The impact on financial stability. As risk in the banking sector rises, sectoral capital requirements can safeguard financial stability at a lower cost for the economy. The energy price channel delivers a cross-sectoral (transversal) risk contagion, implying that higher risk in the fossil energy sector, derived from introducing carbon taxes, spills over to other economic sectors. Our results, in Table 2, show that sectoral capital requirements can reduce average bank failure rates even further than general capital requirements as the policy can be tailored to address energy risk spillovers into each banking exposure differentially.

The optimal sectoral capital requirement policy indirectly supports a *green credit transition*, i.e., credit reallocation towards the low-carbon energy sector. As energy exposures become riskier and capital requirements adjust upwards to mitigate such risks, banks switch credit from the relatively less attractive fossil energy sector to the low-carbon energy sector; such a green credit transition is more pronounced when SCRs are implemented. A key insight arises: Sectoral capital requirements are superior to general capital requirements because they facilitate a

Figure 1: Optimal Capital Requirements. Δ Welfare



Note: Household welfare levels for different combinations of $\{\phi_F, \phi_L\}$ when $\phi_Y = 10.8\%$ is set at its optimal level. Blue regions represent areas with low levels of welfare. Yellow regions represent areas with high levels of welfare. The axis starts at the benchmark level of capital requirements. The dashed black line indicates increases in *general capital requirements*. The blue asterisk corresponds to the optimum $\{\phi_F, \phi_L\} = \{11.1\%, 9.7\%\}$. Welfare is measured in consumption equivalent units.

credit transition from the fossil to the low-carbon energy sector at a lower cost to the economy.[41] In contrast, increasing general capital requirements reduces the speed of credit expansion into the low-carbon energy sector, which slows down the green transition. This occurs because the size of the non-energy sector drives the magnitude of the optimal increase in general capital requirements, which imposes an overly high penalization on the low-carbon lending.

In sum, our results indicate that by pursuing financial stability, a macroprudential authority can indirectly support, in the medium run, a reallocation of resources from the fossil sector to the low-carbon energy sector, even if that is not its primary objective.

4.3 Policy Discussion

Adapting current capital-based macroprudential tools. Although existing capital requirements in the Basel III framework are not specifically designed to address climate-related risks, our exercises shed light on how the framework can be adapted to tackle them. Given the nature of risks posed by the climate transition —long-term, non-cyclical, and possibly impacting an ample set of banks— the most natural macroprudential tools to address spillovers into the financial sector are the systemic risk buffers. For instance, in the context of the Euro Area, a *general* cap-

[41] See Miguel et al. (2024) for recent evidence on the effect on lending of introducing capital assessment that includes environmental risks. In line with our predictions, the authors find that, when accounting for those risks, affected banks tend to reallocate their lending away from exposed sectors.

ital requirements policy can be interpreted as activating a general Systemic Risk Buffer (SyRB) that applies to all banks and all exposures. In contrast, the *sectoral* capital requirements map to activating a Systemic Risk Buffer that varies across banks and/or sectoral exposures.[42]

The analysis in section 4.2 provides suitable insights into adapting the scope of current systemic risk buffers to address climate-related risks. Similar proposals to our model's sectoral capital requirements have been recently discussed in the policy arena. The proposals suggest requiring additional capital for loans in economic sectors that are more exposed to climate transition risks through the adaptation of macroprudential buffers.[43] In practice, European countries have widely used these buffers during the last decade to mitigate risks from external shocks, regional exposures, and increasing exposures to specific economic sectors. For instance, SyRBs have been implemented in Norway to mitigate common exposures to the petroleum sector; Austria and Denmark have implemented SyRBs to address individual banks' exposures to geographical risks; Sweden requires a buffer for large institutions with a similar business model.[44]

Quantifying the impact of climate transition risks associated with carbon mitigation policies, like carbon taxes, in the financial sector remains a major challenge. In this line, the predictions of our dynamic general equilibrium model contribute to the literature in two important aspects. First, it is a forward-looking modeling approach to quantify climate risk spillovers into the banking sector (recall that in the model, agents —households, firms, and banks— make dynamic, forward-looking decisions). Second, our analysis captures feedback loops (second-round effects) between the real and financial sectors, an essential aspect for calibrating macroprudential policy.

Cross-country structural heterogeneity. An important question for policymakers is how the magnitude of the optimal macroprudential policy might depend on the structural parameters of a particular economy. Here, we brief on the main insights from Appendix C, where we do robustness exercises changing the structural parameters —based on empirical moments from European countries— that govern the elasticity of substitution between fossil and clean energy inputs (φ_E), the degree of complementarity between fossil resources and capital in the fossil energy sector (φ_F), the weight of energy in the production of final goods (α_E), and the intensity of the energy price risk channel (β_j).

An economy's capacity to substitute fossil for low-carbon inputs (φ_E) plays a central role in the climate change transition and transformation of the production

[42]The Systemic Risk Buffer (SyRB) is an existing tool within the regulatory space of the European Systemic Risk Board that aims to address systemic risks that are not covered by the Capital Requirements Regulation or by the Counter-Cyclical buffer (CCyB) or other buffers imposed to globally or systemically important institutions (G-SII/O-SII). The level of the SyRB may vary across institutions or sets of institutions as well as across subsets of exposures.

[43]The adaptation of macroprudential tools to address climate-related risk is an ongoing discussion recently addressed by the European Systemic Risk Board (2023). See also Hiebert and Monnin (2023), Monnin (2021), and Coelho and Restoy (2023) for a more in-depth discussion.

[44]See Monnin (2021) for a detailed review of the use of the SRB since 2014 across Europe.

sector towards clean technologies (Acemoglu et al., 2012; Golosov et al., 2014). In the context of the Euro Area, there is substantial heterogeneity across countries in their capacity to substitute energy inputs; the literature reports estimates for this elasticity ranging between 1.5 to 5 (Mattauch et al., 2015; Jo and Miftakhova, 2022). Consequently, the intensity of carbon policies will vary across countries—as some can achieve emission reduction targets more quickly than others—and so does the optimal macroprudential policy, see Appendix C.2. The main insight from these exercises is that stronger capital requirement policies are needed to maintain financial stability in economies with a low capacity to substitute fossil with clean energy inputs. In such economies, capital requirements must act more forcefully since higher carbon taxes are needed to achieve target emission reductions, generating larger energy price spikes and spillover risks into the banking sector.

The complementarity between fossil resources and fossil capital is another structural parameter of interest. As this parameter lacks empirical estimations, we perform a sensitivity analysis for values used in other quantitative works (Diluiso et al. (2021); Coenen et al. (2023)). Nonetheless, our range of values factors in that as the green transition evolves, advancements in fossil fuel extraction technology will likely reduce fossil resources dependency, meaning that the fossil resources and capital complementarity will likely weaken. Our analysis in Appendix C.3 shows that our main conclusion on the use of sectoral capital requirements remains unchanged; the implementation of carbon taxes pushes energy prices up in every alternative economy. The optimal policy stands to increase the capital requirement for fossil energy and non-energy exposures and, to a lesser extent, for the clean energy sector.

We further explore the importance of energy weight in output production, α_E, see Appendix C.4. From 2013 to 2020, the energy share in intermediate input production across economic industries varied significantly among countries; for instance, Germany averaged 5% while Greece averaged 15% during the period. Our previous findings remain robust for the α_E values considered. The main highlight is that optimal sectoral capital requirements tend to be higher in economies with a larger reliance on energy. Intuitively, economies with a large energy sector have a larger share of their banking sector assets exposed to carbon transition policies and, hence, require higher capital requirements to shield against carbon transition risks.

Lastly, in Appendix C.1, we investigate the intensity of the energy price risk channel captured by β_j —a structural parameter that defines the risk spillover of climate policies targeting carbon emissions in energy production to the financial sector in our model. The analysis confirmed the soundness of our previous results. As anticipated, the higher the intensity of the pass-through of energy prices to the volatility of banks' net returns, the stronger the impact on financial stability —measured by bank failure rates and the share of NBFI. Likewise, when the pass-through is lower, the economy adapts to the carbon policy more easily, and a smaller macroprudential intervention is required.

4.4 Bank Capital Requirements as a Climate Policy Tool

A relevant question in the academic and policy arenas is whether macroprudential authorities could not only address climate-related financial risks (a goal within their mandate) but also promote a faster transition to a green economy through regulatory interventions in the credit market —a purpose beyond the macroprudential scope.[45] This section presents a comparative static analysis to assess the medium-run impact of increasing capital requirements to fossil exposure —also known as *fossil penalizing factor*— to reduce carbon emissions in the absence of carbon taxes.[46]

The main message is that capital requirements on their own have a limited impact on reducing carbon emissions and generating an investment transition from fossil to low-carbon energy production. In the credit market, introducing higher capital requirements to banks' fossil exposures induces a strong credit disintermediation in the fossil energy sector, an expansion of non-banking intermediation in the same sector, and an increase in the risk profile of other financial sectors. Such a new financial structure has negative repercussions for the financial stability of the entire banking sector. These observations point out the limitations of using capital-based macroprudential policies in isolation to actively promote a green transition.

We explore the macro-financial effects of introducing a very high level of fossil capital requirement that leads to a large disintermediation of the fossil banking sector while leaving unchanged the capital requirements in non-energy and low-carbon energy banking sectors.[47] For instance, Figure 7 in the Appendix B.2, shows that the fossil-banking sector is largely disintermediated when setting $\phi_F = 50\%$; which implies an equity funding of 50 cents per unit lent. Table 3 reports selected statistics across three identically calibrated economies except for the degree of substitution of energy inputs, which can be low, medium, or high. These exercises provide insights into how capital requirements may enhance or hinder a green transition through its effect on credit markets.

The impact on carbon emissions and the economy. Imposing very high capital requirements on fossil assets has a limited impact on reducing carbon emissions. In the medium run, introducing such an extreme policy could reduce carbon emissions between 7% and 20%, depending on the degree of fossil-clean substitutability in the economy. However, in all economies, energy prices increase substantially,

[45] On the policy side, see the European Commission (2018a,b) Action Plan on Sustainable Growth, which proposes several policies to actively reduce financing of polluting economic activities and favor the ones with low carbon emissions. On the academic side, see Dafermos et al. (2018); Oehmke and Opp (2022) for theoretical assessments of brown penalizing and green supporting capital requirement policies.

[46] We focus on assessing fossil capital requirements (as there is more empirical evidence documenting potential financial risks from these exposures (Dankert et al., 2018)) instead of evaluating a reduction in capital requirements for green sectors. There is less support for the latter policy due to the lack of evidence in risk differential between green and non-green assets (Dankert et al., 2018; Neagu et al., 2024).

[47] Our analysis is positive rather than normative. However, such a stringent capital requirement policy can be rationalized as the optimal policy of a *green* prudential regulator (i.e., a planner that considers a linear welfare cost of the CO2 emissions into her objective function) that has capital requirements as the only policy tool and aims to reduce the stock of carbon emissions.

and energy production and output losses are well beyond those obtained when carbon taxes are used in conjunction with capital requirements to reduce emissions —compare results from Table 3 to Table 6 in the appendix.

Large fossil penalizing capital requirements induce a strong credit disintermediation in the fossil energy sector and an expansion of NBFI in the same sector. Importantly, we find that capital in the fossil energy sector does not experience a similar contraction because NBFI expands to partially compensate for the loss of fossil banking credit; see Table 3. Similar to our results in 4.3, a more pronounced green credit transition occurs in economies with a higher degree of fossil-clean substitution. Despite this, the economy experiences a fall in fossil investment larger than the respective expansion in the low-carbon energy sector. This outcome leads to lower energy production, and since energy is necessary for producing final goods, aggregate output also contracts.

The impact on financial stability. A standalone fossil penalizing factor decreases the financial stability of the banking system through two mechanisms: First, it increases the average bank failure rate, leading to financial instability in the banking sector. Second, it generates an expansion of the non-banking financial sector, which makes it harder for macroprudential policy to address climate-related financial risks.[48]

Table 3: Effects of CR as a Climate Policy Tool

Elasticity of substitution fossil-clean	$\varphi_E = 1.5$	$\varphi_E = 3$	$\varphi_E = 5$
Fossil CR, ϕ_F.	50	50	50
Carbon Emissions, $\%\Delta$.	-7.4	-12.3	-19.8
Price Fossil Energy, $\%\Delta$.	17.4	17.4	17.4
Price Low-Carbon Energy, $\%\Delta$.	0.45	0.44	0.42
Price Energy, $\%\Delta$.	20.4	13.3	12.8
Fossil Energy, ratio $(\%)$.	76.2	71.9	65.4
GDP, $\%\Delta$.	-1.87	-1.71	-1.45
Fossil Bank Credit, $\%\Delta$.	-65.6	-70.7	-78.6
Low-Carbon Bank Credit, $\%\Delta$.	12.0	43.9	92.5
NBFI, ratio $(\%)$.	32.0	31.8	31.5
Bank Failure, annual rate.	1.07	1.04	0.99

Note: All values are in percentage points. Each column reports statistics comparing the benchmark steady-sate to the new steady-state, where capital requirements in the fossil sector ϕ_F equal 50%. Δbp: denotes differences in basis points with respect to the benchmark economy steady state with ϕ_F equal to 9.4%. $\%\Delta$: represents the percentage change with respect to the benchmark. Ratio $(\%)$: reports the ratio in the new steady state.

