The Preferential Treatment of Green Bonds *

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Abstract

We study the preferential treatment of green bonds in the central bank collateral framework as an environmental policy instrument within a DSGE model with environmental and financial frictions. In the model, green and carbon-emitting conventional firms issue defaultable corporate bonds to banks that use them as collateral. The collateral premium associated to a relaxation in collateral policy induces firms to increase bond issuance, investment, leverage, and default risk. Collateral policy solves a trade-off between increasing collateral supply, adverse effects on firm risk-taking, and subsidizing green investment. Optimal collateral policy is characterized by modest preferential treatment, which increases the green investment share and reduces emissions. However, welfare gains fall well short of what can be achieved with optimal emission taxes. Moreover, due to elevated risk-taking of green firms, preferential treatment is a qualitatively imperfect substitute of Pigouvian taxation on emissions: if and only if the optimal emission tax can not be implemented, optimal collateral policy features preferential treatment of green bonds.

Keywords: Green Investment, Collateral Framework, Environmental Policy

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1 Introduction

The ECB [...] stands ready to support innovation in the area of sustainable finance [...], exemplified by its decision to accept sustainability-linked bonds as collateral.
Strategy Review (European Central Bank, 2021a)

The European Central Bank (ECB) announced, after concluding its strategy review in 2021, that it will take a more active role in environmental policy. In addition to accepting sustainability-linked (*green*) bonds as collateral, several central banks contemplate to take one step further and treat them preferentially within their collateral frameworks, i.e., the conditions under which banks can pledge assets to obtain funding from the central bank.[1] The People's Bank of China (PBoC) started accepting green bonds as collateral on preferential terms already in 2018, which resulted in a substantial decline of green bond yields relative to conventional ones (Macaire and Naef, 2022). However, there is limited knowledge about the macroeconomic impact of a preferential collateral policy on green bond issuance, green investment, pollution, and potential adverse side effects on financial markets.

To study the positive and normative implications of preferential treatment, this paper extends the standard RBC-model by (i) an environmental externality (emissions), (ii) green and conventional firms issuing corporate bonds subject to default risk, and (iii) a banking sector using these bonds as collateral. The extent to which corporate bonds can be used as collateral depends on central bank haircuts. Reducing haircuts on green bonds makes holding such bonds more attractive to banks and implies that they pay higher collateral premia on them. This in turn improves financing conditions to green firms, which increase bond issuance, investment, and leverage in response. Consequently, equilibrium green capital share *and* corporate default risk rise. We quantitatively assess the strength of these effects in a calibration to the euro area.

We uncover four main results. First, treating green bonds preferentially can have quantitatively relevant effects on the investment by green firms. Reducing the haircut on conventional bonds from 26% to 4.5% (corresponding to the ECB haircut on BBB and AAA rated corporate bonds, respectively), green firms increase investment by 0.5%. Second, green firms increase leverage by 1.1%, which increases resource losses from costly default. Because of these adverse effects, *optimal* collateral policy features a green haircut of only 10%, such that green capital increases by 0.4%. Third, due to the small elasticity of investment to borrowing conditions in the presence of default risk, the real effects of optimal collateral policy are sizable, but considerably smaller than those of an optimal Pigouvian tax on emissions. Consequently, the welfare gain of an optimal tax exceeds the welfare gain of optimal collateral policy by two orders of magnitude. Fourth, the emission tax does not induce risk-taking, i.e., preferential treatment is an *imperfect substitute* for Pigouvian taxation. The optimal degree of preferential

[1] A similar policy was also proposed in Brunnermeier and Landau (2020).

treatment decreases, the closer the Pigouvian tax gets to its optimal level. When emissions are taxed optimally, green and conventional bonds are treated *symmetrically*.

Our analysis is based on an extended RBC-model that connects collateral policy to financial and environmental frictions. There are two types of intermediate good firms, green and conventional. Conventional firms generate emissions during the production of intermediate goods, while green firms have access to a clean technology. Following Heutel (2012) and Golosov et al. (2014), final good firms combine green and conventional intermediate goods with labor. Accumulated emissions are a real externality, since they have a negative effect of final good firms' productivity. This implies a sub-optimally low investment into the green technology in the competitive equilibrium.

Collateral policy is linked to the real sector by the corporate bond market, where both intermediate good firms issue bonds to banks. Firms have an incentive to issue bonds, because their owners are assumed to be more impatient than households, who own banks. Moreover, firms are subject to idiosyncratic shocks to their productivity and default on their bonds if revenues from production fall short of current repayment obligations. Absent collateral premia, corporate bond issuance is solely determined by a trade-off between relative impatience and bankruptcy costs, similar to Gomes et al. (2016).[2] Banks collect deposits from households, invest into corporate bonds, and incur liquidity management costs. In the spirit of Piazzesi and Schneider (2021), these costs are decreasing in the amount of available corporate collateral reflecting that banks may use it to collateralize short-term borrowing. This introduces a willingness of banks to pay *collateral premia* on corporate bonds.[3]

The central bank sets haircuts on corporate bonds that determine the degree to which bonds can be used as collateral. While low haircuts increase collateral availability for banks, the central bank incurs costs from accepting risky bonds as collateral. The literature has associated these costs with risk management expenses and counterparty default risk that depend on the riskiness of collateral (Bindseil and Papadia, 2006; Hall and Reis, 2015). As in Choi et al. (2021), optimal collateral policy balances the adverse effects of accepting risky collateral with the benefits of liquidity provision to banks. Starting from this point, our paper studies the welfare gains of adding a second variable (the green haircut) to the central bank collateral framework.

The link between collateral policy and the real sector via banks' demand for bonds allows the central bank to affect the relative prices of green vis-a-vis conventional bonds by tilting the

[2]Since our focus is on the collateral framework and thereby on firms that are sufficiently large to issue bonds and related marketable assets, we employ a financial friction that restricts *debt issuance* rather than overall *external financing* as in the canonical financial accelerator model of Bernanke et al. (1999). Moreover, our framework encompasses all marketable debt securities issued by non-financial firms, like syndicated bank loans and commercial paper.

[3]Collateral premia on corporate bonds are documented by Pelizzon et al. (2020) for the euro area, Mota (2020) for the US, and Fang et al. (2020) and Chen et al. (2022) for China.

collateral framework in favor of them. In this case, banks pay higher collateral premia on green bonds, ceteris paribus, since holding them lowers liquidity management costs more effectively. Higher collateral premia make debt financing more attractive to green firms, such that their trade-off between relative impatience and bankruptcy costs is distorted: green firms increase their bond issuance, leverage, and investment. In contrast, conventional firms reduce their bond issuance, leverage, and investment: the green investment share rises. Notably, the effect on the green investment share is *permanent*, i.e., central bank collateral policy is *not neutral* even in the long run. We show in a simplified version of our model that higher risk-taking reduces the expected payoff from green investment compared to a benchmark without endogenous risk-taking. As a result, the transmission of preferential treatment to the green investment share is dampened. The *endogeneity of risk-taking*, which is key for such imperfect pass-through, is consistent with the data.[4]

To quantify the optimal degree of preferential treatment, we calibrate the model to euro area data and show that it can replicate the joint dynamics of macroeconomic, financial, and environmental variables. We also provide evidence that the model can reconcile the effects of collateral premia on corporate bond spreads, investment, and leverage observed in the data. We then conduct a number of policy experiments. First, we study a strong preferential policy, which treats all green bonds as if they where AAA-rated. This policy features a haircut gap of 21.5 percentage points and induces a green-conventional bond spread (also referred to as *greenium*) of 19 basis points, which increases the share of green capital from the calibration target of 20% to 20.09%. However, such a policy increases the collateral supply beyond its optimal level and distorts the risk choice of green firms. Therefore, while still treating green bonds preferentially, *optimal* collateral policy is characterized by a substantial decrease of green haircuts to 10% and a modest increase of the haircut on conventional bonds to 30%, which keeps aggregate collateral supply approximately constant. The relative share of green capital increases to 20.08% in this case.

To put this modest effect of preferential treatment into perspective, we consider Pigouvian taxation of emissions, which is the benchmark policy instrument to address environmental frictions. The optimal tax increases the share of green capital to 28% and substantially reduces the pollution externality *without* adverse effects on firm risk-taking. These results should not be misinterpreted as a call for central bank inaction. If public policy is restricted in its abil-

[4]Risk-taking, as reflected by firms' financing decision, has been reported in the empirical literature on unconventional monetary policy. Bekkum et al. (2018) observe a decrease in repayment performance on the mortgage backed securities market following an eligibility easing. Pelizzon et al. (2020) document positive leverage responses of eligible firms. Harpedanne de Belleville (2019) finds a sizable increase in investment by issuers of newly eligible bonds following a reduction of collateral requirements. Grosse-Rueschkamp et al. (2019), Giambona et al. (2020), and Cahn et al. (2022) document a positive investment and leverage impact of firms eligible for QE and LTRO operations. Kaldorf and Wicknig (2022) provide a structural analysis of eligibility premia and corporate default risk.

ity to set carbon taxes optimally, e.g., due to political economy frictions, the central bank can increase welfare by tilting the collateral framework towards green bonds. The extent of preferential treatment declines, the closer Pigouvian taxation gets to its optimal level: preferential treatment is a qualitatively and quantitatively an imperfect substitute for emission taxes.

Related Literature. There is a small but fast-growing literature that adds environmental aspects to DSGE models suitable for central bank policy analysis at business cycle frequencies, building on Heutel (2012). Punzi (2019) extends this setup by a credit-constrained corporate sector to study differentiated capital requirements on green and conventional firms. Due to our focus on the collateral framework and marketable assets instead of bank loans, our model uses a financial friction related to leverage rather than external financing.

In a specific assessment of green QE, Ferrari and Nispi Landi (2021) find only a modestly positive impact on aggregate environmental performance. Similarly, Abiry et al. (2021) document a small impact of QE, in particular in comparison to a carbon tax, which is similar to our results on collateral policy. Hong et al. (2021) study sustainable investment mandates, which have a similar transmission mechanism, since they affect asset demand by financial intermediaries. In their setup, sustainable investment mandates, in the form of minimum portfolio shares, increase welfare, since they widen the cost of capital wedges between green and conventional firms. We also relate to the work of Papoutsi et al. (2021) who show that in the presence of an optimal carbon tax, asset purchases play no role in addressing the environmental friction, consistently with the Tinbergen Principle in the public economics literature.[5] Different to their paper, we do not discuss the role of market neutrality and a bias in favor of bonds from carbon-intensive issuers stemming from *exogenous* financial frictions. Instead, we assume symmetric but *endogenous* financial frictions between green and conventional firms.

It should be stressed that all these papers at least implicitly add a second policy instrument (preferential treatment) together with the environmental dimension to a setup in which financial policy (size of QE or capital requirements) solves a trade-off related to financial frictions. Our analysis is the first to provide a quantitative evaluation of optimal policy jointly addressing environmental and financial frictions. Moreover, our model is the first that endogenizes risk-taking on financial markets in this context, which enables us to explicitly consider downsides of preferential treatment in the optimal policy problem.

Throughout the paper, we abstract from an analysis of transition risk, which arises if demand for conventional goods suddenly decreases due to ambitious environmental policy. Diluiso et al. (2021) and Carattini et al. (2021) argue that macroprudential policies can address this

[5] On a more general level, all policies that change the relative demand for green and conventional bonds, such as green QE and preferential green capital requirements, will induce firm responses along several dimensions, that have not been studied extensively in the literature so far. However, in our view, a thorough analysis of these additional response margins is necessary to fully assess the effectiveness and efficiency of green policies.

issue. Similar to these papers, we document an interaction between environmental policy and financial frictions and show how policy instruments should be adjusted to account for these interactions.

Outline. The paper is structured as follows. We introduce our model in Section 2 and illustrate the pass-through of collateral policy to the real sector in Section 3. Section 4 presents our calibration and quantitative analysis, while we discuss our policy experiments in Section 5. Section 6 concludes.

2 Model

Time is discrete and indexed by $t = 1, 2, \ldots$. The model is real and features a representative *household*, two types of *intermediate goods firms*, a perfectly competitive *wholesale firm*, aggregating both types of intermediate goods into a composite intermediate good, a competitive *final good producer*, financial intermediaries (*banks*), and a public sector consisting of a fiscal authority and the central bank. One type of intermediate goods producers (*conventional*) generates greenhouse gas emissions when producing intermediate goods, which accumulate over time into socially costly *pollution*. The technology of the *green* firm does not cause emissions and therefore does not contribute to pollution. Both types of intermediate goods are aggregated into a composite intermediate good by a perfectly competitive wholesale firm. A competitive final good producer uses the composite intermediate good and labor to produce the final consumption good. Pollution is a negative externality since it reduces the final good producers' productivity. Banks raise deposits from the household to invest into corporate bonds and incur a liquidity management cost. Finally, the fiscal authority can levy a proportional carbon tax on the conventional firms' output, while the central bank sets the collateral framework and incurs a cost from collateral default.

2.1 Households and Banks

Households. The representative household derives utility from consumption c_t and disutility from supplying labor l_t at the wage w_t. To transfer resources across time, the household saves in deposits d_t. Deposits held from time $t-1$ to t earn the interest rate i_{t-1}. The household's discount factor is denoted by β, ω_l is the utility-weight on labor, and γ_c and γ_l are the inverses of the intertemporal elasticity of substitution and of the Frisch elasticity of labor supply, respectively. The maximization problem of the representative household is given by

$$
\begin{aligned}
V(d_t) = & \max_{c_t, l_t, d_{t+1}} \frac{c_t^{1-\gamma_c}}{1-\gamma_c} - \omega_l \cdot \frac{l_t^{1+\gamma_l}}{1+\gamma_l} + \beta \mathbb{E}_t \left[V(d_{t+1}) \right] , \\
& \text{s.t.} \quad c_t + d_{t+1} = w_t l_t + (1+i_{t-1}) d_t + \Pi_t ,
\end{aligned}
\tag{1}
$$

where Π_t collects profits from banks and final goods producers and we omit the dependency of $V(\cdot)$ on the aggregate state for simplicity. Solving (1) yields standard inter- and intratemporal optimality conditions

$$
c_t^{-\gamma_c} = \beta \mathbb{E}_t \left[(1+i_t) c_{t+1}^{-\gamma_c} \right] , \tag{2}
$$

$$
c_t^{-\gamma_c} w_t = \omega_l l_t^{\gamma_l} . \tag{3}
$$

Banks. There is a unit mass of perfectly competitive banks $i \in (0,1)$ that supply deposits to households and invest into corporate bonds. We assume that financial intermediation is subject to liquidity management costs, represented by the function $\Omega(\overline{b}^i_{t+1})$, which we assume to depend negatively on the collateral value of bank i's corporate bond portfolio,

$$
\overline{b}^i_{t+1} = \int_j (1-\phi_c) q_{j,c,t} b^i_{j,c,t+1} dj + \int_j (1-\phi_g) q_{j,g,t} b^i_{j,g,t+1} dj .
$$

The collateral value of a bank's portfolio is given by the market value of its bonds $\int_j q_{j,\tau,t} b^i_{j,\tau,t+1}$, where j indexes firms within each type $\tau \in \{c, g\}$, weighted by one minus the respective central bank haircut parameter ϕ_τ.[6] The collateral value of bonds is decreasing in haircuts, such that banks directly benefit from a relaxation in collateral policy, since this increases available collateral $\overline{b}^i_{t+1}$ ceteris paribus. The literature has motivated such liquidity management costs as arising from idiosyncratic liquidity shocks associated with deposit or credit line withdrawals (De Fiore et al., 2019 and Piazzesi and Schneider, 2021). Making Ω dependent on available collateral $\overline{b}^i_{t+1}$ captures in reduced form the benefits of collateral to settle these shocks on interbank markets or by tapping central bank facilities.[7]

We follow Cúrdia and Woodford (2011) and assume that banks maximize profits, defined as equity value net of liquidity management costs in (4), subject to the solvency condition (5). Taken the behavior of other banks, intermediate firms, and central bank policy as given, the

[6] We restrict the analysis to time-invariant haircuts. While collateral frameworks are occasionally adjusted, in practice this usually happens in response to large shocks to the financial systems. These events are not of first order importance to the analysis of preferential treatment.

