Optimal Sustainability-Linked Collateral Policy*

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Abstract

We propose a quantitative macro model with energy production and financial frictions in both the firm and banking sectors to study the positive and normative implications of *Sustainability-Linked Collateral Policy* (SLCP). This policy sets larger haircuts on energy sector debt when banks pledge it as collateral with the central bank if energy production is more carbon-intensive. The SLCP improves welfare by incentivizing clean technology adoption within the energy sector - the *emission mitigation channel* - and by insulating the central bank from climate policy transition risk - the *central bank exposure channel*. The welfare gains are larger if the emission tax level is low or the emission tax volatility is high. The welfare gains through the *emission mitigation channel* largely stem from technology adoption within the energy sector rather than a shift towards less emission-intensive sectors. However, the SLCP implies low energy sector haircuts in periods with high taxes, during which energy firms switch to clean technologies and are closer to default. However, it is optimal to reduce central bank exposure in these states, and we propose a climate policy cycle adjustment to the SLCP, which ensures that energy sector haircuts rise if emission taxes are temporarily high.

Keywords: Central Bank Collateral Framework, Climate Policy, Climate Factor, Energy, Macro-Banking Model, Multi-Sector E-DSGE Model.

JEL Classification: E44, G21, G28, Q58.

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1 Introduction

Central banks have recently started to take the interplay between climate policy and macro-financial risks into account when setting their collateral frameworks. Central bank collateral frameworks specify which assets banks can pledge to obtain central bank funding and determine the eligibility and valuation haircut applied to each asset. For instance, corporate bonds issued by high-emission firms receive larger collateral haircuts when banks pledge them with the Eurosystem; and it recently announced that this policy will extend to credit claims such as bank loans by 2027.[1] This measure, known as the *climate factor*, reflects concerns that climate policy shifts may increase default risk and reduce the collateral value of these bonds. The ongoing relevance of such shifts is illustrated by recent changes to the EU emission trading system.[2] Furthermore, the Bank of England recently excluded debt issued by thermal coal mining firms from its list of eligible collateral.[3]

To improve our understanding of the interactions between climate policy and central bank collateral policy, we make two contributions. First, we propose a novel quantitative Environmental Dynamic Stochastic General Equilibrium (E-DSGE) model. Second, we apply this framework to study how optimal collateral policy depends on the climate policy regime. Our model combines elements from the macro-finance, macro-banking, and climate economics literature. There are two types of intermediate good firms (energy and non-energy). Energy firms generate socially harmful carbon dioxide emissions as a by-product of their energy production, but they can switch to a clean technology at a cost (Heutel, 2012). These costs are convex, reflecting the notion that some technologies requiring energy inputs are very costly to operate in an emission-free fashion. The non-energy sector produces intermediate goods without generating emissions and is affected by climate policy through relative prices and general equilibrium effects.

Intermediate good firms are subject to uninsurable idiosyncratic productivity shocks. Following Gomes et al. (2016), firms finance their investment using equity and long-term debt, which is held and priced by banks. Firms have an incentive to use debt financing because their managers are relatively impatient. However, firms default on the maturing share of their debt

[1] The official policy announcement of the ECB can be found here. The *climate factor* is explicitly motivated to "protect the Eurosystem against potential declines in the value of collateral in the event of adverse climate-related transition shocks". The announcement concerning credit claims can be found here.

[2] More information on changes to the EU ETS is available under this link.

[3] The Bank of England's announcement can be found here. Other central banks are considering similar measures (Rischen, 2025).

if current revenues fall short of the repayment obligation, such that corporate debt is risky. The optimal corporate capital structure balances these effects. Climate policy directly affects the amount of debt issued and its default risk.

Banks collect deposits from households and purchase defaultable debt issued by intermediate good firms. We follow the macro banking literature (Bianchi and Bigio, 2022) in assuming that banks are subject to uninsurable idiosyncratic liquidity shocks, which they have to settle by borrowing from the central bank against eligible collateral. Hence, banks are willing to pay an eligibility premium on corporate debt. The central bank sets the collateral framework, i.e., the amount of central bank loans that banks can obtain by pledging corporate debt as collateral. Importantly, accepting risky debt securities as collateral exposes the central bank to losses in the case of a counterparty default. This is captured by a cost function, which increases with the amount of eligible collateral and its riskiness (Hall and Reis, 2015). Collateral policy solves a trade-off between lower liquidity management costs for banks by expanding collateral availability and limiting the central banks' exposure to risky collateral.[4]

We calibrate the model to euro area data from 2001 to 2024. Consistent with ECB policy over the calibration period, we impose a symmetric haircut on energy and non-energy debt and calibrate parameters governing financial frictions to match the leverage ratio and default rate of non-financial firms in the euro area. The central bank collateral parameter is inferred from the ratio of all assets that banks can pledge with the Eurosystem, corrected for valuation haircuts, over total euro area bank assets. This yields a baseline collateral parameter of 65%. Since the central banks' cost of accepting risky collateral is unobservable, we borrow an inverse optimality approach from the public finance literature and calibrate the collateral management costs such that the symmetric collateral haircut parameter is optimal from a utilitarian welfare perspective; see also Giovanardi et al. (2023).

We use the calibrated model to study how optimal central bank collateral policy depends on the climate policy regime. The baseline scenario features a time-invariant tax of 42\$/tCO2, consistent with the full-sample average in the data. In a second scenario, we lower the tax level to its pre-2020 average of 21\$/tCO2. In a third scenario, we assume that climate policy

[4]Such a trade-off between removing costs and frictions in interbank trade and potential losses from lending to banks also arises in Acharya et al. (2012). In our model, the optimal collateral policy response to shocks to banks' liquidity management costs is counter-cyclical, consistent with standard lender-of-last-resort policy and a dominant *collateral availability channel*. It is furthermore optimal to tighten collateral policy in response to negative productivity shocks, which have a pronounced negative effect on collateral quality, such that the *central bank exposure channel* dominates. This is consistent with central banks' practice to tie collateral eligibility to ratings.

varies over time. Several factors, such as technological advances, political feasibility, and news about the costs and benefits of curbing global warming, induce time variation in climate policy.[5] Following the E-DSGE literature, we are agnostic about the origins of climate policy uncertainty and operationalize it using emission tax shocks.

As a first step, we abstract from sector-specific collateral policy and illustrate how each climate policy regime affects macro-financial aggregates that shape the collateral policy trade-off. Compared to the baseline scenario, the low emission tax scenario is characterized by a smaller abatement effort and more investment and more debt issuance in the energy sector. The low substitutability of energy and non-energy goods implies that non-energy firms also invest more and issue more debt, such that overall collateral availability rises. At the same time, the emission tax level does not affect firms' risk-taking incentives, such that the central banks' exposure to default risk does not change. Taken together, a symmetric collateral policy tightening from 65% to 67.4% is optimal. Such a tightening is not negligible, given that the standard deviation of the collateral/bank liabilities ratio is 1.5% in the data. In nominal terms, this amounts to making an additional 500bn EUR of assets ineligible as collateral.

With time-varying taxes, the abatement effort is greater (smaller) in periods with high (low) emission taxes. Since abatement costs are convex, the abatement effort is smaller and investment and debt issuance are larger on average. At the same time, the default rate is larger than in the baseline scenario with constant taxes. Optimal symmetric collateral policy tightens to 67% in this case. Notably, the effect originates almost entirely in the energy sector.

We then consider sectoral tilts, so that energy and non-energy firms can receive different haircuts. Since the energy sector accounts for the lion's share of emissions, this resembles the *climate factor* introduced by the Eurosystem. However, the haircut of energy firms does not depend on technology choices at the firm level, which can be interpreted as a situation in which emission intensities are merely observable at the sectoral level, but not at the firm level. The welfare-maximizing collateral framework implies an energy haircut of 72% and a non-energy haircut of 63.2%. Lowering non-energy haircuts ensures that collateral availability stays approximately constant compared to the symmetric collateral policy. We already discussed that the tax level does not change default risk in either sector, and the welfare improvement associated with sector-specific collateral policy arises from the *emission mitigation channel*.

[5] For analyses of the macro-financial consequences of climate policy uncertainty, see Fried et al. (2022), Hambel and van der Ploeg (2025), and Mourelon (2025) for theoretical macroeconomic models, and Noailly et al. (2022), Meinerding et al. (2023), Marotta et al. (2025), and Gavriilidis et al. (2026) for empirical evidence.

The *emission mitigation channel* becomes more relevant in the scenario with low taxes, where an energy sector haircut of 77.5% is optimal, while the non-energy haircut is 64.8%. The gap between both sectors is much larger, reflecting the larger welfare gains of emission mitigation. The average haircut rises, consistent with the symmetric collateral policy tightening discussed before. Nevertheless, the implied emission reduction and welfare gains are negligible, as sectoral tilts do not affect the emission intensity in the energy sector. Consequently, the emission reduction is very small.

In the scenario with time-varying taxes, sectoral tilts are also stronger than in the baseline scenario. While there is no additional motivation to tilt collateral policy to mitigate emissions, there is considerable scope to reduce the *central bank exposure channel* by raising haircuts on energy sector debt. The energy sector haircut rises to 81%, while the optimal non-energy sector haircut is given by 63.4%. The haircut gap between both sectors and the associated welfare gain are even slightly larger than in the scenario with low taxes, suggesting that the *emission mitigation channel* and the *central bank exposure channel* contribute approximately equally to collateral policy tilting.

Our framework allows us to study sector-specific collateral policy that goes beyond sectoral tilts. Under the Sustainability-Linked Collateral Policy (SLCP), banks receive a higher haircut on energy debt if energy firms have a high emission intensity. They receive the baseline haircut if energy firms fully abate their emissions. As a result, banks can obtain cheaper funding and are willing to offer more favorable debt terms. By improving debt financing conditions for cleaner energy production, the SLCP incentivizes energy firms to increase abatement spending, which in turn has a positive effect on aggregate emissions. Allowing central bank collateral policy to affect firms' technology choices introduces a novel transmission channel relative to the existing E-DSGE models with financial frictions by affecting technology choices *within sectors*. This resembles the situation in which policies can be conditioned on firm-level emission intensities.[6]

Quantitatively, we find that the optimal penalty haircut is 95%. This policy raises the abatement share in the energy sector from 26.67% to 27.1%, which is similar to increasing the emission tax from its current level of 42$/tCO2 to 43$/tCO2. The welfare gains are around 10 times larger than for sectoral tilts. However, given the relatively small contribution of the euro area to global emissions, the resulting welfare gains are modest, amounting to slightly less than

[6] All firms that participate in the EU emission trading system have to disclose emissions every year. This is also reflected in the updating frequency of the Corporate Sector Purchase Programme (CSPP) tilting scores in the Eurosystem.

0.01% in consumption equivalents. Again, optimal penalty haircuts are larger if taxes are either low, so that collateral policy provides more abatement incentives, or if taxes are time-varying, to reduce the central bank's exposure to risky energy sector debt.

So far, we have studied tilted collateral policy from an ex ante perspective, i.e., the sector-specific haircut parameters could not respond to emission tax changes ex post. As a final step, we consider the optimal collateral policy response to emission tax shocks using simple policy rules. A sudden emission tax increase raises *central bank exposure* to risky energy sector debt, but also reduces investment and debt issuance, such that collateral availability declines as well. Importantly, default risk in the non-energy sector drops on impact. By contrast, debt issuance in the non-energy sector also declines due to the complementarities between sectors. At the aggregate level, default risk and central bank exposure rise, while debt issuance and collateral availability decline.

Quantitatively, a dominant *central bank exposure channel* implies that it is optimal to tighten collateral policy. The aggregate haircut rises from 65% to around 70% after a three-standard-deviation tax shock. We consider such a comparatively large shock, corresponding to a 60$/tCO2 tax increase, based on historical EU ETS price increases in 2020. The optimal collateral policy adjustment is a macroeconomically relevant, but arguably an upper bound given the very large shock size. Since energy sector default risk responds more strongly, it is optimal to temporarily increase haircuts on energy sector debt from 65% to around 90%. Conversely, the optimal collateral haircut on non-energy firms falls from 65% to 64%, which ensures that aggregate collateral availability does not fall too much.

Having characterized optimal dynamic central bank collateral policy, we revisit the SLCP. How does tying collateral haircuts to abatement efforts affect the availability of collateral and the central bank's exposure to emission tax shocks? Under the SCLP, the collateral haircut automatically declines if emission taxes and abatement efforts are large. Hence, collateral availability and central bank exposure increase after an emission tax increase. This is inconsistent with the optimal haircut response. Augmenting the SLCP using a dynamic component, similar to a simple collateral policy rule, aligns the energy sector haircuts under the SLCP with optimal policy without compromising its contribution to emission mitigation and the beneficial ex ante reduction of exposure to energy sector debt.

Related Literature. The paper contributes to different strands of literature. *First*, we contribute to the literature exploring the macro-financial impacts of climate policies. A large and rapidly growing body of research studies how climate policies change relative prices across sectors, especially in the energy sector, through the lens of E-DSGE models. Del Negro et al. (2023), Bartocci et al. (2024), Coenen et al. (2024), Olovsson and Vestin (2025), Carli et al. (2026), and Rosas (2025) study the transmission of emission tax shocks in the energy sector to inflation through the production network, stressing the role of relative price adjustments. In more aggregated settings, Fornaro et al. (2024), Annicchiarico et al. (2024), Sahuc et al. (2024), and Ferrari and Nispi Landi (2025) demonstrate emission tax shocks generate inflation–output trade-offs whose severity, and the associated monetary policy response, depend on the role of technological progress, household expectations, and the recycling of fiscal revenues. We contribute to this literature by shifting the focus from conventional monetary policy to central bank collateral policy.

Second, our paper contributes to the literature on central bank policies, which aim to support the green transition. Previous papers have shown how tilted green quantitative easing (Ferrari and Nispi Landi, 2023; Nakov and Thomas, 2026), green-tilted collateral frameworks (Giovanardi et al., 2023), and green-tilted bank capital requirements (Punzi, 2024; Giovanardi and Kaldorf, 2026) improve financing conditions for low-emission activities and induce some reallocation away from fossil-intensive sectors. However, the resulting emissions reductions and welfare gains are quantitatively small relative to those achieved through carbon pricing, and often come at the cost of increased risk-taking or other distortions. Jorda et al. (2026) show how conventional monetary policy affects technological choices, because clean and conventional investments have different payoff profiles. Carattini et al. (2023) study green macroprudential policy in the context of climate policy-induced asset stranding. Relatedly, Diluiso et al. (2021) study tilted policies primarily as stabilization tools against aggregate shocks. We contribute to this literature by studying how central banks can optimally link sectoral collateral haircuts to emissions and, indirectly, to firms' abatement incentives.

Finally, our paper also relates to the literature on central bank collateral policy and its interaction with the macroeconomy. Koulischer and Struyven (2014) study how adverse shocks to the quantity or quality of collateral impair the transmission of conventional monetary policy, which relates to the key collateral policy trade-off in our model. Ashcraft et al. (2011) and Cassola and Koulischer (2019) demonstrate that central bank collateral policy transmits to the real economy through the price of eligible assets and through banks' funding cost, respectively. Bianchi and Bigio (2022) and De Fiore et al. (2024) study the transmission of frictions in the interbank and sovereign bond markets, which have implications for the optimal design of central bank collateral policy. Our paper provides a characterization of optimal collateral policy with sectoral shocks.

Outline. Section 2 and Section 3 describe the model and its calibration, respectively. In Section 4, we use the model to study optimal tilting in the long run and discuss the interplay between sustainability-linked collateral policy and emission mitigation. In Section 5, we compute optimal collateral policy in response to emission tax shocks and discuss the implications for sustainability-linked collateral policy. Section 6 concludes.