[48] Oehmke and Opp (2022) arrives at similar conclusions when evaluating the effectiveness of imposing higher fossil capital requirements to discourage carbon-intensive activities in a stylized theoretical model of bank capital regulation.

Paradoxically, although capital requirements increase, the banking sector does not become safer. Two mechanisms are at play. The first mechanism implies a direct effect from increasing fossil capital requirements to lower bank failure rates by making the fossil banking system more resilient. The second mechanism pushes bank failure rates up through the energy price risk channel. Note that energy production is disrupted as the fossil banking sector becomes smaller, causing the prices of fossil and final energy to increase. Through the energy-price channel, net returns become more volatile for banks —in all sectors— in response to increases in energy prices, leading to higher bank failure rates across banking sectors. In equilibrium, the second effect outweighs the first, and the average bank failure rate is slightly higher than in the benchmark economy. Overall, banks experience a rise in the average cost of capital due to tighter capital regulation, higher bank failure risk, and higher competition for household savings from the non-banking sector.

The banking sector's lower credit intermediation is the second aspect that decreases financial stability. Table 3 shows that NBFI increases its share of total financial intermediation as fossil penalizing capital requirements increase. This growth in market share arises almost exclusively from NBFI becoming the primary funding source of the fossil sector. This financial structure may deteriorate financial stability; switching intermediation from the banking to the non-banking sector makes it harder to address climate-related financial risk through bank capital regulation.

5 Transitional Dynamics

In this section, we investigate the macro-financial effects of the carbon transition due to the introduction of a carbon tax. We first look at how the energy, financial, and real sectors react to the carbon tax along the transition. Then, we investigate the role of bank capital regulation in addressing spillovers from the carbon tax.

In the initial period ($t = 0$), the economy starts at the benchmark steady state with no carbon tax. At the end of the second year ($t = 8$) the introduction of a carbon tax is unexpectedly announced and its implementation path is fully revealed.[49] Two possible transition scenarios are explored: (i) a transition path from our benchmark steady-state towards the *Carbon Tax* steady-state where capital requirements stay at their benchmark values (9.4%) and (ii) a path from an economy where sectoral capital requirements have been preventively increased to their optimal level found in Section 4.2 and transitioning towards the *Carbon Tax* + *SCR* final steady-state.[50]

[49] This path is consistent with a 35% reduction in carbon emissions within ten years in line with our medium-run analysis in Section 4.2. The transitions are implemented by solving non-linearly the equations that define the perfect foresight equilibrium.

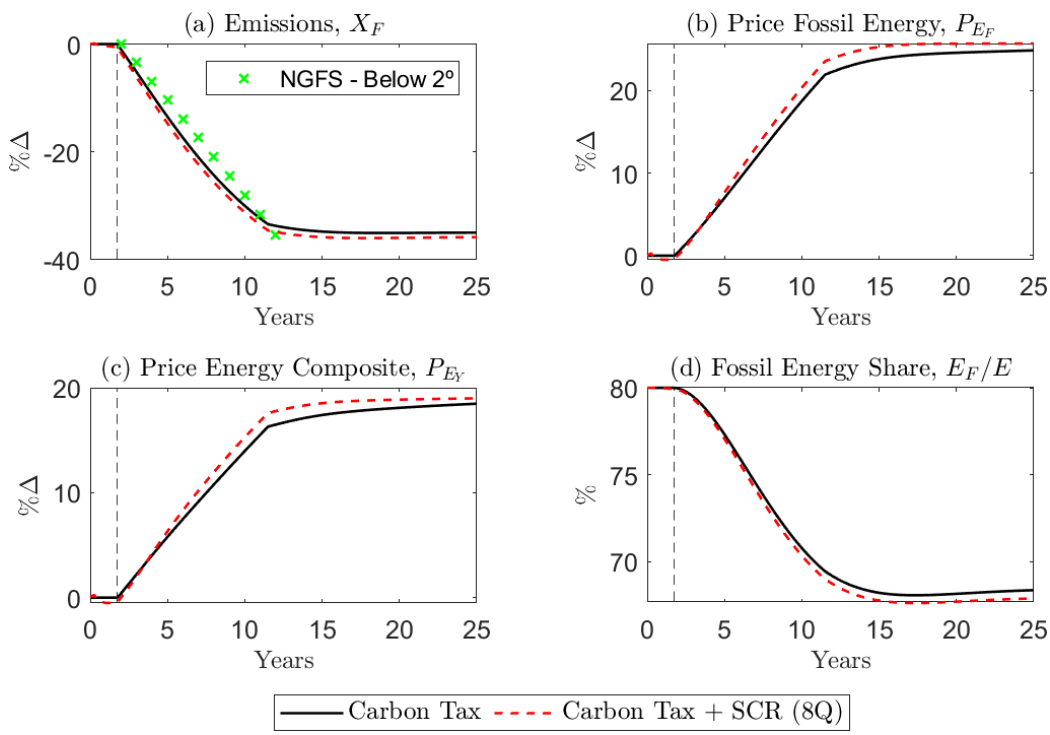
[50] Optimal sectoral capital requirements are introduced gradually during the first eight quarters before the carbon tax is announced and implemented. This modality captures the common regulatory practice of allowing banks to adjust their capital to the new required levels smoothly.

Transition in the real sector. Panel (a) in Figure 2 shows the realized path for emissions associated with the implementation of carbon taxes in our transition exercises. The implied emission's path is in line with an *orderly* scenario from the Network for Greening the Financial System (2021) intending to limit global warming to *below* 2^oC by 2050.[51] The carbon tax policy induces a remarkable transformation of the energy sector as emissions are reduced. The carbon tax reflects directly in the price increase of the fossil resource input needed for fossil energy production; as it gradually rises, fossil energy becomes more expensive, the return to fossil capital falls, and capital investment switches from the fossil to the low-carbon energy sector. Total energy production falls despite the investment expansion in the low-carbon energy sector, as fossil energy production cannot be fully replaced.

Figure 2 also illustrates that the prudential intervention —dash red lines— has no major impact on the energy sector dynamics, which are entirely driven by the carbon tax. However, in panel (d) we observe a faster decrease (increase) in fossil (low-carbon) energy demand consistent with the final steady state differences observed in Section 4.

Transition in the financial sector. On the financial side —see Figure 3, implementing a carbon tax has a negative impact, mainly on the fossil financial sector.

Figure 2: Carbon Transition: Energy sector



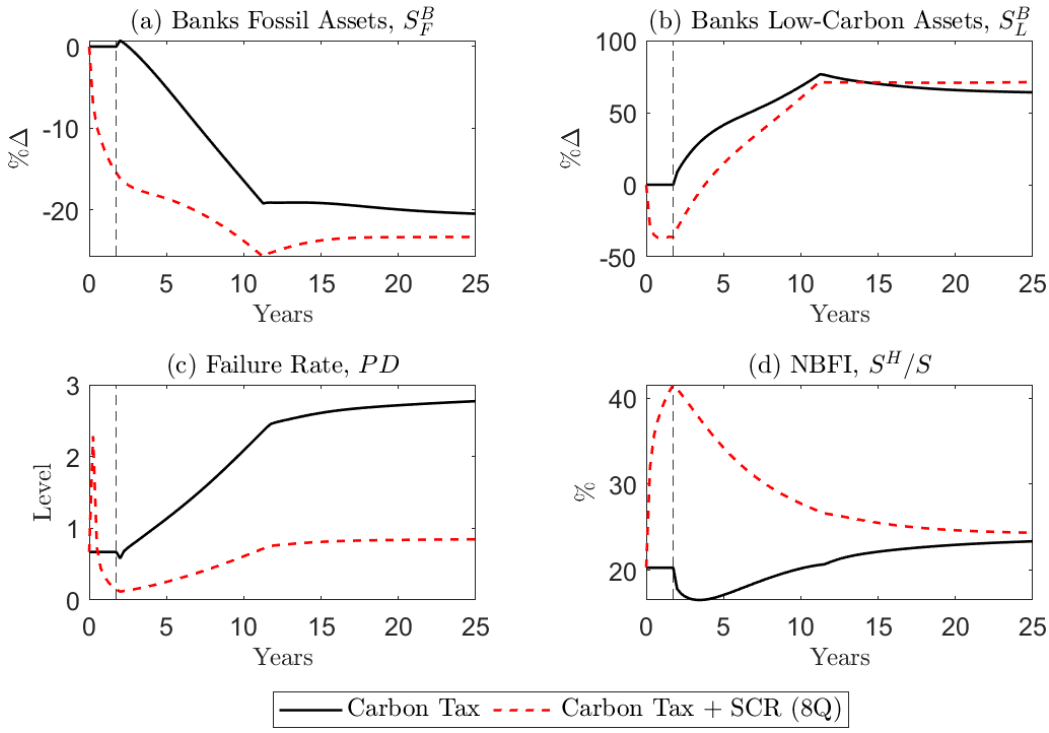
Note: %Δ: represents the percentage change with respect to the initial steady state. %: represents shares. The NGFS emission reduction path corresponds to the projections of Below 2°C scenario in the REMIND-MAgPIE 3.2-4.6 model (Aboumahboub et al., 2020) for the EU-28.

[51] These scenarios assess risks related to the implementation of climate policies and climate-related physical risks that affect the economy and the financial system.

In year two, the credit portfolio in the fossil banking sector shrinks sharply upon introducing the carbon tax because agents expect lower profitability in the fossil energy sector. In contrast, credit is redirected toward the low-carbon energy sector, experiencing rapid growth during the ten years following the introduction of the carbon tax —black continuous line in panel (b). The increase in energy prices observed in Figure 2 triggers a gradual escalation in the average bank failure rate, depicted by the black solid line in panel (c); through the energy price risk channel, carbon taxes increase the risk not only in the fossil sector but also lead to spillovers to the non-energy financial sector. The compound effect increases the average financial risk across the entire banking sector.[52]

The red-dashed lines in Figure 3 show that the impact of carbon taxes on the financial sector is cushioned in an economy with a more resilient banking sector due to optimized sectoral capital requirements. Panel (c) shows how banks sustain systematically lower failure rates throughout the entire transition. After ten years, the banking sector is as robust —measured by failure rates— as it was at the beginning of the transition and before the application of the prudential policy. This is the main source of welfare gains in this economy, as households save on resources from the costly liquidation of assets in case of bank failures. Another benefit of

Figure 3: Carbon Transition: Financial sector



Note: %Δ: represents the percentage change with respect to the initial steady state.

[52] Our model's predictions are in line with recent empirical evidence. Carbon taxes lead to lower fossil credit in the jurisdictions affected by it (Laeven and Popov, 2023). Moreover, Känzig (2023) shows that a tighter carbon pricing regime in Europe leads to higher energy prices, lower emissions, and more green innovation. This increase in energy prices has been shown to lead to lower bank performance in the fossil banking sector (Nasim et al., 2023; Nasim and Downing, 2023; Lee and Lee, 2019).

implementing sectoral capital requirements in anticipation of the carbon tax is the early reduction of bank lending to the fossil sector shown in panel (a), which continues smoothly by the time the carbon tax is activated. Although spare, there is empirical evidence documenting that introducing capital requirements in anticipation of environmental risk affects bank lending to the corporate sector in the direction our model predicts (Miguel et al., 2024).

Importantly, although the increase in low-carbon capital requirements is small, low-carbon credit falls —due to the complementarities between sectors in the economy — after the prudential intervention as shown in panel (b). Once the carbon tax is introduced, low-carbon credit quickly recovers and ends up at a higher level than in a scenario without prudential intervention in line with our results in Section 4. This result is important because it entails a short-run cost for the green credit transition in exchange for long-run gains. Additionally, panel (d) shows how higher capital requirements imply an initial fast growth of NBFI. However, the carbon tax triggers a demand for bank credit to finance the green transition that dampens the initial disintermediating effect of the macroprudential intervention. Overall, our results show that a sectoral capital-based macroprudential policy can indirectly support a faster credit transition while increasing financial stability.