[7] Since neither the sources of liquidity demand, nor the reason why this market is collateralized are at the heart of our paper, we introduce this feature in reduced form and refer to Appendix A.2 for details on a micro-foundation.

maximization problem of bank i reads

$$\max_{d^i_{t+1},b^i_{c,t+1},b^i_{g,t+1}} \Pi^i_t = d^i_{t+1} - \int_j q_{j,c,t} b^i_{j,c,t+1} dj - \int_j q_{j,g,t} b^i_{j,g,t+1} dj - \Omega(\overline{b}^i_{t+1}) \,, \tag{4}$$

$$\text{s.t.} \quad (1+i_t) d^i_{t+1} = \int_j \mathbb{E}_t \left[\mathcal{R}_{j,c,t+1}\right] b^i_{j,c,t+1} dj + \int_j \mathbb{E}_t \left[\mathcal{R}_{j,g,t+1}\right] b^i_{j,g,t+1} dj \,. \tag{5}$$

The expected bond payoff $\mathbb{E}_t \left[\mathcal{R}_{j,\tau,t+1}\right]$ depends on firm j's bond issuance and capital choice via the default decision in period $t+1$ (see below). Taking first order conditions, we obtain the bond price schedule

$$q_{j,\tau,t} = \frac{\mathbb{E}_t \left[\mathcal{R}_{j,\tau,t+1}\right]}{(1+i_t)(1+(1-\phi_\tau)\Omega_{\overline{b},t})} \,, \tag{6}$$

which does not depend on bank i due to the assumption of perfect competition. Note that (6) contains the marginal reduction of liquidity management cost from holding an additional unit of collateral $\Omega_{\overline{b},t} \equiv \partial\Omega/\partial\overline{b}_t$, weighted by one minus the type-specific haircut. We refer to the term $(1-\phi_\tau)\Omega_{\overline{b},t}$ as the *collateral premium*.

2.2 Firms

Final Good Producer. A representative firm produces the final good y_t using a Cobb-Douglas production function that combines an intermediate good z_t and labor l_t

$$y_t = (1-\mathcal{P}_t) A_t z_t^{\theta} l_t^{1-\theta} \,, \tag{7}$$

where θ is a technology parameter. Final good production is negatively affected by pollution $\mathcal{P}_t$ generated by the conventional firm (described below). The economy-wide TFP A_t is normalized to one in the long run and evolves according to

$$\log(A_{t+1}) = \rho_A \log(A_t) + \sigma_A \varepsilon^A_{t+1} \,, \quad \varepsilon^A_{t+1} \sim N(0,1) \,.$$

Solving the maximization problem of the firm, we get standard first order conditions that equate the marginal product of the inputs to their market price

$$\begin{aligned} p_{z,t} &= (1-\mathcal{P}_t)\,\theta A_t z_t^{\theta-1} l_t^{1-\theta} \,, \\ w_t &= (1-\mathcal{P}_t)\,(1-\theta) A_t z_t^{\theta} l_t^{\theta} \,, \end{aligned}$$

where $p_{z,t}$ denotes the intermediate good price.

Wholesale Firm. The competitive wholesale firm bundles green and conventional intermediate goods into an input used by the final good firm through a Cobb-Douglas technology

$$z_t = z_{g,t}^{\nu} z_{c,t}^{1-\nu} \ , \tag{8}$$

where ν determines the relative share of green intermediate goods.[8] The prices of the intermediate good types τ are denoted by $p_{\tau,t}$. Solving the profit maximization problem yields

$$\nu p_{z,t} z_t = p_{g,t} z_{g,t} \ , \tag{9}$$

$$(1-\nu) p_{z,t} z_t = p_{c,t} z_{c,t} \ . \tag{10}$$

Intermediate Good Firms: Technology. There is a continuum of firms for both types. Firm j of type τ invests in physical capital $k_{j,\tau,t}$ to produce $z_{j,\tau,t}$. The production technology is linear and subject to an idiosyncratic productivity shock $m_{j,\tau,t}$, which is i.i.d. across and within firm types

$$z_{j,\tau,t} = m_{j,\tau,t} k_{j,\tau,t} \ . \tag{11}$$

Following Bernanke et al. (1999), the idiosyncratic shock is log-normally distributed with $\mathbb{E}[m_{j,\tau,t}] = 1$. The log-normal distribution satisfies a monotone hazard rate property of the form $\partial(h(m)m)/\partial m > 0$, where $h(m) \equiv f(m)/(1-F(m))$ denotes the hazard rate and $f(m)$ and $F(m)$ denote the pdf and cdf, respectively. Capital $k_{j,\tau,t}$ depreciates at rate δ_k, which is common to both production technologies. Investment is denoted by $i_{j,\tau,t}$ and the capital stock evolves according to

$$k_{j,\tau,t+1} = i_{j,\tau,t} + (1-\delta_k) k_{j,\tau,t} \ . \tag{12}$$

In the spirit of Heutel (2012) and Golosov et al. (2014), we assume that only conventional firms emit greenhouse gases and that emissions accumulate over time while they only depreciate slowly. Specifically, we refer to cumulated emissions as *pollution* $\mathcal{Z}_t$, which is a state variable and follows the law of motion

$$\mathcal{Z}_t = \delta_z \mathcal{Z}_{t-1} + z_{c,t} \ ,$$

[8] In Appendix B.1, we conduct a robustness analysis using a CES-function and find only minor differences.

with $\delta_z < 1$ and $z_{c,t}$ is aggregate conventional production.[9] The cost of pollution incurred by final goods producers satisfies $\partial\mathcal{P}/\partial\mathcal{Z} > 0$. Revenues $p_{\tau,t}z_{j,\tau,t}$ are subject to a time-invariant, type-specific tax χ_τ. A positive χ_c is the Pigouvian instrument at disposal of the fiscal authority to address the pollution externality.[10]

Intermediate Good Firms: Financial Side. As in Gomes et al. (2016), we assume that each firm j of each type τ is managed on behalf of a risk-averse and impatient representative firm owner who consumes dividends $\widetilde{c}_t = \int_j \Pi_{j,c,t}dj + \int_j \Pi_{j,g,t}dj$. The firm owner's instantaneous utility is given by $\frac{\widetilde{c}_t^{1-\gamma_c}}{1-\gamma_c}$, where the utility parameter is the same as the one of households. There is no agency friction between firm managers and owners. The representative firm owner discounts the future with a discount factor $\widetilde{\beta} < \beta$. Making the firm owner impatient ensures that firms borrow from banks in equilibrium. We impose the following timing structure, which allows for exact aggregation into firm types:

- Each firm j draws an idiosyncratic productivity shock $m_{j,\tau,t}$, produces and either repays its maturing debt obligations or defaults (described below).
- Firms adjust capital $k_{j,\tau,t+1}$ and bonds outstanding $b_{j,\tau,t+1}$.
- Firms transfer their dividends $\Pi_{j,\tau,t}$ to the firm owner.

Firms finance their activities by issuing equity (negative dividends) or by issuing corporate bonds.[11] Bonds mature stochastically each period with probability $0 < s \leq 1$ and pay one unit of the final good in the case of no default.[12] Firms mechanically default if their repayment obligation exceeds revenues from production.[13] The default productivity threshold $\overline{m}_{j,\tau,t}$ is implicitly defined as the productivity level at which revenues $(1-\chi_\tau)p_{j,\tau,t}m_{j,\tau,t}k_{j,\tau,t}$ equal repayment obligations $sb_{j,\tau,t}$. In case of default, banks holding distressed bonds effectively replace the firm owner as shareholder: they seize the output *only in the default period*, restructure the firm, and resume to being creditors after the firm's debt has been restructured. With probability $1-s$,

[9] We do not explicitly model emissions by the rest-of-the-world, since our main goal is an analysis of the role of financial frictions when environmental policy operates through firm financing. In unreported policy experiments with positive rest-of-the-world emissions, welfare gains of optimal preferential treatment and optimal tax are smaller than in the closed economy case. However, the relative welfare gain of preferential treatment relative to the gain of carbon taxes is almost identical.

[10] It is not relevant in our setup, whether the intermediate or wholesale firms pay the tax. Attributing it to intermediate good producers, however, gives the cleanest comparison to collateral policy, as both instruments operate through the investment decision.

[11] We verify that *aggregate* dividends are always positive.

[12] Using long-term bonds allows to obtain realistic leverage ratios in the calibration, but is not required for the transmission of collateral policy. Moreover, bonds are cast in real terms. We consider nominal bonds in Appendix B.2.

[13] We implicitly assume that there is no transfer of resources from productive to unproductive firms. This is consistent with the notion of uninsurable idiosyncratic productivity shocks.

the bond does not mature, is unaffected by the restructuring process, and is rolled over at next period's market price. While in practice restructuring takes several periods, we follow Gomes et al. (2016) and take a shortcut by assuming that capital owners can restructure their liabilities without delays, which implies that the debt choice is unaffected from either the default decision in the current period or the productivity shock realization, thus allowing for exact aggregation.

Firms maximize the present value of dividends, discounted by the firm owner's stochastic discount factor $\widetilde{\Lambda}_{t,t+1} \equiv \widetilde{\beta}\,(\widetilde{c}_{t+1}/\widetilde{c}_t)^{-\gamma_c}$. We conjecture that all firms enter any period t with the same legacy debt stock and capital to express dividends as

$$\begin{aligned}\Pi_{j,\tau,t} = {} & \mathbb{1}\{m_{j,\tau,t} > \overline{m}_{j,\tau,t}\}\Big((1-\chi_\tau)p_{\tau,t}m_{j,\tau,t}k_{\tau,t} - sb_{\tau,t}\Big) - k_{j,\tau,t+1} + (1-\delta_k)k_{\tau,t} \\ & + q_{j,\tau,t}\left(b_{j,\tau,t+1} - (1-s)b_{\tau,t}\right) \ .\end{aligned}$$

Under the assumption of no delays in restructuring and i.i.d. productivity shocks, next period's productivity can be integrated out in the objective function and the problem reduces to a two-period consideration. The relevant part of the maximization problem then becomes

$$\begin{aligned}\max_{k_{j,\tau,t+1},b_{j,\tau,t+1},\overline{m}_{j,\tau,t+1}} \; & -k_{j,\tau,t+1} + q_{j,\tau,t}\Big(b_{j,\tau,t+1} - (1-s)b_{j,\tau,t}\Big) \\ & + \mathbb{E}_t\Bigg[\widetilde{\Lambda}_{t,t+1}\Bigg((1-\chi_\tau)p_{\tau,t+1}\int_{\overline{m}_{j,\tau,t+1}}^{+\infty} m\cdot k_{j,\tau,t+1}dF(m) + (1-\delta_k)k_{j,\tau,t+1} \\ & \quad - \int_{\overline{m}_{j,\tau,t+1}}^{+\infty} sb_{j,\tau,t+1}dF(m) + q_{j,\tau,t+1}\Big(b_{j,\tau,t+2} - (1-s)b_{j,\tau,t+1}\Big)\Bigg)\Bigg] \ ,\end{aligned}$$

subject to the default threshold $\overline{m}_{j,\tau,t+1} \equiv \frac{sb_{j,\tau,t+1}}{(1-\chi_\tau)p_{\tau,t+1}k_{j,\tau,t+1}}$ and the bond pricing condition (6), and taking as given the continuation value of bonds $q_{j,\tau,t+1}$. Since dividends of all firms are transferred to the firm owner each period and firms can access capital and bond markets irrespective of a potential default event in the current period, all type τ firms make the same choices $k_{\tau,t+1}$ and $b_{\tau,t+1}$. This allows aggregation into a representative green and conventional firm, respectively, and we will omit the firm index j in the following.

Let the average productivity of type τ defaulting firms be denoted by $G(\overline{m}_{\tau,t}) \equiv \int_0^{\overline{m}_{\tau,t}} m dF(m)$. The share of defaulters is given by $F(\overline{m}_{\tau,t}) \equiv \int_0^{\overline{m}_{\tau,t}} dF(m)$. In case of default, the bank pays restructuring costs φ *per unit*. It is also entitled to the entire output $m_{\tau,t}k_{\tau,t}$, valued at the after-tax price $(1-\chi_\tau)p_{\tau,t}$, which is distributed among holders of the defaulted bond. Output of the defaulting firm is therefore divided by $sb_{\tau,t}$. The payoff in case of repayment is simply given by s. Integrating out the productivity shock, the realized per-unit bond payoff entering the bond pricing condition of banks (6) is given by

$$\mathcal{R}_{\tau,t} = s\left(G(\overline{m}_{\tau,t})\frac{p_{\tau,t}(1-\chi_\tau)k_{\tau,t}}{sb_{\tau,t}} + 1 - F(\overline{m}_{\tau,t})\right) - F(\overline{m}_{\tau,t})\varphi + (1-s)q_{\tau,t}\ . \tag{13}$$

The first term reflects the payoff from the share s of maturing bonds: it consists of the production revenues banks seize in case of default and the repayment of the principal in case of no default. The term $F(\overline{m}_{\tau,t})\varphi$ reflects default costs incurred by banks. The share $(1-s)$ of bonds that are rolled over is valued at market price $q_{\tau,t}$.

Note that, given the definition of the default threshold $\overline{m}_{j,\tau,t} \equiv \frac{sb_{j,\tau,t}}{(1-\chi_\tau)p_{\tau,t}k_{j,\tau,t}}$, we can rewrite (13) as

$$\mathcal{R}_{\tau,t} = s\left(\frac{G(\overline{m}_{\tau,t})}{\overline{m}_{\tau,t}} + 1 - F(\overline{m}_{\tau,t})\right) - F(\overline{m}_{\tau,t})\varphi + (1-s)q_{\tau,t}\ .$$

Hence, the bond price in (6) depends on the firms' choices of debt and capital only through their impact on the risk choice $\overline{m}_{\tau,t+1}$, which is the only firm-specific state variable in this model (Gomes et al., 2016). In the following, we will make this dependence explicit by denoting the bond price of sector τ at time t as $q(\overline{m}_{\tau,t+1})$.

Intermediate Good Firms: Bond Issuance and Investment. Plugging investment (12) and banks' bond pricing condition (6) into the Bellman equation, the first order conditions for bond issuance and capital read

$$\frac{\partial q(\overline{m}_{\tau,t+1})}{\partial b_{\tau,t+1}}\left(b_{\tau,t+1} - (1-s)b_{\tau,t}\right) + q(\overline{m}_{\tau,t+1}) = \mathbb{E}_t\left[\widetilde{\Lambda}_{t,t+1}\left(s(1-F(\overline{m}_{\tau,t+1})) + (1-s)q(\overline{m}_{\tau,t+2})\right)\right], \tag{14}$$

$$1 = \frac{\partial q(\overline{m}_{\tau,t+1})}{\partial k_{\tau,t+1}}\left(b_{\tau,t+1} - (1-s)b_{\tau,t}\right) + \mathbb{E}_t\left[\widetilde{\Lambda}_{t,t+1}\left((1-\delta_k) + (1-\chi_\tau)p_{\tau,t+1}\left(1 - G(\overline{m}_{\tau,t+1})\right)\right)\right]. \tag{15}$$

The analytical steps are relegated to Appendix A.1. Equation (14) requires that the marginal benefit of issuing more bonds (LHS) equals marginal costs (RHS). Each unit of bonds increases funds available in period t by $q(\overline{m}_{\tau,t+1})$ units. By increasing the likelihood of future default, reflected by the term $\frac{\partial q(\overline{m}_{\tau,t+1})}{\partial b_{\tau,t+1}} < 0$, issuing more bonds also dilutes the resources that can be raised by net debt issuance $(b_{\tau,t+1} - (1-s)b_{\tau,t})$. Issuing bonds has also implications for firm dividends in $t+1$. Each unit of bonds involves repayment of s, conditional on not defaulting. In addition, bond issuance also increases the rollover burden in the next period by $(1-s)q(\overline{m}_{\tau,t+2})$.