2 Model

Time is discrete and indexed by $t = 1, 2, ...$, and each period is divided into two sub-periods. The model features households, a continuum of competitive banks, monopolistically competitive final good producers, and competitive intermediate producers in the energy and non-energy sectors, indexed by $s \in \{e, n\}$. Each period is divided into two sub-periods. Production, investment, and consumption take place in the second sub-period. Final good producers combine intermediate goods with labor and are subject to nominal rigidities. Intermediate firms produce their goods using capital, which is financed with equity and debt. Banks collect deposits from households, lend to intermediate good producers, and borrow from the central bank in exchange for collateral. The model is closed by a public sector, which levies emission taxes, conducts monetary policy, and sets the collateral framework.

Households Households choose consumption c_t, labor supply n_t, and deposits d_t to maximize lifetime utility. Deposits pay the nominal interest rate i_t, while the real wage is denoted by w_t. The parameter β is the time-invariant discount factor. The maximization problem can be written recursively:

$$
\begin{aligned}
V_t = \max_{c_t, d_t, n_t} \quad & \log(c_t) - \frac{\Psi_N}{2} n_t^2 + \beta \mathbb{E}_t \left[V_{t+1} \right] \qquad (1) \\
\text{s.t.} \quad & c_t + d_{t+1} = w_t n_t + (1 + i_{t-1}) \frac{d_t}{\pi_t} + div_t + T_t \ ,
\end{aligned}
$$

where div_t denotes dividends from banks and firms, and T_t is a lump sum transfer from the government. Solving the maximization problem (1), we obtain the optimality condition for labor supply and the Euler equation for deposits:

$$c_t^{-1} w_t = \Psi_N n_t \tag{2}$$

$$1 = \mathbb{E}_t \left[\Lambda_{t,t+1} \frac{1 + i_t}{\pi_{t+1}} \right] , \tag{3}$$

where $\Lambda_{t,t+1} \equiv \beta \frac{c_{t+1}^{-1}}{c_t^{-1}}$ is the household's stochastic discount factor (sdf).

Banks There is a continuum of perfectly competitive banks that collect deposits from households and hold corporate debt issued by non-financial firms in the energy and non-energy sectors in the second sub-period. Following Giovanardi et al. (2023) and Kaldorf (2025), banks are subject to liquidity frictions that give rise to collateral premia. In the first sub-period, banks draw uninsurable liquidity shocks that can be microfounded as (unmodeled) deposit withdrawals or similar intra-period liquidity demand (Bianchi and Bigio, 2022). As the focus lies on central bank collateral frameworks, we assume that the banking sector is unable to settle all idiosyncratic liquidity shocks on the interbank market. Consequently, there is a demand for outside liquidity between the first and second sub-period, which takes the form of central bank loans.

Since such intra-period loans are extended before firm-specific productivity shocks are realized in the second sub-period, the collateral value of corporate debt held by banks is uncertain. Consequently, the central bank is exposed to losses from liquidating risky collateral in the event of counterparty default. To cushion against such losses, which we describe in detail below, central banks in practice accept only sufficiently safe assets as collateral and apply valuation haircuts to them. The potentially sector-specific collateral parameter κ_t^s encompasses both eligibility criteria and valuation haircuts in a tractable fashion. Specifically, $\kappa_t^s = 1$ corresponds to the limit case where all debt issued by sector s receives a haircut of 100%, while $\kappa_t^s = 0$ is the most lenient collateral parameter, where banks could pledge the expected payoff from debt in sector s in full. Consequently, the collateral value of each individual bank's debt portfolio is the following:

$$\bar{b}_t = (1 - \kappa_t^e) b_t^e \mathcal{R}_t^e + (1 - \kappa_t^n) b_t^n \mathcal{R}_t^n , \tag{4}$$

where $\mathcal{R}_t^s$ denotes the payoff per unit of debt held in sector s. The collateral value places an

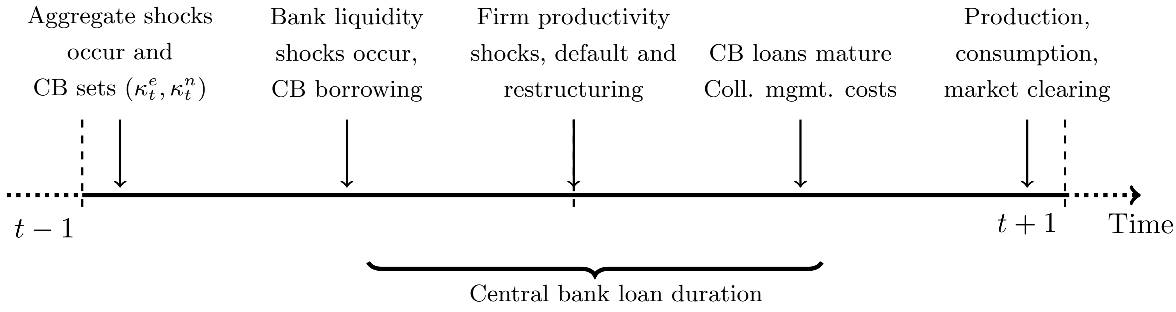

Figure 1: Within-period timing assumption

upper limit on the funds that can be borrowed from the central bank. A more lenient collateral haircut (a lower κ^s) increases the amount of liquidity a bank can tap in case of shortage, at the cost of exposing the central bank to increased collateral risk. The horizontal bracket in Figure 1 highlights the different central bank lending stages.

We assume that a share $\Pi \in (0, 1]$ of banks draws a liquidity deficit. Conditional on drawing a deficit, the demand of individual banks for central bank funding is denoted by λ_t and is assumed to be exponentially distributed with rate parameter l_1.[7] Central bank loans are intra-period, so that their interest rate is zero. If the collateral value of a bank's portfolio falls short of this demand for central bank funding, the bank needs to acquire funds from alternative, more expensive sources, for example, by issuing equity and bank bonds, borrowing on the unsecured money market, or attracting new deposits. We summarize the cost associated with all these (unmodeled) funding sources through the parameter ζ.

The expected cost of liquidity management is obtained by multiplying the probability that the bank draws a liquidity need exceeding the collateral value of its portfolio, $(\exp\{-l_1\bar{b}_t\})$, by the probability Π of receiving a negative liquidity shock and the cost of acquiring external funding, ζ: $\mathcal{L}(\bar{b}_t) = \Pi \cdot \zeta \cdot \exp\{-l_1\bar{b}_t\}$. Since our calibration strategy targets macroeconomic moments, the parameter combination $\Pi \cdot \zeta$ is observationally equivalent. We therefore re-parameterize the cost function as follows:

$$\mathcal{L}(\bar{b}_t) = \frac{l_0}{l_1} \exp\{-l_1\bar{b}_t\} \ . \tag{5}$$

[7] Note that our calibration is annual, such that central bank lending in this model also includes long-term refinancing operations. Funding needs can vary drastically between banks over the course of a year, such that it is reasonable to assume that some banks actually exhaust their collateral over such a horizon.

Bank dividends in period t are then given by:

$$div_t = \sum_s \mathcal{R}_t^s b_t^s - (1 + i_{t-1})d_t + d_{t+1} - \sum_s q(\overline{m}_{t+1}^s)b_{t+1}^s - \mathcal{L}(\bar{b}_t) \ , \tag{6}$$

where $q(\overline{m}_{t+1})$ is the sector-specific debt price, derived below. We follow Cúrdia and Woodford (2011) and assume that banks can invest in corporate debt as long as they can repay depositors in expectation. Solving the shareholder value maximization problem subject to this solvency constraint $(1 + i_t)d_{t+1} = \sum_s \mathbb{E}_t[\mathcal{R}_{t+1}^s b_{t+1}^s]$ yields a break-even condition for corporate debt:

$$q_t^s = \frac{\mathbb{E}_t[\mathcal{R}_{t+1}^s(1 + (1 - \kappa_{t+1}^s)\Omega_{t+1})]}{1 + i_t} \ . \tag{7}$$

Here, $\Omega_{t+1} \equiv -\frac{\partial \mathcal{L}}{\partial \bar{b}_{t+1}}$ is the marginal decline in liquidity management costs that arises if banks hold one additional unit of debt issued by sector s. It is proportional to the per-unit collateral value $(1 - \kappa_{t+1}^s)\mathcal{R}_t^s$. The debt pricing condition connects the expected real debt payoff $\mathcal{R}_{t+1}^s$ to the debt price via the bank sdf, which includes the collateral premium $(1 - \kappa_{t+1}^s)\Omega_{t+1}$. Equation (7) governs the transmission of central bank collateral policy to the real sector via banks' pricing of corporate debt.

Intermediate Good Firms There is a continuum of perfectly competitive intermediate good firms in the energy and non-energy sector, indexed by $s \in \{e, n\}$, which use a linear production technology $z_t^s = m_t^j k_t^s$. Here, m_t^j is an uninsurable idiosyncratic productivity shock that affects the productivity of firm j and realizes at the beginning of each period (before any decisions are made). The productivity shock is i.i.d. log-normally distributed with standard deviation ς_M. We normalize its mean parameter to $-\varsigma_M^2/2$, which ensures that the shock has an expected value of one. The price of capital in each sector is normalized to one. In the following, we focus on energy price firms and present the maximization problem of non-energy firms in A.1. The maximization problem and its solution are very similar for non-energy firms, except that they do not emit carbon dioxide, and, hence, emission taxes and abatement efforts are absent.

Energy, Emission Taxes and Abatement Energy firms sell their output to final good firms, described below, and the energy price is denoted by p_t^e. Energy firms are subject to a tax τ_t^e for each unit of emissions. We assume that emissions are proportional to energy production but that energy firms can undertake a costly abatement effort a_t.[8] Actual emissions are therefore given by $e_t = (1 - a_t) z_t^e$. Abatement costs are convex in the abatement effort and proportional to output:

$$\Theta_t = \frac{\theta_1}{\theta_2 + 1} a_t^{\theta_2 + 1} z_t^e \tag{8}$$

with slope parameter $\theta_1 > 0$ and curvature parameter $\theta_2 > 0$. Hence, we can write the energy price net of emission taxes and abatement costs as:

$$\widetilde{p}_t^e = p_t^e - \tau_t^e (1 - a_t) - \frac{\theta_1}{\theta_2 + 1} a_t^{\theta_2 + 1} \ . \tag{9}$$

Following the literature, we operationalize climate policy uncertainty with emission tax shocks and τ_t^e follows an AR(1) process:

$$\tau_t^e = (1 - \rho_\tau) \overline{\tau}^e + \rho_\tau \tau_{t-1}^e + \sigma_\tau \epsilon_t^\tau \ , \tag{10}$$

where $\overline{\tau}^e$ is the steady state emission tax.

Financial Frictions Energy firms are managed on behalf of households by impatient managers with time preference parameter $\widetilde{\beta} < \beta$, which gives rise to a borrowing motive. To finance their investment, firms can either use equity, which is modelled as a transfer from households and corresponds to negative dividends, or nominal long-term debt b_t, which raises current dividends but reduces expected future dividends through the possibility of default. A share $0 < \chi \leq 1$ of debt matures each period, and the non-maturing share $(1 - \chi)$ is rolled over at the current debt price.

Idiosyncratic productivity shocks imply that borrowing is risky. Firms default on the maturing share χb_t^e, if revenues from production $\widetilde{p}_t^e m_t z_t^e$ fall below the required debt repayment χb_t^e, where $\widetilde{p}_t^e$ is the energy price net of any expenses related to emission taxes, described below. We define the threshold realization of the idiosyncratic productivity shock below which a firm

[8] Following the E-DSGE literature, we borrow the abatement effort formalization from the DICE model (Nordhaus, 2018). Alternatively, the variable a_t can be interpreted as the share of fossil firms switching to a less productive clean energy technology (Acemoglu et al., 2012).

defaults as:

$$\overline{m}^e_{t+1} \equiv \frac{\chi b^e_{t+1}}{\pi_{t+1}\widetilde{p}^e_{t+1}k^e_{t+1}} \ . \tag{11}$$

In the default case, there is no debt recovery, such that the resource loss of default is given by $G(\overline{m}^e_t)k^e_t$. Following Gomes et al. (2016), we assume that firms are restructured immediately, which, together with the i.i.d. nature of idiosyncratic productivity shocks, permits aggregation into a representative firm.

The expected productivity of a defaulting firm is defined as $G(\overline{m}^e_t) \equiv \int_0^{\overline{m}^e_t} mf(m)dm$ while the default probability is given by $F(\overline{m}^e_t) \equiv \int_0^{\overline{m}^e_t} f(m)dm$. We integrate out the idiosyncratic shock to get the average per-unit debt payoff in the energy sector:

$$\mathcal{R}^e_t = (1-\chi)q^e_t + \frac{\chi}{\pi_t}\Big(1 - F(\overline{m}^e_t)\Big) \ . \tag{12}$$

The first term is the share $(1-\chi)$ of debt that is rolled over, valued at market price q^e_t. The second term represents the real payoff from maturing share χ, which is given by the repayment probability $1 - F(\overline{m}^e_t)$, corrected for realized inflation π_t.

Interaction with Collateral Policy The central bank collateral parameter on energy firms κ^e_t is allowed to depend on the abatement effort. We refer to this as sustainability-linked collateral policy and impose a simple linear specification:

$$\kappa^e_t = (1 - a_t) \cdot \overline{\kappa}^{sl} + a_t \cdot \overline{\kappa}^{sym} \ . \tag{13}$$

The harshest penalty haircut is given by $\overline{\kappa}^{sl} = 1$ so that banks cannot pledge debt extended to energy firms if these do not abate $(a_t = 0)$. Energy debt receives a smaller haircut $\overline{\kappa}^n < \overline{\kappa}^{sl}$ under full abatement, i.e., energy firms are treated as the (emission-free) non-energy firms if they fully mitigate their emissions. Notably, the parameters of the collateral framework are time-invariant, while the effective energy haircut κ^e_t is potentially time-varying and co-moves with the abatement effort in the energy sector.

