How unconventional is green monetary policy?*

Melina Papoutsi
European Central Bank

Monika Piazzesi
Stanford & NBER

Martin Schneider
Stanford & NBER

May 5, 2021

Abstract

This paper studies the environmental impact of unconventional monetary policy. Our theoretical framework is a multisector growth model with climate externalities and financial frictions. When central bank asset purchases have real effects on aggregate output, their sectoral composition typically affects the climate. Market neutrality of asset purchases does not follow from simple formulas used by policy makers, but depends on (i) the impact of central bank purchases on firms' cost of capital and (ii) the share of capital funded by bonds. We use micro data on bond holdings, firm characteristics and emissions to show that the ECB's corporate bond portfolio is tilted towards brown sectors relative to a market portfolio of sectoral capital stocks.

*Preliminary, comments welcome. We thank Laura Veldkamp, Michael Woodford, Moto Yogo and seminar participants at the ASSA 2021, Columbia and UCLA. for helpful comments. The views expressed in this paper are the authors' and do not necessarily reflect those of the European Central Bank or the Eurosystem.

1 Introduction

Central bank purchases of corporate bonds have recently become an important policy tool. While their purpose is usually macroeconomic stimulus, their implementation requires selecting a bond portfolio. What should a central bank's corporate bond portfolio look like? Some policy makers emphasize *market neutrality*. The idea is to keep relative prices across assets the same by purchasing bonds in proportion to outstanding quantities of bonds. This formula is commonly used to select the maturity and country composition of government debt portfolios, and has been applied to corporations and sectors as well. Other policy makers have questioned this premise and suggested that green investing might better serve a central bank's mandate of working towards economic efficiency.

This paper develops a theoretical framework for thinking about the environmental impact of unconventional monetary policy and informs it with novel evidence on the ECB's bond portfolio. We start from a multisector growth model with climate externalities and financial frictions. Its key feature is that when central bank asset purchases have real effects on output, their sectoral composition typically also affects the climate. We show that simple formulas equating market neutrality with holding bonds in proportion to outstanding totals are correct only under restrictive conditions. In general, assessing market neutrality requires knowledge of (i) the impact of central bank purchases on firms' cost of capital and (ii) the share of capital funded by bonds, both of which may differ across sectors and are difficult to measure.

Empirically, we make progress on (ii) by comparing the ECB portfolio with capital shares and bond shares across sectors. Our estimates show that the ECB portfolio tilts towards brown, rather than green firms. This is a direct consequence of the structure of the bond market and the simple bond market neutrality formula followed by the ECB. Firms in the energy and certain manufacturing sectors generate relatively more emissions and also issue relatively more bonds. Firms in services sectors are cleaner, but are funded relatively more with equity and loans. In light of our model, the result implies that if the impact of central bank purchases on costs of capital is similar across firms, then current ECB policy actually subsidizes brown firms.

We also use our model to study optimal policy. We consider a social planner who can design both a carbon tax and an asset purchase program. When carbon taxes are available, optimal monetary policy is independent of climate externalities: the carbon tax fixes the climate externality, whereas the asset purchase program handles the financial friction. This result is reminiscent of the "principle of targeting" from optimal taxation, whereby taxing an externality directly is optimal regardless of other tax instruments. The difference here is that the other instrument used by the planner is an asset purchase program that alters the cost structure of the financial system. Moreover, when an optimal carbon tax is not available, tilting the central bank portfolio towards green firms can be beneficial.

Our model incorporates key elements of two distinct literatures: integrated assessment models (IAMs) used to study the effects of climate change and intermediary asset pricing models used to study unconventional monetary policy. Technology and preferences are as in a standard neoclassical growth model, except that TFP depends on the quality of the environment as in the typical IAM. One market imperfection is therefore a standard production externality: production today generates emissions that lower environmental quality and hence future TFP. The second imperfection is that holding assets is costly for intermediaries, for example when the assets are more risky. Government asset purchases are another form of costly intermediation that transforms risky capital for government debt – they have positive real effects if that transformation reduces overall intermediation cost. Those effects can work either through the riskfree interest rate or through lower risk premia, which reflect marginal intermediation costs.

Our model differs from simple IAMs as well as macro models of unconventional policy in its focus on sectoral portfolios. In line with our empirical approach, we allow for multiple sectors that differ in both the intensity of emissions and the shape of intermediation costs. As a result, the optimal carbon tax directs capital and labor towards sectors taking into account their different contributions to damages. At the same time, the optimal asset purchase program loads on sectors where the government can make a greater contribution to reducing overall intermediation cost. While asset purchases can also direct capital towards certain sectors by changing funding costs, it cannot fully substitute for a carbon tax since it affects only marginal conditions for capital, not labor.

Our model also clarifies the relationship between market neutrality and portfolio composition. We take market neutrality to mean that firms' relative costs of capital do not change in response to a purchasing program. In our model, a market neutral policy is an interesting benchmark since it can stimulate the macroeconomy by increasing aggregate investment without altering the market portfolio of sectoral capital shares. In other words, by offering intermediaries cheap-to-hold government debt in exchange for costly-to-hold capital in the right proportions, the government can address the financial friction in the aggregate only.

How should the central bank choose its portfolio in order to be market neutral? We show that the answer depends crucially on the structure of the financial system. We distinguish two cases. In an *integrated* financial system, the typical intermediary holds both government debt and capital (that is, private claims), so asset purchases amount to a swap of positions on the asset side of intermediary balance sheets. Market neutrality then requires the central bank to tilt its portfolio towards relatively safe (or cheap-to-hold) sectors. This is because an increase of safe government debt that strengthens balance sheets has a relatively larger effect on the premia of risky sectors. In contrast, in a *segmented* financial system, capital and government debt are held by different intermediaries. Here, an asset purchase transfers holdings across intermediaries. Since government debt does not strengthen balance sheets, market neutrality requires holding the market portfolio.

Our analysis of optimal policy provides formulas for the sectoral composition of the central bank balance sheet that minimize intermediation costs. The formulas apply not only when the planner can design both a carbon tax and a purchase program, but also when there is no climate externality. When financial frictions differ by sector, optimal policy is typically not market neutral: unless marginal costs of holding capital in the central bank are aligned in a particular way with private sector costs, optimal policy reduces premia of riskier sectors relatively more. In fact, if government asset holdings are sufficiently cheap, it becomes useful to short capital in safer sectors. Optimal central bank operations should thus combine lending to the financial system against safe sector capital as collateral together with purchases of risky sector capital.