The optimality condition for capital (15) requires that the cost of purchasing capital (normalized to one) equals its payoff, which consists of two parts. The first part reflects the bond price increase due to a decrease of the default probability $\frac{\partial q(\overline{m}_{\tau,t+1})}{\partial k_{\tau,t+1}} > 0$, which increases dividends in period t. Investment also increases dividends in $t+1$ directly by raising the marginal value of production net of taxes and conditional on not defaulting.

2.3 Public Policy and Resource Constraint

The central bank sets the collateral framework (ϕ_c, ϕ_g) and incurs costs from collateral default Λ_t. These costs depend positively on the default risk of collateral pledged in the previous period so that $\partial\Lambda/\partial\overline{F}_t > 0$, with $\overline{F}_t$ defined as the firms' probability of default, weighted by the repo size

$$\overline{F}_t \equiv \sum_{\tau}(1-\phi_\tau)b_{\tau,t}q_{\tau,t}F(\overline{m}_{\tau,t}) \ .$$

The weighting $(1-\phi_\tau)b_{\tau,t}q_{\tau,t}$ can be interpreted as the repo size collateralized by green and conventional bonds, respectively. By setting haircuts, the central bank has a direct effect on the costs. Making Λ_t dependent on default risk captures in reduced form a risk management consideration of accepting risky bonds as collateral. In Appendix A.3 we discuss a potential micro-foundation of the cost function, based on central bank solvency concerns (Hall and Reis, 2015). This is a frequently employed argument for why central banks are only willing to lend against sufficiently safe securities. For example, Bindseil and Papadia (2006) argue that central banks are not specialized credit risk management agencies and that higher default risk of accepted collateral makes monetary policy implementation more resource-intensive. Taken together, lowering haircuts reduces banks' liquidity management cost, but directly increases the central bank's cost due to collateral default.

To close the model, we assume that the fiscal authority rebates all tax revenues raised from the conventional sector to green firms to balance its budget,

$$\chi_c p_{c,t} z_{c,t} + \chi_g p_{g,t} z_{g,t} = 0 \ . \tag{16}$$

This fiscal rule allows us to abstract from additional fiscal instruments that would otherwise be necessary to balance the government budget. The resource constraint is given by

$$y_t = c_t + \sum_{\tau}(\tilde{c}_{\tau,t} + i_{\tau,t}) + \Omega(\overline{b}_{t+1}) + \sum_{\tau}\varphi F(\overline{m}_{\tau,t})b_{\tau,t} + \Lambda(\overline{F}_t) \ , \tag{17}$$

where the last three terms represent the resource losses due to the liquidity management costs and corporate default costs, suffered by banks, and collateral default costs, suffered by the central bank.

3 The Transmission of Preferential Treatment

In this section, we demonstrate the pass-through and adverse side effects of a preferential collateral policy in a simplified setting. The discussion will be organized around intermediate good firms' first order condition for capital, which relates the cost of investment to its payoff, which will be denoted by $\Xi_{\tau,t+1}$. We then discuss how the transmission of collateral policy to the investment payoff ($\frac{\partial \Xi_{\tau,t+1}}{\partial (1-\phi_\tau)\Omega_{\overline{b}}}$) and to the equilibrium green capital ratio $k_{g,t}/k_{c,t}$ depends on firms' risk-taking decision.

For the ease of exposition, we consider the case of one-period bonds and full capital depreciation ($s = \delta_k = 1$). It is furthermore helpful to assume that banks cannot seize output of defaulting firms (their revenues are wasted) and do not incur restructuring costs ($\varphi = 0$). Since we do not focus on macroeconomic dynamics in this section, we do not endogenize output prices and the interest rate. Furthermore, we also set firm owner's stochastic discount factor to $\widetilde{\Lambda}_{t,t+1} = \widetilde{\beta}$.

A Benchmark Without Default Risk. To isolate the role of financial frictions in the production sector, it is informative to relate our model to a framework without default risk, but with collateral premia. In this case, firms choose bonds $b_{\tau,t+1}$ and capital $k_{\tau,t+1}$ to maximize the present value of dividends $\Pi_{\tau,t} + \widetilde{\beta}\mathbb{E}_t[\Pi_{\tau,t+1}]$ subject to the standard non-negativity constraints on dividends $\Pi_{\tau,t}, \Pi_{\tau,t+1} \geq 0$. Define with $\tilde{q}_{\tau,t}$ the price of the default-free bond. Without default risk, only expected productivity $\mathbb{E}_t[m_{\tau,t+1}]$ (and not the default threshold) is relevant for the firm problem, which equals one by assumption. Therefore, we can re-write the maximization problem as

$$\max_{b_{\tau,t+1},k_{\tau,t+1}} \; -k_{\tau,t+1} + \tilde{q}_{\tau,t} b_{\tau,t+1} + \widetilde{\beta}\mathbb{E}_t\left[(1-\chi_\tau)p_{\tau,t+1}k_{\tau,t+1} - b_{\tau,t+1}\right]$$
$$\text{s.t.} \quad k_{\tau,t+1} \leq \tilde{q}_{\tau,t} b_{\tau,t+1} \quad \text{and} \quad (1-\chi_\tau)p_{\tau,t+1}k_{\tau,t+1} \geq b_{\tau,t+1}\,.$$

The constraints require that dividends are non-negative in both periods. Note that the bond price $\tilde{q}_{\tau,t}$ does not depend on firm decisions in the default-free benchmark. Since firms effectively have linear preferences with a unitary weight over dividends in t and weight $\widetilde{\beta}$ over dividends in $t+1$, it is optimal to issue bonds up to $b_{\tau,t+1} = (1-\chi_\tau)p_{\tau,t+1}k_{\tau,t+1}$, holding the capital stock constant. Intuitively, while debt issuance allows firms to front-load dividends, there are no (default) costs associated with high debt issuance and the firm optimally chooses a leverage of 100%.[14] Using this, the maximization problem reduces further to

$$\max_{k_{\tau,t+1}} \quad -k_{\tau,t+1} + \tilde{q}_{\tau,t}(1-\chi_\tau)p_{\tau,t+1}k_{\tau,t+1} \ ,$$

which yields the following first order condition for capital

$$1 = \underbrace{(1-\chi_\tau)\mathbb{E}_t[p_{\tau,t+1}]\tilde{q}_{\tau,t}}_{\text{Investment payoff } \Xi^{\text{no default}}_{\tau,t+1}} \ . \tag{18}$$

This condition states that the marginal cost of investment (equal to one) equals the investment payoff $\Xi^{\text{no default}}_{\tau,t+1}$. We now study how the latter changes after a reduction of central bank haircut, by looking at the partial derivative $\partial\Xi_{\tau,t+1}/\partial(1-\phi_\tau)\Omega_{\overline{b}}$. Given that the marginal cost of investment is constant, any increase of $\Xi^{\text{no default}}_{\tau,t+1}$ stimulates investment.

The presence of the bond price in (18) implies that firms' investment decision is influenced by a *financial wedge*, which links central bank policy to the real sector through banks' demand for corporate bonds. The bond price $\tilde{q}_{\tau,t} = \frac{1}{(1+i_t)(1+(1-\phi_\tau)\Omega_{\overline{b}})}$ reflects the discounted bond payoff in $t+1$ and the collateral premium. Since $\tilde{q}_{\tau,t}$ is increasing in the collateral premium $\frac{\partial\tilde{q}_{\tau,t}}{\partial(1-\phi_\tau)\Omega_{\overline{b}}} > 0$, a reduction of central bank haircuts will therefore increase the investment payoff. Since the investment payoff is proportional to the bond price, we refer to the default-free case as *perfect pass-through*:

$$\frac{\partial\Xi^{\text{no default}}_{\tau,t+1}}{\partial(1-\phi_\tau)\Omega_{\overline{b}}} = (1-\chi_\tau)\mathbb{E}_t[p_{\tau,t+1}]\frac{\partial\tilde{q}_{\tau,t}}{\partial(1-\phi_\tau)\Omega_{\overline{b}}} \ . \tag{19}$$

Combining the investment decision (18) for both firm types with the intermediate good demand (9) and (10) yields the equilibrium green capital ratio

$$\frac{k_{g,t}}{k_{c,t}} = \frac{\tilde{q}_{g,t}}{\tilde{q}_{c,t}}\frac{\nu(1-\chi_g)}{(1-\nu)(1-\chi_c)} \ . \tag{20}$$

Equation (20) shows that, in the no-default benchmark, any policy affecting the relative price of green bonds will proportionally affect the green capital ratio.

The Role of Default Risk. Now, consider the model with default risk. With one-period bonds, the default threshold is given by $\overline{m}_{\tau,t+1} = \frac{b_{\tau,t+1}}{(1-\chi_\tau)p_{\tau,t+1}k_{\tau,t+1}}$ and the first order conditions

[14] This definition of leverage relates repayment obligations $b_{\tau,t+1}$ to the production value of assets $(1-\chi_\tau)p_{\tau,t+1}k_{\tau,t+1}$, rather than the re-sale value of capital, which is not well-defined in this model. When allowing for long-term debt in the quantitative analysis, the bond price (indirectly) enters the numerator of the leverage ratio through debt rollover. This notion of indebtedness is linked to the 'going concern' value of firm debt and assets.

for bonds and capital simplify to

$$q'(\overline{m}_{\tau,t+1})\mathbb{E}_t[\overline{m}_{\tau,t+1}] + q(\overline{m}_{\tau,t+1}) = \widetilde{\beta}\mathbb{E}_t[1 - F(\overline{m}_{\tau,t+1})] , \tag{21}$$

$$1 = (1-\chi_\tau)\mathbb{E}_t\left[p_{\tau,t+1}\underbrace{\left(\widetilde{\beta}\left(1 - G(\overline{m}_{\tau,t+1})\right) - q'(\overline{m}_{\tau,t+1})\overline{m}^2_{\tau,t+1}\right)}_{\text{Financial wedge } \Gamma_{\tau,t+1}}\right] . \tag{22}$$

Condition (22) still requires that the investment payoff $\Xi^{\text{default}}_{\tau,t+1} \equiv (1-\chi_\tau)\mathbb{E}_t[p_{\tau,t+1}\Gamma_{\tau,t+1}]$ equals the price of capital. In contrast to the default-free case however, the investment payoff now also depends on the firm's financing decision. The financial wedge entering (22) contains, first, the discounted future output produced by an additional unit of capital conditional on not defaulting, $\widetilde{\beta}\left(1 - G(\overline{m}_{\tau,t+1})\right)$. Second, it contains a bond price appreciation term, $q'(\overline{m}_{\tau,t+1})\overline{m}^2_{\tau,t+1}$, reflecting the reduction in default risk from higher investment. The transmission of collateral policy on the investment payoff is given by

$$\frac{\partial \Xi^{\text{default}}_{\tau,t+1}}{\partial(1-\phi_\tau)\Omega_{\overline{b}}} = (1-\chi_\tau)\mathbb{E}_t\left[p_{\tau,t+1}\frac{\partial \Gamma_{\tau,t+1}}{\partial(1-\phi_\tau)\Omega_{\overline{b}}}\right] , \tag{23}$$

and depends on the financial wedge, which itself is endogenously determined. To characterize the effect of collateral policy on the financial wedge ($\frac{\partial \Gamma_{\tau,t+1}}{\partial(1-\phi_\tau)\Omega_{\overline{b}}}$), we exploit that banks' bond pricing condition is available in closed form. The bond pricing condition and its derivative with respect to the risk choice $\overline{m}_{\tau,t+1}$ can then be written as

$$q(\overline{m}_{\tau,t+1}) = \mathbb{E}_t\left[\frac{1 - F(\overline{m}_{\tau,t+1})}{(1+i_t)(1+(1-\phi_\tau)\Omega_{\overline{b}})}\right] \text{ and } q'(\overline{m}_{\tau,t+1}) = \mathbb{E}_t\left[\frac{-f(\overline{m}_{\tau,t+1})}{(1+i_t)(1+(1-\phi_\tau)\Omega_{\overline{b}})}\right] .$$

Plugging these into (21), we can express the risk-choice as

$$(1+i_t)\left(\frac{1}{1+i_t} - (1+(1-\phi_\tau)\Omega_{\overline{b}})\widetilde{\beta}\right) = \mathbb{E}_t\left[\frac{f(\overline{m}_{\tau,t+1})}{1-F(\overline{m}_{\tau,t+1})}\overline{m}_{\tau,t+1}\right] . \tag{24}$$

In the absence of collateral premia ($\phi_\tau = 1$), the risk choice is determined by equating relative impatience (LHS) and marginal default costs (RHS). Holding the interest rate fixed, a reduction of the haircut ϕ_τ increases the LHS of (24). Due to the monotonicity assumption on the hazard rate, the RHS of (24) increases in $\overline{m}_{\tau,t+1}$. Hence, the effect of relaxing collateral policy on risk-taking is unambiguously positive. Intuitively, firms increase their risk-taking, because lower financing costs make investment *and* front-loading dividend payouts more attractive, holding expected default cost constant.

Lemma 1 demonstrates that the effect of collateral policy on the financial wedge can be simplified into an expression that is directly comparable to the default-free benchmark.

Lemma 1. Imperfect Pass-Through The effect of collateral policy on the investment payoff can be expressed as

$$\frac{\partial \Xi^{\text{default}}_{\tau,t+1}}{\partial(1-\phi_\tau)\Omega_{\overline{b}}} = (1-\chi_\tau)\mathbb{E}_t\left[p_{\tau,t+1}\overline{m}_{\tau,t+1}\big(1-F(\overline{m}_{\tau,t+1})\big)\right]\frac{\partial \tilde{q}_{\tau,t}}{\partial(1-\phi_\tau)\Omega_{\overline{b}}}\,, \tag{25}$$

where $\frac{\partial \tilde{q}_{\tau,t}}{\partial(1-\phi_\tau)\Omega_{\overline{b}}}$ is the response of a default-free bond to collateral premia. Proof: Appendix A.4.

This expression closely resembles the default-free case (19). When $\frac{\partial \Xi^{\text{default}}_{\tau,t+1}}{\partial(1-\phi_\tau)\Omega_{\overline{b}}} < \frac{\partial \Xi^{\text{no default}}_{\tau,t+1}}{\partial(1-\phi_\tau)\Omega_{\overline{b}}}$, the financial wedge dampens the transmission of collateral policy to investment payoffs, which obtains if $\big(1-F(\overline{m}_{\tau,t+1})\big)\overline{m}_{\tau,t+1} < 1$. This condition is trivially satisfied for any $\overline{m}_{\tau,t+1} < 1$, since we normalize the distribution to have a mean of one. In addition, due to the properties of the log-normal distribution, a value of $\overline{m}_{\tau,t+1} = 1$ already corresponds to a default rate of more than 50% per quarter, while the default rate in the calibrated model and the data is around 1% in annualized terms. For any economically reasonable parameterization, the inequality will hold and relaxing collateral policy has a positive but unambiguously smaller effect on investment compared to the no-default case. In (partial) equilibrium, the green capital ratio in the presence of financial frictions can be written

$$\frac{k_{g,t}}{k_{c,t}} = \frac{\mathbb{E}_t\left[\Gamma_{g,t+1}\right]}{\mathbb{E}_t\left[\Gamma_{c,t+1}\right]}\frac{\nu(1-\chi_g)}{(1-\nu)(1-\chi_c)}\,. \tag{26}$$

Absent preferential treatment, risk choice and bond prices are identical across firm types such that the financial wedges $\Gamma_{\tau,t+1}$ in the payoffs from investment $\Xi_{\tau,t+1}$ cancel out. Then, as in the no-default case, the relative size of both sectors would be solely determined by the technology parameter ν and the environmental policy regime. Setting $\chi_c > 0$ and $\chi_g < 0$ directly increases the green capital ratio. Note that this policy also operates through the marginal payoff from investment, which increases (decreases) in the subsidy (tax) from (18). However, in sharp contrast to collateral policy, the tax rate χ_τ does not affect risk-taking, since it does not separately affect the risk-choice (24). The preferential treatment of green bonds in the collateral framework also increases the green capital ratio, but endogenous default risk impairs the effectiveness of this policy.