Maximization Problem Period t dividends of an energy firm can be written

$$div^j_t = \mathbb{1}\{m^j_t > \overline{m}_t\}\big(m^j_t p^e_t k^e_t - \chi b^e_t\big) - i^e_t + q(\overline{m}^e_{t+1})(b^e_{t+1} - (1-\chi)b_t) \tag{14}$$

Firm managers choose abatement effort, debt, and capital to maximize the present value of dividends $\mathbb{E}_0 \sum_{t=0}^{\infty} \widetilde{\Lambda}_{0,t} div_t$. They take equation (11) as given, which links debt and capital choices to default risk, and the pricing schedule on corporate debt. The pricing schedule is obtained from substituting the debt payoff (12) and the sustainability-linked collateral haircut (13) into the debt pricing condition (7):

$$q(\overline{m}^e_{t+1}, a_t) = \mathbb{E}_t \left[\left\{ (1-\chi) q(\overline{m}^e_{t+2}, a_{t+2}) + \frac{\chi}{\pi_t} \Big(1 - F(\overline{m}^e_t) \Big) \right\} \frac{(1 + \big(1 - (1-a_t) \cdot \kappa^{sl}_t - a_t \cdot \kappa^n_t \big) \Omega_{t+1})}{1 + i_t} \right] . \tag{15}$$

The partial derivative of the debt pricing schedule with respect to abatement investment is given by:

$$\frac{\partial q^e_t}{\partial a_t} = \mathbb{E}_t \Big[\Big(\kappa^{sl} - \kappa^n \Big) \Omega_{t+1} \frac{\mathcal{R}^e_{t+1}}{1 + i_t} \Big] . \tag{16}$$

The partial derivative of the debt price schedule with respect to abatement effort is large if either the SLCP is very tilted, i.e., $\kappa^{sl} - \kappa^n$ is large, or if the collateral premium Ω_{t+1} is high, which reflects a high collateral demand by banks. Managers take into account that a change in debt issuance affects the debt price through the default probability in future periods. Denoting the Lagrange-multiplier on the default threshold (11) by μ^e_t, the first-order condition for debt issuance is:

$$q(\overline{m}^e_{t+1}, a_t) - \mu^e_t \frac{\overline{m}^e_{t+1}}{b^e_{t+1}} = \mathbb{E}_t \left[\frac{\widetilde{\Lambda}_{t,t+1}}{\pi_{t+1}} \Big\{ \chi(1 - F(\overline{m}^e_{t+1})) + (1-\chi) q(\overline{m}^e_{t+2}, a_{t+1}) \Big\} \right] . \tag{17}$$

The LHS collects the additional dividends from issuing one unit of debt, where $\mu^e_t \frac{\overline{m}^e_{t+1}}{b^e_{t+1}}$ is a debt dilution term, while the RHS summarizes the expected repayment obligation $\chi(1 - F(\overline{m}^e_{t+1}))$ and the rollover of the non-maturing share $(1-\chi) q(\overline{m}^e_{t+2}, a_{t+1})$. Optimal investment balances the cost of purchasing capital in period t (LHS) with its benefits, consisting of next period's value of undepreciated capital $(1 - \delta_K)$ and the revenues from selling output, conditional on not defaulting $\widetilde{p}^e_{t+1} \big(1 - G(\overline{m}^e_{t+1})\big)$:

$$1 - \mu^e_t \frac{\overline{m}^e_{t+1}}{k^e_{t+1}} = \mathbb{E}_t \left[\widetilde{\Lambda}_{t,t+1} \Big\{ (1 - \delta_K) + \widetilde{p}^e_{t+1} \big(1 - G(\overline{m}^e_{t+1})\big) \Big\} \right] . \tag{18}$$

Emission taxes affect the first-order condition for capital by reducing the expected payoff from production revenues by decreasing the after-tax price $\widetilde{p}^e_{t+1}$. The first-order condition for abatement is given by

$$a^*_t = \left(\frac{\tau^e_t + \frac{\partial q^e_t}{\partial a_t}\left(b^e_{t+1} - (1-\chi)\frac{b^e_t}{\pi_t}\right)\frac{1}{z^e_t}}{\theta_1} \right)^{1/\theta_2} . \tag{19}$$

and reduces to the familiar expression $\left(\frac{\tau^e_t}{\theta_1}\right)^{1/\theta_2}$ without the SLCP. Consistent with the data, the abatement effort does not co-move with the business cycle to a quantitatively relevant degree. The risk choice $\overline{m}_{t+1}$ solves:

$$-\mu^e_t - \frac{\partial q^e_t}{\partial \overline{m}^e_{t+1}}\left(b^e_{t+1} - (1-\chi)\frac{b^e_t}{\pi_t}\right) = \mathbb{E}_t\left[\widetilde{\Lambda}_{t,t+1}\left(b^e_{t+2} - (1-\chi)\frac{b^e_{t+1}}{\pi_{t+1}}\right)\frac{\partial q^e_{t+1}}{\partial \overline{m}^e_{t+2}}\frac{\partial \overline{m}^e_{t+2}}{\partial \overline{m}^e_{t+1}}\right] . \tag{20}$$

In Appendix A.1, we provide further details on the firm maximization problem and its solution.

Final good firms Monopolistically competitive final good firms are subject to price adjustment costs (Rotemberg, 1982) and combine the bundle of intermediate goods $\widetilde{z}_t$ with labor n_t using a nested CES technology:

$$y_t = A_t \exp\{-\psi_E E_t\}(\widetilde{z}_t)^\alpha n_t^{1-\alpha} , \tag{21}$$

where the parameter α governs the share of intermediate goods, which are given by:

$$\widetilde{z}_t = \left(\nu(z^e_t)^{\frac{\epsilon-1}{\epsilon}} + (1-\nu)(z^n_t)^{\frac{\epsilon-1}{\epsilon}}\right)^{\frac{\epsilon}{\epsilon-1}} . \tag{22}$$

Here, ν is the weight of energy goods in the basket and ϵ is the substitution elasticity between energy and non-energy goods. A_t is exogenous total factor productivity that follows an AR(1) process: $\log(A_t) = \rho_A \log(A_{t-1}) + \sigma_A \epsilon^A_t$ with $\epsilon^A_t \sim N(0,1)$. The term $\exp\{-\psi_E E_t\}$ reflects productivity losses from climate change damages, where the parameter ψ_E governs the damage-to-GDP ratio. Emissions accumulate into a stock E_t according to:

$$E_t = \delta_E E_{t-1} + e_t + e_{row} , \tag{23}$$

where δ_E is a decay rate and e_{row} are exogenously given rest-of-the-world emissions. Solving the profit maximization problem yields standard demand functions for labor and intermediate goods and the New Keynesian Phillips curve. We relegate the analytical steps to Appendix A.2.

Public policy and resource constraint The central bank extends intra-period loans to banks at a zero interest rate against collateral. Following Bindseil and Papadia (2006) and Hall and Reis (2015), accepting risky debt as collateral is costly for at least three reasons. First, central banks need to operate a credit risk management system, which is not directly related to their typical monetary policy activities and might be costly for operational reasons. Second, central banks might be less effective in monitoring and disciplining banks; see Freixas and Holthausen (2005) for a model of interbank lending under asymmetric information. Third, the central bank needs to liquidate the pledged collateral, potentially at a loss, in the case of a counterparty default. The central bank might generally be averse to losses from lending operations with the private sector (Goncharov et al., 2023). Following Giovanardi et al. (2023), we operationalize these different microfoundations in a parsimonious way and impose the following cost function $\mathcal{C}_t$ from accepting risky collateral:

$$\mathcal{C}_t = \frac{c_0}{c_1} \cdot \left((1-\kappa_t^e) b_t^e \mathcal{R}_t^e F(\overline{m}_t^e)^{c_1} + (1-\kappa^n) b_t^n \mathcal{R}_t^n F(\overline{m}_t^n)^{c_1} \right) . \tag{24}$$

The central bank's exposure to risky collateral in each sector depends on the size of central bank loans that can be obtained by pledging debt of each sector $(1-\kappa_t^s) b_t^s \mathcal{R}_t^s$. Second, it depends on the riskiness of the underlying collateral, i.e., the potential loan size is weighted by the default rate $F(\overline{m}_t)$ of the pledged collateral. We focus on the contemporaneous default rate because central bank losses are realized in the second sub-period, when the intra-period central bank loans mature. The nominal interest rate follows a standard Taylor-type rule:

$$r_t = \rho_R r_{t-1} + (1-\rho_R)\big(\overline{r} + \varphi_\pi(\pi_t - 1)\big), \tag{25}$$

where φ_π governs the response to inflation, ρ_R governs the policy rate's persistence, and $\overline{r} = 1/\beta - 1$ is the risk-free rate in steady state. The model is closed by assuming that emission tax revenues are rebated in lump-sum fashion to households, such that the resource constraint of the economy is given by:

$$y_t = c_t + \sum_s i_t^s + \frac{\Psi_P}{2}(\pi_t - 1)^2 + \frac{\theta_1}{\theta_2 + 1}\left(\frac{\tau_t^e}{\theta_1}\right)^{\frac{\theta_2+1}{\theta_2}} z_t^e + \sum_s G(\overline{m}_t^s) k_t^s + \mathcal{L}(\bar{b}_t) + \mathcal{C}(\overline{F}_t) . \tag{26}$$

In addition to investment adjustment costs and Rotemberg costs, the cost functions associated with emission abatement, corporate default, banks' liquidity management, and losses on the central bank's collateral portfolio also affect aggregate consumption and, hence, welfare. Productivity losses from emissions enter through the aggregate production function (21).

3 Calibration

The model is calibrated to annual euro area data.[9]. Throughout the calibration, TFP shocks are the only source of uncertainty in the model. All data moments are based on the sample period from 2001 to 2022. Macroeconomic data are obtained from Eurostat, while the default frequency is obtained from publicly available data from S&P. Details on all data sources are summarized in Appendix B.

3.1 Parameter Choices

We now describe the parameters affecting each group of agents. Our baseline parameterization is summarized in Table 1.

Households and Banks We set the weight on labor disutility to $\Psi_N = 8$, which yields a steady state labor supply $n^{SS} = 0.3$. The household discount factor is set to $\beta = 0.99$, implying an annualized real interest rate of 1%. The key parameter $l_0 =$ associated with banks' liquidity management cost is set to 0.01, which implies a collateral premium of 10bps, consistent with the collateral premium on ECB-eligible corporate bonds (Pelizzon et al., 2024=.

Final Good Firms The Cobb-Douglas coefficient in the production function of final good producers is fixed at $\alpha = 1/3$. The weight of energy in the Intermediate Goods bundle (22) is set to $\widetilde{\nu} = 0.0015$, which implies an energy share in production of 7%, consistent with euro area data. The elasticity of substitution between energy and non-energy goods ϵ in equation (22) is set to 0.4 in line with multi-sector E-DSGE models calibrated to EU data (see e.g. Coenen et al., 2024). The elasticity of substitution between final goods varieties $\phi = 6$ implies a markup of 20%. We set the Rotemberg price adjustment parameter to $\Psi_P = 4.5$, which implies an average price duration of five quarters. Following Bergeaud et al. (2016), the persistence and standard deviation of the aggregate TFP shock are set to $\rho_A = 0.9$ and $\sigma_A = 0.01$.

[9]The model is solved and simulated based on a second-order approximation around the deterministic steady state using Dynare (Adjemian et al., 2024)

Parameter	Value	Source/Target
Households		
Household discount factor β	0.99	Risk-free rate 1% p.a.
Labor supply weight Ψ_N	8	Steady state labor 0.3
Technology		
Cobb-Douglas coefficient α	1/3	Capital share 1/3
Capital depreciation rate δ_K	0.08	Capital/GDP ratio 2.1
Price adjustment cost Ψ_P	4.5	5 quarters price duration
Final good CES ϕ	6	20% Price Markup
Energy weight $\widetilde{\nu}$	0.0325	Energy share 7%
Energy/non-energy CES $\widetilde{\epsilon}$	0.4	Euro area data
Abatement cost slope θ_1	0.075	Nordhaus (2018)
Abatement cost curvature θ_2	1.6	Nordhaus (2018)
Emission decay δ_E	0.99	Carbon dioxide half-life
Rest-of-world emissions e_{row}	2.16	EU/global emissions
Emission damage parameter Ψ_E	2e-04	4% Damage/GDP ratio
Financial Markets and Policy		
Firm-owner discount factor $\widetilde{\beta}$	0.971	Firm default rate 0.9%
St. dev. firm risk ς_m	0.2	Firm leverage 29%
Debt maturity χ	0.2	5 year maturity
Average collateral parameter κ_{sym}	0.65	Euro area data
Collateral mgmt. cost slope c_0	0.03945	Optimality of κ_{sym}
Liquidity mgmt. cost slope l_0	0.01	Collateral premium 10bps
Taylor rule coefficient φ_π	2	Standard
Taylor rule persistence ρ_R	0.65	Standard
Shocks		
Persistence TFP ρ_A	0.9	Bergeaud et al. (2016)
TFP shock st. dev. σ_A	0.01	Bergeaud et al. (2016)
Persistence TFP ρ_τ	0.86	EU ETS data
TFP shock st. dev. σ_τ	20\$/tCO2	EU ETS data

Table 1: Baseline Calibration

Intermediate Good Firms The parameters governing financial frictions of Intermediate Good firms are set to match moments typically used in the macro-finance literature. We set the annual capital depreciation rate to a standard value of $\delta_K = 0.08$ and the average debt maturity to five years, implying a debt maturity parameter χ of 0.2. We jointly calibrate the standard deviation of idiosyncratic productivity shocks, $\varsigma_M = 0.24$, and the firm owner discount factor, $\widetilde{\beta} = 0.971$, to match a corporate default rate $F(\overline{m})$ of 0.9% and a leverage ratio ($lev \equiv l/k$) of 29% at book values. In the data, leverage is measured as the ratio of all outstanding corporate debt to physical assets at book values and (consolidated) financial assets.

The curvature parameter of the abatement cost function is set to $\theta_2 = 1.6$, which is a

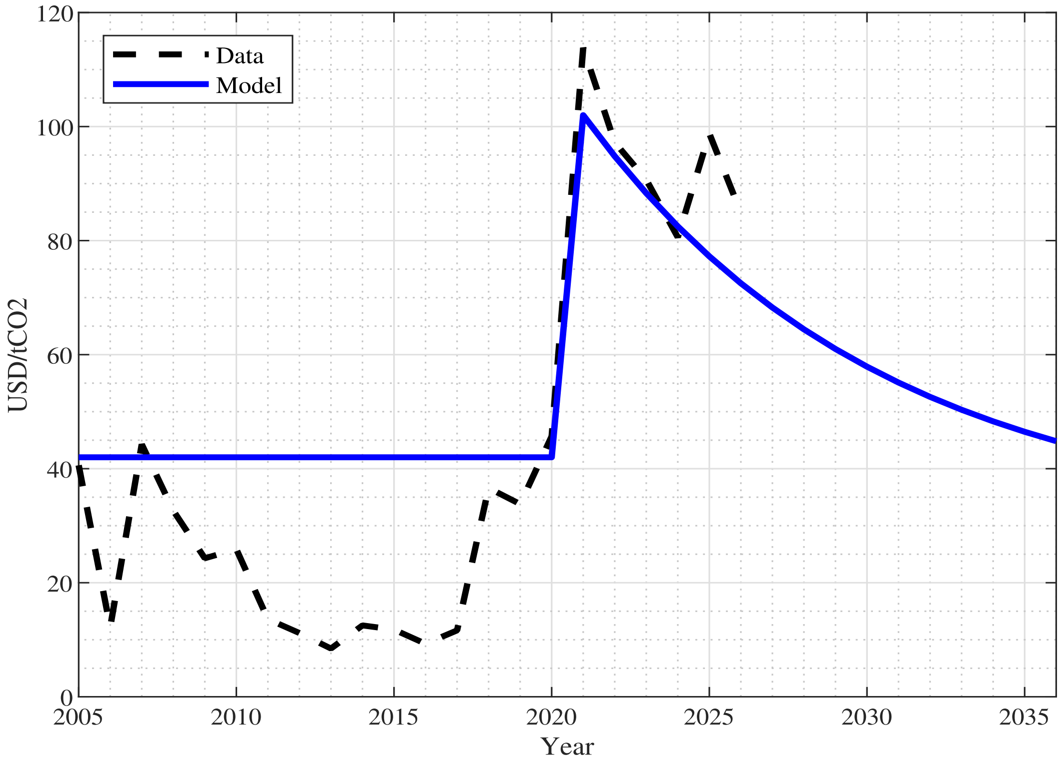

Figure 2: ETS Price: Data and Model. This graph displays the EU ETS price in the data (dotted black line) and a three-standard-deviation emission tax shock used in the quantitative analysis (solid blue line).

standard value in the literature (Nordhaus, 2018). Following the calibration strategy of Carattini et al. (2023), we calibrate its slope parameter θ_1 based on the DICE model, which implies an abatement cost-to-GDP ratio of 1.5% over the next 250 years of the net zero transition. Importantly, in Nordhaus (2018), abatement costs apply to the entire economy, whereas in our model, they affect only the energy sector. We therefore adjust them for the relative size of the energy sector in the initial steady state y/z^e, and arrive at $\theta_1 = 0.075$.

Climate Block Rest-of-the-world emissions e_t^{row} are constructed based on CO2 emissions in the energy sector in 2024, which are provided by the IEA.[10] EU emissions amount to 2.5 GtCO2 in 2024, compared to 37 GtCO2 globally. We can back out the rest-of-the-world emissions based on model-implied emissions and obtain $e_t^{row} = 2.01$. The parameter $\Psi_E = 2 - E04$ implies a damage-to-GDP ratio of 9.5% in the long run, if there is no further climate policy tightening, consistent with recent estimates by Nath et al. (2024) and with values used in similar models.