Table 4 reports the differences between the two transition scenarios for selected variables at various time horizons.[53] In sum, preventively increasing sectoral capital requirements to their optimal medium-run level can build absorption capacity in the banking sector to address financial risk spillovers coming from distortions in the energy sector. Most importantly, optimal macroprudential policy indirectly supports a transition towards a greener economy in the long-run —at the expense of a credit contraction in the very short run— while supporting financial stability. During the first years, higher sectoral capital requirements induces lower invest-

Table 4: Transitional effects of optimal capital requirements

Horizon (Year)	1	5	10	25	50
Fossil energy share [a]	-0.11	-0.35	-0.44	-0.48	-0.53
Fossil bank credit[b]	-16.8	-10.9	-6.1	-2.7	-2.2
Low-carbon bank credit [b]	-37.2	-18.8	-4.6	7.5	9.32
NBFI [a]	22.5	12.9	5.69	0.85	0.35
Bank failure [a]	-0.62	-1.07	-1.69	-1.93	-2.00
GDP [b]	-1.23	-1.04	-0.63	-0.29	-0.05
Welfare [b]	0.46	-0.14	-0.34	0.04	0.18

Note: Each column represents the additional deviations (from the initial steady-state in the Benchmark) experienced in a given year in an economy implementing Carbon Tax + Optimal SCR compared to an economy implementing Carbon Tax only. (a) Corresponds to percentage changes. (b) Corresponds to absolute differences. All numbers are in percentage points.

[53] Appendix C.6 provides complementary figures with the evolution of energy, financial, and real variables during the carbon transition.

ment; however, in the following years, the benefits of capital requirements become tangible through lower bank failure rates, higher credit towards the low-carbon energy sector, and overall welfare gains in the long run.

6 Concluding Remarks

Achieving net zero carbon emission targets in the following years will likely require fast and intense climate policy interventions. In this context, central banks and prudential regulators might become key players in ensuring the stability of the financial system while not hindering a transition towards a greener economy. By analyzing the interactions between climate policy, energy price risks, financial frictions, and bank capital regulation within our model, we provide valuable insights for adapting the current macroprudential policy toolkit to address climate-related financial risks.

We build a DSGE model with two distinct features: an energy sector subject to climate policy and a financial sector with banks and non-banks intermediating sectoral capital. Importantly, through the energy price risk channel, climate policy affecting energy prices directly impacts banks' performance and, therefore, financial stability. By simulating the introduction of a carbon tax aligned with European carbon emission reduction targets, we find complementarities between climate policy and macroprudential policy. In particular, increasing capital requirements (asymmetrically) in proportion to the risk borne by a bank's exposures to energy price risks enhances financial stability by reducing bank failure rates and indirectly supporting a green credit transition.

Our analysis underscores that bank capital requirements, on their own, are not an ideal tool to promote a transition to a green economy. Instead, by focusing on maintaining a resilient banking system, they indirectly support carbon policies through their complementary effects on credit markets. These complementarities highlight the importance of coordination between fiscal and macroprudential authorities to optimally lessen welfare costs along the transition to a greener economy —a relevant insight for policy design.

Despite its tractability, our model has some limitations. By not including a climate externality, our results compare to a benchmark where no climate action is taken, and there are no costs from climate change. In that sense, our results can be interpreted as a lower bound for the potential complementarities between climate and macroprudential policies. Our analysis also highlights the need for further research on the energy price risk channel; further empirical estimates of the elasticity of banks' portfolio returns to energy prices, particularly across different EU economies, can help to better inform capital-based macroprudential decisions —which are set a national level.

References

Aboumahboub, Tino, Cornelia Auer, Nico Bauer, Lavinia Baumstark, Christoph Bertram, Stephen Bi, Jan Dietrich, Alois Dirnaichner, Anastasis Giannousakis, Markus Haller, Jerome Hilaire, David Klein, Johannes Koch, Alexander Körner, Elmar Kriegler, Marian Leimbach, Antoine Levesque, Alexander Lorenz, Gunnar Luderer, ... Falko Ueckerdt.(2020). *REMIND - REgional Model of INvestments and Development.* Version 2.1.0. https://www.pik-potsdam.de/en/institute/departments/transformation-pathways/models/remind

Acemoglu, Daron, Philippe Aghion, Leonardo Bursztyn and David Hemous. (2012). "The Environmentand Directed Technical Change". *American Economic Review,* 102(1), pp. 131-166. https://doi.org/10.1257/aer.102.1.131

Aguilar, Pablo, Stephan Fahr, Eddie Gerba and Samuel Hurtado. (2019). "Quest for robust optimal macroprudential policy". Documentos de Trabajo, 1916, Banco de España. https://repositorio.bde.es/handle/123456789/9802

Aguilar, Pablo, Beatriz González and Samuel Hurtado. (2023). "Green policies and transition risk propagation in production networks". *Economic Modelling,* 126, p. 106412. https://doi.org/10.1016/j.econmod.2023.106412

Airaudo, Florencia S., Evi Pappa and Hernan D. Seoane. (2023). "The Green Metamorphosis of a Small Open Economy". CEPR Discussion Paper, 17863, Centre for Economic Policy Research. https://cepr.org/publications/dp17863

Annicchiarico, Barbara, Stefano Carattini, Carolyn Fischerand Garth Heutel. (2021). "Business Cycles and Environmental Policy: Literature Review and Policy Implications". NBER Working Paper Series, 29032, National Bureau of Economic Research. https://doi.org/10.3386/w29032

Annicchiarico, Barbara, and Fabio Di Dio. (2015). "Environmental policy and macroeconomic dynamics in a new Keynesian model". *Journal of Environmental Economics and Management,* 69, pp. 1-21. https://doi.org/10.1016/j.jeem.2014.10.002

Bahaj, Saleem, and Frederic Malherbe. (2020). "The Forced Safety Effect: How Higher Capital Requirements Can Increase Bank Lending". *The Journal of Finance,* 75(6), pp. 3013-3053. https://doi.org/10.1111/jofi.12958

Baldwin, Elizabeth, Yongyang Cai and Karlygash Kuralbayeva. (2020). "To build or not to build? Capital stocks and climatepolicy". *Journal of Environmental Economics and Management,* 100, p. 102235. https://doi.org/10.1016/j.jeem.2019.05.001

Behn, Markus, Elena Rancoita and Costanza Rodriguez d'Acri. (2020). "Macroprudential capital buffers - objectives and usability". *Macroprudential Bulletin - European Central Bank,* 11. https://www.ecb.europa.eu/pub/financial-stability/macroprudential-bulletin/html/ecb.mpbu202010_1~01c4f1a5f4.en.html

Benmir, Ghassane, and Josselin Roman. (2020). "Policy Interaction and the Transition To Clean Technology". Centre for Climate Change Economics and Policy Working Paper, 368, London School of Economics and Political Science. https://www.lse.ac.uk/granthaminstitute/wp-content/uploads/2020/04/working-paper-337-Benmir-Roman-Jul21.pdf

Bernanke, Ben S., Mark Gertler and Simon Gilchrist. (1999). "The financial accelerator in a quantitative business cycle framework". In *Hand book of Macroeconomics.* Elsevier, Vol. 1 pp. 1341-1393. https://doi.org/10.1016/S1574-0048(99)10034-X

Bhattacharya, Sudipto, Arnoud W. A. Boot and Anjan V. Thakor. (1998). "The Economics of Bank Regulation". *Journal of Money, Credit and Banking,* 30(4), p. 745. https://doi.org/10.2307/2601127

Blickle, Kristian, Cecilia Parlatore and Anthony Saunders. (2023). "Specialization in Banking". NBER Working Paper Series, 31077, National Bureau of Economic Research. https://doi.org/10.3386/w31077

Böser, Florian, and Chiara Colesanti Senni. (2021). "CAROs: Climate Risk-Adjusted Refinancing Operations". *SSRN Electronic Journal.* https://doi.org/10.2139/ssrn.3985230

Buchner, Barbara, Baysa Naran, Rajashree Padmanabhi, Sean Stout, Constanza Strinati, Dharshan Wignarajah, Gaoyi Miao, Jake Conolly and Nikita Marini. (2023). *Global Landscape of Climate Finance.* Climate Policy Institute. https://www.climatepolicyinitiative.org/wp-content/uploads/2023/11/Global-Landscape-of-Climate-Finance-2023.pdf

Campiglio, Emanuele. (2016). "Beyond carbon pricing: The role of banking and monetary policy in financing the transition to a low-carbon economy". *Ecological Economics,* 121, pp. 220-230. https://doi.org/10.1016/j.ecolecon.2015.03.020

Carattini, Stefano, Garth Heutel and Givi Melkadze. (2023). "Climate policy, financial frictions, and transition risk". *Review of Economic Dynamics,* 51, pp. 778-794. https://doi.org/10.1016/j.red.2023.08.003

Carney, Mark. (2015). *Breaking the Tragedy of the Horizon - climate change and financial stability.*

Clerc, Laurent, Alexis Derviz, Caterina Mendicino, Stephane Moyen, Kalin Nikolov, Livio Stracca, Javier Suarez and Alexandros P. Vardoulakish. (2015). "Capital regulation in a macroeconomic model with three layers of default". *International Journal of Central Banking,* June 2015, p. 55. https://www.ijcb.org/journal/ijcb15q3a1.htm

Coelho, Rodrigo, and Fernando Restoy. (2023). "Macroprudential policies for addressing climate-related financial risks: challenges and trade-offs". FSI Briefs, 18, Financial Stability Board. https://www.bis.org/fsi/fsibriefs18.pdf

Coenen, Günter, Romanos Priftis and Matija Lozej. (2023). "Macroeconomic Effects of Carbon Transition Policies: An Assessment Based on the Ecb's New Area-Wide Model with a Disaggregated Energy Sector". *SSRN Electronic Journal.* https://doi.org/10.2139/ssrn.4451815

Dafermos, Yannis, Maria Nikolaidi and Giorgos Galanis. (2018). "Climate Change, Financial Stability and Monetary Policy". *Ecological Economics,* 152, pp. 219-234. https://doi.org/10.1016/j.ecolecon.2018.05.011

Dankert, Jacob, Lars van Doorn, Henk Jan Reinders and Olaf Sleijpen. (2018). "A Green Supporting Factor – The Right Policy?". SUERF Policy Note, 43, SUERF. https://www.suerf.org/publications/suerf-policy-notes-and-briefs/a-green-supporting-factor-the-right-policy/

Daumas, Louis. (2023). "Financial stability, stranded assets and the low-carbon transition – A critical review of the theoretical and applied literatures". *Journal of Economic Surveys*, p. 12551. https://doi.org/10.1111/joes.12551

Demirgüç-Kunt, Asli, Edward Kane and Luc Laeven. (2015). "Deposit insurance around the world: A comprehensive analysis and database". *Journal of Financial Stability*, 20, pp. 155-183. https://doi.org/10.1016/j.jfs.2015.08.005

Diluiso, Francesca, Barbara Annicchiarico, Matthias Kalkuhl and Jan C. Minx. (2021). "Climate actions and macro-financial stability: The role of central banks". *Journal of Environmental Economics and Management*, 110, p. 102548. https://doi.org/10.1016/j.jeem.2021.102548

European Central Bank. (2022). *2022 Climate Risk Stress Test*. https://data.europa.eu/doi/10.2866/97350

European Central Bank. (2023). "The macroeconomic implications of the transition to alow-carbon economy". *Economic Bulletin*, 5. https://www.ecb.europa.eu/pub/pdf/ecbu/eb202305.en.pdf

European Commission. (2018a). *High-Level Expert Group on sustainable finance*. https://finance.ec.europa.eu/publications/high-level-expert-group-sustainable-finance-hleg_en

European Commission. (2018b). *Sustainable finance: Commission's Action Plan for a greener and cleaner economy*. https://ec.europa.eu/commission/presscorner/detail/en/IP_18_1404

European Commission. (2020). *Energy prices and costs in Europe*. https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1602774170631&uri=CELEX:52020DC0951

European Commission. (2023). *2030 Climate Target Plan*. https://climate.ec.europa.eu/eu-action/european-green-deal/2030-climate-target-plan_en

European Securities and Markets Authority. (2023). *The European sustainable debt market: do issuers benefit from an ESG pricing effect?* https://data.europa.eu/doi/10.2856/468709

European Systemic Risk Board. (2023). *Towards macroprudential frameworks for managing climate risk*. https://www.esrb.europa.eu/pub/pdf/reports/esrb.report202312~d7881028b8.en.pdf?bc89d982ac0f87466507bbe82686f64a

Fagan, Gabriel, Jérôme Henry and Ricardo Mestre. (2005). "An area-wide model for the euro area". *Economic Modelling*, 22(1), pp. 39-59. https://doi.org/10.1016/j.econmod.2004.04.002

Financial Stability Board. (2022). *Supervisory and Regulatory Approaches to Climate-related Risks: Final report*. https://www.fsb.org/wp-content/uploads/P131022-1.pdf

Gertler, Mark, and Nobuhiro Kiyotaki. (2010). "Financial Intermediation and Credit Policy in Business Cycle Analysis". In *Handbook of Monetary Economics*. Elsevier, Vol. 3, pp. 547-599. https://doi.org/10.1016/B978-0-444-53238-1.00011-9

Giglio, Stefano, Bryan Kelly and Johannes Stroebel. (2021). "Climate Finance". *Annual Review of Financial Economics*, 13(1), pp. 15-36. https://doi.org/10.1146/annurev-financial-102620-103311

Golosov, Mikhail, John Hassler, Per Krussell and Aleh Tsyvinski. (2014). "Optimal Taxes on Fossil Fuel in General Equilibrium". *Econometrica,* 82(1), pp. 41-88. https://doi.org/10.3982/ECTA10217