Our theoretical results have a number of implications for how to assess market neutrality and the design of asset purchase programs in practice. First, the key price through which real effects arise is firms' cost of capital, or their marginal cost of external finance. Here *all* sources of external finance are relevant: if a firm has easy access to equity, then checking neutrality also requires measuring the effect of policy on stock prices. Second, the observable counterpart of the market portfolio in the model is the sum of debt and equity in the data. There is no reason to expect that holding bonds in proportion to totals guarantees neutrality. While it is possible that leverage is correlated with firm characteristics that affect bank holdings costs – for example, safer firms may issue more debt – neutrality would be a coincidence.

Finally, the structure of the financial system is also important for the price impact of central bank policy. We illustrate this by contrasting integrated and segmented systems: market neutrality has a different meaning in banking systems where safe and risky assets interact on balance sheets than in securitized systems where public and private bonds are held by different intermediaries. In addition, costs of holding sectors may reflect regulation or intermediaries' concerns with ESG investing. Together these observation suggests that a promising way forward is to study the price impact on the cost of capital in the cross section of firms in order to identify intermediation costs by sector or group of firms. Our model provides an organizing framework for such an approach.

Our empirical exercise takes a first step by comparing the carbon footprint of the ECB's corporate bond portfolio with that of a "market portfolio" of equity plus debt in the Eurozone. The comparison is performed at the sector level. To determine the composition of the ECB's holdings, we merge firm level ECB bond holding data with Orbis data as well as emissions data from Urgentem. A key step here is to handle the large share of financial sector bonds held by the ECB. A large majority of those bonds are issued by special purpose entities that provide funding for large nonfinancial corporations, including non-Eurozone corporations that have established SPEs to tap the European bond market. By hand-matching SPEs to their parent firms, we can reduce the share of financial sector bonds in the ECB's portfolio from 56% to 11%. We combine ECB holdings data aggregated to the NACE 2 sector level with several alternative measures of capital stocks derived from firm data, as well as emissions totals from Eurostat's air emission accounts.

Related Literature. In the low interest rate environment of the last two decades, monetary policy has adopted unconventional measures, most importantly central bank asset purchases. Initially, these purchases concentrated on government bonds, and then expanded to agency mortgage-backed securities and other agency bonds. Many papers have documented the price impact of these purchases (for example, Gagnon, Raskin, Remache and Sack (2011), Krishnamurthy and Vissing-Jorgensen (2011), D'Amico and King (2013), and Krishnamurthy, Nagel and Vissing-Jorgensen (2018)). Most recently, central banks started buying corporate bonds (Mota and Papoutsi (2020), Boyarchenko, Kovner and Shachar (2020), Koijen, Koulischer, Nguyen and Yogo (2021)). Other papers study the economic mechanisms behind these price impacts and, more generally, the real effects of unconventional monetary policy (for example, Gertler and Karadi (2011), Cúrdia and Woodford (2011), Piazzesi and Schneider (2018), Piazzesi, Rogers and Schneider (2020)).

Our model is a multisector general equilibrium model in which productivity depends on the climate, as in integrated assessment models by Nordhaus. However, unlike IAMs, we do not distinguish between energy goods and other goods. We assume linear dynamics for the climate which is permanently affected by emissions (as in Hassler, Krusell and Smith (2016), Hambel, Kraft and van der Ploeg (2021)) that are generated by the production of various sectors in the economy. These emissions may increase firms' cost of capital, as documented in the empirical asset pricing literature (Baker, Bergstresser, Serafeim and Wurgler (2018) and Zerbib (2019)) for bonds, Hong and Kacperczyk (2009), Bolton and Kacperczyk (2021a), Bolton and Kacperczyk (2021b), Hsu, Li and Tsou (2021) for stocks.) More generally, our paper is related to the exploding literature on climate finance (for a survey, see Giglio, Kelly and Stroebel (2021); Engle, Giglio, Kelly, Lee and Stroebel (2020), Baldauf, Garlappi and Yannelis (2020), Choi, Gao and Jiang (2020)).

The rest of the paper is structured as follows. Section 2 presents the model and Section 3 contains the empirical results.

2 Model

2.1 Preferences & technology

The representative household cares about consumption of a single final good. Preferences are represented by the utility function

$$\sum_{t=0}^{\infty} \beta^t u\left(C_t\right), \tag{1}$$

where the discount factor β is less than one and u is increasing and strictly concave. The household also inelastically supplies one unit of labor every period.

The final good is made from N intermediate goods according to the production function

$$Y_t = \prod_{n=1}^{N} y_{t,n}^{\gamma_n}, \tag{2}$$

where $y_t = (y_{t,1}, .., y_{t,N})$ is the vector of intermediate inputs.

Production of intermediate goods generates emissions, and is in turn affected by the quality of the environment. Making $y_{t,n}$ units of good n creates $\varepsilon_{t,n}\, y_{t,n}$ units of emissions (measured in tons of CO2 equivalent). The quality of the environment is described by a one dimensional index η_t. Its evolution reflects the accumulation of emissions and is described recursively by

$$\eta_{t+1} = \eta_t + \sum_{n=1}^{N} \varepsilon_{t,n}\, y_{t,n}. \tag{3}$$

The quality of the environment is persistent and more emissions make the planet hotter.

Intermediate good n is made at date t from capital $k_{t,n}$ installed one period in advance as well as labor $l_{t,n}$ according to the production function

$$y_{t,n} = z_{t,n}\left(\eta_t\right)\; k_{t-1,n}^{\alpha_n}\, l_{t,n}^{1-\alpha_n}, \tag{4}$$

where $z_{t,n}\left(\eta_t\right)$ is total factor productivity in sector n. The latter may depend on the quality of the environment—this is how emissions generate economic and hence welfare costs. Capital is made one-for-one from final goods and fully depreciates after one period.