We estimate the parameters governing the emission tax process directly from the data. In Figure 2, we plot the EU ETS price in USD/tCO2 over time, adjusted for euro area inflation and expressed in 2025 USD. The average ETS price was 42USD/tCO2 throughout the sample

[10]Emission data available at this link.

period. This corresponds to $\tau^e = 0.009$ in the model. In Appendix B, we demonstrate how model-implied tax rates can be transformed into emission prices. To parameterize the emission tax shocks, we fit an AR(1) process, equation (10), to the ETS prices at annual frequency and obtain a tax shock standard deviation σ_τ of 20SD/tCO2 and a persistence parameter of $\rho_\tau = 0.86$.

Central Bank Policy We set the interest rate smoothing parameter in the Taylor rule to $\rho_R = 0.65$ and the parameter governing the response to inflation to $\phi_\pi = 2$, in line with the literature. To calibrate the model, we impose a symmetric collateral treatment of energy and non-energy debt, consistent with the current Eurosystem collateral framework. We set the long-run collateral haircut to $\overline{\kappa}^e = \overline{\kappa}^n = \overline{\kappa}^{sym} = 65\%$. This value is based on the ratio of eligible over total debt issued by non-financial firms (Kaldorf, 2025), corrected for an additional valuation haircut of 10% that corresponds to the Eurosystem haircut on BBB-rated corporate bonds. The haircut parameter should be interpreted as the stance of collateral policy, encompassing both eligibility requirements and valuation haircuts, since a substantial share of bank assets is not eligible at all (corresponding to a 100% haircut), while others can be pledged at substantially lower haircuts. Finally, inspired by the public finance literature, we back out the central banks' cost parameter through an "inverse optimality" approach. Specifically, we set the cost parameter $c_0 = 0.0385$ in equation (24), such that the symmetric collateral framework observed in the data is optimal from a utilitarian welfare perspective. Appendix C.1 provides further details on the long-run implications of changing κ^{sym}.

3.2 Model Fit

Panel A of Table 2 presents the model fit to targeted first moments. Panel B demonstrates the model's ability to reconcile untargeted excess volatilities of key endogenous variables over the volatility of output, which are typically used in the macro-finance literature. Panel C reports correlations of key financial variables with GDP. Consumption, investment, and emissions are highly pro-cyclical. Similarly, key financial indicators, such as debt issuance and leverage, exhibit pro-cyclicality, while corporate default risk is counter-cyclical, consistent with the data. Matching these moments and their cyclical properties is crucial to assessing the macroeconomic effects of tilted collateral policy and its interplay with climate policy uncertainty.

To further corroborate the model's validity, Appendix C.1 displays the transmission of shocks

Moment	**Model**	**Data**
Panel A: Targeted Means		
Collateral premium $ave(r_0 - r)$ in bps	-10	-10
Corporate leverage $ave(lev)$ in %	29	30
Corporate default $ave(F(\overline{m}))$ in %	0.9	0.9
Panel B: Excess Volatilities		
Relative vol. investment $\sigma(i)/\sigma(y)$	3.41	2.66
Relative vol. debt $\sigma(b)/\sigma(y)$	0.91	1.10
Relative vol. debt issuance $\sigma(\Delta b)/\sigma(y)$	3.38	4.75
Relative vol. leverage $\sigma(lev)/\sigma(y)$	0.38	0.79
Relative vol. corporate default $\sigma(F(\overline{m}))/\sigma(y)$	0.10	0.30
Panel C: Correlations		
Emissions-GDP $cor(y, e)$	0.41	0.78
Consumption-GDP $cor(y, c)$	0.89	0.76
Investment-GDP $cor(y, i)$	0.81	0.76
Debt-GDP $cor(y, b)$	0.91	0.61
Debt Issuance-GDP $cor(y, \Delta b)$	0.91	0.46
Leverage-GDP $cor(y, lev)$	0.51	0.24
Firm default-GDP $cor(y, F(\overline{m}))$	-0.29	-0.49

Table 2: Model Fit. All model-implied moments are computed based on a second-order approximation around the deterministic steady state, expressed in deviations from their steady state value. All data moments are based on real data and de-trended using an HP-filter with a smoothing parameter of 6.25. Debt issuance is defined as $\Delta b_t \equiv b_t - (1-\chi)b_{t-1}$.

to banks' liquidity management costs, which affect collateral demand, and to TFP shocks, which mostly affect collateral quality. We show that optimal central bank collateral policy is relaxed in response to an increase in banks' liquidity management costs. The *collateral availability channel* dominates, and the model-implied response is consistent with the lender-of-last-resort policies of all central banks. By contrast, collateral policy tightens in response to negative productivity shocks, which deteriorate collateral quality in the short term and have a less pronounced effect on collateral availability. A dominant *central bank exposure channel* is consistent with the Eurosystem's practice to condition collateral eligibility and valuation haircuts on credit ratings, which generally decrease during a recession. Furthermore, such pro-cyclicality also characterizes optimal repo contracts in the presence of limited commitment by banks and uncertainty about collateral quality (Gotardi et al., 2019). This further corroborates the external validity of our model and its policy implications.

	Baseline	Low tax	Time-varying tax		
	(1)	(2)	(3) Full	(4) < Mean	(5) > Mean
Abatement share (%)	26.6	17.2	24.1	14.8	39.4
Climate policy wedge (%)	0.75	0.40	0.70	0.32	1.33
Energy debt/GDP (%)	15.12	15.37	15.11	15.48	14.51
Non-energy debt/GDP (%)	60.41	60.65	60.45	60.59	60.23
Agg. debt/GDP (%)	75.53	76.02	75.56	76.06	74.74
Energy default (bps)	92	92	95	84	112
Non-energy default (bps)	92	92	92	92	92
Agg. default (bps)	92	92	93	91	96

Table 3: Macroeconomic Effects of Climate Policy. Column (1) refers to the baseline emission tax of 42\$/tCO2. Column (2) refers to a lower value of 21\$/tCO2. Columns (3)-(5) report the results with time-varying emission taxes. Column (3) corresponds to the full sample, column (4) to the sub-sample with below-mean taxes, and column (5) corresponds to the sub-sample with above-mean taxes. The collateral framework is kept at its symmetric and time-invariant baseline value $\overline{\kappa}^{sym} = 65\%$.

4 Optimal Collateral Policy in the Long Run

In this section, we use our calibrated model to study how the conduct of climate policy shapes optimal collateral policy in the long run. We consider three scenarios. In the first scenario, we keep emission taxes constant at their full sample average of 42\$/tCO2. In the second scenario, we lower the emission tax level to its pre-2020 average of 21\$/tCO2. In the third scenario, we introduce time variation in emission taxes by setting $\sigma_\tau = 20$ USD/tCO2 and $\rho_\tau = 0.86$, while the average tax again corresponds to the full sample average of 42\$/tCO2.

4.1 Macro-Financial Effects of Climate Policy

As a preliminary step, we examine the behavior of key macro-financial variables in the different climate policy scenarios. To do so, we fix collateral policy at its symmetric and time-invariant baseline value of $\overline{\kappa}^{sym} = 65\%$. We focus on the abatement effort a_t and the climate-policy wedge ξ_t in the first-order condition for investment, equation (18), which governs the transmission of climate policy to non-financial firms and their debt issuance. We also display aggregate and sector-specific debt issuance and default risk. These variables jointly shape the collateral policy trade-off between collateral availability and the central bank's exposure to default risk.

Table 3 presents the results. The first column refers to a constant emission tax level of 42\$/tCO2, consistent with the full-sample average in the data. The sector-specific debt/GDP ratios of around 15% and 60% reflect the sectoral shares, respectively. The sectoral shares are jointly governed by the coefficients in the production function of final good firms and the climate policy wedge in energy firms' first-order condition for capital. Since time-invariant emission taxes do not enter firms' first-order condition for the default threshold, default risk is symmetric across sectors. Abatement efforts are still below 100%, and the only reason to deviate from symmetric collateral haircuts is welfare-enhancing emission mitigation.

Column (2) corresponds to a lower steady-state tax of 21\$/tCO2, and we still abstract from tax shocks. Since the abatement share and the associated climate policy wedge ξ are lower than in the baseline scenario, energy firms invest more and issue more debt. Since energy and non-energy goods are complements, this has positive spillovers to the non-energy sector, such that aggregate debt is unambiguously larger (76.02%) than in the baseline (75.53%). Furthermore, the default rates are identical to the baseline climate policy specification. In addition to a stronger motive to reduce emissions, greater collateral availability than in the baseline will determine how collateral policy is adjusted optimally.

In columns (3)-(5), we consider the third scenario with emission tax shocks. The full-sample mean in column (3) indicates that both the abatement effort and the associated climate policy wedge are smaller than in the scenario with constant taxes. The lower abatement effort in the full sample is a direct consequence of the convex abatement cost function, equation (8). If taxes are one standard deviation above their mean, the additional abatement effort rises by less than they decline if taxes are one standard deviation below their mean. Consequently, we observe a slightly larger aggregate debt/GDP ratio (75.56%) than in the baseline (75.53%) and, hence, greater collateral availability. Aggregate default risk is slightly larger in the full sample at 93 bps instead of 92bps.

This seemingly small effect of one basis point masks considerable heterogeneity across sectors. To see this, it is helpful to consider the sub-samples with an above- and below-mean emission tax in columns (4) and (5). If taxes are below their mean, the abatement effort is around 12 percentage points smaller than in the baseline, such that energy firms invest more and issue more debt (15.48%) than in the baseline (15.12%), while their default risk is smaller (84bps) than in the baseline (92bps). Positive spillovers to the non-energy sector imply a similar picture for debt issuance and default risk, although the effects are less pronounced. The opposite picture emerges if taxes are above their mean. The default rate in the energy sector increases from 92bps in the baseline by 20bps to 112bps with time-varying taxes. This asymmetry between the sub-samples translates into a higher full-sample energy default rate of 95bps.

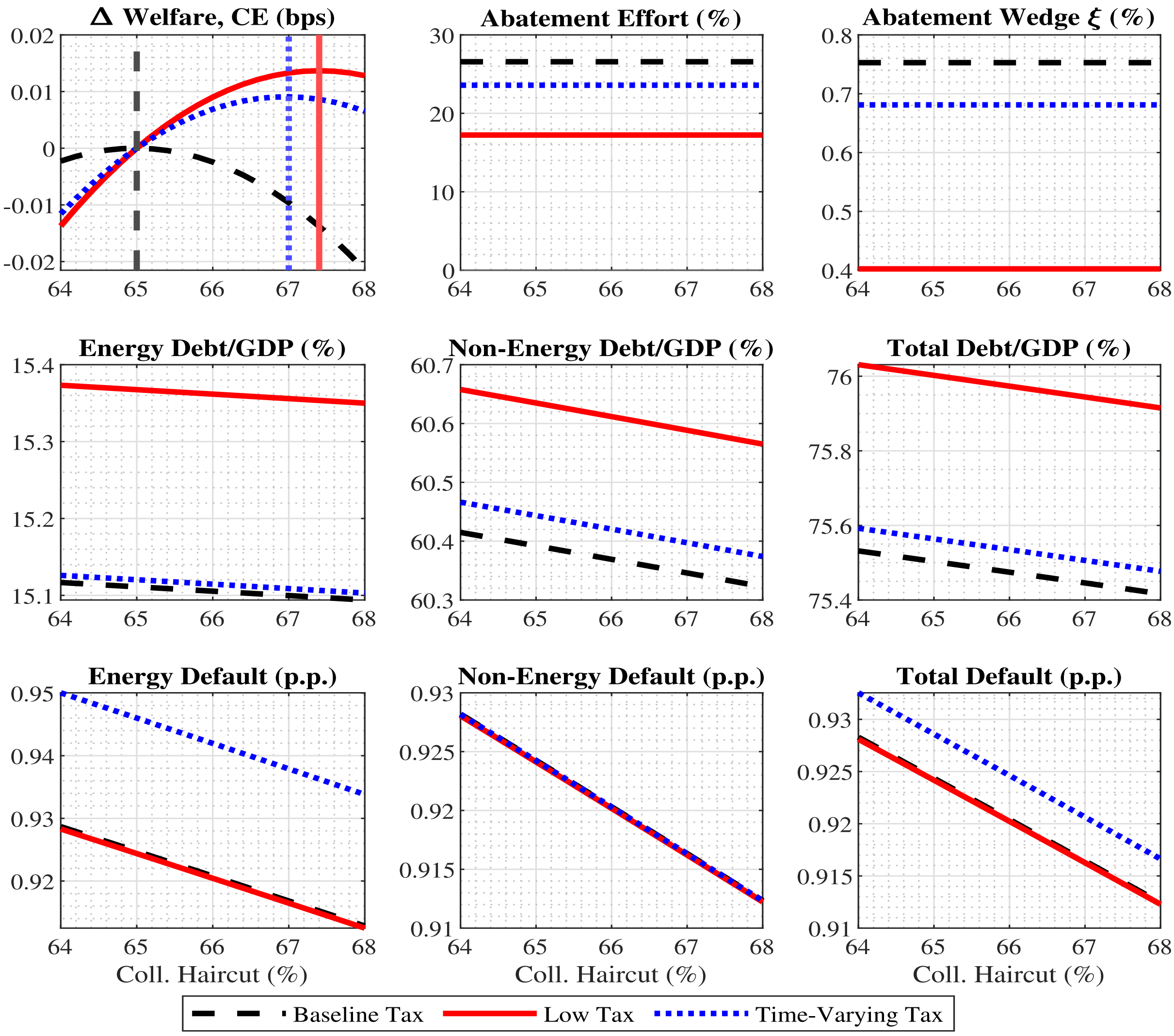

Figure 3: Long-run Effects of Symmetric Collateral Policy. This figure displays the long-run effects of symmetric collateral policy $\overline{\kappa}^{sym}$. Dotted black lines indicate the baseline tax of 42\$/tCO2; solid red lines indicate the lower tax of 21\$/tCO2; and dotted blue lines indicate the time-varying tax with a mean of 42\$/tCO2 and a tax shock standard deviation of 20\$/tCO2. All moments are asymptotic means, based on a second-order approximation around the deterministic steady state.

With emission tax shocks, the collateral policy trade-off is also affected by higher central bank exposure to firm default risk. The larger *central bank exposure* is driven by the energy sector, in particular in states with high taxes. Consequently, there is additional scope for differentiating collateral haircuts across sectors, beyond welfare-enhancing emission reduction.

4.2 Optimal Symmetric Collateral Policy

The macroeconomic effects of the emission tax level and its time variation suggest that the collateral policy trade-off is resolved differently in each climate policy scenario. As a first step, we discuss optimal symmetric collateral policy. In Figure 3, we display how varying $\overline{\kappa}^{sym}$ on the x-axis affects key welfare-relevant variables.

The dashed black lines in Figure 3 correspond to the time-invariant baseline tax of 42\$/tCO2. The upper panel shows that collateral policy does not affect the abatement effort and the associated wedge ξ in energy firms' first-order condition for investment. Raising $\overline{\kappa}^{sym}$ mechanically lowers collateral availability $\overline{b}$, which in turn raises banks' liquidity management cost, equation (5). At the same time, the central bank's exposure to risky collateral and hence the collateral management cost, equation (24), declines.

In addition to these mechanical effects, collateral policy affects debt and default risk in the non-financial sector. If $\overline{\kappa}^{sym}$ is larger, firm debt is less useful as collateral, such that the collateral premium banks are willing to pay on it falls, and firms face worse debt financing conditions. This tilts their financing away from debt issuance and also lowers the default rate. As the lower panels of Figure 3 show, this effect is symmetric across sectors. The optimal collateral parameter $\kappa^{sym} = 65\%$ balances these effects by construction and welfare peaks at this value; see the top left panel.