Hall, Bronwyn H., and Josh Lerner. (2010). "The Financing of R&D and Innovation". In *Handbook of the Economics of Innovation,* Elsevier, Vol. 1, pp. 609-639. https://doi.org/10.1016/S0169-7218(10)01014-2

Hiebert, Paul, and Pierre Monnin. (2023). *Climate-related systemic risks and macroprudential policy.* Policy Briefing, 14, Grantham Research Institute on Climate Change and the Environment. https://www.lse.ac.uk/granthaminstitute/publication/climate-related-systemic-risks-and-macroprudential-policy/

International Energy Agency. (2023). *Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach.* https://www.iea.org/reports/net-zero-roadmap-a-global-pathway-to-keep-the-15-0c-goal-in-reach

Jo, Ara, and Alena Miftakhova. (2022). "How Constantis Constant Elasticity of Substitution? Endogenous Substitution between Clean and Dirty Energy". *SSRN Electronic Journal.* https://doi.org/10.2139/ssrn.4243349

Känzig, Diego. (2023). "The Unequal Economic Consequences of Carbon Pricing". NBER Working Paper Series, 31221, National Bureau of Economic Research. https://doi.org/10.3386/w31221

Kareken, John H., and Neil Wallace. (1978). "Deposit Insurance and Bank Regulation: A Partial-Equilibrium Exposition". *The Journal of Business,* 51(3), pp. 413-438. http://www.jstor.org/stable/2352275

Laeven, Luc, and Alexander Popov. (2023). "Carbon taxes and the geography of fossil lending". *Journal of International Economics,* 144, p. 103797. https://doi.org/10.1016/j.jinteco.2023.103797

Lee, Chi-Chuan, and Chien-Chiang Lee. (2019). "Oil price shocks and Chinese banking performance: Do country risks matter?". *Energy Economics,* 77, pp. 46-53. https://doi.org/10.1016/j.eneco.2018.01.010

Mattauch, Linus, Felix Creutzig and Ottmar Edenhofer. (2015). "Avoiding carbon lock-in: Policy options for advancing structural change". *Economic Modelling,* 50, pp. 49-63. https://doi.org/10.1016/j.econmod.2015.06.002

Mendicino, Caterina, Kalin Nikolov, Javier Suarez and Dominik Supera. (2018). "Optimal Dynamic Capital Requirements". *Journal of Money, Credit and Banking,* 50(6), pp. 1271-1297. https://doi.org/10.1111/jmcb.12490

Mendicino, Caterina, Kalin Nikolov, Javier Suarez and Dominik Supera. (2020). "Bank capital in the short and in the long run". *Journal of Monetary Economics,* 115, pp. 64-79. https://doi.org/10.1016/j.jmoneco.2019.06.006

Miguel, Faruk, Alvaro Pedraza and Claudia Ruiz-Ortega. (2024). "Climate-change regulations: Bank lending and real effects". *Journal of Financial Stability,* 70, p. 101212. https://doi.org/10.1016/j.jfs.2023.101212

Monasterolo, Irene. (2020). "Climate Change and the Financial System". *Annual Review of Resource Economics*, 12(1), pp. 299-320. https://doi.org/10.1146/annurev-resource-110119-031134

Monnin, Pierre. (2021). "Systemic Risk Buffers - The missing piece in the prudential response to climate risks". CEP Policy Brief, Council on Economic Policies. https://www.cepweb.org/systemic-risk-buffers-the-missing-piece-in-the-prudential

Nasim, Asma, and Gareth Downing. (2023). "Energy shocks and bank performance in the advanced economies". *Energy Economics*, 118, p. 106517. https://doi.org/10.1016/j.eneco.2023.106517

Nasim, Asma, Subhan Ullah, Ja Ryong Kim and Affan Hameed. (2023). "Energy shocks and bank efficiency in emerging economies". *Energy Economics*, 126, p. 107005. https://doi.org/10.1016/j.eneco.2023.107005

Neagu, Florian, Luminita Tatarici, Florin Dragu and Amalia Stamate. (2024). "Are green loans less risky? Micro-evidence from a European Emerging Economy". *Journal of Financial Stability*, 70, p. 101208. https://doi.org/10.1016/j.jfs.2023.101208

Network for Greening the Financial System. (2021). *Climate Scenarios for central banks and supervisors.* https://www.ngfs.net/en/ngfs-climate-scenarios-phase-iv-november-2023

Nordhaus, William D. (2017). *A Question of Balance: Weighing the Options on Global Warming Policies.* Yale University Press. https://doi.org/10.12987/9780300165982

Oehmke, Martin, and Marcus M. Opp. (2022). "Green Capital Requirements". *SSRN Electronic Journal.* https://doi.org/10.2139/ssrn.4040098

Papageorgiou, Chris, Marianne Saam and Patrick Schulte. (2017). "Substitution between Clean and Dirty Energy Inputs: A Macroeconomic Perspective". *The Review of Economics and Statistics*, 99(2), pp. 281-290. https://doi.org/10.1162/REST_a_00592

Peersman, Gert, and Ine Van Robays. (2009). "Oil and the Euro area economy". *Economic Policy*, 24(60), pp. 603-651. https://doi.org/10.1111/j.1468-0327.2009.00233.x

Peersman, Gert, and Ine Van Robays. (2012). "Cross-country differences in the effects of oil shocks". *Energy Economics*, 34(5), pp. 1532-1547. https://doi.org/10.1016/j.eneco.2011.11.010

Repullo, Rafael, and Javier Suarez. (2004). "Loan pricing under Basel capital requirements". *Journal of Financial Intermediation*, 13(4), pp. 496-521. https://doi.org/10.1016/j.jfi.2004.07.001

Ueda, Masako. (2004). "Banks versus Venture Capital: Project Evaluation, Screening, and Expropriation". *The Journal of Finance*, 59(2), pp. 601-621. https://doi.org/10.1111/j.1540-6261.2004.00643.x

Varga, Janos, Werner Roeger and Jan in 't Veld. (2022). "E-QUEST: A multisector dynamic general equilibrium model with energy and a model-based assessment to reach the EU climate targets". *Economic Modelling*, 114, p. 105911. https://doi.org/10.1016/j.econmod.2022.105911

Appendix

A Analytical Appendix

A.1 Capital Producing Firms

At the end of each period, competitive capital producers in each sector $j \in \{Y, L, F\}$ buy capital from intermediate goods producing firms, repair capital depreciated at rate δ_j, and build new one. Once production is done they sell everything. Therefore, capital evolves according to

$$K_{j,t+1} = I_{j,t} + (1 - \delta_j)K_{j,t} \tag{A.1}$$

Capital producers face quadratic investment adjustment costs[54], with parameter ϱ_j, when producing new capital. They solve the following profit maximization problem:

$$\max_{I_{j,t}} \mathbb{E}_t \sum_{t=0}^{\infty} \beta^t \Lambda_{t+1} \left\{ Q_{j,t} I_{j,t} - \left[1 + \frac{\varrho_j}{2} \left(\frac{I_{j,t}}{I_{j,t-1}} - 1 \right)^2 \right] I_{j,t} \right\}, \tag{A.2}$$

where, as previously introduced, $Q_{j,t}$ is the value of a unit of new capital.

A.2 Capital Management Firms

There is a measure-one continuum of firms managing households direct capital investments $S^H_{j,t}$ at a fee $z_{j,t}$. These firms face a quadratic cost function with parameter ζ_j.[55] Under perfect competition, maximizing profits implies the following equilibrium fees for each unit of capital managed

$$z_{j,t} = \zeta_j S^H_{j,t} \quad j \in \{Y, L, F\} \tag{A.3}$$

A.3 Market Clearing

Market equilibrium is achieved when the bond market, capital market, loan market, deposit market, and goods markets clear. A detail account of these conditions can be found in Appendix A.5.

Finally, the resource constraint of the economy is given by the sum of private consumption, public consumption, and private investments net of capital adjustments, capital management and bank failure costs:

$$\widetilde{Y}_t = C_t + G_t + \sum_j I_{j,t} + \sum_j \frac{\gamma_j}{2} \left(\frac{I_{j,t}}{I_{j,t-1}} - 1 \right)^2 I_{j,t} \tag{A.4}$$

[54] Notice that outside the steady state $Q_{j,t} > 1$ due to the adjustment costs. This generates endogenous variation in asset prices due to aggregate shocks.

[55] These costs may reflect marginally increasing screening costs or other costs of expanding their portfolios, such as competing more fiercely to attract clients.

$$+\sum_j \frac{\zeta_j}{2}(S^H_{j,t})^2 + \sum_j \mu G_{j,t}(\overline{\omega}_{j,t}) R_{j,t} Q_{j,t-1} S^B_{j,t-1}$$

A.4 Bank's Asset Return Risk

Following Bernanke et al. (1999) we assume that idiosyncratic shocks to banks' portfolio returns are log-normally distributed:

$$\omega_{j,t} \sim \log \mathcal{N}(-\frac{\widetilde{\sigma}^2_{j,t}}{2}, \widetilde{\sigma}^2_{j,t}), \quad j \in \{Y, F, L\}\,. \tag{A.5}$$

with CDF and PDF denoted as F_j and f_j, respectively, with mean $E[\omega_{j,t}] = 1$ and standard deviation $\tilde{\sigma}_{j,t}$ given by (25).

We define some useful objects; first, the gross share of the bank's assets that goes to the bankers $\Gamma_{j,t+1}(\bar{\omega}_{j,t+1})$ after taking into account banks' failures:

$$\Gamma_j(\overline{\omega}_{j,t}) = \int_0^{\overline{\omega}_{j,t}} \omega dF_j(\omega) + \overline{\omega}_{j,t} \int_{\overline{\omega}_{j,t}}^{\infty} dF_j(\omega) \tag{A.6}$$

$$= \Phi\left(\frac{log(\overline{\omega}_{j,t}) - \frac{\widetilde{\sigma}^2_{j,t}}{2}}{\widetilde{\sigma}_{j,t}}\right) + \overline{\omega}_{j,t}\left[1 - \Phi\left(\frac{log(\overline{\omega}_{j,t}) + \frac{\widetilde{\sigma}^2_{j,t}}{2}}{\widetilde{\sigma}_{j,t}}\right)\right] \tag{A.7}$$

and

$$G_j(\overline{\omega}_{j,t}) = \int_0^{\overline{\omega}_{j,t}} \omega dF_j(\omega) = \Phi\left(\frac{log(\overline{\omega}_{j,t}) - \frac{\widetilde{\sigma}^2_{j,t}}{2}}{\widetilde{\sigma}_{j,t}}\right) \tag{A.8}$$

where Φ is the CDF of the standard normal distribution $\mathcal{N}(0,1)$.

The expected share of assets belonging to banks is $\mathbb{E}[\max\{\omega_{j,t+1} - \bar{\omega}_{j,t+1}, 0\}] = 1 - \Gamma_{j,t+1}(\bar{\omega}_{j,t+1})$. This last object is useful to rewrite (19) as:

$$\begin{aligned}
&\max\left[\omega_{j,t+1} - \overline{\omega}_{j,t+1}, 0\right] R_{j,t+1}\frac{NW_{j,t}}{\phi_{j,t}} \\
=&\left[\int_{\overline{\omega}_{j,t+1}}^{\infty} \omega_{j,t+1} f_j\left(\omega_{j,t+1}\right) d\omega_{j,t+1} - \overline{\omega}_{j,t+1}\int_{\overline{\omega}_{j,t+1}}^{\infty} f_j\left(\omega_{j,t+1}\right) d\omega_{j,t+1}\right] \\
&\times R_{j,t+1}\frac{NW_{j,t}}{\phi_{j,t}}.
\end{aligned}$$

Then, using the definitions in (A.6) and (A.8) leads to (23). Bankers' return on equity can be expressed as a function of the return on the asset and the regulatory capital requirement net of expected default losses:

$$\rho_{j,t+1} = \left[1 - \Gamma_{j,t+1}\left(\overline{\omega}_{j,t+1}\right)\right]\frac{R_{j,t+1}}{\phi_{j,t}} \tag{A.9}$$

Also, given that bank failures entail liquidations and repossession costs μ, the net share of assets that accrues to bankers is $\Gamma_{j,t+1}(\bar{\omega}_{j,t+1}) - \mu_j G_{j,t+1}(\bar{\omega}_{j,t+1})$. On the fiscal side, net losses for the deposit insurance scheme in each banking sector are:

$$\Omega_{j,t} = [\overline{\omega}_{j,t} - \Gamma_{j,t}(\overline{\omega}_{j,t}) + \mu_j G_{j,t}(\overline{\omega}_{j,t})]\frac{R_{j,t}}{1-\phi_{j,t}}, \quad j \in \{Y, L, F\}.$$

Finally, the aggregate losses to depositors across all bank classes amount to:

$$\Omega_t = \sum_j \frac{D_{j,t-1}}{D_{t-1}}\Omega_{j,t}.$$

A.5 Model Equations

Households.