Financial frictions. We assume that there are costs associated with capital holdings. Holding capital requires not only savings—output that is not consumed—but also balance sheet costs per unit of asset held. These costs are a simple way to capture risk. When capital is invested in projects, some projects do not succeed, and resources are lost. These holding costs are resource costs, measured in units of final consumption good. The more capital is invested, the more risk is involved, so more losses occur.

To capture the role of the government, we distinguish two technologies for holding capital, a *public* and a *private* technology. Holding a portfolio of capital given by the vector $\tilde{k}_t = \left(\tilde{k}_{t,1}, ..., \tilde{k}_{t,N}\right)$ through the public technology incurs a holding cost of $\tilde{h}\left(\tilde{k}_t\right)$ units of the final good, where the cost function $\tilde{h}$ is increasing, quasiconvex, and homogeneous of degree one. Moreover, public capital holdings $\tilde{k}_t$ lead to $D_t = \tilde{k}_{t,1} + ... + \tilde{k}_{t,N}$ units of government debt. In other words, we assume that the government finances its asset purchases with bonds.

Holding capital and government debt via the private technology is also costly: holding a portfolio of capital given by the vector $k_t^i = \left(k_{t,1}^i, ..., k_{t,N}^i\right)$ as well as government debt d_t through the private technology incurs a holding cost $h(k_t^i, d_t)$, where h is increasing and quasiconvex in k_t^i and homogeneous of degree one in $\left(k_t^i, d_t\right)$. If the partial derivative h_{N+1} is positive, the idea is that investing in safe government bonds lowers risk and reduces holding costs. Homogeneity of both cost functions in asset holdings implies that the financial system operates under constants return to scale: replicating it requires scaling up both private assets and government debt.

We refer to private intermediaries as being *integrated* if they hold capital and bonds on the same balance sheets. If private intermediation is *segmented*, some intermediaries specialize in capital holdings, while others specialize in the holdings of government bonds. Integrated intermediation may feature a holding cost function h that is nonseparable in holdings of capital k_t^i and government bonds d_t. For example, holding more government bonds may make it cheaper for intermediaries to hold capital. In contrast, if these assets are held by different intermediaries, it will make sense to assume that the holding cost function is separable in capital and government bonds.

Holding costs will depend on the health of the financial system. For example, temporary distress of financial intermediaries will increase their increase holding costs. In general, the cost functions $h^t(k_t^i, d_t)$ and $\tilde{h}^t(\tilde{k}_t)$ will depend on calendar time. Below, we will suppress this time dependence in our notation to simplify the expressions.

The cost structure here captures two mechanisms for how central bank purchases affect intermediation. One is that the government through its ability to tax or negotiate as a big player may be able to enforce contracts better than the private sector. As a result, it can allow for more overall lending at a reasonable cost even if private intermediaries face high costs due to weak balance sheets. This mechanism is present even if private holding costs h do not depend on d_t: because both functions are quasiconvex in capital, holding some capital through the public technology may lower total holding costs. A second mechanism is that government debt directly strengthens the balance sheets of private banks. To accommodate this, we allow for h to be decreasing in d_t.

We emphasize three further properties of our setup. First, government action is beneficial only through its effect on frictions in private intermediation—if the private holding cost h is zero, then public holdings add no value. Second, convexity of both cost functions in capital will typically imply that there is an optimal size of government, to be determined in equilibrium. Finally, the cost structure is compatible with a two-step intermediation process: government holdings of claims on firms are funded by government debt that is in turn held by private intermediaries. We will use this property when we define market equilibrium below.

Resource constraints. Capital holding costs use up final output so resource constraints for the economy are

$$C_t + \sum_{n=1}^{N} k_{t,n} + h\left(k_t - \tilde{k}_t, \sum_{n=1}^{N} \tilde{k}_{t,n}\right) + \tilde{h}\left(\tilde{k}_t\right) = Y_t, \tag{5}$$

$$\sum_{n=1}^{N} l_{t,n} = 1. \tag{6}$$

Here k_t is the vector of sectoral capital stocks. Since all capital must be held using one of the two technologies, organization of the financial sector amounts to a split of total k_t into public holdings $\tilde{k}_t$ and private holdings $k_t^i = k_t - \tilde{k}_t$.

2.2 Market equilibrium

We now describe a system of goods and securities markets and define equilibrium. We normalize prices so the final good is the numeraire.

Firms and production. Intermediate good firms issue shares—claims to capital income—in a competitive securities market. They hire labor and sell goods in competitive spot markets. We write $p_{t,n}$ for the date t price of good n and w_t for the date t wage. We further denote by R_t^n the rate of return on holding claims on sector n from $t-1$ to t, or the funding cost of sector n firms. An intermediate goods firm in sector n pays a carbon tax of τ_t per unit of emissions. It takes as given prices and the quality of the environment and maximizes

$$\left(p_{t,n} - \tau_t \varepsilon_{t,n}\right)\ z_{t,n}\left(\eta_t\right)\ k_{t-1,n}^{\alpha_n}\, l_{t,n}^{1-\alpha_n} - w_t\ l_t - R_t^n\ k_{t-1,n}. \tag{7}$$

The final goods firm buys intermediate goods in date t spot markets at prices $p_{t,n}$ and sells final goods at the price of one.

Intermediate goods firms equate the marginal product of capital net of the carbon tax with the cost of capital. They also equate the marginal product of labor net of the carbon tax with the wage. The final good firm equates its marginal revenues and costs. These FOCs are

$$\begin{aligned}
\left(p_{t,n} - \tau_t \varepsilon_{t,n}\right) \alpha_n \frac{y_{t,n}}{k_{t-1,n}} &= R_t^n, \\
\left(p_{t,n} - \tau_t \varepsilon_{t,n}\right) \left(1-\alpha_n\right) \frac{y_{t,n}}{l_{t,n}} &= w_t, \\
\gamma_n \frac{Y_t}{y_{t,n}} &= p_{t,n}.
\end{aligned} \tag{8}$$

Private intermediaries. Competitive intermediaries owned by households invest in capital using the private asset holding technology. They can also invest in government debt. For simplicity, we assume that intermediaries exist for two periods only and issue shares, that is, claims to their asset portfolio. We write R_{t+1}^D for the rate of return on government debt from t to $t+1$ and denote by M_{t+1} the price of a one period riskfree asset, that is, the discount factor used to value all assets held by the household. Intermediaries face asset holdings costs $h\left(k_t^i, d_t\right)$ when they hold the portfolio $\left(k_t^i, d_t\right)$ of capital and government debt.