For a lower emission tax level, the abatement share drops from 26.6% to 17.2% and the debt/GDP ratio increases in both sectors for any symmetric collateral parameter $\overline{\kappa}^{sym}$; see the solid red lines in Figure 3. Notably, the transmission of collateral policy to non-financial firms' debt issuance and their default risk does not depend on the climate policy scenario: the slope of all welfare-relevant variables with respect to $\overline{\kappa}^{sym}$ is identical in each case. However, the collateral parameter at which the welfare maximum is obtained changes. Due to greater collateral availability, it becomes optimal to increase κ^{sym} from 65% to 67.4%. In nominal terms, this amounts to making around 500bn EUR of assets ineligible as collateral. Such a collateral policy tightening also lowers the central bank exposure below its baseline level.

If we add time-varying taxes, represented by the dotted blue lines in Figure 3, the abatement effort also declines. Consequently, the abatement wedge is smaller, and we observe a small increase in collateral availability. While this resembles the case of lower taxes, the bottom left panel of Figure 3 also reveals a strongly elevated rise in energy default risk. It is, therefore, optimal to tighten collateral policy. Quantitatively, $\overline{\kappa}^{sym}$ increases from 65% to 67%.

Taken together, both a lower tax level and higher tax volatility render a more stringent collateral policy optimal. While emission mitigation does not play a role in symmetric collateral policy adjustments, it is worth noting that a lower tax level primarily shifts the collateral policy trade-off by increasing collateral availability uniformly across sectors. Higher tax volatility, instead, is associated with a larger central bank exposure stemming almost exclusively from the energy sector. This already suggests that the central bank exposure channel might give rise to optimal sector-specific haircuts only if there are tax shocks and that sector-specific collateral policy can only be motivated with emission mitigation objectives if climate policy is constant, as we see next.

4.3 Optimal Sectoral Tilts

As a next step, we consider optimal sectoral tilts. Collateral policy can differ between sectors, but the sector-specific haircuts $\kappa_t^e = \overline{\kappa}^e$ and $\kappa_t^n = \overline{\kappa}^n$ are kept constant over time. In Figure 4, we plot the transmission of energy sector haircuts to key welfare-relevant variables. For any $\overline{\kappa}^e$, we show all variables after optimizing the non-energy collateral parameter $\overline{\kappa}^n$, shown in the top right panel of Figure 4. As for the symmetric policy, the transmission of sectoral tilts does not depend on the climate policy specification: the solid red lines, reflecting the low tax scenario, and the dotted blue lines, reflecting time-varying taxes, have the same slope as the baseline scenario (dashed black lines).

Long-run tilts introduce a sectoral re-allocation, similar to Giovanardi et al. (2023). However, the sectoral re-allocation contributes relatively little to the total emissions, as such a policy does not affect technology choices and the abatement share in the energy sector. Nevertheless, the welfare-maximizing long-run collateral framework is given by $\overline{\kappa}^e = 72.0\%$ and $\overline{\kappa}^n = 63.2\%$. While the welfare gains are still small, they still exceed welfare under the symmetric baseline policy.

In the previous section, we discussed that the optimal collateral policy trade-off is not asymmetrically affected by the emission tax level. Therefore, we can attribute any tilting towards the energy sector to the emission mitigation channel. Consistent with this argument, the optimal extent of tilting is larger when we reduce emission taxes to 21\$/tCO2. The energy-sector haircut rises to 77.5%, and the welfare gain is almost five times larger than the simple symmetric adjustment discussed in the previous section.

The extent of steady-state tilting is also considerably larger with time-varying emission taxes, where the energy-sector haircut increases to 81%. This can be attributed to the central bank exposure channel and primarily reflects the higher default risk in the energy sector. The large scope for tilted collateral policy due to emission tax shocks is also illustrated by the welfare gain, which is 10 times larger than for the symmetric adjustment.

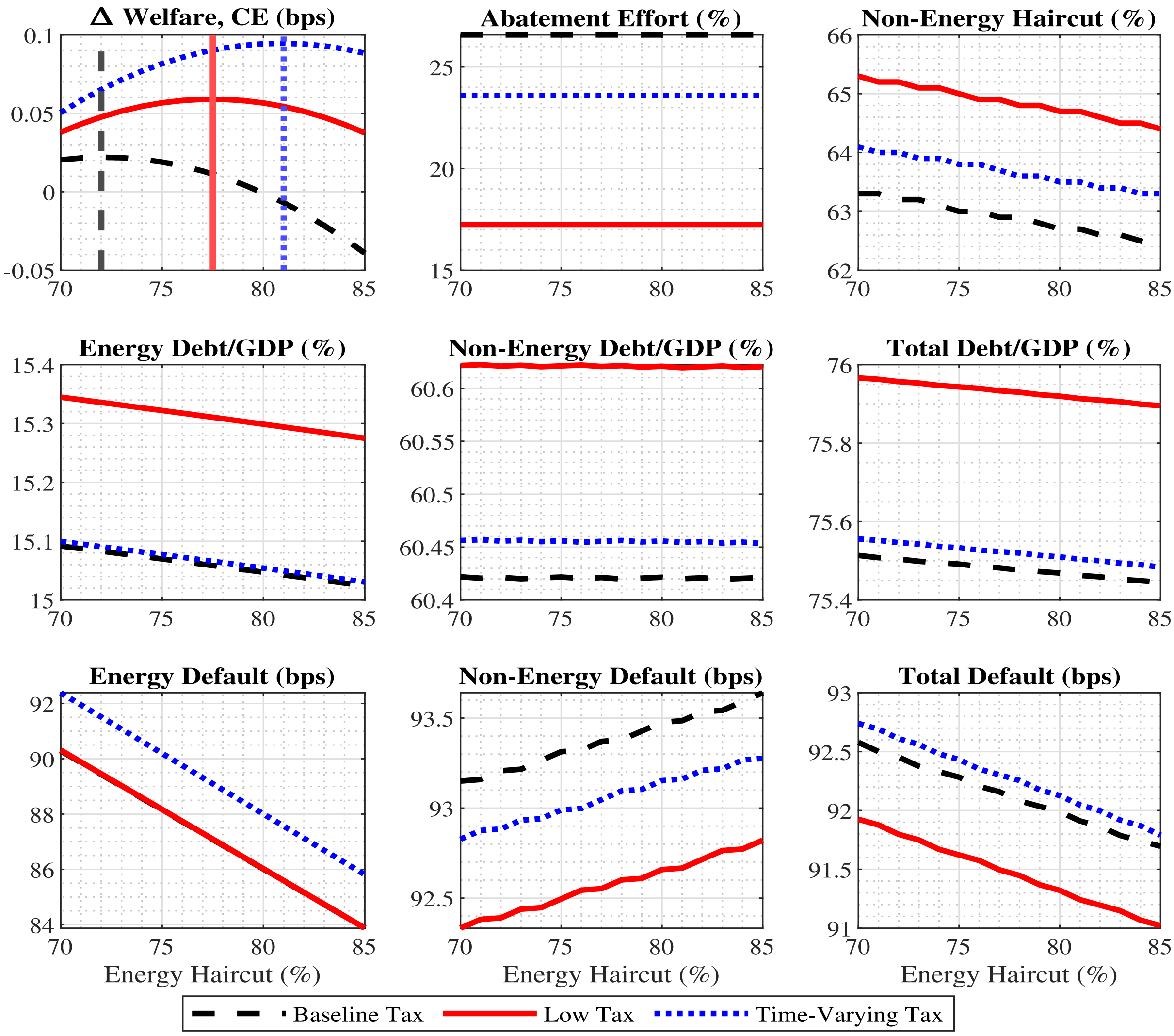

Figure 4: Long-run Effects of Sectoral Tilts. This figure displays the long-run effects of varying the energy-sector haircut $\overline{\kappa}^e$. For each $\overline{\kappa}^e$, the non-energy sector haircut $\overline{\kappa}^n$ is set to its optimal value. Dotted black lines indicate the baseline tax of 42\$/tCO2; solid red lines indicate the lower tax of 21\$/tCO2; and dotted blue lines indicate the time-varying tax with a mean of 42\$/tCO2 and a tax shock standard deviation of 20\$/tCO2. All moments are asymptotic means, based on a second-order approximation around the deterministic steady state.

4.4 Optimal Sustainability-Linked Collateral Policy

We now introduce sustainability-linked collateral policy and study the welfare-maximizing policy parameter $\overline{\kappa}^{sl}$ and the implications for macro-financial variables. The results are displayed in Figure 5. Similar to the long-run tilts, we optimize $\overline{\kappa}^n$ for every $\overline{\kappa}^{sl}$. For the baseline tax level, a collateral parameter of $\overline{\kappa}^{sl} = 95\%$ is optimal. This raises the optimal abatement effort by around 0.5 percentage points and increases welfare through the emission mitigation channel.

However, high values of $\overline{\kappa}^{sl}$ are associated with side effects on financial markets, in particular, the availability of collateral to banks. By raising aggregate haircuts, the SLCP mechanically lowers collateral considerably. This mechanical effect is reinforced by a decline in debt issuance in the energy sector, because energy firms experience a decline in their borrowing conditions and substitute their financing away from debt. Therefore, the haircut on non-energy firms and energy firms that fully abate their emissions declines to $\overline{\kappa}^n = 59.9\%$.

Why is the optimal $\overline{\kappa}^{sl}$ so close to its maximum value of 100%? As before, emission mitigation is the only reason for tilting under constant emission taxes. In the previous section, we have demonstrated that collateral policy tilts at the sectoral level imply a small emission reduction by downsizing the energy sector, and a correspondingly small welfare gain. This modest effect is consistent with generally small effects of sector-specific macro-financial policies, such as collateral frameworks, asset purchases, bank regulation, and macroprudential policies, which have been established in prior literature (Giovanardi et al., 2023; Ferrari and Nispi Landi, 2023; Giovanardi and Kaldorf, 2026). However, policies studied in this literature do not affect technology choices within energy-intensive sectors. By contrast, under the sustainability-linked collateral policy, a greater abatement effort by energy firms reduces the effective haircut κ_t^e on their debt when banks pledge it with the central bank. This makes energy sector debt more valuable as collateral to banks. Formally, the collateral premium in the debt pricing condition, equation (15), rises, and energy firms are rewarded for their greater abatement effort by higher loan prices.

The possibility to affect technology choices *within* sectors through collateral frameworks adds a novel dimension to the literature on central banks and climate change. The top middle panel of Figure 5 demonstrates that the abatement effort in the energy sector rises as the SLCP becomes more stringent. Again, the transmission of the SLCP to macro-financial variables does not depend on the climate policy scenario, but the tax level and the tax volatility determine the optimal $\overline{\kappa}^{sl}$. The relevance of the *technology adoption channel* is also underscored by the welfare gain, which exceeds the sectoral tilts by a factor 10.

For the low tax level and high tax volatility, the maximum value of $\overline{\kappa}^{sl} = 100\%$ is optimal. Note that this does not exclude energy sector firms from the set of eligible collateral. The central bank only stops lending against energy firms that use an entirely fossil technology. Nevertheless, effective haircuts rise to more than 80% at the optimal SLCP. Consequently, energy firms issue much less debt and default less often, while the opposite picture emerges for the non-energy sector. These effects are similar to the sectoral tilts and further reduce emissions by downsizing the energy sector.

Table 4 summarizes the optimal collateral policy and the associated welfare gains for each climate policy scenario. It should be noted that the welfare gains of central bank collateral

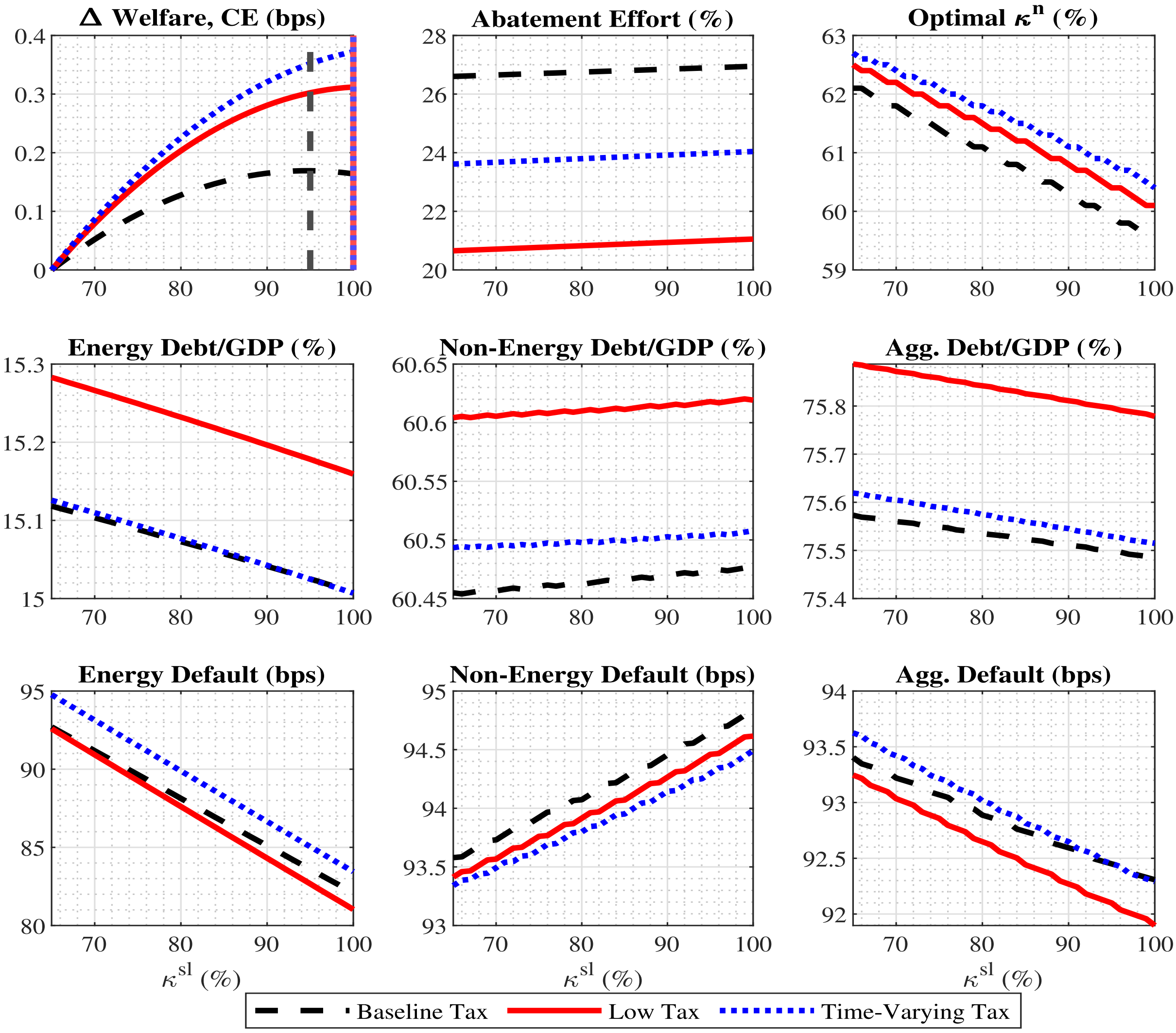

Figure 5: Long Run Effects of SLCP. This figure displays the long-run effects of varying the energy-sector haircut $\overline{\kappa}^{sl}$. For each $\overline{\kappa}^{sl}$, the non-energy sector haircut $\overline{\kappa}^{n}$ is set to its optimal value. Dotted black lines indicate the baseline tax of 42\$/tCO2; solid red lines indicate the lower tax of 21\$/tCO2; and dotted blue lines indicate the time-varying tax with a mean of 42\$/tCO2 and a tax shock standard deviation of 20\$/tCO2.

policy at the macro level are generally modest, but the magnitudes differ considerably between different scenarios. The left panel shows that symmetric collateral policy is more stringent if emission taxes are low or their volatility is high. These adjustments reflect changes in collateral availability and central bank exposure, but no emission mitigation objectives. The middle panel reveals that a quantitatively relevant haircut gap of 8.8 percentage points is optimal in the baseline, while it widens to 12.7 percentage points with low taxes, exclusively reflecting the emission mitigation channel. Substantial tilting of 17.6 percentage points is also optimal for empirically plausible emission tax volatilities, where the welfare gains are also greatest due to the central bank exposure channel.