It follows that the optimal degree of preferential treatment of green collateral in the full model will depend on the quantitative relevance of such an impairment driven by higher endogenous risk-taking in the green sector. In the following sections, we calibrate the full model to the euro area, show that it can match some key financial and real elasticities that we observe in the data, and perform several policy experiments.

4 Quantitative Analysis

We calibrate the model to euro area data. All data sources are summarized in Appendix D. After describing the parameter choices, we show the model's fit regarding (untargeted) macroeconomic dynamics. To enhance the plausibility of our optimal policy analysis in the next section, we also demonstrate the model's ability to replicate the effect of preferential treatment on borrowing costs between sectors and the responses of financial market and real sector variables to collateral policy in Section 4.2.

4.1 Calibration

Each period corresponds to one quarter. The parameters governing macroeconomic dynamics at business cycle frequencies are set to standard values. We assume log-utility over consumption, fix the inverse Frisch elasticity at 1, and set the household discount factor β to 0.995. The Cobb-Douglas coefficient in the final good production technology is set to $\theta = 1/3$ to imply a labor share of $2/3$. We set the weight ω_l in the household utility function to be consistent with a steady state labor supply of 0.3. The TFP shock parameters are conventional values in the RBC literature. The capital depreciation rate δ_k is set to match the capital/GDP ratio of 2.1. Having fixed these parameters, the calibration can then be divided into parameters related to environmental, firm-, and bank-specific frictions.

Environmental Part. Parameters regarding pollution and the green technology share are important drivers of environmental DSGE models. For the relative share of the green sector, we use the most recent data on the share of renewable energies in the euro area. Although this is only a subset of intermediate goods, it has the advantage that, since renewable energy is a prominent feature of the public discussion, the data quality is excellent. In 2018, renewable energy sector's size was 20%, which directly informs the Cobb-Douglas parameter of the wholesale goods producers ν.[15] The persistence of pollution is set to $\delta_z = 0.997$, following Heutel (2012). We assume that pollution costs can be expressed as

$$\mathcal{P}_t = 1 - \exp\{-\gamma_P \mathcal{Z}_t\} \,,$$

which corresponds to a percentage loss in the final good producer's production (7). Using this, we can directly relate pollution costs $\mathcal{P}$ to observable (long-run) quantities $1 - y/z^{\theta} l^{1-\theta}$. We inform γ_P using estimates of direct costs from pollution and indirect costs from adverse environmental conditions, which Muller (2020) quantifies at 10% in 2016 for the US. The value of 10% has also been reported in the fourth National Climate Assessment in the US (Reidmiller

[15]Renewable energy statistics for the EU are accessible here. See also the guide by Eurostat (2020).

et al., 2018). Since economic activity in this dimension can be assumed to be similar in the US and the euro area, we adopt the same value.[16]

Intermediate Good Firms and Corporate Bonds. The next group of parameters is associated with intermediate good firms. We assume that both firm types are subject to the same financial friction. This assumption is supported by the findings of Larcker and Watts (2020) and Flammer (2021), who find no effect of environmental performance on spreads in the US fixed income market.[17] Average maturity of corporate bonds is set to five years ($s = 0.05$) and corresponds to average maturity in the *Markit iBoxx* corporate bond index between 2010 and 2019. The idiosyncratic productivity shock is log-normally distributed with variance ς_M^2 and mean $-\varsigma_M^2/2$ to ensure that it satisfies $\mathbb{E}_t[m_{\tau,t}] = 1$. The discount factor $\widetilde{\beta}$ of firm owners and the variance of idiosyncratic productivity shocks ς_M^2 are set to match steady-state bond spread and corporate debt-GDP ratio. The model-implied bond spread is defined as

$$x_{\tau,t} \equiv \left(1 + \frac{s}{q(\overline{m}_{\tau,t+1})} - s\right)^4 - (1+i_t)^4 \,.$$

For the data moment on spreads, we use the *IHS Markit* data from 2010 until 2019. We compute the median bond spread over the entire corporate bond sample and average over time, which yields a value of 100bp. The data moment on corporate debt is the ratio of non-financial firm debt to GDP, taken from the ECB.

Banks and Collateral Premia. The final group of parameters is related to banks and collateral policy. Restructuring costs φ are set to get a steady-state leverage qb/k of 40% as in Gomes et al. (2016). We impose symmetric collateral treatment and set $\phi_{sym} \equiv \phi_c = \phi_g = 0.26$, which corresponds to the haircut on BBB-rated corporate bonds with five to seven years maturity in the ECB collateral framework prior to 2020 (Nyborg, 2017). The BBB-haircut can be reasonably assumed to be representative for the firm cross-section. Liquidity management costs are specified as

$$\Omega\left(\overline{b}_{t+1}^i\right) = \max\left\{l_0 - \frac{l_1}{0.5}\left(\overline{b}_{t+1}^i\right)^{0.5}, 0\right\} \,. \tag{27}$$

Their concave shape captures that the marginal cost reduction of collateral is decreasing (in absolute terms), i.e. banks will have a very high willingness to pay collateral premia if collateral

[16] The environmental block of our model is intentionally simplistic, since we consider time-invariant Pigouvian taxes and haircuts. In this case, optimal policy is primarily governed by long run default risk and environmental damage, both of which are calibration targets. Adding "climate tipping points" which might interact with financial risk is a promising extension of our analysis, but beyond the scope of this paper.

[17] Our paper abstracts from risk factors affecting both sectors in a heterogeneous way, such as transition risk. In this context, differentiated haircuts can be motivated on financial stability considerations.

Table 1: Baseline Calibration

Parameter	Value	Source/Target
Households		
CRRA-coefficient γ_c	1	Log-utility
Household discount factor β	0.995	Standard
Labor disutility convexity γ_l	1	Inverse Frisch
Labor disutility weight ω_l	12	Labor supply
Firms		
Cobb-Douglas coefficient θ	1/3	Labor share
Green goods share ν	0.20	Renewable energy share
Externality parameter γ_P	5.5e-5	Pollution damage/GDP
Pollution decay parameter δ_z	0.997	Heutel (2012)
Capital depreciation rate δ_k	0.0288	Capital/GDP
Discount factor $\widetilde{\beta}$	0.988	Debt/GDP
Standard deviation idiosyncratic risk ς_M	0.21	Bond spread
Bond maturity parameter s	0.05	*IHS Markit*
Financial Markets		
Restructuring costs φ	1.2	Leverage
Collateral default cost parameter η_1	0.0555	Optimality of ϕ_{sym}
Liquidity management intercept l_0	0.05	Ensures positive cost
Liquidity management slope l_1	0.0075	Eligibility premium
Haircut parameter ϕ_{sym}	0.26	ECB collateral framework
Shocks		
Persistence TFP shock ρ_A	0.95	Standard
Variance TFP shock σ_A	0.005	Standard

is scarce. For a micro-foundation of the concavity, we refer to Appendix A.2. The intercept parameter l_0 will be set sufficiently high to ensure that $\Omega(\overline{b}^i_{t+1})$ is positive for all considered collateral policy specifications.[18] Plugging $\overline{b}^i_{t+1} = 0$ into (27) can be interpreted as the cost level of an entirely un-collateralized banking system. The marginal benefit of collateral is then given by $\Omega_{\overline{b},t} = -l_1(\overline{b}^i_{t+1})^{-0.5}$, which increases in the parameter l_1 and declines in available collateral $\overline{b}^i_{t+1}$.

We calibrate l_1 to match the eligibility premium reported by the empirical literature: using the ECB list of collateral eligible for main refinancing operations, Pelizzon et al. (2020) identify an eligibility premium of -11bp. The model implied eligibility premium is given by the yield differential of the traded bond and a synthetic bond that is not eligible in period t, but becomes eligible in $t+1$, corresponding to the identification strategy of Pelizzon et al. (2020). The advantage of this procedure is that the eligibility premium can be backed out from bond prices in closed form and is given by

$$\widetilde{x}_{\tau,t} \equiv \left(1 + \frac{s}{q(\overline{m}_{\tau,t+1})} - s\right)^4 - \left(1 + \frac{s}{q(\overline{m}_{\tau,t+1})(1+(1-\phi_\tau)\Omega_{\overline{b},t})} - s\right)^4 .$$

In the spirit of Bindseil and Papadia (2006), the costs of accepting risky collateral follow

$$\Lambda(\overline{F}_t) = \frac{\eta_1}{0.5}\left(\overline{F}_t\right)^{0.5} . \tag{28}$$

The concave specification reflects that there is a fixed cost component to set up a proper risk management infrastructure as well as a marginal cost component from adding additional risk to the central bank's collateral portfolio, for example through more frequent collateral default. The parameter η_1 governs the level of collateral default costs and is set so that the empirical haircut value $\phi_{sym} = 0.26$ is optimal according to an utilitarian welfare criterion. Put differently, we assume that the status-quo ECB collateral policy is optimal under the restriction of symmetric collateral policy and parameterize (28) accordingly. Finally, we define the *greenium* as the spread of conventional over green bonds with corresponding maturity

$$\widehat{x}_t = x_{g,t} - x_{c,t} .$$

Note that the greenium is zero in our baseline calibration due to the assumption of symmetric financial frictions and haircuts. The parameterization is summarized in Table 1, while targeted moments are presented in Table B.1.

[18] We verify that l_0 does not visibly affect our results.

Table 2: Model Fit - Untargeted Moments

Moment	**Model**	**Data**	**Source**
Annualized default rate	0.02	0.01	Gomes et al. (2016)
Volatilities			
Bond spread $\sigma(x)$	31bp	50-100bp	Gilchrist and Zakrajšek (2012)
Relative vol. consumption $\sigma(c)/\sigma(y)$	0.64	0.70	Euro area data
Relative vol. investment $\sigma(i)/\sigma(y)$	4.38	3.80	Euro area data
Persistence			
GDP $corr(y_t, y_{t-1})$	0.71	0.90	Euro area data
Consumption $corr(c_t, c_{t-1})$	0.87	0.80	Euro area data
Investment $corr(i_t, i_{t-1})$	0.61	0.80	Euro area data
Correlations with GDP			
Consumption $corr(y, c)$	0.89	0.60	Euro area data
Investment $corr(y, i)$	0.90	0.70	Euro area data
Debt $corr(y, b)$	0.71	0.65	Jungherr and Schott (2022)
Default risk $corr(y, F)$	-0.76	-0.55	Kuehn and Schmid (2014)
Pollution $corr(y, \mathcal{P})$	0.34	0.30	Doda (2014)

Notes: All data and model-implied moments are based on HP-filtered data.

Macroeconomic Dynamics. In Table 2, we compare untargeted model-implied first and second moments with the data. Notably, they are broadly consistent with each other, even though our model only uses one exogenous shock to TFP and does not feature frictions related to firm investment or to the relationship between households and banks. The time series volatility of bond spreads is slightly smaller than the value reported by Gilchrist and Zakrajšek (2012) for US data, since bonds are priced using a log-utility pricing kernel and only contain default risk compensation and the collateral premium.

The relative volatilities of consumption and investment to output are consistent with euro area data. The slightly elevated investment volatility and its low autocorrelation can at least partly be attributed to the absence of investment adjustment costs. The model also captures the cyclical properties of debt and default risk, which are key financial market variables in the context of risk-taking effects induced by collateral policy. In addition, we also match closely the cyclicality of emissions, which has been estimated by Doda (2014) for a large sample of countries.

4.2 Financial and Real Effects of Preferential Treatment

To additionally corroborate the external validity of our quantitative analysis, we compare the model-implied impact of haircuts to effects estimated in the empirical literature. We proceed in two steps, since there are in principle two partial effects that shape the effect of preferential treatment and the extent to which financial frictions dampen it: (i) the response of relative bond prices between sectors to preferential treatment and (ii) the elasticities of leverage and capital to bond price changes. We relate the model-implied reactions in these dimensions to the data. Separating between-sector effects on borrowing costs from sector-specific effects of borrowing conditions on real outcomes is relevant from an empirical point of view: as preferential policies are not enacted yet, this decomposition allows to assess the model predictions' plausibility.

Preferential Treatment and Relative Borrowing Costs. To examine the effect of preferential central bank policy on (relative) bond prices, we exploit the yield reaction of green and conventional bonds around ECB announcements regarding environmental policy.[19] We identify four relevant speeches by ECB board members between 2018 and 2020, which explicitly mention environmental concerns for the conduct of central bank policy. Using data from *IHS Markit* and *Thomson Reuters Datastream*, we generate a panel of green-conventional bond pairs, obtained by a nearest-neighbor matching. We then compute the average yield difference between green bonds and their respective conventional counterparts for a 20 trading day window around each announcement. Averaging over all announcements and the entire post-treatment window, the announcement effect is significant in statistical terms: after an ECB announcement, green bond yields drop by 4.8bp on average over a 20 trading day window. This is economically meaningful and lies in a plausible range, compared to the empirical literature on collateral premia of corporate bonds. The result indicates that bond investors are willing to pay premia on green bonds if there is the prospect of future preferential treatment.

Since the ECB so far did not implement preferential treatment, these announcements can be mapped into our model by interpreting them as a news shock (see Beaudry and Portier, 2004 and Barsky and Sims, 2011). Specifically, we assume that preferential treatment will be implemented with certainty but at some point in the future. We enrich the baseline calibration by a news shock to the green collateral parameter ϕ_g for various time horizons,

$$\log(\phi_{g,t}) = (1-\rho_\phi)\log(\phi_{sym}) + \rho_\phi \log(\phi_{g,t-1}) + \sigma_\phi \varepsilon^{\phi}_{t-h} \quad \varepsilon^{\phi}_{t-h} \sim N(0,1)\,, \tag{29}$$

where ϕ_{sym} is the green collateral parameter corresponding to the baseline calibration and h denotes the announcement horizon. We choose a high value of $\rho_\phi = 0.95$ for the haircut persistence, since changes to the collateral framework only occur infrequently. The shock size σ_ϕ is set such that $\phi_g = 0.045$ in two, three, four, or five years. The haircut value of 4.5% corresponds to the treatment of AAA-rated corporate bonds with 5 year maturity in the ECB collateral framework. This haircut appears to be a reasonable value for a strong preferential policy and opens a considerable haircut gap. Moreover, the considered horizons appear plausi-

[19]See Appendix C for details on the announcements and the data.

Table 3: Greenium Reaction - Announcement Effects

Data	**Model: News Shock Horizon**			
	2 years	3 years	4 years	5 years
-4.8bp	-7.1bp	-5.5bp	-4.2bp	-3.3bp

ble, given that the ECB strategy review itself took two years and that the actual implementation of preferential treatment takes some additional time. The announcement effect on the greenium is shown in Table 3 and lies between -7.1bp and -3.3bp. Naturally, the effect peters out as the announcement horizon increases. The model-implied yield response closely resembles the value estimated in our event-study at the four-year horizon.

Relative Borrowing Costs and their Real Effects. In the second step, we consider the firm level effects of a change in borrowing cost induced by central bank policy. We build on literature studying firm responses following QE-programs and collateral framework changes. From the point of view of firms (the collateral supply side), the effects of QE and collateral eligibility are identical, since in both cases banks increase demand for their bonds for reasons unrelated to firm fundamentals. Specifically, we compare empirical estimates from the literature to the model-implied effect of a haircut reduction from $\phi_{sym} = 1$ (no eligibility) to $\phi_{sym} = 0.26$ (our baseline value). We assume that the collateral policy relaxation is *unanticipated*, comes into effect *immediately*, and is *permanent*. To ensure consistency with the event-study approaches of the empirical literature, we do not take into account general equilibrium effects and fix $\Omega_{\bar{b},t}$ at the baseline calibration's steady state. We focus on the reaction of bond yields, capital, and leverage, since our discussion of the imperfect pass-through of preferential treatment in Section 3 is centered around these variables .