Intermediaries maximize shareholder value

$$\max_{k_t^i, d_t} M_{t+1} \left(\sum_{n=1}^{N} R_{t+1}^n k_{t,n}^i + R_{t+1}^D d_t \right) - h\left(k_t^i, d_t\right) - \left(\sum_{n=1}^{N} k_{t,n}^i + d_t \right), \tag{9}$$

where the first term is discounted payoffs at date $t+1$, the second is asset holding costs incurred at date t and the final one is capital raised at date t by issuing shares. Since asset pricing is linear and holding costs are homogeneous of degree one in asset holdings $\left(k_t^i, d_t\right)$, the intermediary problem exhibits constant returns to scale.

The intermediary first order conditions for capital in sector n and government debt are

$$\begin{aligned} M_{t+1} R_{t+1}^n &= 1 + h_n\left(k_t^i, d_t\right), \\ M_{t+1} R_{t+1}^D &= 1 + h_{N+1}\left(k_t^i, d_t\right). \end{aligned} \tag{10}$$

Without financial frictions ($h = 0$), all returns are equated at the risk-free rate $R_{t+1}^S = M_{t+1}^{-1}$ from time t to $t+1$, as is standard in deterministic models. More generally, we have assumed that h is increasing in k_t^i, so financial frictions increase firms' cost of capital. The reason is that intermediaries want compensation for holding capital, because they incur marginal holding costs h_n when investing in sector n. Financial frictions therefore lead to a *return premium* h_n that firms in sector n have to pay over the short rate R_{t+1}^S. At the same time, we allow for h to be decreasing in government debt: a convenience yield can push its interest rate below the rate of a safe asset held directly by households.

Households and government. The representative household invests in private intermediary shares with return R_t^S and receives a (possibly negative) lump sum transfer T_t from the government. The government raises carbon taxes and uses those to pay for asset management costs and transfers. The budget constraints of the household and the government are then

$$C_t + S_t = R_t^S S_{t-1} + w_t + T_t, \tag{11}$$

$$\sum_{n=1}^{N} R_t^n \tilde{k}_{t-1,n} + D_t + \tau_t \sum_{n=1}^{N} \varepsilon_{t,n}\, y_{t,n} = R_t^D D_{t-1} + \sum_{n=1}^{N} \tilde{k}_{t,n} + \tilde{h}\left(\tilde{k}_t\right) + T_t, \tag{12}$$

where S_t is household savings in intermediary shares. If there is no convenience yield on government bonds, $h_{N+1} = 0$ in the intermediaries' FOC (10), household savings may also be invested in government bonds.

Household optimization equates the price of a risk-free asset to the household's marginal rate of substitution:

$$M_{t+1} = \beta \frac{u'\left(C_{t+1}\right)}{u'\left(C_t\right)}. \tag{13}$$

This is the standard Euler equation in representative agent models. We emphasize, however, that intertemporal substitution as captured by the Euler equation is only one force that affects the return on capital in our model. Financial frictions introduce a return premium through the first-order conditions of intermediaries (10). Therefore firms face a higher cost of capital R_t^n in their first order conditions (8).

Equilibrium. A feasible allocation consists of sequences of sectoral labor and capital inputs as well as sectoral outputs and emissions together with capital holdings in the two technologies such that the resource constraints (2)-(6) hold. Given a government investment strategy $\tilde{k}_t$ and carbon tax τ_t, an equilibrium is a feasible allocation as well as sequences for prices $p_{n,t}$, asset returns R_t^S, R_t^D and R_t^n, and transfers T_t such that firms maximize profits (7), private intermediaries maximize shareholder value (9), households maximize utility (1) subject to their budget constraints (11), the market for government debt clears, and the government budget constraint (12) holds.

2.3 Characterizing equilibrium without a carbon tax

In this section we characterize equilibrium when there is no carbon tax, that is, $\tau_t = 0$. The only government policy is therefore investment $\tilde{k}_t$ and its transformation into debt $D_t = \tilde{k}_{t,1} + \ldots + \tilde{k}_{t,N}$. It is helpful to introduce additional notation for portfolio weights. Let K_t denote the sum of all capital stocks and let $\delta_t = D_t/K_t$ denote the share of debt in capital, which equals the share of capital held by the government. We also write $\kappa_t = k_t/K_t$ for the *market portfolio*, sector shares of total capital. The government portfolio $\tilde{\kappa}_t = \tilde{k}_t/D_t$ consists of sector shares of its total capital holdings. In particular, $\tilde{\kappa}_t = \kappa_t$ means that the government's portfolio is capital neutral, that is, government, private and overall capital holdings across sectors are all proportional.

For a government policy formulated in terms of a debt share δ_t and portfolio weight $\tilde{\kappa}_t$, equilibrium can be conveniently characterized in two steps. The first shows how banks and firms respond to government policy to allocate resources across sectors within a period. The second then shows the macro and climate dynamics. The system of equations is block recursive in the sense that the effect of policy on sector shares can be determined independently of the macro and climate dynamics of the economy. This is a consequence of our assumptions on technology; in particular, the Cobb–Douglas production functions.

Consider first the sectoral allocation of capital. Combining the first order conditions of firms (8) and intermediaries (10), we have that markets determine capital shares to equate effective returns on capital $R^n_{t+1} / \left(1 + h_n(k^i_t, d_t)\right)$ across sectors n. For a given government debt share δ_t and portfolio weight $\tilde{\kappa}_t$, we have

$$\frac{\alpha_n \gamma_n}{\kappa_{t,n}} \frac{1}{1 + h_n\left(\kappa_t - \delta_t \tilde{\kappa}_t, \delta_t\right)} = \frac{\alpha_1 \gamma_1}{\kappa_{t,1}} \frac{1}{1 + h_1\left(\kappa_t - \delta_t \tilde{\kappa}_t, \delta_t\right)}. \tag{14}$$

The $N - 1$ equations here pin down a vector of capital shares κ_t that sum to one. In a frictionless economy, we recover the familiar result that sectoral capital shares only reflect preferences and production technology: there is relatively more investment in sector n (higher $\kappa_{t,n}$) if sector n is more capital intensive (higher α_n) or households spend more on sector n (higher γ_n). Financial frictions lead to an adjustment from this benchmark so sectors with lower marginal funding costs (lower h_n) receive more investment.