$$\begin{aligned} &C_t + B_t + D_t + \sum_j (Q_{j,t} + z_{j,t})S^H_{j,t} \\ &= W_t L_t + R_{t-1}B_{t-1} + \widetilde{R}^D_t D_{t-1} + \sum_j R_{j,t}S^H_{j,t-1} - T_t + \Pi_t \end{aligned} \tag{A.10}$$

$$C_t^{-\varsigma} = \lambda_t, \tag{A.11}$$

$$\eta L_t^{\nu} = \lambda_t W_t, \tag{A.12}$$

$$\mathbb{E}_t\left[\Lambda_{t+1}R_{t+1}\right] = 1 \tag{A.13}$$

$$\mathbb{E}_t\left[\Lambda_{t+1}\widetilde{R}^D_{t+1}\right] = 1 \tag{A.14}$$

$$\mathbb{E}_t\left[\Lambda_{t+1}\frac{Q_{j,t}}{Q_{j,t}+z_{j,t}}R_{j,t+1}\right] = 1, \quad j \in \{Y, L, F\} \tag{A.15}$$

$$\Lambda_{t+1} = \beta\frac{\lambda_{t+1}}{\lambda_t} \tag{A.16}$$

$$\widetilde{R}^D_t = R^D_{t-1} - (1-\kappa)\Omega_t \tag{A.17}$$

$$\Pi_t = \Pi^X_t + \Pi^B_t + \Pi^K_t + \Pi^H_t \tag{A.18}$$

Final goods producers.

$$\widetilde{Y}_t = \left[(1-\alpha_E)^{1/\varphi_Y} Y_t^{\frac{(\varphi_Y-1)}{\varphi_Y}} + \alpha_E^{1/\varphi_Y} E_t^{\frac{(\varphi_Y-1)}{\varphi_Y}}\right]^{\frac{\varphi_Y}{(\varphi_Y-1)}} \tag{A.19}$$

$$Y_t = A_Y\left(K_{Y,t}\right)^{\alpha_Y}\left(L_t\right)^{1-\alpha_Y} \tag{A.20}$$

$$E_t = \left[(1-\alpha_F)^{1/\varphi_E} E_{L,t}^{\frac{(\varphi_E-1)}{\varphi_E}} + \alpha_F^{1/\varphi_E} E_{F,t}^{\frac{(\varphi_E-1)}{\varphi_E}}\right]^{\frac{\varphi_E}{(\varphi_E-1)}} \tag{A.21}$$

$$W_t = \widetilde{Y}_t^{\frac{1}{\varphi_Y}}(1-\alpha_E)^{\frac{1}{\varphi_Y}} Y_t^{\frac{(\varphi_Y-1)}{\varphi_Y}}(1-\alpha_Y)\frac{1}{L_t} \tag{A.22}$$

$$E_t = \alpha_E \left(\frac{P_{E_Y,t}}{P_t} \right)^{-\varphi_Y} Y_t \tag{A.23}$$

$$E_{L,t} = (1-\alpha_F) \left(\frac{P_{E_L,t}}{P_{E_Y,t}} \right)^{-\varphi_E} \tag{A.24}$$

$$E_{F,t} = \alpha_F \left(\frac{P_{E_F,t}}{P_{E_Y,t}} \right)^{-\varphi_E} \tag{A.25}$$

$$R_{Y,t+1} = \frac{(Q_{Y,t+1} - \delta_Y) + \frac{W_t L_t \frac{\alpha_Y}{1-\alpha_Y}}{K_{Y,t+1}}}{Q_{Y,t}} \tag{A.26}$$

Energy producers.

$$E_{L,t} = A_L K_{L,t} \tag{A.27}$$

$$R_{L,t+1} = \frac{(Q_{L,t+1} - \delta_L) + \frac{P_{E_{L,t+1}}}{P_{t+1}} \frac{E_{L,t+1}}{K_{L,t+1}}}{Q_{L,t}} \tag{A.28}$$

$$E_{F,t} = \left[(1-\alpha_X)^{1/\varphi_F} (A_F K_{F,t})^{\frac{(\varphi_F - 1)}{\varphi_F}} + \alpha_X^{1/\varphi_F} X_{F,t}^{\frac{(\varphi_F - 1)}{\varphi_F}} \right]^{\frac{\varphi_F}{(\varphi_F - 1)}} \tag{A.29}$$

$$R_{F,t+1} = \frac{(Q_{F,t+1} - \delta_F) + \frac{P_{E_F,t+1}}{P_{t+1}} \frac{E_{F,t+1}^{1/\varphi_F} \alpha_X^{1/\varphi_F} (A_F K_{F,t})^{(\varphi_F - 1)/\varphi_F}}{K_{F,t+1}}}{Q_{F,t}} \tag{A.30}$$

$$P_{X,t} + \tau_{X,t} = \frac{P_{E_F,t}}{P_t} E_{F,t}^{1/\varphi_F} \alpha_X^{1/\varphi_F} X_{F,t}^{-1/\varphi_F} \tag{A.31}$$

$$\Pi_t^X = P_{X,t} X_{F,t} \tag{A.32}$$

Bankers.

$$V_t = v_t NW_t \tag{A.33}$$

$$\Lambda_{t+1}^B = \Lambda_{t+1} \left[(1-\theta) + \theta v_{t+1} \right] \tag{A.34}$$

$$\mathbb{E}_t \left[\Lambda_{t+1}^B \rho_{Y,t+1} \right] = \mathbb{E}_t \left[\Lambda_{t+1}^B \rho_{F,t+1} \right] = v_t \tag{A.35}$$

$$\mathbb{E}_t \left[\Lambda_{t+1}^B \rho_{F,t+1} \right] = \mathbb{E}_t \left[\Lambda_{t+1}^B \rho_{L,t+1} \right] = v_t \tag{A.36}$$

$$NW_{t+1} = \theta \left(\sum_j \rho_{j,t+1} NW_{j,t} \right) + \iota_t \tag{A.37}$$

$$\iota_t = \chi (1-\theta) \left(\sum_j \rho_{j,t+1} NW_{j,t} \right) \tag{A.38}$$

$$\Pi_t^B = (1-\chi)(1-\theta)\left(\sum_j \rho_{j,t+1} NW_{j,t}\right) \tag{A.39}$$

Banks.

$$Q_{j,t} S_{j,t}^B = NW_{j,t} + D_{j,t}, \quad j \in \{Y, L, F\} \tag{A.40}$$

$$\phi_{j,t} = \frac{NW_{j,t}}{Q_{j,t} S_{j,t}^B}, \quad j \in \{Y, L, F\} \tag{A.41}$$

$$\overline{\omega}_{j,t+1} = (1-\phi_{j,t}) \frac{R_t^D}{R_{j,t+1}}, \quad j \in \{Y, L, F\} \tag{A.42}$$

$$\rho_{j,t+1} = \left[1 - \Gamma_{j,t+1}\left(\overline{\omega}_{j,t+1}\right)\right] \frac{R_{j,t+1}}{\phi_{j,t}}, \quad j \in \{Y, L, F\} \tag{A.43}$$

$$\begin{aligned} \Gamma_j(\overline{\omega}_{j,t}) &= \int_0^{\overline{\omega}_{j,t}} \omega dF_j(\omega) + \overline{\omega}_{j,t} \int_{\overline{\omega}_{j,t}}^{\infty} dF_j(\omega) \\ &= \Phi\left(\frac{log(\overline{\omega}_{j,t}) - \frac{\widetilde{\sigma}_{j,t}^2}{2}}{\widetilde{\sigma}_{j,t}}\right) + \overline{\omega}_{j,t}\left[1 - \Phi\left(\frac{log(\overline{\omega}_{j,t}) + \frac{\widetilde{\sigma}_{j,t}^2}{2}}{\widetilde{\sigma}_{j,t}}\right)\right], \quad j \in \{Y, F, L\} \end{aligned} \tag{A.44}$$

$$G_j(\overline{\omega}_{j,t}) = \int_0^{\overline{\omega}_{j,t}} \omega dF_j(\omega) = \Phi\left(\frac{log(\overline{\omega}_{j,t}) - \frac{\widetilde{\sigma}_{j,t}^2}{2}}{\widetilde{\sigma}_{j,t}}\right), \quad j \in \{Y, F, L\} \tag{A.45}$$

$$\widetilde{\sigma}_{j,t} = \sigma_j [P_{E_j,t}]^{\beta_j}, \quad j \in \{Y, F, L\} \tag{A.46}$$

Capital producing firms.

$$\begin{aligned} Q_{j,t} &= 1 + \frac{\varrho_j}{2}\left(\frac{I_{j,t}}{I_{j,t-1}} - 1\right)^2 + \varrho_j\left(\frac{I_{j,t}}{I_{j,t-1}} - 1\right)\frac{I_{j,t}}{I_{j,t-1}} \\ &- \mathbb{E}_t \beta \Lambda_{t+1} \varrho_j \left(\frac{I_{j,t+1}}{I_{j,t}} - 1\right)\left(\frac{I_{j,t+1}}{I_{j,t}}\right)^2, \quad j \in \{Y, L, F\} \end{aligned} \tag{A.47}$$

$$K_{j,t+1} = I_{j,t} + (1-\delta_j) K_{j,t}, \quad j \in \{Y, L, F\} \tag{A.48}$$

$$\Pi_t^K = \sum_j \left\{ Q_{j,t} I_{j,t} - \left[1 + \frac{\varrho_j}{2}\left(\frac{I_{j,t}}{I_{j,t-1}} - 1\right)^2\right] I_{j,t} \right\} \tag{A.49}$$

Capital management firms.

$$\Pi_t^H = \sum_j \left\{ z_{j,t} S_{j,t}^H - \frac{\zeta_j}{2}\left(S_{j,t}^H\right)^2 \right\} \tag{A.50}$$

$$z_{j,t} = \zeta_j S_{j,t}^H, \quad j \in \{Y, L, F\} \tag{A.51}$$

Public sector.

$$\Omega_{j,t} = [\overline{\omega}_{j,t} - \Gamma_{j,t}(\overline{\omega}_{j,t}) + \mu_j G_{j,t}(\overline{\omega}_{j,t})]\frac{R_{j,t}}{1-\phi_{j,t}}, \quad j \in \{Y, L, F\} \tag{A.52}$$

$$\Omega_t = \sum_j \frac{D_{j,t-1}}{D_{t-1}}\Omega_{j,t} \tag{A.53}$$

$$T_t^{DIS} = \kappa \Omega_t D_{t-1} \tag{A.54}$$

$$B_t + T_t = T_t^{DIS} + G_t - \tau_{X,t} X_t - R_t B_{t-1} \tag{A.55}$$

Market clearing.

$$B_t = 0 \tag{A.56}$$

$$K_{j,t+1} = S_{j,t}^B + S_{j,t}^H, \quad j \in \{Y, L, F\} \tag{A.57}$$

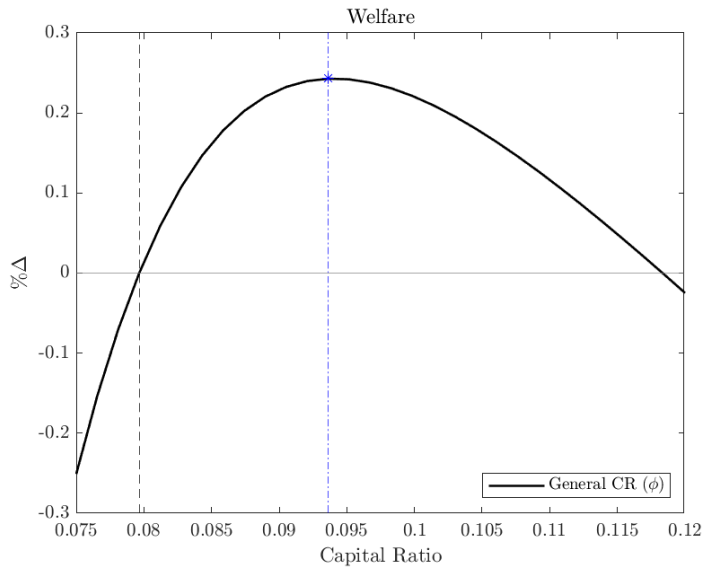
$$D_t = \sum_j D_{j,t} \tag{A.58}$$

$$\begin{aligned} \widetilde{Y}_t &= C_t + G + \sum_j I_{j,t} + \sum_j \frac{\gamma_j}{2}\left(\frac{I_{j,t}}{I_{j,t-1}} - 1\right)^2 I_{j,t} \\ &+ \sum_j \frac{\zeta_j}{2}(K_{j,t}^H)^2 + \sum_j \mu G_{j,t}(\overline{\omega}_{j,t}) R_{j,t} Q_{j,t-1} S_{j,t-1}^B \end{aligned} \tag{A.59}$$