Since the eligibility premium as defined in Pelizzon et al. (2020) is a calibration target, we instead examine the yield spread between eligible and non-eligible bonds. Fang et al. (2020) study the impact of an easing of collateral eligibility requirements by the PBoC and identify a yield reaction on treated bonds of 42-62bp (their Table 5). Using a similar approach, Chen et al. (2022) find a yield reaction of 39-85bp (their Tables 5 and 8).

Regarding the financing of firms, Grosse-Rueschkamp et al. (2019) show that the introduction of the Corporate Sector Purchase Program (CSPP) triggered a positive response of total debt to assets for eligible firms relative to non-eligible firms prior to CSPP. The magnitude of the effect is estimated between 1.1pp and 2.0pp, depending on the empirical specification (see their Table 2). Cahn et al. (2022) document that newly eligible firms increase their leverage by 1.2 to 2.4pp in response to a relaxation of collateral eligibility requirements for the ECB's very long term refinancing operations (VLTRO). Pelizzon et al. (2020) report an increase of total debt/total assets between 2.5pp and 10.8pp (their Table 10). Giambona et al. (2020) consider the impact of QE and find increases in total debt/total assets of around 1.8pp (their Table 15).

On the same sample, Giambona et al. (2020) report an increase in investment between 4.9pp and 15.1pp for QE-eligible firms when controlling for firm characteristics (their Tables 3 - 13). Harpedanne de Belleville (2019), Table 4.1, finds a 5.4pp increase in investment after the introduction of the Additional Credit Claims program using French data, which contains a large amount of small firms without bond market access. Grosse-Rueschkamp et al. (2019) and Cahn et al. (2022) on the other hand only document a mild effect of 1pp and 2.6pp on asset growth (their Table 5 and Table 9, respectively).

Table 4: Firm Reaction: Model vs. Data

	Δ Yield	**Δ Capital**	**Δ Leverage**
Model	70bp	4.9pp	5.1pp (market value)
			2.1pp (book value)
Data	39 - 85bp	1 - 15pp	1 - 11pp

Notes: Difference between baseline of 26% to 100% haircut in the first row. Range of estimated effects taken from the literature in the second row.

Table 4 summarizes, in its second row, these empirical estimates into ranges, and compares them to the model-implied responses. The elasticities of bond yields, capital, and leverage comfortably fall into the range of empirical estimates.

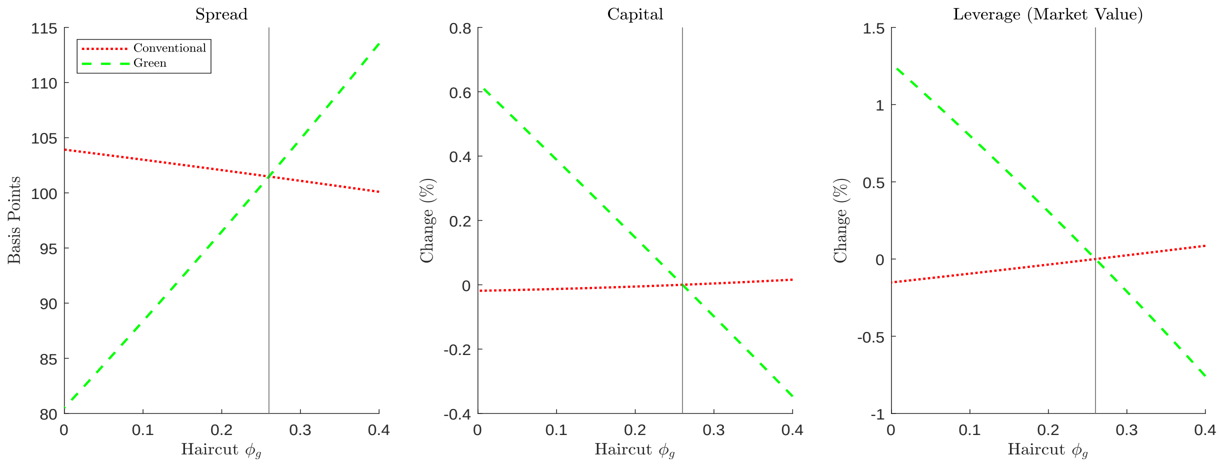
5 Policy Analysis

Using the calibrated model, we now conduct policy experiments regarding the collateral framework and its interactions with direct Pigouvian taxation of emissions. We employ an utilitarian welfare criterion based on household's (unconditional) expected utility (1) and follow Schmitt-Grohé and Uribe (2007) by approximating it, together with the policy functions, up to second order. Given the log-utility assumption on consumption, the consumption equivalent (CE) welfare gain follows as $c^{CE,policy} \equiv 100(\exp\{(1-\beta)(V^{policy} - V^{base})\} - 1)$, where V^{base} and V^{policy} are obtained from evaluating the household's value function (1) under the baseline and alternative policies, respectively.[20]

[20] We also explore welfare gains conditionally on being at the deterministic steady state of the baseline calibration and taking into account the transition period to the new steady state. Results are virtually unchanged. In Appendix B.1, we also show that introducing nominal rigidities does not affect our results.

The Effects of Preferential Treatment. Since intermediate good firms are at the heart of the transmission mechanism of both policies, we begin by showing the model-implied means of bond spreads, capital, and leverage for different green haircuts in Figure 1. The left panel shows that lowering the green haircut induces a sizable decline of the green bond spread relative to the baseline calibration (solid vertical line), which is accompanied by an increase in capital and leverage. The reaction of conventional firms mirrors the response of their green counterparts, although to a smaller extent. This is an equilibrium effect operating through the perfect substitutability of green and conventional bonds as collateral: the conventional collateral premium $(1-\phi_c)\Omega_{\overline{b},t}$ depends on haircuts and *aggregate* collateral supply. If $\overline{b}_t$ increases due to preferential treatment, this has a negative effect on the conventional collateral premium.

Figure 1: Firm Response to Preferential Treatment



Notes: We display long-run means for different green haircuts ϕ_g. Spreads are expressed in basis points, leverage is relative to the baseline calibration of $\phi_{sym} = 0.26$ (vertical line).

The case of strong preferential treatment ($\phi_g = 0.045$) is shown in the first column of Table 5. Consistent with our analysis in Section 4.2, we use this value since it corresponds to the treatment of AAA-rated corporate bonds in the ECB collateral framework and leave $\phi_c = 0.26$ at its baseline value.[21] The eligibility premium on green bonds increases to -14bp, translating into a bond spread reduction of almost 20bp, which is sizable when comparing it to the (targeted) baseline value of 100bp. This increases green investment by 0.5%, while leverage of green firms (computed at market prices of debt) increases by 1.1%. Since conventional capital falls by less then 0.1%, pollution cost fall only marginally. While restructuring and collateral

[21]Our model is not necessarily well suited to study more drastic haircut values, such as a 100% haircut on conventional bonds, sometimes referred to as complete decarbonization. Since corporate bonds are the only assets in the model, such a policy would imply a drastic reduction in available collateral and might therefore predict unreasonably large effects on green collateral premia.

default costs are higher than under the baseline scenario, liquidity management cost decrease due to the higher corporate bond issuance.

Table 5: Time Series Means for Different Policies

Moment	**Strong Pref**	**Opt Coll**	**Opt Tax**	**Glob Opt**
Tax Parameter χ_c	0	0	10.2%	10.2%
Haircut ϕ_g	4.5%	10%	26%	20%
Haircut ϕ_c	26%	30%	26%	20%
Welfare (CE, Change)	+0.015%	+0.016%	+1.490%	+1.491%
Conv. Elig. Premium	-10bp	-10bp	-11bp	-11bp
Green Elig. Premium	-14bp	-13bp	-11bp	-11bp
Conv. Bond Spread	103bp	105bp	102bp	99bp
Green Bond Spread	84bp	87bp	102bp	99bp
Conv. Leverage (Change)	-0.1%	-0.2%	0%	+0.1%
Green Leverage (Change)	+1.1%	+0.9%	0%	+0.1%
Conv. Capital (Change)	0%	-0.1%	-9.5%	-9.4%
Green Capital (Change)	+0.5%	+0.4%	+40.8%	41.0%
Green Capital Share	0.209	0.208	0.280	0.280
GDP	+0.04%	+0.02%	+0.61%	+0.64%
Restr. Cost/GDP (Change)	+1.32%	+0.01%	-0.14%	+1.68%
Coll. Default Cost/GDP (Change)	+3.90%	+0.31%	-0.38%	+4.57%
Liq. Man. Cost/GDP (Change)	-1.74%	-0.04%	-0.77%	-3.11%
Pollution Cost/GDP (Change)	-0.02%	-0.08%	-9.01%	-8.92%

Notes: Strong preferential treatment (*Strong Pref*) is based on a collateral framework set to $\phi_g = 0.045$ and $\phi_c = 0.36$. The optimal collateral policy (*Opt Coll*) is computed holding $\chi_g = 0$ constant. For the optimal tax (*Opt Tax*), we hold haircuts fixed at their baseline values and vary the tax rate. The global optimum (*Glob Opt*) is obtained by jointly maximizing over taxes and haircuts. "*Change*" refers to percentage differences from the baseline calibration. The baseline green capital share of 0.2 is a calibration target.

Optimal Collateral Policy. The second column of Table 5 is associated with the optimal collateral framework of $\phi_g = 0.10$ and $\phi_c = 0.30$, conditional on an emission tax of zero. While the haircut gap of 20% is very similar to the case of strong preferential treatment, the average haircut is higher in this case such that aggregate collateral stays approximately constant. This is also mirrored in the very small change of aggregate liquidity management and default cost of this policy relative to the baseline. While the green capital share is slightly smaller than in the strong preferential treatment case, pollution cost is lower due to the relatively high haircut on conventional bonds. In a similar vein, a strongly punishing haircut on conventional bonds is not optimal either, since liquidity management cost would increase beyond their optimal level. Put differently, the optimal average haircut is determined by the trade-off between default and liquidity management cost, while the haircut gap depends on the environmental impact of

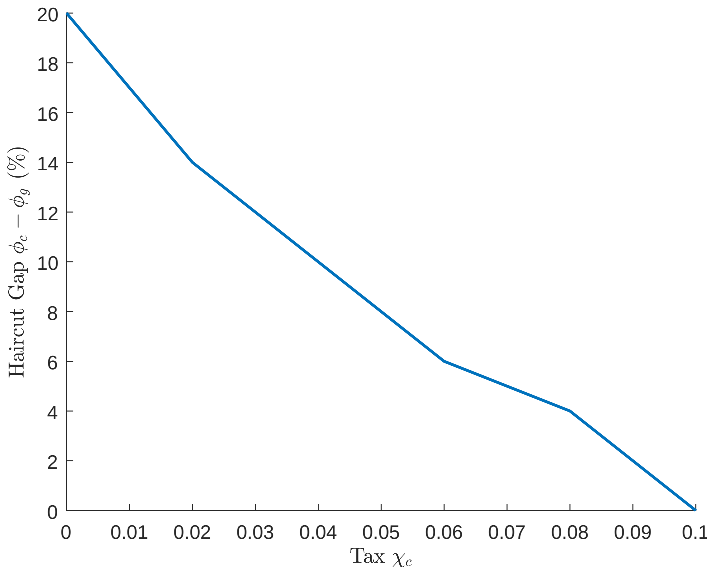


Figure 2: Optimal Collateral Policy Under Sub-Optimal Taxation

Notes: For different levels of the Pigouvian tax, we maximize CE over a grid of haircuts and display the result as the difference between optimal conventional and green haircuts.

collateral policy.

Interaction with Direct Taxation. So far, our analysis showed that the central bank can affect the relative size of green and conventional capital and thereby reduce emissions, while at the same time inducing non-negligible side-effects. In this section, we benchmark these results against direct Pigouvian taxation. The simplified version of our model in Section 3 already suggested that taxes have a direct effect on capital shares, rather than operating indirectly through the firm financing decision. This section confirms that this also holds in a more general setting. In addition to this qualitative difference, we also can evaluate the quantitative relevance of preferential collateral policy by comparing the green capital ratio in both cases.

The third column of Table 5 corresponds to optimal Pigouvian taxation, holding the collateral framework at its baseline value. The optimal tax on conventional production is 10.2%. Compared to the baseline scenario, the green capital share rises from the targeted baseline value of 0.2 to 0.28, which reduces the pollution externality by around 9%. At the same time, there are no adverse effects on firm risk-taking: the leverage ratio of firms is unchanged. Taken together, the welfare improvement of optimal Pigouvian taxation exceeds the improvement from optimal preferential treatment by two orders of magnitude.

However, this result should not be misinterpreted as a call for central bank inaction, since Pigouvian taxation affects the (optimal) conduct of collateral policy, as reported in the fourth column of Table 5. Pigouvian taxation increases GDP but simultaneously reduces collateral availability due to the drop in bond issuance of conventional firms. Put differently, the baseline collateral framework is not solving the optimal collateral policy problem in the presence of Pigouvian taxes. As a result, the globally optimal collateral framework becomes more lenient. Notably, this relaxation is symmetric and the green capital share is not affected by the relaxation. This incentivizes all firms to increase their bond issuance, implying a slight increase of default cost while liquidity management cost decline substantially.[22] The welfare gains of adjusting collateral frameworks to mitigate negative effects on collateral availability are positive, but of very small size compared to the welfare gains of optimal taxation.

The symmetry result hinges on the assumption that optimal Pigouvian taxes are available, which is arguably not an empirically plausible case, at least in the short run. In Figure 2, we compute the optimal degree of preferential treatment, represented by the optimal haircut differential, for different levels of the Pigouvian tax. At $\chi_c = 0$, the haircut gap is 20%, corresponding to the third column of Table 5, i.e., optimal collateral policy in the absence of taxation. At the globally optimal tax of $\chi_c = 0.013$, the optimal haircut gap is zero. While we are not explicit about why the Pigouvian might be too low, our model implies that preferential treatment is welfare-enhancing if and only if environmental policy is unable to implement the optimal Pigouvian tax and that the degree of preferential treatment decreases so long as the Pigouvian tax gets closer to its optimal level.

6 Conclusion

In this paper, we examine the effectiveness of the preferential collateral treatment of green bonds in an augmented RBC-model. Preferential treatment stimulates investment into green capital, but simultaneously induces an increase in green firms' leverage and default risk. In a calibration to euro area data, we show that optimal collateral policy takes into account these adverse effects and is considerably less effective than Pigouvian taxes, but still increases welfare. Preferential treatment is a qualitatively and quantitatively imperfect substitute for Pigouvian taxes and is desirable if and only if Pigouvian taxes are set below their optimal level.

Our results can be read as a call for (i) central bank action if tax policy is not able to adequately address climate externalities associated with carbon emissions, (ii) a careful design of preferential treatments that take into account the side effects on firm risk-taking.

[22] This is similar to Carattini et al. (2021), who show that macroprudential policy can alleviate adverse effects of carbon taxation. In their model, adverse effects take the form of asset stranding, while in our case adverse effects are linked to collateral availability if conventional firms shrink their balance sheet size. Notably, optimal macroprudential policy is also symmetric in their model.