We emphasize that financial frictions in intermediation, as we assume here, can lead to either over- or underinvestment in capital at the sectoral level. In typical macroeconomic models with financial frictions in firms, the marginal funding cost is always higher than the rate of return on savings, so the return on capital is too high relative to the first best, and there is an underinvestment problem. The same is true here if there is only one sector and no government debt. With multiple sectors, however, relatively lower cost sectors may have a marginal funding cost below the interest rate on savings. As a result, there is more investment in those sectors than in the first best. This is because low cost sectors may make it cheaper for the financial system to hold capital of higher cost sectors.

We now turn to aggregates. For given sector weights and total capital K_t, the bank and firm first order conditions further give rise to an aggregated production function that determines output as

$$Y_{t+1} = \psi \prod_{n=1}^{N} z_{t+1,n} \left(\eta_{t+1}\right)^{\gamma_n} \; \kappa_{t,n}^{\alpha_n \gamma_n} \; K_t^{\bar{\alpha}}, \qquad \bar{\alpha} = \sum_{n=1}^{N} \alpha_n \gamma_n. \tag{15}$$

where ψ is a constant that depends only on the parameters of the production function. In a frictionless model, the first best weights $\kappa_{t,n} = \alpha_n \gamma_n$ are constant and we obtain standard Cobb-Douglas aggregation. With financial frictions, measured aggregate TFP reflects misallocation of capital across sectors: any deviation of the weights from the first best lowers the product that enters the aggregate production function.

The macro dynamics now follow from combining

$$\beta \frac{u'(C_{t+1})}{u'(C_t)} \frac{Y_{t+1}}{K_t} \sum_{n=1}^{N} \frac{\alpha_n \gamma_n}{1 + h_n(\kappa_t - \delta_t \tilde{\kappa}_t, \delta_t)} = 1, \tag{16}$$

$$C_t + K_{t-1}\left(1 + h(\kappa_t - \delta_t \tilde{\kappa}_t, \delta_t) + \tilde{h}(\delta_t \tilde{\kappa}_t)\right) = Y_t. \tag{17}$$

Here the first equation is an intertemporal Euler equation for aggregate capital. In the frictionless benchmark, the sum simplifies to the average sectoral capital share, so we have the standard expression for the return on capital in a Cobb-Douglas economy. The second equation is the resource constraint that also includes holding costs.

Quadratic costs as tractable example. For our applications below, we often use a quadratic holding cost function. Intuitively, a quadratic cost works like disutility from portfolio risk in a mean variance framework. We specify two functions to describe an integrated and a segmented financial system. For an *integrated* system, consider

$$h\left(k_t^i, d_t\right) = \frac{1}{2} \frac{\rho}{\sum_{n=1}^{N} k_{t,n}^i + d_t} \left(\sum_{n=1}^{N} \left(k_{n_t}^i\right)^2 \sigma_n^2 + d_t^2 \sigma_d^2 \right) \tag{18}$$

with positive coefficients ρ, σ_n^2 and σ_d^2. The parameters σ_n^2 and σ_d^2 describe the cost or risk of sector n capital and government debt, respectively. A riskier sector is more costly to hold. Alternatively, a sector with the same risk but higher emissions than another sector may be more costly to hold. The parameter ρ captures the overall sensitivity of the banking sector to risk. If the bank holds only one asset, its cost is increasing in the size of the position. Moreover, adding an asset to an existing position may lower overall cost, and in fact the first dollar of a new position always lowers cost—the benefit of diversification. What is special to an integrated system is that government debt also alters the costs associated with holding capital.

The equilibrium return premium on sector n capital now becomes

$$h_n(\kappa_t - \delta_t \tilde{\kappa}_t, \delta_t) = \rho \sigma_n^2 (\kappa_{t,n} - \delta_t \tilde{\kappa}_{t,n}) - \frac{1}{2} \rho \left(\sum_{n=1}^{N} (\kappa_{t,n} - \delta_t \tilde{\kappa}_{t,n})^2 \sigma_n^2 + \delta^2 \sigma_d^2 \right) \tag{19}$$

Premia depend on risk sensitivity ρ, sectoral risk σ_n^2 and sectoral exposure by the financial system given by its portfolio share $\kappa_t - \delta_t \tilde{\kappa}_t$. Sectors with low enough risk will have negative premia, or convenience yields. For example, the last term is the convenience yield on a completely riskless asset with $\sigma_n^2 = 0$. The return on this asset is below the short rate at which the household saves because the asset helps the financial system manage risk.

In an integrated financial system, government policy affects premia in two ways. On the one hand, government purchases $\tilde{\kappa}_t$ change the profile of sectoral holdings by the financial system $\kappa_t - \delta_t \tilde{\kappa}_t$. On the other hand, asset purchases are funded with debt, which has its own risk parameter σ_d^2. For example, when government debt is safer than capital, that is, $\sigma_d^2 < \sigma_n^2$ for all n, then its presence is a force that reduces premia even if government policy is capital neutral, that is, $\tilde{\kappa}_t = \kappa_t$. Indeed, government then increases the convenience yield term for any κ_t. Intuitively, safe bonds make it cheaper for intermediaries to bear risk, so they demand less compensation for it. The integrated system cost structure is useful to think about an economy with a large banking system, where central bank asset purchases effectively replace bank capital holdings with government bonds.

To describe a *segmented* system, we make the quadratic cost function separable in capital and government debt:

$$h\left(k_t^i, d_t\right) = \frac{1}{2} \frac{\rho}{\sum_{n=1}^N k_t^i} \sum_{n=1}^N k_{t,n}^2 \sigma_n^2 + \frac{1}{2} \rho \, d_t \, \sigma_d^2. \tag{20}$$

One interpretation is that there are two distinct intermediaries, one of which holds only capital whereas the other is a government bond fund. The intermediary optimization problem effectively splits into two separate problems of choosing capital and bond holdings. An equivalent interpretation is that households directly hold government bonds and incur the cost parametrized by σ_d^2. In general, the segmented system cost structure better captures a heavily securitized financial system.