B Quantitative Appendix

B.1 Optimal Capital Requirements in the Benchmark Economy

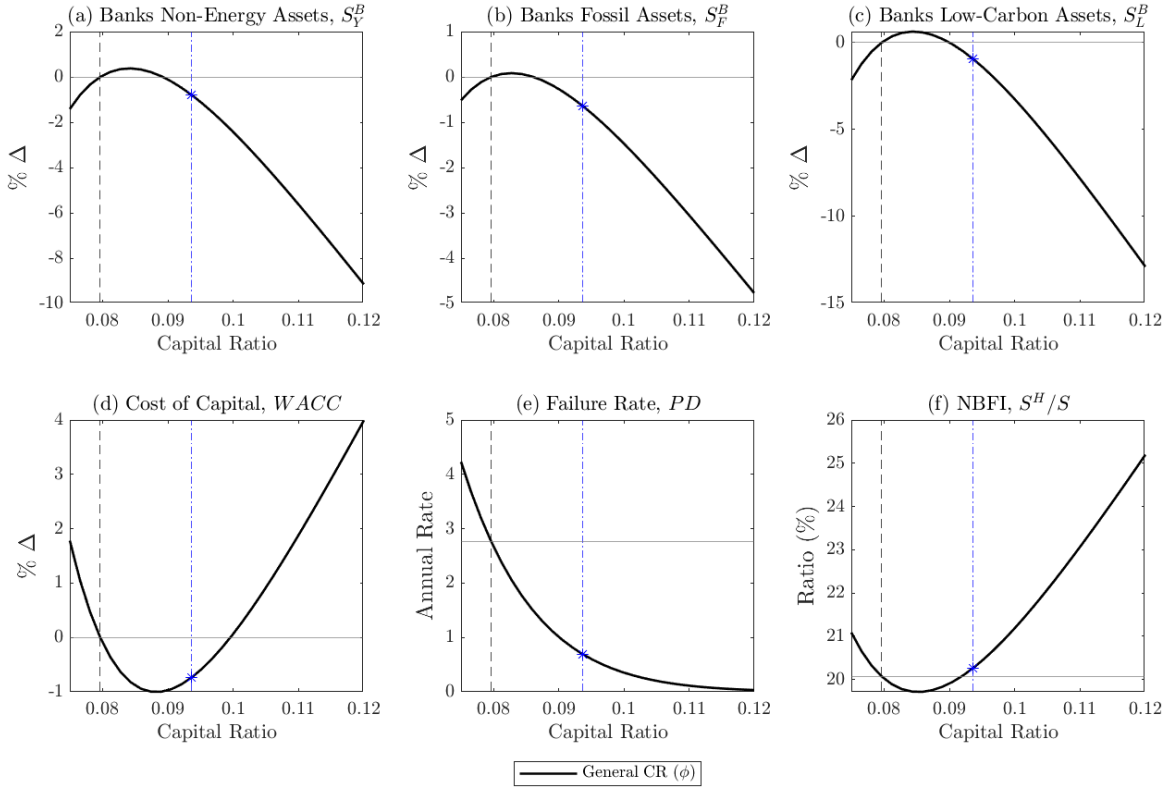
Figure 4: Optimal Capital Requirements: Welfare



The level of capital requirements is the same for all sectors in our benchmark calibration; this resembles the current homogeneous capital requirement applied uniformly to all banks; we label this policy *general* capital requirements. To keep consistency in the calibration, we assume that our banking sectors start with the same level of risk and no return premium between sectors—recall that bankers' non-arbitrage conditions (16) and (17) imply that individual equity returns across banking sectors are equalized. Thus, we start the economy at a *general* capital ratio of 8% (minimum regulatory capital according to Basel III) consistent with bank failure rates of 2.75% and compute the optimal *general* CR by targeting an average bank failure rate of 0.67%, which results in the 9.4%—the number reported for the benchmark calibration.

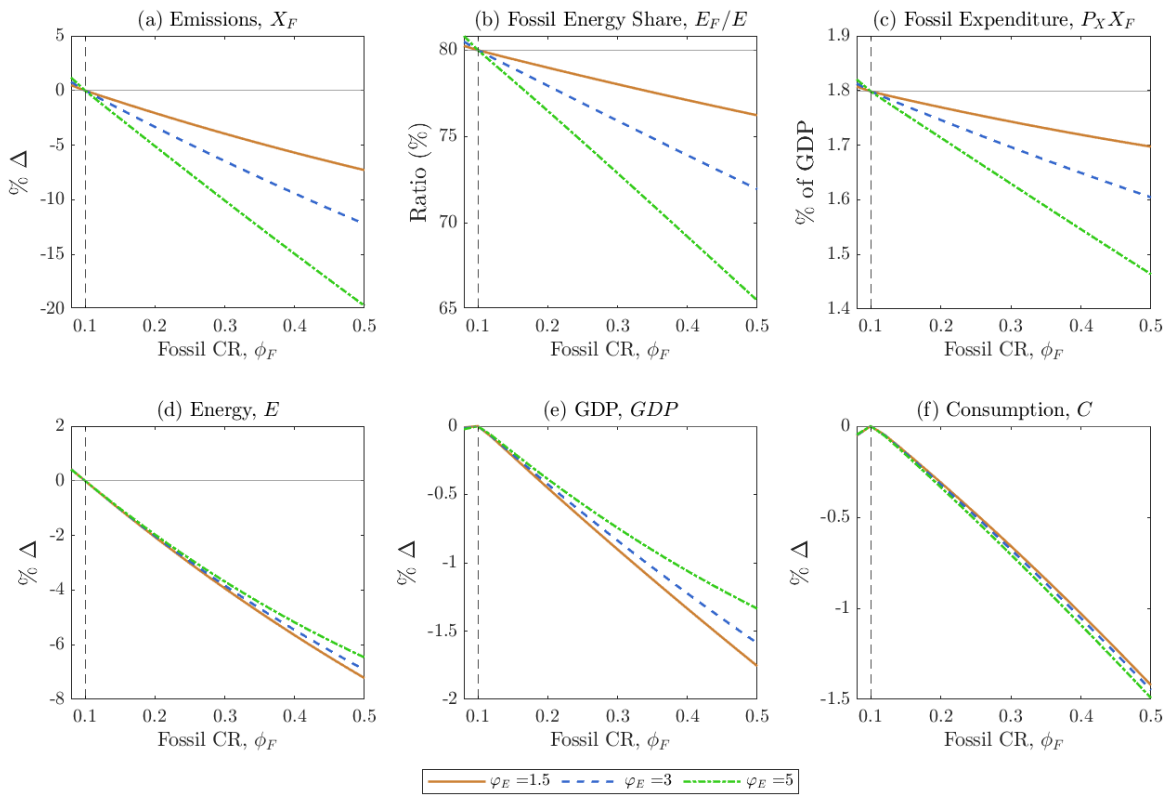
Figure 4 illustrates households' welfare for a sequence of *general* capital requirements, ϕ, in steady state. The blue asterisk represents the benchmark economy with a *general* capital requirement set at 9.4%, which maximizes welfare. Figure 5 shows similar comparative statics for other macroeconomic aggregates. Starting at ϕ equal to 8%, increasing *general* capital requirements to 9.4% leads to a decrease in bank credit, accompanied by a corresponding increase in NBFI. The average bank failure rate in the economy drops from 2.75% to 0.67%. The reduction in the associated costs of bank failure boosts consumption. This rise in consumption, outweighs the slowdown in credit and drives the optimality of general capital requirements.

Figure 5: Optimal Capital Requirements: Financial Sector



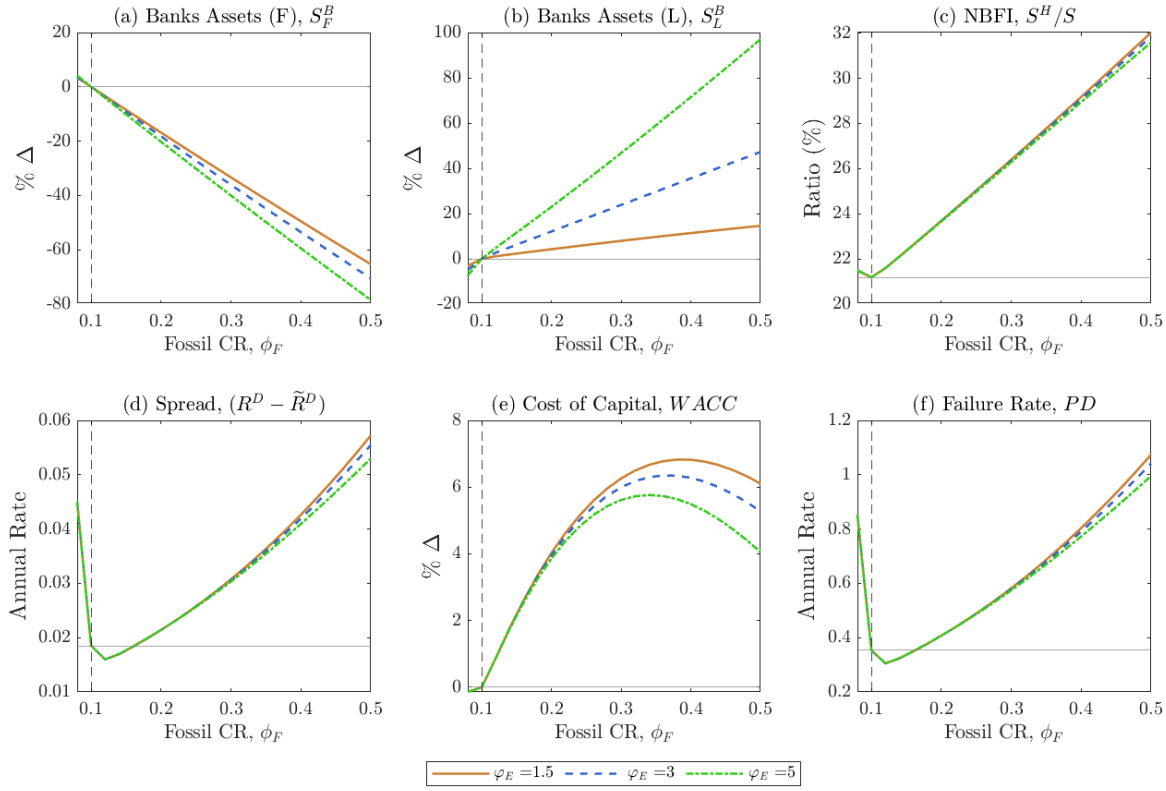
B.2 Capital Requirements as a Climate Policy Tool

Figure 6: Medium-Run Effects of Fossil CR: Real Variables



Note: Each panel shows three dashed lines corresponding to economies with different elasticity of substitution between fossil and low-carbon energy inputs, φ_E. Each line represents an economy's steady-state values for a sequence of capital ratios in the fossil sector, ϕ_F, represented in the x-axis. The dashed vertical line represents the benchmark economy's steady state where $\phi_F = 9.4\%$.

Figure 7: Medium-Run Effects of Fossil CR: Financial Variables



Note: Each panel shows three dashed lines corresponding to economies with different elasticity of substitution between fossil and low-carbon energy inputs, φ_E. Each line represents an economy's steady-state values for a sequence of capital ratios in the fossil sector, ϕ_F, represented in the x-axis. The dashed vertical line represents the benchmark economy's steady state where $\phi_F = 9.4\%$.

C Robustness Exercises

C.1 The energy price risk channel

An important determinant of how climate policies targeting the energy sector affect the financial sector in our model is the intensity of the energy price risk channel. Table 5, the risk pass-through from the real energy sector to the financial sector is captured by β_j. Our benchmark scenario is the middle column ($\beta_j = 1$). As anticipated, the higher the intensity in the pass-through of energy prices to the volatility of banks' net returns ($\beta_j = 1.5$), the stronger the impact in financial stability —measured by bank failure rates and the share of NBFI. This calls for a stronger prudential intervention. The opposite argument follows through for a lower intensity ($\beta_j = 0.5$).

Table 5: Optimal CR under different energy price risk intensity

Intensity		$\beta_j = 0.5$		$\beta_j = 1$		$\beta_j = 1.5$	
	B	CT	CT+SCR	CT	CT+SCR	CT	CT+SCR
Non-Energy CR, ϕ_Y. Δbp.	9.4	-	66	-	142	-	226
Fossil CR, ϕ_F. Δbp.	9.4	-	88	-	172	-	286
Low-Carbon CR, ϕ_L. Δbp.	9.4	-	37	-	29	-	20
Carbon Emissions, $\%\Delta$.	-	-35.4	-35.7	-35.3	-36.0	-35.0	-36.4
Price Fossil Energy, $\%\Delta$.	-	25.4	25.6	25.7	26.0	26.1	26.5
Price Low-Carbon Energy, $\%\Delta$.	-	0.29	0.22	0.87	0.23	1.90	0.24
Price Energy, $\%\Delta$.	-	18.8	19.0	19.2	19.3	19.9	19.6
Fossil Energy, ratio $(\%)$.	80.0	68.1	68.0	68.3	67.8	68.3	67.5
GDP, $\%\Delta$.	-	-1.86	-1.93	-2.12	-2.16	-2.50	-2.41
Welfare, cons. equivalent $\%\Delta$.	-	-1.89	-1.85	-2.17	-1.98	-2.65	-2.13
Fossil Bank Credit, $\%\Delta$.	-	-20.5	-21.6	-21.2	-23.5	-22.1	-25.4
Low-Carbon Bank Credit, $\%\Delta$.	-	69.7	71.1	62.4	72.0	48.9	72.9
NBFI, ratio $(\%)$.	20.3	21.9	22.5	23.9	24.2	27.4	28.6
Bank Failure, annual rate.	0.67	1.44	0.75	2.90	0.86	5.49	1.01

Note: All values are in percentage points. *B* column represent the benchmark economy. *CT* compares the benchmark steady-sate to the new economy with carbon taxes. *CT + SCR* compares the benchmark steady-state to the new economy with carbon taxes and optimal capital requirements. Δbp: denotes differences in basis points with respect to the benchmark economy steady state with ϕ_F equal to 9.4%. $\%\Delta$: represents the percentage change with respect to the benchmark. Ratio $(\%)$: reports the ratio in the new steady state.