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A Model Appendix

A.1 Intermediate Good Firms' Debt and Investment Choice

We start with observing that the default threshold of a type-τ intermediate good firm in period $t+1$ is given by $\overline{m}_{\tau,t+1} \equiv \frac{sb_{\tau,t+1}}{(1-\chi_\tau)p_{\tau,t+1}k_{\tau,t+1}}$. The threshold satisfies the following properties:

$$\frac{\partial \overline{m}_{\tau,t+1}}{\partial b_{\tau,t+1}} = \frac{s}{(1-\chi_\tau)p_{\tau,t+1}k_{\tau,t+1}} = \frac{b_{\tau,t+1}}{(1-\chi_\tau)p_{\tau,t+1}k_{\tau,t+1}}\frac{s}{b_{\tau,t+1}} = \frac{\overline{m}_{\tau,t+1}}{b_{\tau,t+1}}\,, \tag{A.1}$$

$$\frac{\partial \overline{m}_{\tau,t+1}}{\partial k_{\tau,t+1}} = -\frac{sb_{\tau,t+1}}{(1-\chi_\tau)p_{\tau,t+1}k^2_{\tau,t+1}} = -\frac{b_{\tau,t+1}}{(1-\chi_\tau)p_{\tau,t+1}k_{\tau,t+1}}\frac{s}{k_{\tau,t+1}} = -\frac{\overline{m}_{\tau,t+1}}{k_{\tau,t+1}}\,. \tag{A.2}$$

We assume that $\log(m_{\tau,t})$ is normally distributed with mean μ_M and standard deviation ς_M. In the calibration, we ensure that $\mathbb{E}[m_{\tau,t}] = 1$ by setting $\mu_M = -\varsigma_M^2/2$. The CDF of $m_{\tau,t}$ is given by $F(m_{\tau,t}) = \Phi\left(\frac{\log m_{\tau,t} - \mu_M}{\varsigma_M}\right)$, where $\Phi(\cdot)$ is the cdf of the standard normal distribution. The conditional mean of m at the threshold value $\overline{m}_{\tau,t+1}$ can be expressed as

$$G(\overline{m}_{\tau,t+1}) = \int_0^{\overline{m}_{\tau,t+1}} mf(m)dm = e^{\mu_M + \frac{\varsigma_M^2}{2}}\Phi\left(\frac{\log \overline{m}_{\tau,t+1} - \mu_M - \varsigma_M^2}{\varsigma_M}\right),$$

$$1 - G(\overline{m}_{\tau,t+1}) = \int_{\overline{m}_{\tau,t+1}}^{\infty} mf(m)dm = e^{\mu_M + \frac{\varsigma_M^2}{2}}\Phi\left(\frac{-\log \overline{m}_{\tau,t+1} + \mu_M + \varsigma_M^2}{\varsigma_M}\right).$$

Note that the derivative of the conditional mean $g(\overline{m}_{\tau,t+1})$ satisfies

$$g(\overline{m}_{\tau,t+1}) = \overline{m}_{\tau,t+1} f(\overline{m}_{\tau,t+1})\,. \tag{A.3}$$

For notational convenience, we write the bond price schedule as function of the default threshold $\overline{m}_{\tau,t}$ throughout this section. The bond payoff is given by

$$\mathcal{R}_{\tau,t} = s\left(G(\overline{m}_{\tau,t})\frac{(1-\chi_\tau)p_{\tau,t}k_{\tau,t}}{sb_{\tau,t}} + 1 - F(\overline{m}_{\tau,t})\right) - F(\overline{m}_{\tau,t})\varphi + (1-s)q(\overline{m}_{\tau,t})\,,$$

such that we can write the bond price as

$$q(\overline{m}_{\tau,t+1}) = \mathbb{E}_t\left[\frac{s\left(\frac{G(\overline{m}_{\tau,t+1})}{\overline{m}_{\tau,t+1}} + 1 - F(\overline{m}_{\tau,t+1})\right) - F(\overline{m}_{\tau,t+1})\varphi + (1-s)q(\overline{m}_{\tau,t+2})}{(1+(1-\phi_\tau)\Omega_{b,t})(1+i_t)}\right]. \tag{A.4}$$

The partial derivatives with respect to bonds and capital is given by

$$q'(\overline{m}_{\tau,t+1}) = -\mathbb{E}_t\left[\frac{sG(\overline{m}_{\tau,t+1})/\overline{m}^2_{\tau,t+1} + \varphi f(\overline{m}_{\tau,t+1})}{(1+(1-\phi_\tau)\Omega_{b,t})(1+i_t)}\right], \tag{A.5}$$

Taken as given the bond pricing condition, firms choose $k_{\tau,t+1}$ and $b_{\tau,t+1}$ to maximize

$$\begin{aligned}
&-k_{\tau,t+1} + q(\overline{m}_{\tau,t+1})\Big(b_{\tau,t+1} - (1-s)b_{\tau,t}\Big)\\
&+\mathbb{E}_t\Bigg[\widetilde{\Lambda}_{t,t+1}\Bigg((1-G(\overline{m}_{\tau,t+1}))(1-\chi_\tau)p_{\tau,t+1}k_{\tau,t+1} + (1-\delta_k)k_{\tau,t+1}\\
&\quad -s\Big(1-F(\overline{m}_{\tau,t+1})\Big)b_{\tau,t+1} + q(\overline{m}_{\tau,t+2})\Big(b_{\tau,t+2} - (1-s)b_{\tau,t+1}\Big)\Bigg)\Bigg].
\end{aligned}$$

FOC w.r.t $b_{\tau,t+1}$. The first order condition for bonds is given by

$$\begin{aligned}
0 =& \frac{\partial q(\overline{m}_{\tau,t+1})}{\partial b_{\tau,t+1}}\Big(b_{\tau,t+1} - (1-s)b_{\tau,t}\Big) + q(\overline{m}_{\tau,t+1})\\
&+\mathbb{E}_t\Bigg[\widetilde{\Lambda}_{t,t+1}\Bigg(-(1-\chi_\tau)p_{\tau,t+1}k_{\tau,t+1}g(\overline{m}_{\tau,t+1})\frac{\partial \overline{m}_{\tau,t+1}}{\partial b_{\tau,t+1}}\\
&\qquad -s\Big(-f(\overline{m}_{\tau,t+1})\frac{\partial \overline{m}_{\tau,t+1}}{\partial b_{\tau,t+1}}b_{\tau,t+1} + 1 - F(\overline{m}_{\tau,t+1})\Big) - (1-s)q(\overline{m}_{\tau,t+2})\Bigg)\Bigg],
\end{aligned}$$

which can be expressed as

$$\begin{aligned}
0 =& \frac{\partial q(\overline{m}_{\tau,t+1})}{\partial b_{\tau,t+1}}\Big(b_{\tau,t+1} - (1-s)b_{\tau,t}\Big) + q(\overline{m}_{\tau,t+1})\\
&+\mathbb{E}_t\Bigg[\widetilde{\Lambda}_{t,t+1}\Bigg(-sg(\overline{m}_{\tau,t+1})\frac{\overline{m}_{\tau,t+1}\cancel{(1-\chi_\tau)p_{\tau,t+1}k_{\tau,t+1}}}{sb_{\tau,t+1}}\\
&-s\Big(\cancel{-f(\overline{m}_{\tau,t+1})\overline{m}_{\tau,t+1}} + 1 - F(\overline{m}_{\tau,t+1})\Big) - (1-s)q(\overline{m}_{\tau,t+2})\Bigg)\Bigg],
\end{aligned}$$

and then yields (14).

FOC w.r.t $k_{\tau,t+1}$. The first order condition for capital is given by

$$\begin{aligned}
1 =& \frac{\partial q(\overline{m}_{\tau,t+1})}{\partial k_{\tau,t+1}}\Big(b_{\tau,t+1} - (1-s)b_{\tau,t}\Big)\\
&+\mathbb{E}_t\Bigg[\widetilde{\Lambda}_{t,t+1}\Bigg(1-\delta_k - g(\overline{m}_{\tau,t+1})\frac{\partial \overline{m}_{\tau,t+1}}{\partial k_{\tau,t+1}}(1-\chi_\tau)p_{\tau,t+1}k_{\tau,t+1} + (1-G(\overline{m}_{\tau,t+1}))(1-\chi_\tau)p_{\tau,t+1}\\
&\qquad + sb_{\tau,t+1}f(\overline{m}_{\tau,t+1})\frac{\partial \overline{m}_{\tau,t+1}}{\partial k_{\tau,t+1}}\Bigg],
\end{aligned}$$

which can be rearranged to

$$
\begin{aligned}
1 = & \frac{\partial q(\overline{m}_{\tau,t+1})}{\partial k_{\tau,t+1}} \Big(b_{\tau,t+1} - (1-s) b_{\tau,t} \Big) \\
& + \mathbb{E}_t \Bigg[\widetilde{\Lambda}_{t,t+1} \Bigg(1 - \delta_k + \cancel{g(\overline{m}_{\tau,t+1}) \overline{m}_{\tau,t+1} (1-\chi_\tau) p_{\tau,t+1}} + \big(1 - G(\overline{m}_{\tau,t+1})\big)(1-\chi_\tau) p_{\tau,t+1} \\
& \qquad - \cancel{f(\overline{m}_{\tau,t+1}) \overline{m}^2_{\tau,t+1} (1-\chi_\tau) p_{\tau,t+1}} \Bigg) \Bigg] ,
\end{aligned}
$$

and further to (15). Gomes et al. (2016) consider explicitly the impact of today's debt choice on *tomorrows* debt choice, which further reduces tomorrow's bond price. Since tomorrow's bond price is part of today's bond price by the rollover value in the bond pricing condition, this *stickiness* of leverage has a dynamic feedback effect into today's debt choice. We verify that this effect does not materially change the cyclical properties of our model or the optimal policy results.

A.2 Bank Liquidity Management Costs

In the quantitative analysis, we assume that banks incur liquidity management costs $\Omega(\overline{b}^i_{t+1})$, which gives rise to collateral premia. In this section, we demonstrate that the resulting first order conditions for corporate bonds are observationally equivalent to the most common micro-foundation used in this context, which are stochastic bank deposit withdrawals, see Corradin et al. (2017), De Fiore et al. (2019), Piazzesi and Schneider (2021), or Bianchi and Bigio (2022). The standard modeling device in this literature is a two sub-period structure, where banks participate in asset markets sequentially: in the first sub-period, banks trade with households on the deposit market and with intermediate good firms on the corporate bond market. In the second sub-period, bank i faces a liquidity deficit $\omega^i_t > 0$, which it settles on a collateralized short-term funding market, e.g., with the central bank.

If bank i is unable to collateralize its entire funding need, it must borrow on the (more expensive) unsecured segment. More specifically, since all banks hold the same amount of collateral $\overline{b}_{t+1}$ before the deposits are withdrawn, there is a cut-off withdrawal $\overline{\omega}_t = \overline{b}_{t+1}$ above which a bank needs to tap the unsecured segment. The amount borrowed on the unsecured segment for all banks follows as

$$
\widetilde{b}_{t+1} \equiv \int_{\overline{b}_{t+1}}^{\infty} \big(\omega^i_{t+1} - \overline{b}_{t+1}\big)\, dW(\omega) ,
$$

where W denotes the cdf of the withdrawal shock distribution. Due to its analytical tractability, it is convenient to assume that withdrawals follow a Lomax distribution. This distribution is supported on the right half-line and characterized by a shape $\widetilde{\alpha}$ and a scale $\widetilde{\lambda}$ parameter. This allows us to write the expected amount of borrowing on the unsecured segment in closed form:

$$
\begin{aligned}
\widetilde{b}_{t+1} &= \int_{\overline{b}_{t+1}}^{\infty} \omega_{t+1}^{i} \frac{\widetilde{\alpha}}{\widetilde{\lambda}} \left(1+\frac{\omega_{t+1}^{i}}{\widetilde{\lambda}}\right)^{-\widetilde{\alpha}-1} d\omega - \overline{b}_{t+1} \int_{\overline{b}_{t+1}}^{\infty} \frac{\widetilde{\alpha}}{\widetilde{\lambda}} \left(1+\frac{\omega_{t+1}^{i}}{\widetilde{\lambda}}\right)^{-\widetilde{\alpha}-1} d\omega \\
&= \overline{b}_{t+1} \left(1+\frac{\overline{b}_{t+1}}{\widetilde{\lambda}}\right)^{-\widetilde{\alpha}} + \frac{\widetilde{\lambda}}{\widetilde{\alpha}-1} \left(1+\frac{\overline{b}_{t+1}}{\widetilde{\lambda}}\right)^{-\widetilde{\alpha}+1} - \overline{b}_{t+1} \left(1+\frac{\overline{b}_{t+1}}{\widetilde{\lambda}}\right)^{-\widetilde{\alpha}} \\
&= \frac{\widetilde{\lambda}}{\widetilde{\alpha}-1} \left(1+\frac{\overline{b}_{t+1}}{\widetilde{\lambda}}\right)^{-\widetilde{\alpha}+1} .
\end{aligned}
$$

When $\widetilde{\alpha} > 1$, the aggregate amount of unsecured borrowing falls, the more collateral is held. The benefit of holding collateral corresponds to the secured-unsecured spread ξ that is paid on borrowing $\widetilde{b}_{t+1}$, which we assume to be an exogenous parameter. These expected cost $\xi \widetilde{b}_{t+1}$ enter bank profits in the first sub-period

$$
\Pi_t^i = d_{t+1}^i - q_{c,t+1} b_{c,t+1}^i - q_{g,t+1} b_{g,t+1}^i - \xi \widetilde{b}_{t+1} .
$$

The cost depend negatively on $\overline{b}_{t+1}$, but the marginal cost reduction is falling in $\overline{b}_{t+1}$. Since very large withdrawal shocks are unlikely, the additional benefit of holding another unit of collateral is positive but decreasing. The properties of our concave liquidity cost function $\Omega(\overline{b}_{t+1}^i)$ are closely related to the common micro-foundation using bank liquidity risk.

A.3 Collateral Default Costs

In the main text we assume an exogenous cost function from collateral default $\Lambda(\overline{F}_t)$. In this section, we provide a micro-foundation based on central bank solvency concerns (see Hall and Reis, 2015). We show that this yields a loss function $\Lambda(\overline{F}_t)$ which is increasing in $\overline{F}_t$, consistent with our assumption in the main text. Similar to Appendix A.2, assume that every bank i incurs a liquidity shock ω in every period, which they settle by borrowing from the central bank via repos against collateral. To introduce an economically meaningful role for collateral, we assume that some banks will default on their central bank repos. Since the collateral banks pledge is subject to default risk, the central bank will subject itself to corporate default risk when entering repurchase agreements. The central bank haircut ϕ directly affects exposure to this risk.

The timing is as follows: in the beginning of period t, before the corporate bond market opens, banks incur the exogenous liquidity need and tap the central bank facility. Repos mature at the end of period t, after collateral and bank default materializes, but before the corporate bond market opens again. Therefore, only corporate bonds b_t held from the previous period can be used as collateral. Since the bond payoff is still uncertain when banks enter repos, they are valued at price q_t. Consistent with actual practice on repo markets, banks can borrow up to the (haircut-corrected) market value of bonds $(1-\phi)q_t b_t$. To be consistent with positive collateral premia, we assume that the liquidity shock exceeds available collateral and, therefore, banks pledge the full collateral value of their corporate bond portfolio.