Premia in a segmented system are given by

$$h_n\left(\kappa_t - \delta_t \tilde{\kappa}_t, \delta_t\right) = \rho \sigma_n^2 \frac{\kappa_{t,n} - \delta_t \tilde{\kappa}_{t,n}}{1 - \delta_t} - \frac{1}{2} \rho \sum_{n=1}^N \frac{\left(\kappa_{t,n} - \delta_t \tilde{\kappa}_{t,n}\right)^2}{\left(1 - \delta_t\right)^2} \sigma_n^2. \tag{21}$$

The effect of government purchases on exposure of intermediaries is the same as before. However, a capital neutral purchasing program with $\tilde{\kappa}_t = \kappa_t$ now leaves premia unchanged as δ_t cancels out of the formula. The scale of the purchase program matters only to the extent that the government tilts its portfolio towards specific sectors away from the market portfolio κ_t.

2.4 Directing capital towards green sectors

Can monetary policy direct capital towards sectors that produce fewer emissions? When the government absorbs risk in a particular sector, banks require less compensation for the sector's risk and are more willing to hold its capital. As a result, while banks may reduce their portfolio share of the sector somewhat, they will not "undo" the government purchase. It is important for this mechanism that the premium h_n is not constant. We illustrate the effect with the quadratic cost function of an integrated financial system (18). Combining the firm and bank first order conditions in the quadratic case equates the discounted return on capital to the return on bank assets

$$\frac{\alpha_n \gamma_n}{\kappa_{t,n}} \frac{Y_{t+1}}{K_t} M_{t+1} = 1 + \rho \sigma_n^2 \left(\kappa_{t,n} - \delta_t \tilde{\kappa}_{t,n}\right) - \frac{1}{2} \rho \left(\sum_{n=1}^{N} \left(\kappa_{t,n} - \delta_t \tilde{\kappa}_{t,n}\right)^2 \sigma_n^2 + \delta_t^2 \sigma_d^2 \right). \tag{22}$$

To think about the cross section of sectors, we can hold fixed the common terms and view both returns as functions of the portfolio share $\kappa_{t,n}$: the left-hand side is firms' downward sloping demand for funds and the premium on the right-hand side is the upward sloping supply of funds from the financial system and the government.

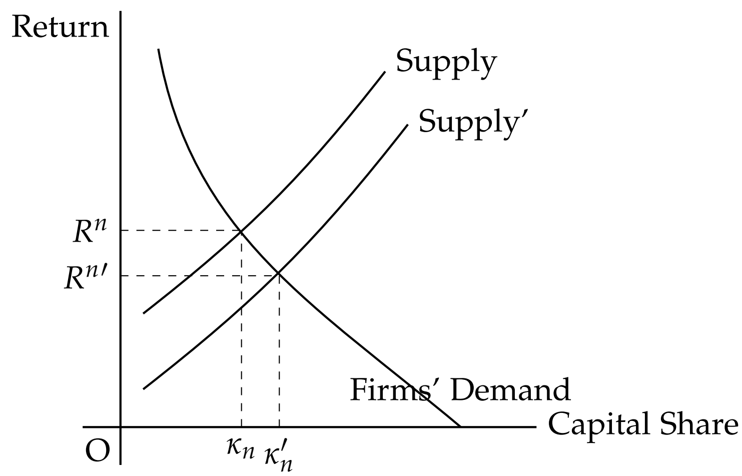


Figure 1: Government directs funds towards green sector

For a simple example, assume that two sectors—green and brown—have the same risk parameter σ_n^2. What happens if the government tilts its portfolio towards the green sector? More precisely, the government increases its weight $\tilde{\kappa}_{t,n}$ on the green sector and lowers that on the brown sector by the same amount. The effect on the convenience yield of a riskfree asset (the last term on the right-hand side) is second order. However, the government purchase shifts supply curves: at the same premium, there is more supply of funds to the green sector, as shown in Figure 1, and less to the brown sector. As a result, the total share of capital $\kappa_{t,n}$ invested in the green sector increases, while that in the brown sector decreases. At the same time, there is a lower premium on the green sector, while there is a higher premium on the brown sector. Because firms' demand for funds is not perfectly elastic, the portfolio weight on the green sector in the portfolio of the financial system $\kappa_{t,n} - \delta_t \tilde{\kappa}_{t,n}$ declines: intermediaries sell capital to the government, partly (but not fully) undoing the larger supply from the government. Finally, nothing happens to the shares on the other sectors, since the effect of a small capital change on the convenience yield is second order.

2.5 Market neutrality and portfolio weights

We now consider the connection between various definitions of market neutrality that are important in policy discussions. In particular, we are interested in how government effects on returns relate to its holdings of quantities. A *laissez-faire equilibrium* is an equilibrium with no government capital holdings, or $\delta_t = 0$. We say that government holdings are *market neutral* when relative costs of capital across sectors R^n/R^1 in an equilibrium with government holdings are the same as in the laissez-faire equilibrium. In our model, market neutrality implies that government policy does not alter capital shares. Indeed, from (14) and (10), relative costs of capital are the same across two equilibria if and only if overall capital shares are also the same: this is because the technology parameters α_n and γ_n remain fixed when comparing equilibria.

What portfolio does the government need to hold to be market neutral? The answer depends crucially on the structure of the financial system. We consider first an integrated system with quadratic cost function (18). To obtain transparent formulas, we further assume in this section that return differences in logs and levels are the same, or $\log\left(R^n/R^1\right) = R^n - R^1$. This is a good approximation if all net returns are small decimal numbers, as one would expect in the typical application. For an economy with laissez-faire equilibrium capital shares κ_t, a policy $(\delta_t, \tilde{\kappa}_t)$ is then market neutral if and only if the premia on all sectors n relative to sector 1 are the same as in the laissez faire equilibrium, or

$$\rho\sigma_n^2\left(\kappa_{t,n} - \delta_t\tilde{\kappa}_{t,n}\right) - \rho\sigma_1^2\left(\kappa_{t,1} - \delta_t\tilde{\kappa}_{t,1}\right) = \rho\sigma_n^2\kappa_{t,n} - \rho\sigma_1^2\kappa_{t,1}. \tag{23}$$

This condition follows from (19) together with the fact that relative premia are the same if and only if capital shares are the same.