The right panel of Table 4 suggests that tying collateral haircuts in the energy sector to the

	Symmetric		Sectoral tilts			SLCP		
	$\overline{\kappa}^{sym}$	ΔV	$\overline{\kappa}^{e}$	$\overline{\kappa}^{n}$	ΔV	$\overline{\kappa}^{sl}$	$\overline{\kappa}^{n}$	ΔV
42$/tCO2 tax	65.0	-	72.0	63.2	0.022	95.0	59.9	0.235
21$/tCO2	67.4	0.013	77.5	64.8	0.059	100.0	60.1	0.326
Time-varying tax	67.0	0.009	81.0	63.4	0.094	100.0	60.4	0.382

Table 4: Emission Taxes and Collateral Policy: Long Run. This table reports the optimal collateral framework for both climate policy scenarios. The shock volatility is set to $\sigma_\tau = 20\$/tCO2$. Welfare gains are expressed in consumption equivalents (basis points), relative to the symmetric baseline collateral policy $\kappa^{sym} = 65\%$.

abatement effort at the firm level implies much larger welfare gains by reducing emissions more effectively than simple long-run tilts. This is due to the emission mitigation channel, which is much stronger if central banks directly affect the abatement effort at the firm level. By contrast, the welfare gains with time-varying taxes are still considerable but much less pronounced than under constant taxes. The last row of Table 4 indicates that the welfare gain of SCLP exceeds the welfare gains of optimal long-run tilts merely by a factor of three. We therefore discuss the interactions between central bank collateral policy and time-varying emission taxes in the next section.

5 Optimal Dynamic Collateral Policy

In the previous section, we have shown that long-run tilts and sustainability-linked collateral policy improve welfare, and more so if emission taxes are either low or time-varying. Importantly, we have studied these effects from an ex ante perspective, i.e., the central bank takes into account how emission tax shocks affect sector-specific default risk and the central bank's exposure. In this section, we take an ex post perspective and characterize the optimal collateral policy response to emission tax shocks. We take a particularly close look at the implications of sustainability-linked collateral policy for the joint dynamics of emission taxes and energy sector haircuts: by tying haircuts to the abatement effort, this policy induces time variation into the collateral framework which does not have to align with the optimal policy.

We operationalize the optimal (sector-specific) response to emission tax shocks via the following simple rules:

$$\kappa_t^e = \overline{\kappa}^{sym} + \varphi_\tau^e(\tau_t^e - \overline{\tau}^e) \,, \tag{27}$$

$$\kappa_t^n = \overline{\kappa}^{sym} + \varphi_\tau^n(\tau_t^e - \overline{\tau}^e) \,, \tag{28}$$

where $\overline{\tau}^e$ is the long-run emission tax of 42\$/tCO2. We optimize over the coefficients φ_τ^e and φ_τ^n, using a utilitarian welfare criterion, i.e., we maximize equation (1), subject to the equilibrium conditions of the model.

Our quantitative results are illustrated using historical EU ETS prices, which we have also used to calibrate the AR(1) process for the emission tax. Figure 2 in Section 3 also shows that the ETS price was quite stable for more than a decade before experiencing a large and persistent increase from 42USD/tC02, its full-sample mean, in 2019 to almost 100USD/tC02 in 2021. Hence, we compute IRFs under the assumption that all shocks have been zero for many periods, such that the economy is in the stochastic steady state, and then subject the economy to a three-standard-deviation shock, i.e., we set $\epsilon_t^\tau = 3$ in equation (10). In this case, the emission tax jumps to 100USD/tCO2 on impact.

Emission Tax Shocks Before characterizing the optimal collateral policy, we shed light on the transmission of emission tax shocks to key macro-financial variables. Figure 6 displays the impulse response to a 60\$/tCO2 tax increase, holding collateral policy constant. Higher emission taxes are associated with a greater abatement share and higher energy prices. Consistent with empirical evidence, there is a decline in investment in both sectors, which is more pronounced in the directly affected energy sector, but still sizable in the non-energy sector due to the low substitutability of energy and non-energy goods. Debt and collateral availability decline, again with stronger effects in the energy sector.

The bottom row of Figure 6 shows that the default rate in the energy sector more than doubles from 90bps to 200bps, while it declines by around 5bps in the non-energy sector. Despite its small size, the large response of energy sector default risk dominates, such that aggregate default risk rises, while collateral availability declines. This points towards a non-trivial collateral policy trade-off from an aggregate perspective, since less collateral is available and the central bank is larger. Furthermore, these opposing responses of the central bank exposure to an emission tax shock suggest that a sector-specific collateral policy adjustment may be beneficial.

Optimal Collateral Policy Rules As a next step, we examine how the (sector-specific) responses of debt and default risk affect the collateral policy trade-off. The solid blue lines in **??** represent the case of constant collateral policy and reveal that the collateral value of energy sector debt $\overline{b}_t^e \equiv (1-\kappa_t^e) b_t^e \mathcal{R}_t^e$ and of non-energy debt $\overline{b}_t^n \equiv (1-\kappa_t^n) b_t^n \mathcal{R}_t^n$ both decline. The

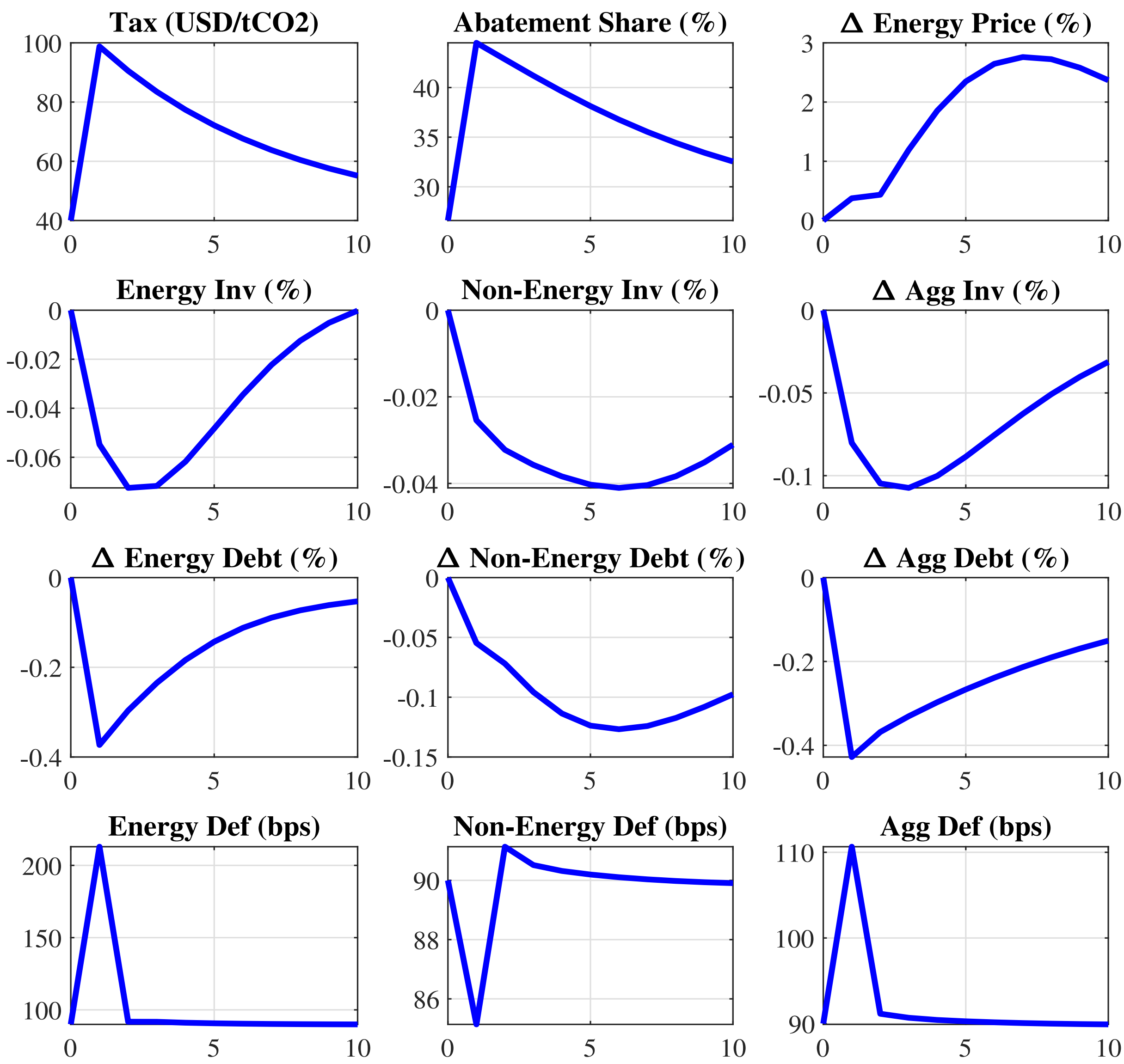

Figure 6: Impulse Response to Emission Tax Shock, Additional Variables. This graph displays the impulse response to a 60\$/tCO2 emission tax shock.

central bank's exposure to energy default risk, defined as $\overline{F}_t^e \equiv (1-\kappa_t^e)b_t^e\mathcal{R}_t^e F(\overline{m}_t^e)^{c_1}$, rises considerably. The exposure $\overline{F}_t^n \equiv (1-\kappa^n)b_t^n\mathcal{R}_t^n F(\overline{m}_t^n)^{c_1}$ from accepting non-energy debt falls.

The optimal collateral policy response to an emission tax shock depends on the relative strength of the *collateral availability* and *central bank exposure* channels. Quantitatively, the latter channel dominates, and it is optimal to tighten collateral policy. The optimized coefficients in equations (27) and (28) are $\varphi_\tau^e = 0.007$ and $\varphi_\tau^n = -0.0003$. The lower panel of Figure 7 illustrates that it is optimal to tighten collateral haircuts in the energy sector if emission taxes are above their mean, while the optimal non-energy haircut is lower. The aggregate haircut response is positive, such that the overall central bank exposure is lower, but tilted towards the relatively safer non-energy sector.

Quantitatively, it is optimal to raise the energy collateral parameter κ_t^e by more than 20 percentage points. In practice, this can be implemented by reducing the share of energy debt that can be pledged with the central bank from 35% to 15%, or by substantially raising the valuation haircuts on eligible energy debt. At the same time, the reduction in exposure to non-energy default risk renders a temporary relaxation of κ_t^n optimal. Lowering the non-energy collateral parameter also stabilizes aggregate collateral availability, which still falls by almost ten percent.

Re-optimizing the coefficients under the adjusted κ^{sym} or under the optimal steady state tilting yields remarkably similar coefficients φ_τ^e and φ_τ^n, suggesting that both the long-run implications of emission tax shocks on collateral availability and default risk, as well as stabilization over the climate policy cycle are important determinants of optimal collateral policy.[11]

Sustainability-Linked Collateral Policy We also assess whether the SLCP replicates the optimal collateral policy response. The dotted orange lines in Figure 7 correspond to the optimized SLCP. If emission taxes rise, firms abate a larger share of their emissions and the effective energy haircut κ_t^e in equation (13) falls. This is indicated by the dotted orange line in the lower middle panel of Figure 7. Crucially, the reduction in collateral haircuts has the opposite sign to the optimal energy haircut response and is significantly more muted in magnitude. By contrast, the non-energy haircut does not respond to emission tax shocks under the SLCP. Contrary to the optimal policy response, aggregate collateral increases, and the central bank's exposure to energy collateral remains very high.

The misalignment of the SLCP and the optimal energy-sector haircuts suggests that such a policy should be augmented by a dynamic component. Specifically, we add the term $\phi^{sl}(\tau_t^e - \overline{\tau}^e)$ to the energy-sector haircut, equation (13):

$$\kappa_t^e = (1 - a_t) \cdot \overline{\kappa}^{sl} + a_t \cdot \overline{\kappa}^{sym} + \phi^{sl}(\tau_t^e - \overline{\tau}^e) \ . \tag{29}$$

Jointly optimizing the coefficient $\phi^{sl} = 0.008$ and $\phi^n = -0.0007$ in equation (28) yields slightly

[11] Formally, we obtain the same coefficients if we increase the symmetric long-run collateral parameter to $\overline{\kappa}^{sym} = 67\%$. The same coefficients are also obtained if we set the long-run collateral parameters to their optimal values $\overline{\kappa}^e = 81\%$ and $\overline{\kappa}^n = 63.4\%$; and modify equations (27) and (28) as follows:

$$\kappa_t^e = \overline{\kappa}^e + \varphi_\tau^e(\tau_t^e - \overline{\tau}^e) \ ,$$
$$\kappa_t^n = \overline{\kappa}^n + \varphi_\tau^n(\tau_t^e - \overline{\tau}^e) \ .$$

The optimized coefficients are virtually identical to the case with the symmetric long-run value from our baseline calibration.

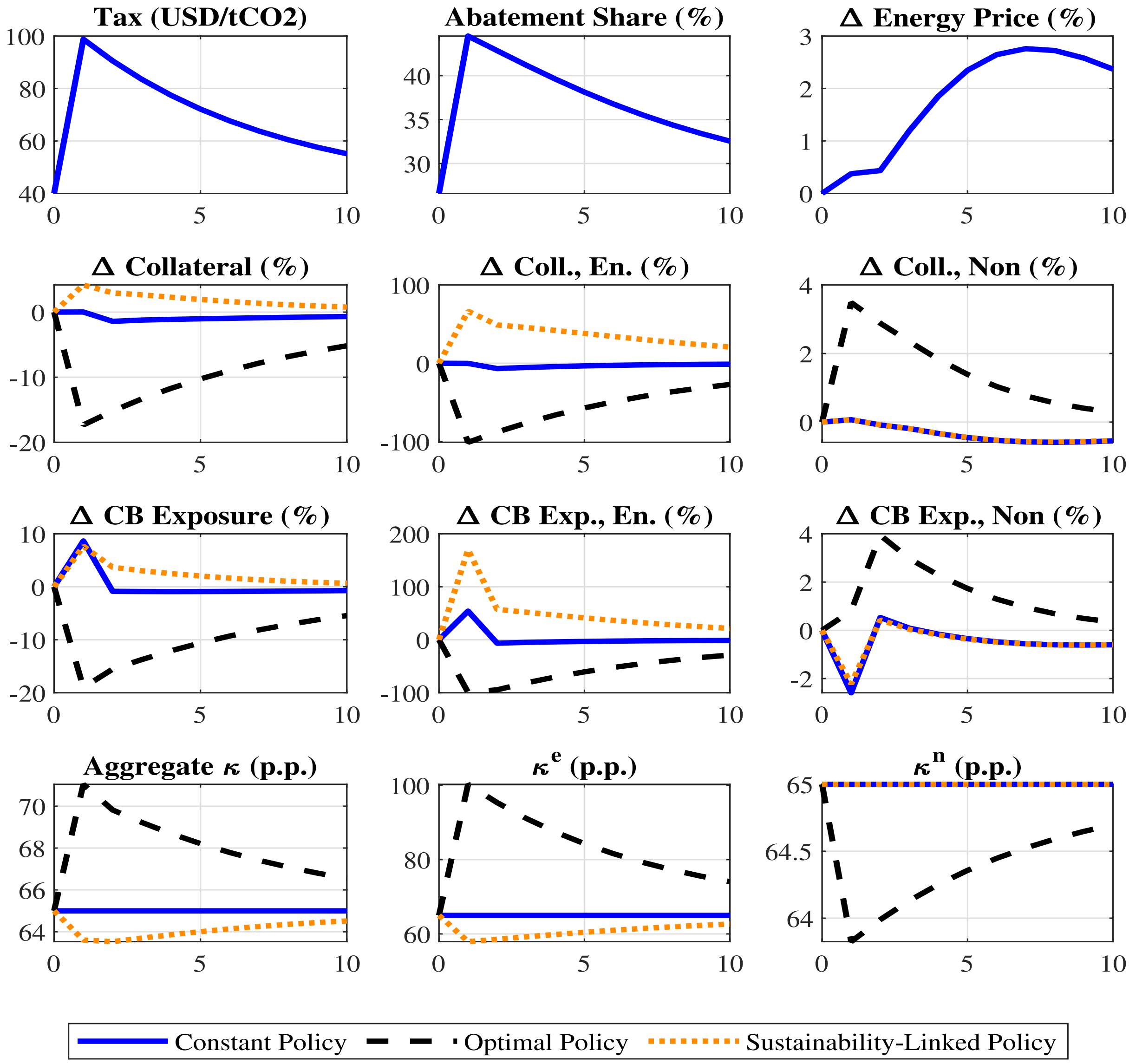

Figure 7: SLCP: Impulse Response to an Emission Tax Shock. This graph displays the impulse response to a 45\$/tCO2 emission tax shock with a persistence of $\rho_\tau = 0.86$. The solid line reflects the constant baseline collateral framework $\kappa_t^e = \kappa_t^n = \kappa^{sym} = 65\%$; the dashed black line reflects the optimal collateral policy response, and the dotted orange line reflects the SLCP.

more aggressive haircut responses than before, but of very similar magnitudes. This suggests that augmenting the SLCP by a dynamic component can contribute to aligning energy sector haircuts with the optimal policy response while preserving the additional abatement incentives provided by the SLCP. Since this policy is symmetric with respect to high and low emission taxes, it also does not interfere with the desirable ex ante reduction of exposure to energy sector default risk.