Since every bank i incurs the liquidity shock, i indexes both banks and repo contracts. We assume that bank default is independent across banks and over time, and that it can be represented by the random variable ζ^i with cdf Z and pdf z, and with support $[0,1]$. The bond-specific default risk is denoted F_t. In case of a bank default, the central bank seizes the posted collateral to cover its losses. However, since the collateral itself defaults at rate F_t, the central bank will not recover the full amount of the defaulted repo. The expected loss on repo i follows as

$$\mathcal{F}_t^i = \zeta^i \cdot (1-\phi)q_t b_t F_t \; .$$

To make the results more easily interpretable, it is helpful to assume central bank also generates seignorage revenues from lending through its facilities. As customary in the literature, we assume that seignorage revenues are bounded from above by the (time-invariant) constant $\mathcal{M}$. Consequently, the central bank incurs a loss from bank default if the default shock exceeds $\overline{\zeta}_t = \mathcal{M}/(\omega \cdot F_t)$. We can then denote the expected central bank loss as

$$\mathcal{L}_t = \int_{\overline{\zeta}_t}^{1} \zeta^i \cdot (1-\phi)q_t b_{t+1} \cdot F_t \cdot z(\zeta) d\zeta = (1-\phi)q_t b_t F_t \cdot \int_{\overline{\zeta}_t}^{1} \zeta^i z(\zeta) d\zeta \; . \tag{A.6}$$

The central bank haircut and bond default risk affect the expected loss in two ways. The first part of (A.6) show that irrespective of the distributional assumption on ζ^i, the expected loss rises in bond default risk F_t and that a higher haircut ϕ, by lowering the repo size, reduces cost. Second, note that the threshold value for bank default can be expressed as $\overline{\zeta}_t = \mathcal{M}/((1-\phi)q_t b_t F_t)$: a higher haircut increases the default risk threshold beyond which central bank profits are negative and, thereby, lowers the expected loss. Defining collateral default risk as the repo size times bond default risk $\overline{F}_t = (1-\phi)q_t b_t F_t$, the convex relationship between default risk and central bank losses arising from these two margins is directly reflected in the cost function $\Lambda(\overline{F}_t)$ that we use in the quantitative analysis.

A.4 Proof of Lemma 1

The proof uses the closed-form expressions for bond prices together with the first order conditions for capital and bonds to express the effect of collateral policy on the investment payoff in an easily interpretable way.

Combining the first order conditions (21) with (22), and differentiating the financial wedge

$\Gamma_{\tau,t+1}$ with respect to the collateral premium, we can decompose the total effect into the increase of bond prices $\frac{\partial q(m_{\tau,t+1})}{\partial(1-\phi_\tau)\Omega_{\overline{b}}}$ that is also present in the default-free case and three terms associated with risk-taking:

$$\frac{\partial \Gamma_{\tau,t+1}}{\partial(1-\phi_\tau)\Omega_{\overline{b}}} = \mathbb{E}_t\Bigg[\Big(\frac{\partial q(m_{\tau,t+1})}{\partial(1-\phi_\tau)\Omega_{\overline{b}}} + q'(\overline{m}_{\tau,t+1})\frac{\partial \overline{m}_{\tau,t+1}}{\partial(1-\phi_\tau)\Omega_{\overline{b}}}\Big)\overline{m}_{\tau,t+1} \tag{A.7}$$

$$+q(\overline{m}_{\tau,t+1})\frac{\partial \overline{m}_{\tau,t+1}}{\partial(1-\phi_\tau)\Omega_{\overline{b}}} - \widetilde{\beta}\big(1-F(\overline{m}_{\tau,t+1})\big)\frac{\partial \overline{m}_{\tau,t+1}}{\partial(1-\phi_\tau)\Omega_{\overline{b}}}\Bigg].$$

The first term $\frac{\partial q(m_{\tau,t+1})}{\partial(1-\phi_\tau)\Omega_{\overline{b}}}$ reflects the reduction in financing costs, holding firm behavior constant, and is closely related to the default-free benchmark. The term $q'(\overline{m}_{\tau,t+1})\frac{\partial \overline{m}_{\tau,t+1}}{\partial(1-\phi_\tau)\Omega_{\overline{b}}} < 0$ is a negative risk-taking effect, which lowers the bond price and thereby makes investment less attractive in period t. The positive term $q_{\tau,t}\frac{\partial \overline{m}_{\tau,t+1}}{\partial(1-\phi_\tau)\Omega_{\overline{b}}}$ captures a bond price appreciation from investment, since higher investment lowers default risk, ceteris paribus. Last, $\widetilde{\beta}\big(1-F(\overline{m}_{\tau,t+1})\big)\frac{\partial \overline{m}_{\tau,t+1}}{\partial(1-\phi_\tau)\Omega_{\overline{b}}}$ reflects the dividend reduction in $t+1$ due to higher default rates. Using the definitions of $q(\overline{m}_{\tau,t+1})$ and $q'(\overline{m}_{\tau,t+1})$, we can express (A.7) as

$$\frac{\partial \Gamma_{\tau,t+1}}{\partial(1-\phi_\tau)\Omega_{\overline{b}}} = \Bigg(\underbrace{\frac{1-\frac{f(\overline{m}_{\tau,t+1})}{(1-F(\overline{m}_{\tau,t+1}))}\overline{m}_{\tau,t+1}}{(1+i_t)(1+(1-\phi_\tau)\Omega_{\overline{b}})}}_{=\widetilde{\beta}\text{ from (24)}}(1-F(\overline{m}_{\tau,t+1})) - \widetilde{\beta}\big(1-F(\overline{m}_{\tau,t+1})\big)\Bigg)\frac{\partial \overline{m}_{\tau,t+1}}{(1-\phi_\tau)\Omega_{\overline{b}}}$$

$$+\frac{\partial q(\overline{m}_{\tau,t+1})}{\partial(1-\phi_\tau)\Omega_{\overline{b}}}\overline{m}_{\tau,t+1} = \frac{\partial q(\overline{m}_{\tau,t+1})}{\partial(1-\phi_\tau)\Omega_{\overline{b}}}\overline{m}_{\tau,t+1}\,.$$

Using the derivative of the bond pricing condition with respect to the collateral premium, this expression further simplifies to

$$\frac{\partial \Gamma_{\tau,t+1}}{\partial(1-\phi_\tau)\Omega_{\overline{b}}} = \overline{m}_{\tau,t+1}(1-F(\overline{m}_{\tau,t+1}))\frac{\partial \tilde{q}(\overline{m}_{\tau,t+1})}{\partial(1-\phi_\tau)\Omega_{\overline{b}}}\,,$$

where $\frac{\partial \tilde{q}(\overline{m}_{\tau,t+1})}{\partial(1-\phi_\tau)\Omega_{\overline{b}}}$ is the response of the bond in the case without default risk. Plugging this condition into (23) we get to (25) □

B Additional Numerical Results

Table B.1 summarizes the targeted moments in our calibration, complementing Table 1.

Table B.1: Targeted Moments

Moment	Data	Model
Labor supply	0.3	0.305
Emission damage/GDP	0.1	0.105
Capital/GDP	2.1	2.13
Debt/GDP	0.8	0.83
Bond spread	100bp	99bp
Leverage	0.4	0.39
Eligibility premium	-11bp	-11bp

B.1 The Role of the Green-Conventional Substitution Elasticity

In this section, we provide a robustness check regarding the production technology of wholesale goods producers. By assuming a Cobb-Douglas production function in (8), we implicitly assume an elasticity of substitution of one between green and conventional intermediate goods. When strictly interpreting green and conventional firms as energy producers, this elasticity is usually estimated to be larger than one. Therefore, we repeat our policy analysis when replacing the wholesale producers' technology by a general CES-function

$$z_t = \left(\nu z_{g,t}^{\frac{\varepsilon_\nu - 1}{\varepsilon_\nu}} + (1-\nu) z_{c,t}^{\frac{\varepsilon_\nu - 1}{\varepsilon_\nu}} \right)^{\frac{\varepsilon_\nu}{\varepsilon_\nu - 1}}, \tag{B.1}$$

and set the elasticity of substitution $\varepsilon_\nu = 1.6$, following the point estimate in Papageorgiou et al. (2017). The parameter ν is set to keep the green production share at 20%, consistent with the baseline. To ensure an apples-to-apples comparison with the baseline model, we recalibrate the idiosyncratic productivity variance to $\varsigma_M = 0.195$, the externality parameter to $\gamma_P = 6e-5$, the slope parameter in the collateral default cost function to $\eta_1 = 0.0352$, and the slope parameter in the liquidity management cost function to $l_1 = 0.0065$.

Table B.2: Greenium Reaction - Announcement Effects with CES

Data	Model: News Shock Horizon			
	2 years	3 years	4 years	5 years
-4.8bp	-7.6bp	-5.4bp	-4.1bp	-3.2bp

Results are shown in Table B.4. The optimal tax is much higher and optimal collateral policy implies a much larger degree of preferential treatment. Intuitively, when conventional and green intermediate goods are easier to substitute, any policy-induced reduction in the size of conventional firms is less costly for final good production. In contrast, the effect of collateral policy on bond prices, leverage, and investment is similar to the baseline calibration (see Table B.2 and Table B.3). Therefore, the *relative welfare gains* of optimal collateral policy still exceed the gains of optimal taxation by a very similar factor as in the baseline case of a Cobb-Douglas production function.

Table B.3: Firm Reaction: Model vs. Data with CES

	Δ Yield	**Δ Capital**	**Δ Leverage**
Model	81bp	5.2pp	6.3pp (market value)
			3.0pp (book value)
Data	39 - 85bp	1 - 15pp	1 - 11pp

Notes: Difference between baseline of 26% to 100% haircut in the first row. Range of estimated effects in the literature in the second row.

Table B.4: Time Series Means with $\varepsilon_v = 1.6$

Moment	**Strong Pref**	**Opt Coll**	**Opt Tax**	**Glob Opt**
Tax Parameter χ_c	0	0	12%	12%
Haircut ϕ_g	4.5%	4%	26%	18%
Haircut ϕ_c	26%	32%	26%	18%
Welfare (CE, Change)	+0.012%	+0.015%	+1.490%	+1.491%
Conv. Elig. Premium	-10bp	-10bp	-11bp	-11bp
Green Elig. Premium	-13bp	-14bp	-11bp	-11bp
Conv. Bond Spread	99bp	102bp	98bp	95bp
Green Bond Spread	84bp	81bp	98bp	95bp
Conv. Leverage (Change)	-0.1%	-0.3%	0%	+0.2%
Green Leverage (Change)	+0.9%	+1.1%	0%	+0.2%
Conv. Capital (Change)	-0.1%	-0.2%	-16.2%	-16.1%
Green Capital (Change)	+0.6%	+0.8%	+67.9%	+68.1%
Green Capital Share	0.2060	0.2065	0.3406	0.3406
GDP (Change)	+0.04%	+0.03%	+1.06%	+1.10%
Restr. Cost/GDP (Change)	+1.28%	-0.05%	-0.25%	+2.19%
Coll. Default Cost/GDP (Change)	+3.70%	+0.40%	-0.64%	+5.89%
Liq. Man. Cost/GDP (Change)	-1.30%	+0.01%	-1.28%	-3.69%
Pollution Cost/GDP (Change)	-0.05%	-0.16%	-15.47%	-15.38%

Notes: Strong preferential treatment (*Strong Pref*) is based on a collateral framework set to $\phi_g = 0.045$ and $\phi_c = 0.36$. The optimal collateral policy (*Opt Coll*) is computed holding $\chi_g = 0$ constant. For the optimal tax (*Opt Tax*), we hold haircuts fixed at their baseline values and vary the tax rate. The global optimum (*Glob Opt*) is obtained by jointly maximizing over taxes and haircuts. "*Change*" refers to percentage differences from the baseline calibration. The baseline green capital share of 0.2 is a calibration target.

B.2 The Role of Nominal Rigidities

In this section, we add nominal rigidities to the model following the standard New Keynesian model. In particular, bonds are assumed to be denominated in nominal terms, i.e., inflation has a direct effect on corporate bonds and the supply side. Households consume a final goods basket c_t given by

$$c_t = \left(\int_0^1 c_{i,t}^{\frac{\varepsilon-1}{\varepsilon}} \, dj \right)^{\frac{\varepsilon}{\varepsilon-1}} ,$$

where $\varepsilon > 1$ is the elasticity of substitution among the differentiated final goods. The demand schedule for final good i is given by

$$c_{j,t} = \left(\frac{P_{j,t}}{P_t} \right)^{-\varepsilon} c_t \ , \tag{B.2}$$

where P_t denotes the CES price index for the final consumption bundle. Final good firms sell their differentiated good with a markup over their marginal costs. However, the price of firm j, $P_{j,t}$, can only be varied by paying a quadratic adjustment cost à la Rotemberg (1982) that is proportional to the nominal value of aggregate production, $P_t y_t$. Firm j's marginal costs are denoted by $\mathrm{mc}_{j,t} \equiv \partial \mathcal{C}_t^W / \partial y_{j,t}$, where the wholesale firm's cost minimization problem is given by

$$\mathcal{C}_t^W(y_{j,t}) = \min_{z_{j,t}, l_{j,t}} \quad P_{z,t} z_{j,t} + W_t l_{j,t} \quad \text{s.t.} \quad y_{j,t} = (1 - \mathcal{P}_t) A_t z_{j,t}^{\theta} l_{j,t}^{1-\theta} ,$$

and $P_{z,t}$ is the price of the wholesale good. From the minimization problem we obtain *real* marginal costs

$$\mathrm{mc}_t = \frac{1}{(1-\mathcal{P}_t) A_t} \left(\frac{p_{z,t}}{\theta} \right)^{\theta} \left(\frac{w_t}{1-\theta} \right)^{1-\theta} ,$$

where $p_{z,t} = P_{z,t}/P_t$ is the relative price of the wholesale good and w_t is the real wage. Hence, total nominal profits of firm j in period t are given by

$$\widehat{\Pi}_{j,t} = \left(P_{j,t} - \mathrm{mc}_t P_t \right) y_{j,t} - \frac{\psi}{2} \left(\frac{P_{j,t}}{P_{j,t-1}} - 1 \right)^2 P_t y_t ,$$

where ψ measures the degree of the nominal rigidity. Each wholesale good firm j maximizes the expected sum of discounted profits

$$\max_{P_{j,t+s}, y_{j,t+s}} \mathbb{E}_t \left[\sum_{s=0}^{\infty} \beta^s \frac{c_{t+s}^{-\gamma_c}/P_{t+s}}{c_t^{-\gamma_c}/P_t} \widehat{\Pi}_{j,t+s} \right] ,$$

subject to the demand schedule (B.2). Plugging in the demand function yields the first order condition

$$\begin{aligned} &\left(\frac{P_{j,t}}{P_t} \right)^{-\varepsilon} Y_t - \varepsilon \left(P_{j,t} - \mathrm{mc}_t P_t \right) \left(\frac{P_{j,t}}{P_t} \right)^{-\varepsilon} \frac{y_t}{P_t} - \psi \left(\frac{P_{j,t}}{P_{j,t-1}} - 1 \right) \frac{P_t}{P_{j,t-1}} y_t \\ &+ \mathbb{E}_t \left[\frac{c_{t+1}^{-\gamma_c}/P_{t+1}}{c_t^{-\gamma_c}/P_t} \psi \left(\frac{P_{j,t+1}}{P_{j,t}} - 1 \right) \frac{P_{j,t+1}}{P_{j,t}^2} P_{t+1} y_{t+1} \right] = 0 . \end{aligned}$$

In a symmetric price equilibrium, $P_{j,t} = P_t$ for all j. Using this, we rearrange and get

$$(1 - \varepsilon(1 - \mathrm{mc}_t)) y_t + \mathbb{E}_t \left[\beta \frac{c_{t+1}^{-\gamma_c}/P_{t+1}}{c_t^{-\gamma_c}/P_t} y_{t+1} \pi_{t+1} \psi (\pi_{t+1} - 1) \pi_{t+1} \right] = \psi (\pi_t - 1) \pi_t y_t ,$$

where $\pi_t = \frac{P_t}{P_{t-1}}$. Dividing both sides by y_t and Ψ we arrive at the New Keynesian Phillips Curve

$$\mathbb{E}_t\left[\beta\frac{c_{t+1}^{-\gamma_c}/P_{t+1}}{c_t^{-\gamma_c}/P_t}\frac{y_{t+1}\pi_{t+1}}{y_t}\left(\pi_{t+1}-1\right)\pi_{t+1}\right]+\frac{\varepsilon}{\psi}\left(\mathrm{mc}_t-\frac{\varepsilon-1}{\varepsilon}\right)=\left(\pi_t-1\right)\pi_t\ .$$