With an integrated financial system, a market neutral government portfolio is

$$\tilde{\kappa}_{n,t} = \frac{\sigma_n^{-2}}{\sum_{n=1}^{N} \sigma_n^{-2}} =: \kappa_{t,n}^{*}. \tag{24}$$

The market neutral portfolio κ_t^* is the portfolio that minimizes total cost—it is the analogue of the minimal variance portfolio in classic portfolio analysis. It requires that the government should overweigh sectors that are relatively safer or lower cost. The reason is that a unit of government investment has a larger effect on riskier sectors. Investing the same amount in two sectors with different σ_ns cannot be market neutral since the relative premium of the riskier sector will fall by more. To achieve market neutrality the government must therefore invest relatively less in those risky sectors.

In an integrated financial system, even a market neutral policy typically has an effect on the level of premia. This is due to the role of government debt in intermediary portfolios. For example, if government debt is sufficiently safe relative to capital, then all premia fall by the same amount. With more safe debt, banks are happy to invest in riskier capital. There is more investment in all sectors, leaving the sectoral composition of the capital stock unchanged. It is not crucial here that government debt is entirely safe; it is enough that it represents a risk that is not the same as that of capital, for example because government debt is backed by future taxes on labor income.

In a segmented system, market neutrality and capital neutrality coincide. Indeed, from (21), a market neutral portfolio solves

$$\rho\sigma_n^2 \frac{\kappa_{t,n} - \delta_t \tilde{\kappa}_{t,n}}{1-\delta_t} - \rho\sigma_1^2 \frac{\kappa_{t,1} - \delta_t \tilde{\kappa}_{t,1}}{1-\delta_t} = \rho\sigma_n^2 \kappa_{t,n} - \rho\sigma_1^2 \kappa_{t,1}$$

for all sectors n which implies $\tilde{\kappa}_t = \kappa_t$. In a segmented system, premia are determined by the risk appetite of the capital holding intermediary only. Issuing government debt does not affect that intermediary's balance sheet. When the government invests in capital, private intermediation is scaled down, but due to constant returns to scale marginal costs of holding capital are unchanged. A market neutral policy not only leaves relative premia unchanged, but also keeps premia h_n relative to the rate on savings unchanged.

Nevertheless, even with a segmented system a market neutral policy can have real effects. Even if government holdings do not affect relative marginal costs across sectors, they may nevertheless lower the total cost of holding capital and hence the real interest rate M_{t+1}^{-1}. This feature can be seen from the equations for the macro dynamics (15)-(17). When h is separable and policy is market neutral, the Euler equation and the aggregate production function remain unchanged as we vary δ_t. However, the resource constraint may change if government can hold capital more cheaply than the private sector.

2.6 Social planner problem

The social planner chooses an allocation $(C_t, k_t, \tilde{a}_t, y_t, l_t)$ to maximize utility (1) subject to technology and resource constraints (2)-(5). Let μ_t denote the multiplier on the evolution of the environment (3), that is, the shadow cost of the environment. The first order condition for capital in sector n is

$$u'(C_t)\left(1 + h_n\left(k_t - \tilde{k}_t, \sum_{n=1}^{N} \tilde{k}_t\right)\right) = \beta\left(u'(C_{t+1})\,\gamma_n \frac{Y_{t+1}}{y_{t+1,n}} - \varepsilon_{t+1,n}\mu_{t+1}\right)\alpha_n \frac{y_{t+1,n}}{k_{t,n}}. \quad (25)$$

Suppose there are no market imperfections: no climate externalities ($\varepsilon_{t+1,n} = 0$) and no financial frictions ($h = 0$). Then this condition reduces to a standard intertemporal Euler equation: the cost of investment today—the marginal utility of consumption—is equated to the discounted future benefit of consumption times the marginal product of capital.

Imperfections alter this tradeoff in two ways. First, financial frictions increase the marginal cost of investment by h_n on the left-hand side and hence discourage capital accumulation. The additional cost depends on the amount of investment through the public technology. It follows that for two sectors with identical production functions, it is optimal to invest more in the sector that is less costly to hold. Second, the marginal benefit of investment on the right-hand side is reduced by the marginal cost of emissions. For two sectors with the same technology and holding costs, it is optimal to invest more in the sector that produces lower emissions.

The shadow cost of temperature μ_t reflects all future damages to production. From the planner's first order condition for environmental quality η_t, it evolves according to

$$\mu_t = \beta\left(\mu_{t+1} + \sum_{n=1}^{N}\left(u'(C_{t+1})\,\gamma_n \frac{Y_{t+1}}{y_{t+1,n}} - \mu_{t+1}\varepsilon_{t+1,n}\right) z'_{t+1,n}(\eta_{t+1})\; k_{t,n}^{\alpha_n}\, l_{t+1,n}^{1-\alpha_n}\right). \quad (26)$$

Allowing the environment to degrade at date t has persistent effects by changing TFP. The overall effect consists of two parts: lower TFP, say, not only lowers the marginal product of capital but also lowers future emissions, a counteracting force.

Optimal choice of labor equates marginal products across sectors. For any two sectors n and m, we have the static first order condition

$$\left(u'(C_t)\,\gamma_n \frac{Y_t}{y_{t,n}} - \varepsilon_{t,n}\mu_t\right)(1-\alpha_n)\frac{y_{t,n}}{l_{t,n}} = \left(u'(C_t)\,\gamma_m \frac{Y_t}{y_{t,m}} - \varepsilon_{t,m}\mu_t\right)(1-\alpha_m)\frac{y_{t,m}}{l_{t,m}}. \quad (27)$$

Again marginal products take into account not only marginal utility from consumption, but also marginal environmental cost. For example, for two sectors that are identical in TFP, the optimal labor to capital ratio should be higher in the sector that produces fewer emissions. An important difference between labor and capital choice is that labor choice does not depend on holding costs. This is because labor choice in our model is not an intertemporal decision.