C.2 Energy inputs substitutability

The literature has established that the elasticity of substitution between fossil and low-carbon inputs must necessarily be greater than 1 to favor green long-run growth (i.e. long-term growth sustained by low-carbon technologies). Moreover, the larger the degree of substitutability between fossil and low-carbon inputs, the faster the economy can transition to such a structure (Acemoglu et al., 2012). Estimates for this elasticity usually range between 1.5 to 5 depending on the selected sample and the data used, see Papageorgiou et al. (2017); Jo and Miftakhova (2022). Table 6

reports selected steady-state statistics for economies with low, medium, and high elasticity of substitution between fossil and low-carbon energy inputs. To keep consistency with our previous simulations, in each economy, we consider an increase in carbon taxes that delivers a 35% emissions reduction and the optimal level of sectoral capital requirements that maximizes welfare.[56]

Table 6: Optimal Capital Requirements and energy input substitutability

Elasticity of substitution fossil-clean	Low $\varphi_E = 1.5$	Medium $\varphi_E = 3$	High $\varphi_E = 5$
Non-Energy CR, ϕ_Y. Δbp.	190	142	103
Fossil CR, ϕ_F. Δbp.	254	172	119
Low-Carbon CR, ϕ_L. Δbp.	0	29	58
Carbon Emissions, $\%\Delta$.	-35.9	-36.0	-35.9
Price of Fossil Energy, $\%\Delta$.	34.3	26.0	19.2
Price of Low-Carbon Energy, $\%\Delta$.	0.11	0.23	0.35
Price of Energy Bundle, $\%\Delta$.	26.2	19.3	13.9
Fossil Energy, ratio $(\%)$.	72.8	67.8	63.7
GDP, $\%\Delta$.	-3.11	-2.16	-1.40
Fossil Bank Credit, $\%\Delta$.	-19.5	-23.5	-26.7
Low-Carbon Bank Credit, $\%\Delta$.	31.0	72.0	104.5
NBFI, ratio $(\%)$.	25.7	24.2	23.1
Bank Failure, annual rate.	0.94	0.86	0.81

Note: All values are in percentage points. φ_E indicates the elasticity of substitution between fossil and low-carbon energy inputs in each economy. Each column compares the benchmark steady-state to the new economy with carbon taxes achieving a 35% emissions reduction and the level of sectoral capital requirements that maximizes welfare. Δbp: denotes differences in basis points with respect to the benchmark economy steady state with ϕ_F equal to 9.4%. $\%\Delta$: represents the percentage change with respect to the benchmark. Ratio $(\%)$: reports the ratio in the steady of the new economy.

Economies with low substitution capacity between fossil and low-carbon energy inputs require higher carbon taxes to achieve the desired emission reduction target. Higher carbon taxes imply higher energy prices and a stronger contraction of GDP than in an economy with medium fossil-low-carbon substitution capacity —the one presented in section 4.2. The energy price risk channel induces stronger spillovers into the financial sector reflecting on a higher average bank failure rate. As banking intermediation falls in the fossil sector, non-banking financial intermediation grows, reaching one-fourth of the credit in the economy.

Macroprudential policy becomes more forceful, reflecting higher spillovers from the real sector to the banking sector through the energy price risk channel; the optimal sectoral capital requirement increases in the fossil banking sector and in the non-energy banking sector. Despite this, the banking sector settles at a marginally higher average bank failure rate. This pattern arises due to the difficulty of the economy in substituting energy inputs; although the fossil banking sector is disintermediated at a similar rate to other scenarios, credit flows into the low-carbon-

[56] To facilitate comparison across economies, in Table 6, we present the economy with medium elasticity, $\varphi_E = 3$ (benchmark calibration), which is also reported in column (CT+SCR) in Table 2

energy sector at a slower rate. This result is similar to the one obtained by Oehmke and Opp (2022), who find that a combination of additional capital requirements for fossil exposures and relatively lower capital for green sectors might be optimal in certain scenarios.

C.3 Fossil inputs complementarity

Production of fossil energy requires complementarity ($\varphi_F < 1$) between fossil capital and fossil natural resources. In this section, we study how optimal sectoral capital requirements change when this degree of complementarity becomes stronger ($\varphi_F \to 0$) or weaker ($\varphi_F \to 1$). To keep consistency with our previous simulations, in each economy, we consider an increase in carbon taxes that delivers a 35% emissions reduction and the optimal level of sectoral capital requirements that maximizes welfare.[57] Table 7 shows that the main conclusion in section 4 on the use of sectoral capital requirements remains unchanged; implementing carbon taxes pushes energy prices up in every alternative economy. The magnitudes of changes in capital requirements adjust accordingly. Still, the optimal policy stands to increase the capital requirement for fossil energy and non-energy exposures and, to a lesser extent, for the low-carbon energy sector.

Table 7: Optimal Capital Requirements and fossil input complementarity

Complementarity of fossil resources and capital	High $\varphi_F = 0.1$	Medium $\varphi_F = 0.3$	Low $\varphi_F = 0.5$
Non-Energy CR, ϕ_Y. Δbp.	195	142	109
Fossil CR, ϕ_F. Δbp.	298	172	142
Low-Carbon CR, ϕ_L. Δbp.	38	29	22
Carbon Emissions, $\%\Delta$.	-36.8	-36.0	-35.7
Price Fossil Energy, $\%\Delta$.	36.8	26.0	20.2
Price Low-Carbon Energy, $\%\Delta$.	0.30	0.23	0.18
Price Energy, $\%\Delta$.	26.3	19.3	15.3
Fossil Energy, ratio $(\%)$.	62.6	67.8	70.8
GDP, $\%\Delta$.	-3.09	-2.16	-1.57
Fossil Bank Credit, $\%\Delta$.	-36.8	-23.5	-15.0
Low-Carbon Bank Credit, $\%\Delta$.	101	72.0	56.1
NBFI, ratio $(\%)$.	25.9	24.2	23.3
Bank Failure, annual rate.	0.96	0.86	0.81

Note: All values are in percentage points. φ_F indicates the elasticity of substitution between fossil capital and fossil natural resources in each economy. Each column compares the benchmark steady-state to the new economy with carbon taxes achieving a 35% emissions reduction and the level of sectoral capital requirements that maximizes welfare. Δbp: denotes differences in basis points with respect to the benchmark economy steady state with ϕ_F equal to 9.4%. $\%\Delta$: represents the percentage change with respect to the benchmark. Ratio $(\%)$: reports the ratio in the new steady state.

[57] To facilitate comparison across economies, in Table 7, we present the economy with medium $\varphi_F = 0.3$ (benchmark calibration), which is also reported in column (CT+SCR) in Table 2.

C.4 Energy weight of final output

We further explore the importance of energy weight in goods production, α_E. From 2013 to 2020, the energy share in intermediate input production across economic industries averaged 7% for the European Union.[58] Nonetheless, the share of energy as intermediate input varies significantly among countries; for instance, Germany averaged 5% while Greece averaged 15% during the period.[59] In the real sector, we observe that economies with higher reliance on the energy sector experience higher GDP losses when carbon taxes are introduced. In the financial sector, the main highlight is that sectoral capital requirements tend to be higher in economies with a larger reliance on energy, see Table 8. Intuitively, economies with a large energy sector have a larger share of their banking sector assets exposed to carbon transition policies and, hence, require higher capital requirements to shield against carbon transition risks.

Table 8: Optimal Capital Requirements and Energy Weight

	$\alpha_E = 0.05$	$\alpha_E = 0.1$	$\alpha_E = 0.15$
Non-Energy CR, ϕ_Y. Δbp.	151	142	129
Fossil CR, ϕ_F. Δbp.	134	172	189
Low-Carbon CR, ϕ_L. Δbp.	-26	29	38
Carbon Emissions, $\%\Delta$.	-36.0	-36.0	-36.2
Price Fossil Energy, $\%\Delta$.	26.3	26.0	25.7
Price Low-Carbon Energy, $\%\Delta$.	-0.05	0.23	0.33
Price Energy, $\%\Delta$.	19.4	19.3	19.1
Fossil Energy, ratio $(\%)$.	67.5	67.8	68.0
GDP, $\%\Delta$.	-1.25	-2.16	-3.11
Fossil Bank Credit, $\%\Delta$.	-27.6	-23.5	-22.4
Low-Carbon Bank Credit, $\%\Delta$.	153	72.0	59.4
NBFI, ratio $(\%)$.	26.9	24.2	21.6
Bank Failure, annual rate.	0.90	0.86	0.89

Note: All values are in percentage points. φ_F indicates the elasticity of substitution between fossil capital and fossil natural resources in each economy. Each column compares the benchmark steady-state to the new economy with carbon taxes achieving a 35% emissions reduction and the level of sectoral capital requirements that maximizes welfare. Δbp: denotes differences in basis points with respect to the benchmark economy steady state with ϕ_F equal to 9.4%. $\%\Delta$: represents the percentage change with respect to the benchmark. Ratio $(\%)$: reports the ratio in the new steady state.

C.5 Shock to fossil natural resources

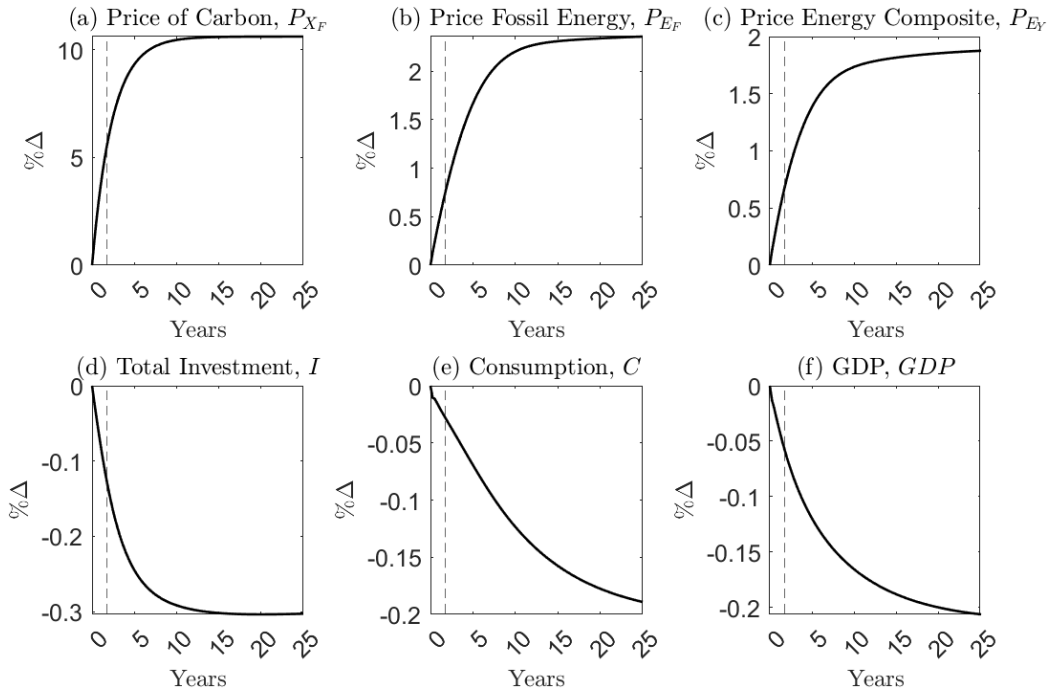
In order to quantitatively validate our model and calibration we perform the following exercise as in Coenen et al. (2023). We simulate a permanent increase in the price of fossil natural resources and compare our model responses to the em-

[58] The energy share in intermediate inputs is measured by adding up the intermediate consumption shares of electricity, manufacture of coke and refined petroleum products, and mining and quarrying from the national accounts aggregates at the industry level from all economic activities in the European Union (NACE), see Eurostat.