In addition, nominal rigidities also affect intermediate good firms, since inflation affects the default threshold $\overline{m}_{\tau,t+1} \equiv \frac{sb_{\tau,t+1}}{\pi_{t+1}(1-\chi_\tau)p_{\tau,t+1}k_{\tau,t+1}}$ and the *real per-unit* bond payoff is

$$\mathcal{R}_{\tau,t}=s\left(G(\overline{m}_{\tau,t})\frac{\pi_t p_{\tau,t}(1-\chi_\tau)k_{\tau,t}}{sb_{\tau,t}}+1-F(\overline{m}_{\tau,t})\right)-F(\overline{m}_{\tau,t})\varphi+(1-s)q_{\tau,t}\ .$$

Their first order conditions are now given by

$$\begin{aligned}
&q'(\overline{m}_{\tau,t+1})\frac{\mathbb{E}_t[\overline{m}_{\tau,t+1}]}{b_{\tau,t+1}}\left(b_{\tau,t+1}-(1-s)\frac{b_{\tau,t}}{\pi_t}\right)+q(\overline{m}_{\tau,t+1})\\
&\quad=\widetilde{\beta}\mathbb{E}_t\left[\widetilde{\Lambda}_{t,t+1}\frac{s(1-F(\overline{m}_{\tau,t+1}))+(1-s)q_{\tau,t+1}}{\pi_{t+1}}\right]
\end{aligned}$$

and

$$\begin{aligned}
1=&-q'(\overline{m}_{\tau,t+1})\frac{\mathbb{E}_t[\overline{m}_{\tau,t+1}]}{k_{\tau,t+1}}\left(b_{\tau,t+1}-(1-s)\frac{b_{\tau,t}}{\pi_t}\right)\\
&+\mathbb{E}_t\left[\widetilde{\Lambda}_{t,t+1}\left((1-\delta_k)+(1-\chi_\tau)p_{\tau,t+1}\left(1-G(\overline{m}_{\tau,t+1})\right)\right)\right]\ .
\end{aligned}$$

The resource constraint now also includes Rotemberg cost

$$y_t=c_t+\sum_\tau(c_{\tau,t}+i_{\tau,t})+\Lambda(\overline{F}_{t+1})+\Omega(\overline{b}_{t+1})+\frac{\psi}{2}(\pi_t-1)^2y_t+\sum_\tau\varphi F(\overline{m}_{\tau,t})\frac{b_{\tau,t}}{\pi_t}\ .$$

To close the model, we assume that the central bank sets i_t according to a Taylor rule

$$i_t = i\pi_t^{\phi_\pi}\ . \tag{B.3}$$

We choose standard parameters for the final goods elasticity $\varepsilon = 6$, implying a markup of 20% in the deterministic steady state, and a Rotemberg parameter $\psi = 57.8$, consistent with a Calvo parameter of 0.75. The parameter on inflation stabilization in the monetary policy rule is set to $\phi_\pi = 5$, which ensures determinacy for all policy experiments. We slightly re-calibrate the slope parameter $\eta_1 = 0.0371$ in the collateral default cost function, the slope parameter $l_1 = 0.0065$ in the liquidity management cost function, the capital depreciation rate $\delta_k = 0.0175$, and the idiosyncratic shock volatility $\varsigma_M = 0.16$. The relationship between haircuts, bond prices, and firms' financing and investment decision is largely unaffected by the presence of nominal rigidities (see Table B.5 and Table B.6).

Table B.5: Greenium Reaction - Announcement Effects with Nominal Rigidities

Data	**Model: News Shock Horizon**			
	2 years	3 years	4 years	5 years
-4.8bp	-9.1bp	-6.6bp	-5.1bp	-4.1bp

Table B.6: Firm Reaction: Model vs. Data with Nominal Rigidities

	Δ Yield	**Δ Capital**	**Δ Leverage**
Model	72bp	4.1pp	5.2pp (market value)
			2.1pp (book value)
Data	39 - 85bp	1 - 15pp	1 - 11pp

Notes: Difference between baseline of 26% to 100% haircut in the first row. Range of estimated effects in the literature in the second row.

Results are reported in Table B.7 and show very similar implications for optimal collateral policy and its interaction with Pigouvian taxation. In particular, the inflation volatility under optimal preferential treatment is almost unchanged with respect to the baseline in column one, alleviating concerns that preferential treatment jeopardizes price stability, the central bank's primary policy objective. As before, the welfare gain of optimal taxation exceeds the welfare gain by a factor of almost 100.

Table B.7: Time Series Means with Nominal Rigidities

Moment	**Strong Pref**	**Opt Coll**	**Opt Tax**	**Glob Opt**
Tax Parameter χ_c	0	0	12%	12%
Haircut ϕ_g	4.5%	4%	26%	18%
Haircut ϕ_c	26%	32%	26%	18%
Welfare (CE, Change)	+0.019%	+0.021%	+1.483%	+1.485%
Conv. Elig. Premium	-11bp	-11bp	-11bp	-12bp
Green Elig. Premium	-14bp	-14bp	-11bp	-12bp
Conv. Bond Spread	101bp	104bp	100bp	97bp
Green Bond Spread	83bp	80bp	100bp	97bp
Conv. Leverage (Change)	-0.1%	-0.3%	0%	+0.2%
Green Leverage (Change)	+1.0%	+1.1%	0%	+0.2%
Conv. Capital (Change)	0.0%	-0.1%	-9.6%	-9.4%
Green Capital (Change)	+0.5%	+0.6%	+41.3%	+41.4%
Green Capital Share	0.2008	0.2010	0.281	0.281
GDP (Change)	+0.04%	+0.03%	+0.62%	+0.65%
Restr. Cost/GDP (Change)	+1.21%	+0.31%	-0.14%	+1.83%
Coll. Default Cost/GDP (Change)	+3.51%	+1.26%	-0.38%	+4.90%
Liq. Man. Cost/GDP (Change)	-1.18%	-0.33%	-0.74%	-2.61%
Rotemberg Cost/GDP (Change)	+0.11%	-0.14%	+0.53%	+0.90%
Pollution Cost/GDP (Change)	-0.01%	-0.09%	-9.10%	-9.00%

Notes: Strong preferential treatment (*Strong Pref*) is based on a collateral framework set to $\phi_g = 0.045$ and $\phi_c = 0.36$. The optimal collateral policy (*Opt Coll*) is computed holding $\chi_g = 0$ constant. For the optimal tax (*Opt Tax*), we hold haircuts fixed at their baseline values and vary the tax rate. The global optimum (*Glob Opt*) is obtained by jointly maximizing over taxes and haircuts. "*Change*" refers to percentage differences from the baseline calibration. The baseline green capital share of 0.2 is a calibration target.

C Yield Reaction to Central Bank Policy Announcements

C.1 Construction of the Dataset

The first step of our analysis is to identify a list of relevant pieces of ECB communication with significant space or time devoted to environmental policy. To identify relevant speeches for our empirical analysis, we rely on a dataset published by the ECB that contains date, title (including sub-titles), speaker, content, and footnotes of nearly all speeches by presidents and board members since 1999 (see European Central Bank, 2021b). We perform the following steps:

- We string-match titles and content separately for the following keywords: climate, green, sustainable, greenhouse, environment, warming, climatic, carbon, coal.

- We designate a speech for manual inspection as soon as we have one match for a title or three matches for content (variations did not change results).
- We exclude a speech if insufficient space is devoted to the topic, there is no monetary policy relation, or for a wrong positive (e.g., *environment* refers to low interest rates).
- We exclude speeches that address climate risk or transition risk.
- Speeches within 20 trading days of the previous speech are excluded to avoid overlapping treatment periods.

We exclude communication that refer to *climate risk* and *transition risk*, since these refer to improving disclosure standards, the extent to which climate risk should be considered in credit risk assessment, and asset stranding. These issues are important for the conduct of central bank policy in general, but do not specifically address bond markets. This leaves us with four speeches. Table C.1 contains details regarding the key content that motivates our classification.

Table C.1: Relevant ECB Policy Announcements

Date	Person	Link	Relevant Quotes
08-11-2018	Benoît Cœuré	ECB	• (...) the ECB, acting within its mandate, can – and should – actively support the transition to a low carbon economy (...) second, by acting accordingly, without prejudice to price stability. • Purchasing green bonds (...) could be an option, as long as the markets are deep and liquid enough.
27-02-2020	Christine Lagarde	ECB	• (...) reviewing the extent to which climate-related risks are understood and priced by the market (...) • (...) evaluate the implications for our own management of risk, in particular through our collateral framework.
17-07-2020	Isabel Schnabel	ECB	• (...) way in which we can contribute is by taking climate considerations into account when designing and implementing our monetary policy operations. • (...) Of course, central banks would need to be mindful of their effects on market functioning. • (...) severe risks to price stability, central banks are required, within their traditional mandates, to strengthen their efforts (...)
21-09-2020	Christine Lagarde	ECB	• We cannot miss this opportunity to reduce and prevent climate risks and finance the necessary green transition. • The ECB's ongoing strategy review will ensure that its monetary policy strategy is fit for purpose (...) • (...) Jean Monnet's words, (...) opportunity for Europe to take a step towards the forms of organisation of the world of tomorrow.

Notes: Speeches are taken from European Central Bank (2021b).

The classification of securities into "green" and "conventional" is based on bonds listed in the "ESG" segments of *Euronext*, the *Frankfurt Stock Exchange* and the *Vienna Stock Exchange*, all of which offer publicly available lists. We limit the analysis to bonds classified as "green" or "sustainable". Since many green bonds do not show up in the *IHS Markit* database, we additionally obtain data from *Thomson Reuters Datastream*. We match green and conventional bonds *one trading-day before* each announcement date using a nearest-neighbors procedure involving coupon, bid-ask spread, maturity, notional amount, and yield spreads. Specifically, we identify an appropriate untreated bond as control group, which is the conventional bond with the smallest distance to the green bond. We drop a green bond if the distance to the closest conventional bond is too high. Table C.2 contains summary statistics regarding the matching. Coupon and bid-ask spreads are very similar for both types of bonds. Spreads of green bonds are higher by between 5 and 8bp, while their maturity is higher by 1.5 years on average.

Table C.2: Matching Green to Conventional Bonds: Summary Statistics

Date		**BA-Spread**		**Coupon**		**Spread**		**Maturity**		**Amount**	
	#	Green	Conv.	Green	Conv.	Green	Conv.	Green	Conv.	Green	Conv.
08-11-2018	80	0.34	0.33	1.08	1.05	47.50	42.20	7.6	6.0	716	719
27-02-2020	83	0.36	0.32	1.18	1.15	51.66	44.82	6.7	5.2	695	690
17-07-2020	77	0.45	0.38	1.22	1.22	77.49	72.00	6.6	4.9	693	689
21-09-2020	79	0.38	0.36	1.18	1.14	64.94	56.68	6.3	4.6	701	709

Notes: We denote the number of matches by #. Conv. denotes a *conventional* bond. Bond yield spreads over the Euribor/Swap are expressed in basis points. Bid-ask spread and coupon are relative to a face value of 100, maturity is in years. Amount outstanding is in million EUR.

C.2 Yield Reactions

In Figure C.1, we display the average response across treatment dates. The greenium becomes significant two trading days after each announcement and widens to around 16bp after 20 trading days.

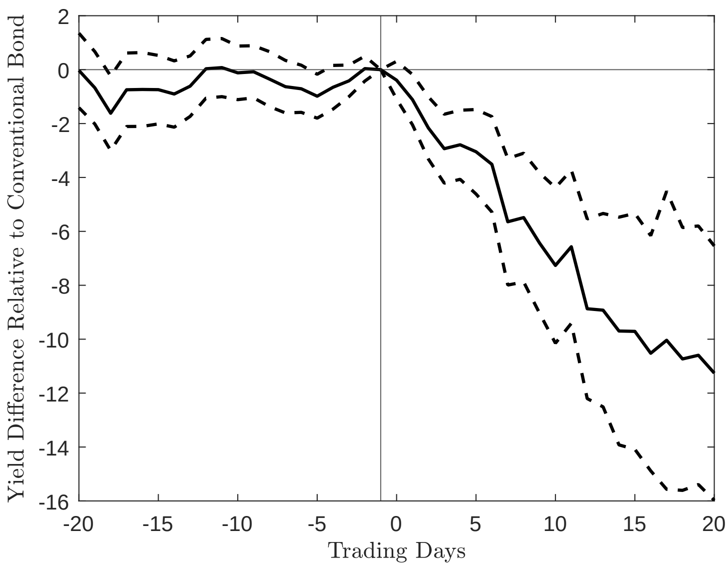

Figure C.1: Average Yield Reaction around Treatment Window

Notes: Results are averaged over all policy announcements. Dashed lines represent 95% confidence intervals. All values in basis points.

Table C.3 gives details on single events. We observe significantly negative premia for green bonds up to one month after the treatment events. The strongest effect is visible for ECB president Christine Lagarde's speech on February 27th 2020, which included the first explicit reference to the ECB's collateral framework. Moreover, the speech delivered by Isabel Schnabel on July 17th 2020 stands out, since yields on green bonds significantly increased compared to their conventional counterparts following the event. However, the tone regarding future ECB environmental policy is much more modest than in other speeches. There is also no explicit prospect of preferential treatment in this speech.[23]

Table C.3: Yield Reaction Around ECB Policy Announcements

Date	**Type**	**Yield Reaction**	**Standard Error**
08-11-2018	Board Member Speech	-7.9***	1.78
27-02-2020	President Speech	-19.4***	3.89
17-07-2020	Board Member Speech	6.8***	1.67
21-09-2020	President Speech	1.3	1.23

Notes: We display the *average* yield over 20 days after minus *average* yield over 20 trading day before the policy announcement , relative to the matched control group (in basis points). Significance levels correspond to 10 % (*), 1 % (**) and 0.1 % (***) of Welch's t-test.

D Data Sources

Table D.1 summarizes the data sources on which our empirical analysis and calibration are based. The classification of bonds as "green" is based on publicly available lists of securities traded via various stock exchanges. Based on the list of ISINs, we retrieve bond-specific info from Datastream. Data on conventional bonds in the control group is taken from Markit. EURIBOR data are also obtained through Datastream. We use the ECB to obtain data on non-financial firm debt, GDP, employment, gross fixed capital formation, private consumption, and the GDP deflator.

[23]For example, central banks "*need to be mindful of their effects on market functioning*" and are required to exert effort towards environmental concerns only "*within their traditional mandates*".

Table D.1: Data Sources and Ticker

Series	**Source**	**Mnemonic**
Green Bond List I	Euronext	List retrieved Nov-30-2020
Green Bond List II	Frankfurt SE	List retrieved Nov-30-2020
Green Bond List III	Vienna SE	List retrieved Nov-30-2020
Constant Maturity Ask Price	Datastream	CMPA
Constant Maturity Bid Price	Datastream	CMPB
Coupon	Datastream	C
Issue Date	Datastream	ID
Amount Outstanding	Datastream	AOS
Currency	Datastream	PCUR
Life At Issue	Datastream	LFIS
Redemption Date	Datastream	RD
EURIBOR rates (... = maturity)	Datastream	TRE6S...Y
Debt-to-GDP	ECB	QSA.Q.N.I8.W0.S11.S1.C.L.LE.F3T4.T._Z.XDC_R_B1GQ_CY._T.S.V.N._T
Markit iBoxx Components	IHS Markit	-
GDP	ECB	MNA.Q.Y.I8.W2.S1.S1.B.B1GQ._Z._Z._Z.EUR.V.N
Gross fixed capital formation	ECB	MNA.Q.Y.I8.W0.S1.S1.D.P51G.N11G._T._Z.EUR.V.N
Consumption	ECB	MNA.Q.Y.I8.W0.S1M.S1.D.P31._Z._Z._T.EUR.V.N
GDP Deflator	ECB	MNA.Q.Y.I8.W2.S1.S1.B.B1GQ._Z._Z._Z.IX.D.N
Employment	ECB	ENA.Q.Y.I8.W2.S1.S1._Z.EMP._Z._T._Z.PS._Z.N