6 Conclusion

In this paper, we have proposed and calibrated an E-DSGE model with an energy and non-energy sector, banks, and financial frictions. Banks lend to non-financial firms and are willing to pay collateral premia on corporate debt because they can pledge it with the central bank to obtain short-term funding. In a calibration to the euro area, we examine how the conduct of climate policy shapes optimal collateral policy.

We find that optimal collateral policy is generally tighter if taxes are low, as investment, debt, and collateral availability are larger than under high taxes, or if taxes are time-varying, as default risk is larger. Sector-specific collateral policy tilts further improve welfare. If taxes are low, these gains arise from a relatively more important contribution to emission mitigation, because higher energy sector haircuts reduce aggregate emissions. If taxes are time-varying, higher energy sector haircuts mitigate the central bank exposure to energy sector default risk. Quantitatively, time-varying taxes appear to induce stronger sectoral tilts, pointing towards an important central bank exposure channel.

If collateral haircuts also reward clean technology adoption at the firm level, they improve welfare even further, as these additional incentives reduce emission intensities to a meaningful extent. As long as energy firms are not completely emission-free, they also reduce the central bank's exposure to risky energy. Consequently, the extent of such a sustainability-linked collateral policy is greater if taxes are either low or time-varying.

Lastly, we study the optimal collateral policy response to emission tax shocks. Energy sector haircuts optimally increase when taxes suddenly rise, thereby reducing exposure to elevated energy sector default risk. By contrast, non-energy default risk and haircuts optimally decline, such that aggregate collateral availability remains approximately constant without adding substantial central bank exposure to default risk. Importantly, energy sector haircuts decline under the SLCP after an emission tax increase, as firms abate more emissions and are rewarded with lower haircuts. This response is inconsistent with the optimal dynamic collateral policy. Augmenting the SLCP using a dynamic component, similar to a simple collateral policy rule, aligns the energy sector haircuts under the SLCP with optimal policy without compromising its contribution to emission mitigation and the beneficial ex ante reduction of exposure to energy sector debt.

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Online Appendix to "Optimal Sustainability-Linked Collateral Policy"

Francesca Diluiso, Francesco Giovanardi and Matthias Kaldorf

A Model Appendix

A.1 Intermediate Good Firms

The i.i.d. productivity shock and intermediate restructuring assumption allow us to write the shareholder maximization problem as a two-period problem:

$$\begin{aligned}\max_{a_t, b^e_{t+1}, k^e_{t+1}, \overline{m}^e_{t+1}} \; & - k^e_{t+1} + q(\overline{m}^e_{t+1}, a_t)\Big(b^e_{t+1} - (1-\chi)\frac{b^e_t}{\pi_t}\Big) \\ & + \mathbb{E}_t\Bigg[\widetilde{\Lambda}_{t,t+1} \cdot \Bigg\{\int_{\overline{m}^e_{t+1}}^{\infty} \widetilde{p}^e_{t+1} m k^e_{t+1} - \frac{\chi b^e_{t+1}}{\pi_{t+1}} f(m) dm \\ & \qquad + (1-\delta_K)k^e_{t+1} + q(\overline{m}^e_{t+2}, a_{t+1})\Big(b^e_{t+2} - (1-\chi)\frac{b^e_{t+1}}{\pi_{t+1}}\Big)\Bigg\}\Bigg] .\end{aligned}$$

Since the corporate debt maturity exceeds one period, today's risk choice $\overline{m}^e_{t+1}$ affects tomorrow's risk choice $\overline{m}_{t+2}$ through the roll-over terms in the first-order condition for next period's default threshold and also in the derivative of the debt price schedule (Gomes et al., 2016). To handle this in a computationally efficient way, we derive an additional equilibrium condition to pin down the slope of the policy function for leverage $\frac{\partial \overline{m}^e_{t+2}}{\partial \overline{m}^e_{t+1}}$. Specifically, we can use the first-order condition for debt, equation (17), to write the Lagrange multiplier on the risk choice as:

$$\mu^e_t = \frac{b^e_{t+1}}{\overline{m}^e_{t+1}} q(\overline{m}^e_{t+1}) - \mathbb{E}_t \frac{\widetilde{\Lambda}_{t,t+1}}{\pi_{t+1}} \frac{b^e_{t+1}}{\overline{m}^e_{t+1}} \Big(\chi(1 - F(\overline{m}^e_{t+1})) + (1-\chi) q(\overline{m}^e_{t+2})\Big) . \tag{A.30}$$

Using this expression in the first-order condition for capital, equation (18),

$$
\begin{aligned}
1-&\mathbb{E}_t \frac{b^e_{t+1}}{\pi_{t+1} k^e_{t+1}} \left(q(\overline{m}^e_{t+1})\pi_{t+1} - \widetilde{\Lambda}_{t,t+1} \left\{ \chi(1-F(\overline{m}^e_{t+1})) + (1-\chi) q(\overline{m}^e_{t+2}) \right\} \right) \\
=&\mathbb{E}_t \widetilde{\Lambda}_{t,t+1} \left((1-\delta_k)\psi^e_{t+1} + (1-G(\overline{m}^e_{t+1}))\widetilde{p}^e_{t+1} \right) .
\end{aligned}
$$

and multiplying both sides by $\frac{\chi}{\widetilde{p}^e_{t+1}}$, we get

$$
\begin{aligned}
\frac{\chi}{\widetilde{p}^e_{t+1}} - &\overline{m}^e_{t+1} \mathbb{E}_t \left(q(\overline{m}^e_{t+1})\pi_{t+1} - \widetilde{\Lambda}_{t,t+1} \left\{ \chi(1-F(\overline{m}^e_{t+1})) + (1-\chi) q(\overline{m}^e_{t+2}) \right\} \right) \\
&= \mathbb{E}_t \widetilde{\Lambda}_{t,t+1} \left(\frac{\chi}{\widetilde{p}^e_{t+1}} (1-\delta_k)\psi^e_{t+1} + \chi(1-G(\overline{m}^e_{t+1})) \right) .
\end{aligned}
$$

We then differentiate with respect to $\overline{m}^e_{t+1}$ and obtain

$$
\begin{aligned}
&- q(\overline{m}^e_{t+1})\pi_{t+1} + \mathbb{E}_t \widetilde{\Lambda}_{t,t+1} \left(\chi(1-F(\overline{m}^e_{t+1})) + (1-\chi) q(\overline{m}^e_{t+2}) \right) \\
&- \overline{m}^e_{t+1} \mathbb{E}_t \widetilde{\Lambda}_{t,t+1} \left(\frac{\partial q^e_t}{\partial \overline{m}^e_{t+1}} \pi_{t+1} + \chi f(\overline{m}^e_{t+1}) + (1-\chi) \frac{\partial q^e_{t+1}}{\partial \overline{m}^e_{t+2}} \frac{\partial \overline{m}^e_{t+2}}{\partial \overline{m}^e_{t+1}} \right) = -\chi \mathbb{E}_t \widetilde{\Lambda}_{t,t+1} g(\overline{m}^e_{t+1}) ,
\end{aligned}
$$

We exploit that the derivative of the partial expectation $G(\overline{m}^e_{t+1}) = \int_0^{\overline{m}^e_{t+1}} m f(m) dm$ satisfies $g(\overline{m}^e_{t+1}) = \overline{m}^e_{t+1} f(\overline{m}^e_{t+1})$, which directly follows from Leibniz' integral rule. Hence, we get an additional equilibrium condition that pins down the slope of the policy function for leverage $\frac{\partial \overline{m}^e_{t+2}}{\partial \overline{m}^e_{t+1}}$:

$$
q(\overline{m}^e_{t+1}) + \overline{m}^e_{t+1} \frac{\partial q^e_t}{\partial \overline{m}^e_{t+1}} = \mathbb{E}_t \frac{\widetilde{\Lambda}_{t,t+1}}{\pi_{t+1}} \left(\chi(1-F(\overline{m}^e_{t+1})) + (1-\chi) \left\{ q(\overline{m}^e_{t+2}) + \overline{m}^e_{t+1} \frac{\partial q^e_{t+1}}{\partial \overline{m}^e_{t+2}} \frac{\partial \overline{m}^e_{t+2}}{\partial \overline{m}^e_{t+1}} \right\} \right) , \tag{A.31}
$$

The LHS of equation (A.31) summarizes the additional dividends today financed by issuing one unit of debt net of a debt dilution term, as $q'(\overline{m}^e_{t+1})$ is negative. The RHS of equation (A.31) indicates that increasing leverage today increases the expected repayment obligation from the maturing debt share χ and also affects how a higher leverage affects the additional dividends tomorrow that can be financed by issuing one unit of debt. This condition is derived entirely analogously for clean and non-energy firms.

Non-Energy Firms The maximization problem has a similar structure to energy firms, but does not include the abatement effort as a choice variable:

$$\max_{b^n_{t+1},k^n_{t+1},\overline{m}^n_{t+1}} - k^n_{t+1} + q(\overline{m}^n_{t+1})\Big(b^n_{t+1} - (1-\chi)\frac{b^n_t}{\pi_t}\Big)$$
$$+ \mathbb{E}_t\Bigg[\widetilde{\Lambda}_{t,t+1}\cdot\Bigg\{\int_{\overline{m}^n_{t+1}}^{\infty} p^n_{t+1} m k^n_{t+1} - \frac{\chi b^n_{t+1}}{\pi_{t+1}} f(m)dm$$
$$+ (1-\delta_K)k^n_{t+1} + q(\overline{m}^n_{t+2})\Big(b^n_{t+2} - (1-\chi)\frac{b^n_{t+1}}{\pi_{t+1}}\Big)\Bigg\}\Bigg],$$

The debt price schedule simplifies to

$$q(\overline{m}^n_{t+1}) = \mathbb{E}_t\left[\left\{(1-\chi)q(\overline{m}^n_{t+2}) + \frac{\chi}{\pi_t}\Big(1 - F(\overline{m}^n_t)\Big)\right\}\cdot\frac{(1 + (1-\kappa^n_t)\Omega_{t+1})}{1+i_t}\right]. \tag{A.32}$$

Now, μ^n_t denotes the Lagrange-multiplier on the default threshold (11), so that the first-order condition for debt issuance is:

$$q(\overline{m}^n_{t+1}) - \mu^n_t\frac{\overline{m}^n_{t+1}}{b^n_{t+1}} = \mathbb{E}_t\left[\frac{\widetilde{\Lambda}_{t,t+1}}{\pi_{t+1}}\Big\{\chi(1 - F(\overline{m}^e_{t+1})) + (1-\chi)q(\overline{m}^n_{t+2})\Big\}\right]. \tag{A.33}$$

while optimal investment is given by:

$$1 - \mu^n_t\frac{\overline{m}^n_{t+1}}{k^n_{t+1}} = \mathbb{E}_t\left[\widetilde{\Lambda}_{t,t+1}\Big\{(1-\delta_K) + p^n_{t+1}\big(1 - G(\overline{m}^n_{t+1})\big)\Big\}\right]. \tag{A.34}$$

The risk choice $\overline{m}^n_{t+1}$ solves:

$$-\mu^n_t - \frac{\partial q^n_t}{\partial \overline{m}^n_{t+1}}\Big(b^n_{t+1} - (1-\chi)\frac{b^n_t}{\pi_t}\Big) = \mathbb{E}_t\left[\widetilde{\Lambda}_{t,t+1}\Big(b^n_{t+2} - (1-\chi)\frac{b^n_{t+1}}{\pi_{t+1}}\Big)\frac{\partial q^n_{t+1}}{\partial \overline{m}^n_{t+2}}\frac{\partial \overline{m}^n_{t+2}}{\partial \overline{m}^n_{t+1}}\right]. \tag{A.35}$$

The derivative of the debt price schedule (A.32) with respect to the risk choice in the non-energy sector reads:

$$\frac{\partial q^n_t}{\partial \overline{m}^n_{t+1}} = \mathbb{E}_t\left[\left\{-\chi\frac{F'(\overline{m}^n_{t+1})}{\pi_{t+1}} + (1-\chi)\frac{\partial q^n_{t+1}}{\partial \overline{m}^n_{t+2}}\frac{\partial \overline{m}^n_{t+2}}{\partial \overline{m}^n_{t+1}}\right\}\cdot\frac{1 + (1-\kappa^n_{t+1})\Omega_{t+1}}{1+i_t}\right]. \tag{A.36}$$

To fully characterize the solution to the firm problem, we take the derivative of banks' debt price schedule (15) with respect to the risk choice:

$$\frac{\partial q^e_t}{\partial \overline{m}^e_{t+1}} = \mathbb{E}_t\left[\left\{-\chi\frac{F'(\overline{m}^e_{t+1})}{\pi_{t+1}} + (1-\chi)\frac{\partial q^e_{t+1}}{\partial \overline{m}^e_{t+2}}\frac{\partial \overline{m}^e_{t+2}}{\partial \overline{m}^e_{t+1}}\right\}\cdot\frac{1 + (1-\kappa^e_{t+1})\Omega_{t+1}}{1+i_t}\right]. \tag{A.37}$$

A.2 Final Good Firms

The cost minimization problem of final good firms

$$\min_{z_t^e, z_t^n, n_t} p_t^e z_t^e + p_t^n z_t^n + w_t n_t \quad \text{s.t.} \quad y_t = A_t \exp\{-\psi_E E_t\}\Big(\big(\nu(A_t^e z_t^e)^{\frac{\epsilon-1}{\epsilon}} + (1-\nu)(z_t^n)^{\frac{\epsilon-1}{\epsilon}}\big)^{\frac{\epsilon}{\epsilon-1}}\Big)^{\alpha} n_t^{1-\alpha}$$

yields the following standard first-order conditions:

$$A_t^e mc_t \alpha \nu \frac{y_t}{z_t}\left(\frac{z_t}{A_t^e z_t^e}\right)^{\frac{1}{\epsilon}} = p_t^e \ , \tag{A.38}$$

$$mc_t \alpha (1-\nu) \frac{y_t}{z_t}\left(\frac{z_t}{z_t^n}\right)^{\frac{1}{\epsilon}} = p_t^n \ , \tag{A.39}$$

$$mc_t (1-\alpha)\frac{y_t}{n_t} = w_t \ , \tag{A.40}$$

where mc_t is the real marginal cost of production for the final good. Denoting with ϕ the elasticity of substitution across final goods, final good monopolists face price rigidities à la Rotemberg, with Ψ_P being the parameter governing the degree of nominal rigidity. The price-setting maximization problem of final good producer i is then given by

$$\max_{P_t(i)} \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \frac{c_t^{-1}}{c_0^{-1}} \left\{ \left(\frac{P_t(i)}{P_t}\right)^{-\phi} \left(\frac{P_t(i)}{P_t} - mc_t\right) y_t - \frac{\Psi_P}{2}\left(\frac{P_t(i)}{P_{t-1}} - 1\right)^2 y_t \right\} .$$

Solving the maximization problem and imposing symmetry among producers, we arrive at the standard New Keynesian Phillips curve,

$$\mathbb{E}_t \Lambda_{t,t+1} \frac{y_{t+1}}{y_t} \left(\pi_{t+1} - 1\right) \pi_{t+1} + \frac{\phi}{\Psi_P}\left(\mathrm{mc}_t - \frac{\phi - 1}{\phi}\right) = \left(\pi_t - 1\right) \pi_t \ . \tag{A.41}$$

B Calibration

In this section, we provide additional details on the model calibration and the data sources. Figure 8 displays the evolution of investment, debt issuance, GDP, and emissions. While emissions closely track GDP, investment and debt issuance also exhibit substantial pro-cyclicality. They are also considerably more volatile than output, which our model matches well.