[59] In view of this, we set our benchmark to $\alpha_E = 0.1$ consistent with other e-DSGE models (Diluiso et al. (2021)).

pirical estimates found in Peersman and Van Robays (2009, 2012). They find that a 10% increase in the price of fossil natural resources implies a fall in GDP of 0.3%. Figure 8 shows how our economy reacts: GDP falls by around 0.2% in the short-run and settles at 0.24% in the long-run. This illustrates that our model is able to replicate empirically observed reactions to shocks into the fossil energy sector, which is key to validate our results when climate policies (carbon tax) are implemented.

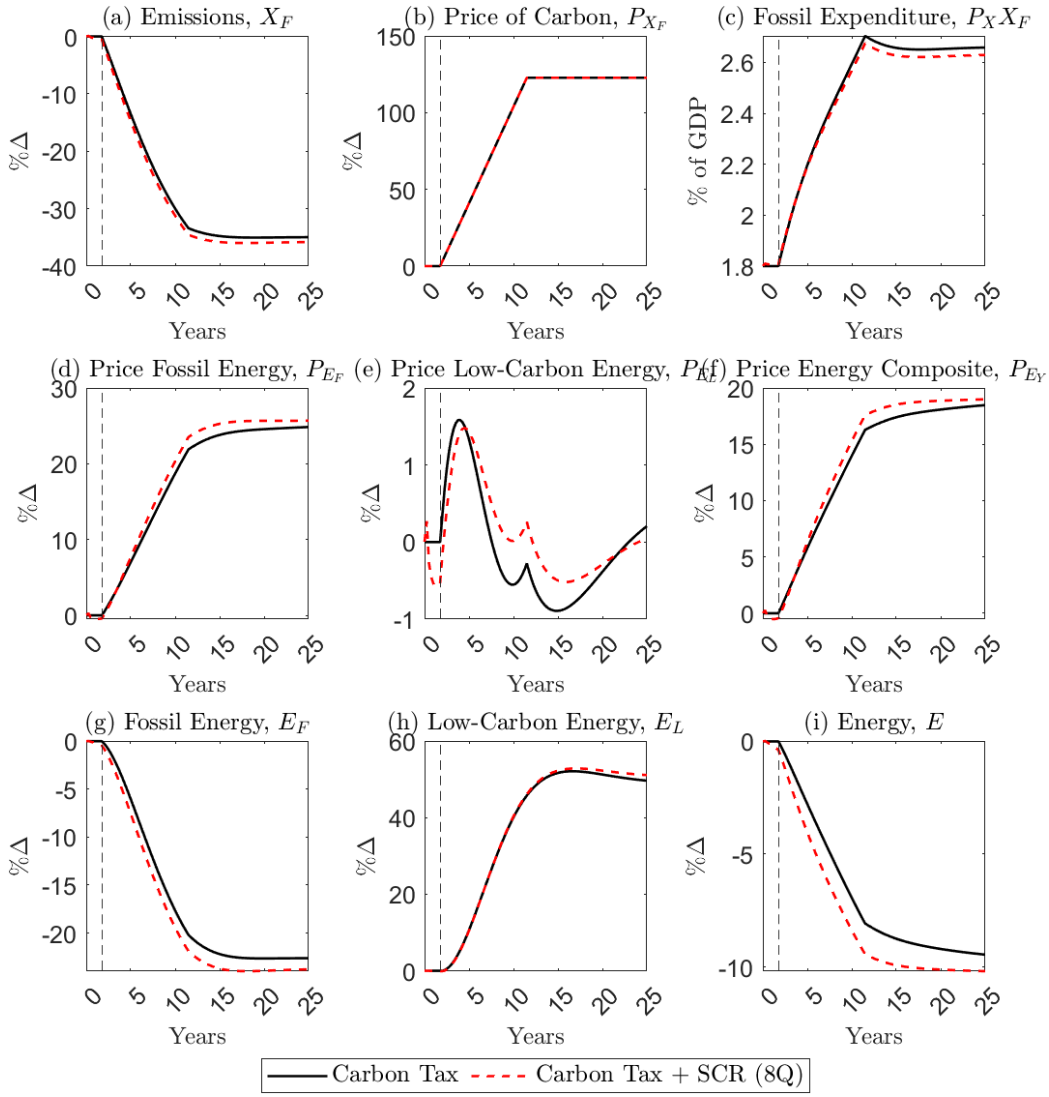
Figure 8: Effects of a 10% increase in the price of fossil resources



Note: %Δ: represents the percentage change with respect to the initial steady state.

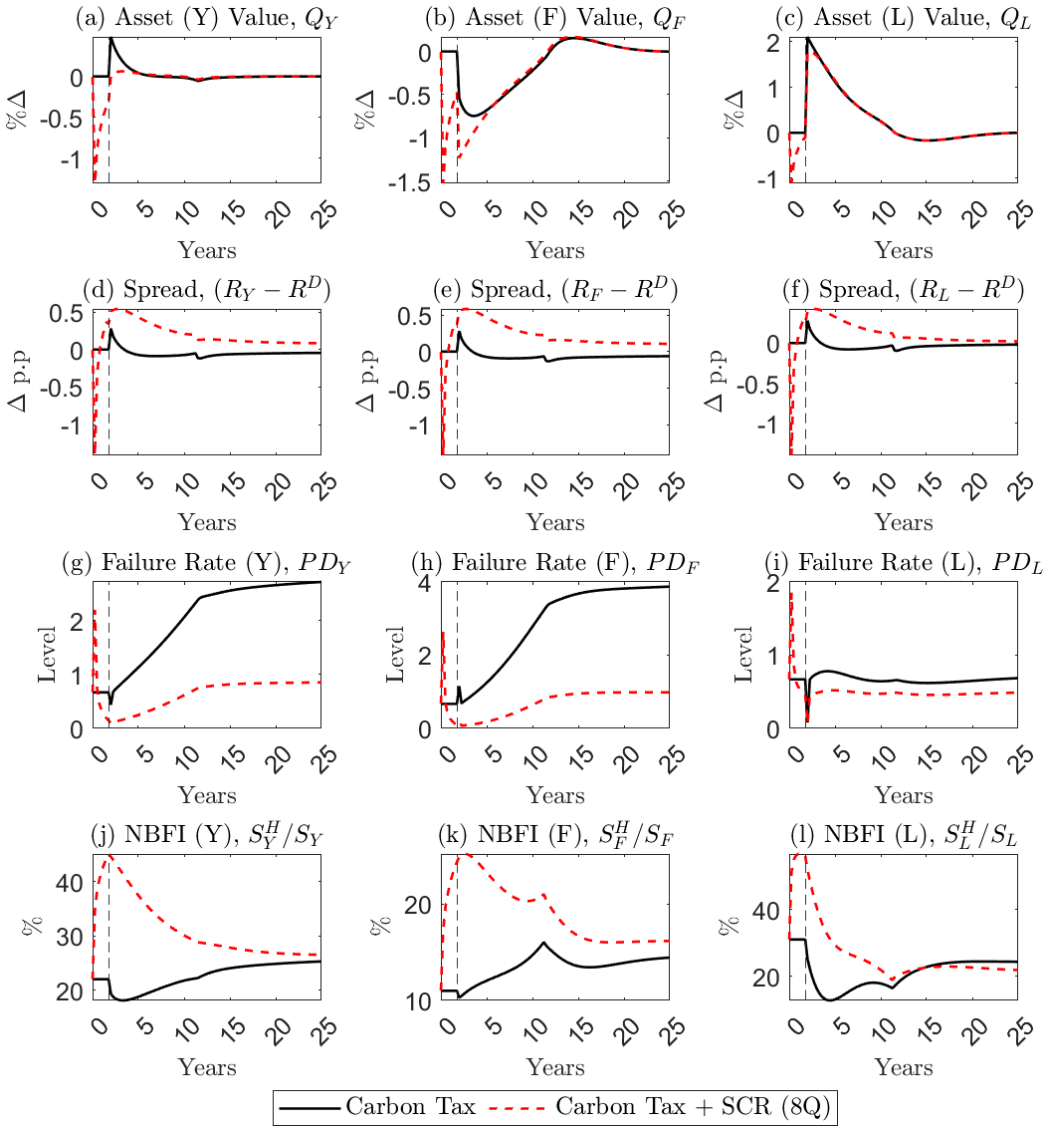
C.6 Carbon Transition

Figure 9: Carbon Transition and Optimal CR: Energy sector



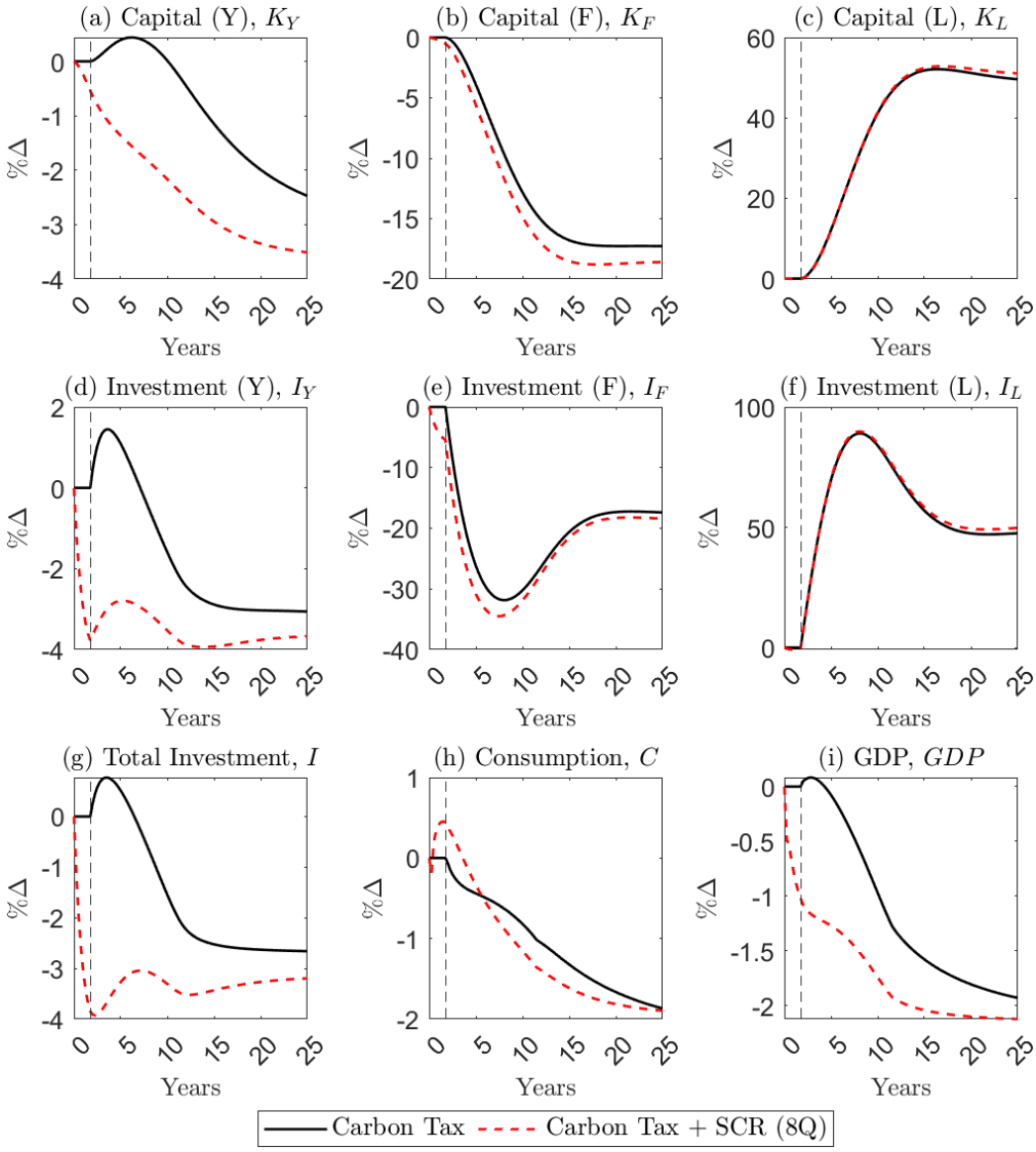
Note: Carbon transition starts in quarter 8 with the unexpected introduction of a carbon tax. %Δ: represents the percentage change with respect to the initial steady state. Δp.p.: are percentage point differences. Ratio (%): reports the ratio in the new steady state. NBFI stands for non-bank financial intermediation.

Figure 10: Carbon Transition and Optimal CR: Financial sector



Note: Carbon transition starts in quarter 8 with the unexpected introduction of a carbon tax. %Δ: represents the percentage change with respect to the initial steady state. Δp.p.: are percentage point differences. Ratio (%): reports the ratio in the new steady state. NBFI stands for non-bank financial intermediation.

Figure 11: Carbon Transition and Optimal CR: Real Sector



Note: Carbon transition starts in quarter 8 with the unexpected introduction of a carbon tax. %Δ: represents the percentage change with respect to the initial steady state. Δp.p.: are percentage point differences. Ratio (%): reports the ratio in the new steady state. NBFI stands for non-bank financial intermediation.

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