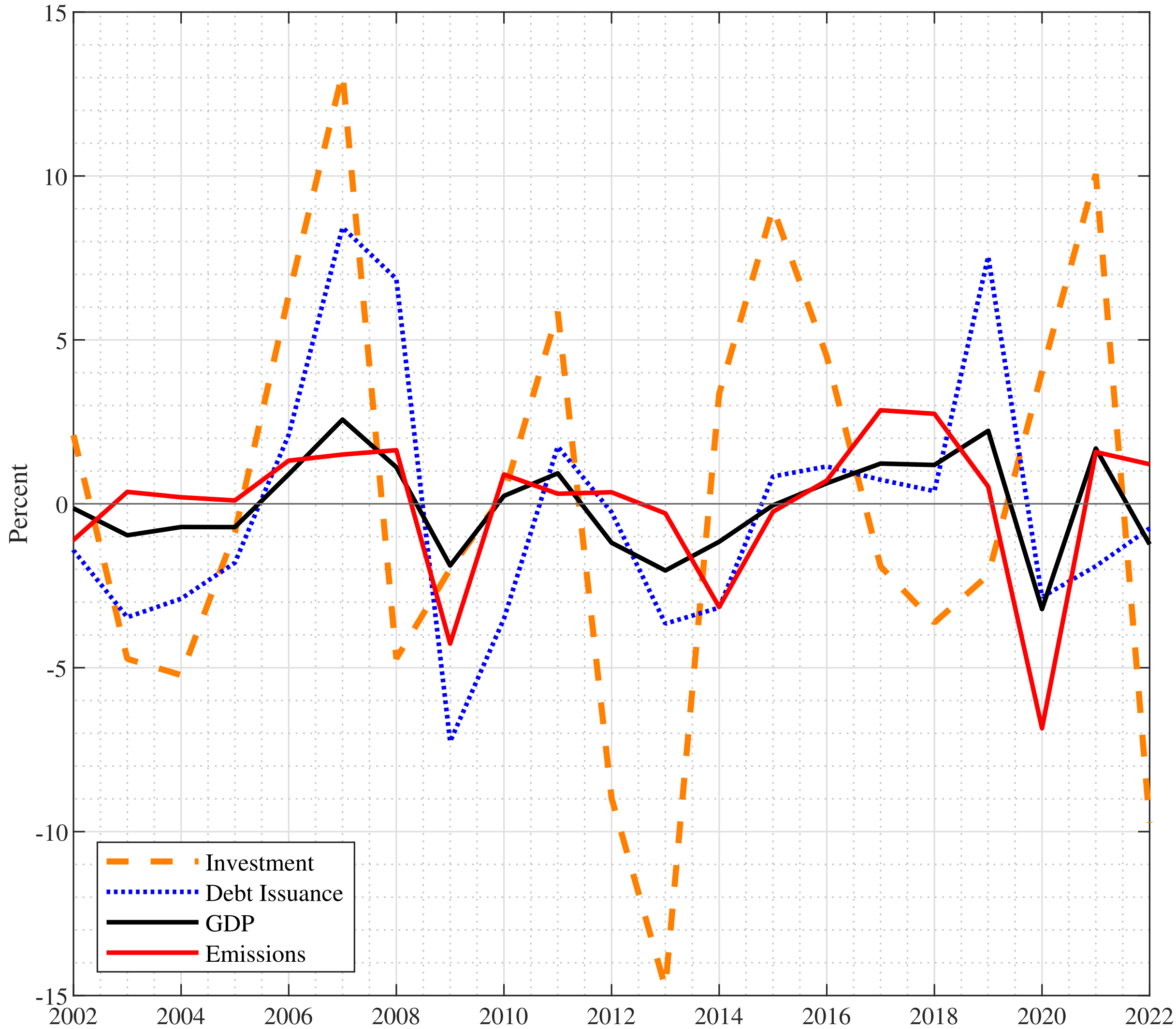

Figure 8: Euro Area Data. All data are de-trended using a one-sided HP-filter with smoothing parameter 6.25.

Mapping Model Emission Taxes into the Data. The model-implied emission tax is converted into \$/tCO2 by converting model units of output and emissions into their data counterparts. As customary in the literature, we relate model output $y^{model} = 0.102$ in the steady state without emission taxes into European GDP ($y^{EU} = 20$ trillion USD in 2022). In a similar fashion, we convert model emissions $e^{model} = 0.054$ into European emissions ($e^{EU} = 2.4$ GtCO2 in 2022). From the expression $p^e \cdot \frac{e^{\mathrm{EU}}}{y^{\mathrm{EU}}} = \tau^e \cdot \frac{e^{\mathrm{model}}}{y^{\mathrm{model}}}$, the model-implied emission price in \$/tCO2 is given by $p^e = \frac{y^{\mathrm{EU}}/y^{\mathrm{model}}}{e^{\mathrm{EU}}/e^{\mathrm{model}}} \tau^e = 4411 \cdot \tau^e$. Fixing the model-implied values for output and emissions to the initial steady state with $\tau^e = 0.007$ ensures that the mapping from model-implied taxes to their data counterparts does not depend on the emission tax level.

C Additional Numerical Results

This section presents additional quantitative analyses complementing Section 5 and ??.

C.1 Optimal Symmetric Collateral Policy

In Figure C.1, we plot the impulse response functions to a negative aggregate productivity shock. For every relevant variable, the sectoral and aggregate responses coincide, which contrasts sharply with the transmission of energy sector shocks. Since productivity shocks are quite persistent, the decline in investment and debt is much more long-lived than the rise in the corporate default rate. This implies that banks' liquidity management costs rise persistently, too, while the central bank's collateral management costs only rise on impact. Consequently, it is optimal to slightly reduce the collateral haircut parameter.

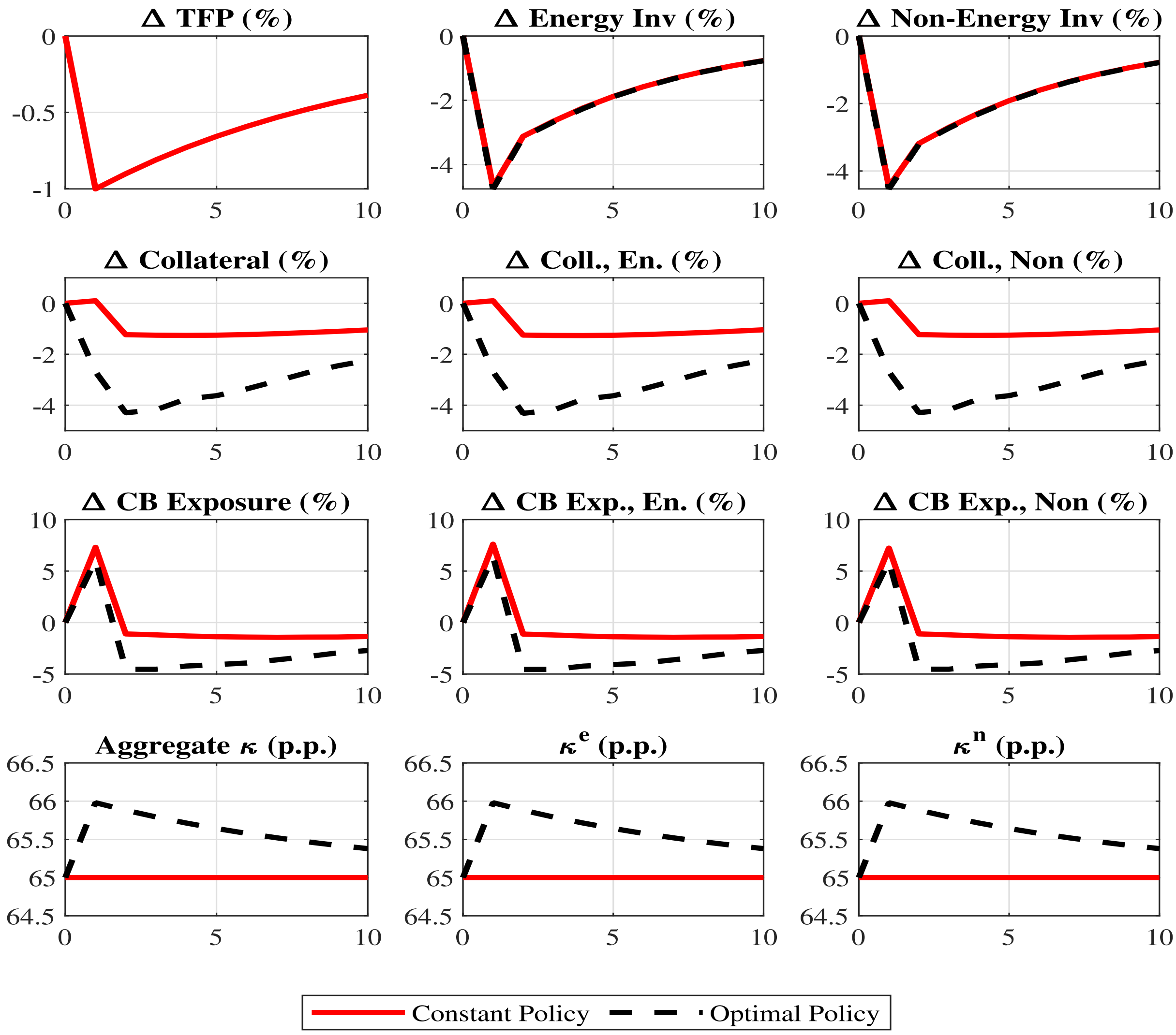

Figure C.1: Impulse Response to a TFP Shock. This graph displays the impulse response to a one-standard deviation TFP shock. The red line represents a constant collateral policy, and the dashed black line represents optimal collateral policy.

The dashed blue lines represent the optimal collateral policy response, which we again operationalize as a simple rule:

$$\kappa_t^e = \overline{\kappa}^{sym} + \varphi_A \log(A_t) + \varphi_L(l_{0,t} - \bar{l}_0) \; , \tag{B.42}$$

$$\kappa_t^n = \overline{\kappa}^{sym} + \varphi_A \log(A_t) + \varphi_L(l_{0,t} - \bar{l}_0) \; . \tag{B.43}$$

The optimized value for the response parameter is $\varphi_A = 0.002$. Quantitatively, a one standard deviation TFP decline lowers the optimal symmetric collateral haircut from 65% to 64.8%. This result further corroborates the model's external validity, since counter-cyclical collateral policy is a distinctive feature of monetary policy implementation.

Figure C.2 displays the effects and optimal central bank response to an increase in banks' liquidity management cost $l_{0,t}$.

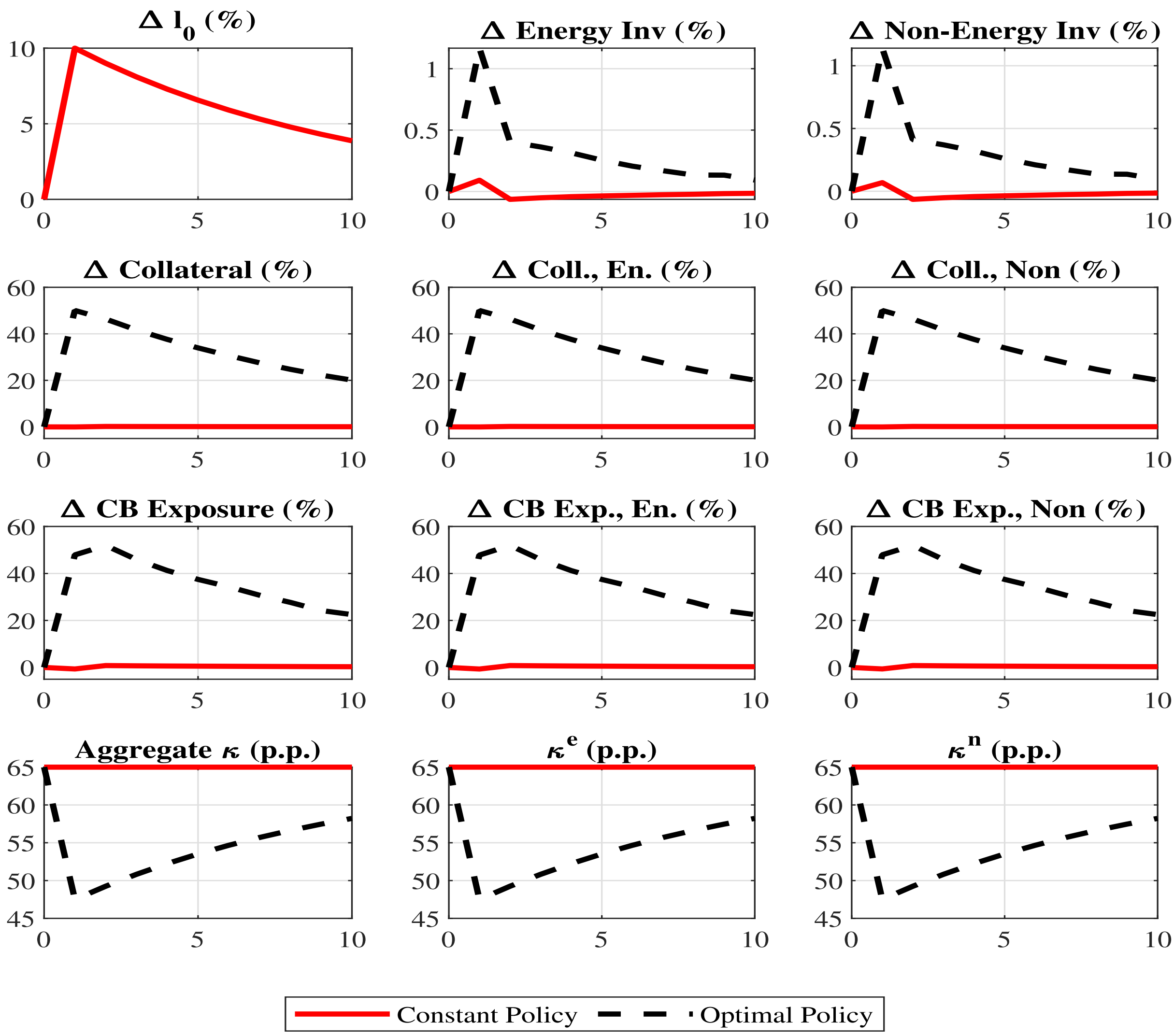

Figure C.2: Impulse Response to a Liq. Mgmt. Cost Shock. This graph displays the impulse response to a one-standard deviation TFP shock. The red line represents a constant collateral policy, and the dashed black line represents optimal collateral policy.