Optimal public holdings of capital satisfy

$$h_n\left(k_t - \tilde{k}_t, \sum_{n=1}^{N} \tilde{k}_t\right) = \tilde{h}_n\left(\tilde{k}_t\right) + h_{N+1}\left(k_t - \tilde{k}_t, \sum_{n=1}^{N} \tilde{k}_t\right). \tag{28}$$

This first order condition is static: the planner divides up the capital portfolio into public and private holdings in order to minimize the cost of holding that capital from t to $t+1$. In particular, the marginal cost of holding capital through the private technology must equal the cost of investing through the public technology plus the spillover cost of public on private investment. The decision can be taken independently of any climate consideration: the condition looks the same whether or not there are climate externalities. Of course, this does not mean that the public technology for holding capital has no impact on the climate: the optimal public holdings matter for the investment decision in (25).

To interpret the condition, it is helpful to again express it in terms of portfolio weights. Since cost functions are homogeneous of degree one, we can rewrite (29) as

$$h_n\left(\kappa_t - \delta_t \tilde{\kappa}_t, \delta_t\right) = \tilde{h}_n\left(\tilde{\kappa}_t\right) + h_{N+1}\left(\kappa_t - \delta_t \tilde{\kappa}_t, \delta_t\right). \tag{29}$$

The N equations here determine $N-1$ portfolio weights for the public sector together with the public share δ_t. If there is only one sector, then $\kappa_t = \tilde{\kappa}_t = 1$ and the equation pins down the optimal public share δ_t. In our setting here, the planner also determines the sectoral composition of holdings.

Implementing optimal policies with carbon taxes. Can we implement the social planner solution as an equilibrium? Consider an allocation that solves the planner problem, involves public holdings $\tilde{k}_t$ and implies a shadow cost of the environment μ_t. Substituting out prices from firms' and banks' first order conditions (8) and (10) we can rewrite Euler equations for capital and labor as

$$u'\left(C_t\right)\left(1 + h_n\left(k_t - \tilde{k}_t, \sum_{n=1}^{N} \tilde{k}_{t,n}\right)\right) = \beta\left(u'\left(C_{t+1}\right)\ \gamma_n \frac{Y_{t+1}}{y_{t+1,n}} - \tau_{t+1}\ \varepsilon_{t+1,n}\right)\alpha_n \frac{y_{t+1,n}}{k_{t,n}},$$

$$\left(\gamma_n \frac{Y_t}{y_{t,n}} - \tau_t \, \varepsilon_{t,n}\right)(1-\alpha_n)\,\gamma_n \frac{Y_t}{l_{t,n}} = \left(\gamma_m \frac{Y_t}{y_{t,m}} - \tau_t \, \varepsilon_{t,m}\right)(1-\alpha_m)\,\gamma_m \frac{Y_t}{l_{t,m}}. \tag{30}$$

Define the carbon tax as $\tau_t = \mu_t / u'(C_t)$, the relative value of environmental quality relative to resources at date t. Substituting into (30) we recover the planner first order conditions (25) and (27). It follows that the allocation that solves the planner problem also describes an equilibrium with policy path $(\tilde{k}_t, \tau_t)$.

Optimal policy and market neutrality in an integrated system. With quadratic costs, we can clarify how the optimal asset purchase program relates to market neutrality benchmarks. We assume that the cost function of the government takes the same form as that of private intermediaries up to a scale factor $\tilde{\rho}$:

$$h\left(\tilde{k}_t\right) = \frac{1}{2} \frac{\tilde{\rho}}{\sum_{n=1}^{N} \tilde{k}_{t,n}} \sum_{n=1}^{N} \tilde{k}_{t,n}^2 \sigma_n^2.$$

In other words, the government faces the same relative costs by sector as other intermediaries, but its sensitivity to that cost may be different. For example, in a recession the sensitivity ρ of private intermediaries to risk may increase, whereas that of the government $\tilde{\rho}$ may remain the same because it has the power to tax.

With an integrated financial system, the condition (29) for the optimal government portfolio is

$$\rho\sigma_n^2\left(\kappa_{t,n} - \delta_t \tilde{\kappa}_{t,n}\right) - \rho\sigma_b^2 \delta_t = \tilde{\rho}\sigma_n^2 \tilde{\kappa}_{t,n} - \frac{1}{2}\tilde{\rho} \sum_{n=1}^{N} \tilde{\kappa}_{t,n}^2 \sigma_n^2. \tag{31}$$

The right-hand side is the relative premium of sector n capital over government debt, which should be equal to the marginal cost of government holdings of sector n on the right hand side. Equality implies that the government is indifferent to transforming another dollar of capital into government debt.

It follows that the optimal portfolio is a convex combination of the market portfolio κ_t and the market neutral minimum cost portfolio κ_t^* defined in (24):

$$\tilde{\kappa}_t = \frac{\rho}{\delta_t \rho + \tilde{\rho}} \kappa_t + \left(1 - \frac{\rho}{\delta_t \rho + \tilde{\rho}}\right) \kappa_t^* \tag{32}$$

The weights in this "two-fund" representation depend on the optimal scale of the government purchase program δ_t as well as the sensitivity to risk in private and government holding costs. It follows that neither market neutrality nor capital neutrality is typically optimal. Indeed, for any $\rho = \tilde{\rho}$, the weight on the market portfolio is strictly between zero and one for any positive government capital share δ_t. Market neutrality and capital neutrality can then coincide only when $\kappa_t = \kappa_t^*$. This is generically not true since the optimal κ_t will reflect sectors' capital shares and expenditure shares.

In contrast to market neutrality, optimality is not about equating premia, or marginal costs of private intermediaries, but instead about equating costs for society as a whole. To see the difference, consider the relative premia that obtain in an efficient equilibrium. Substituting (32) into (19), we have that relative premia take the form

$$\rho\sigma_n^2\left(\kappa_{t,n} - \delta_t\tilde{\kappa}_{t,n}\right) = \rho\sigma_n^2\frac{\tilde{\rho}}{\delta_t\rho + \tilde{\rho}}\kappa_{t,n} + x_t,$$

for some number x_t that does not depend on the sector. Premia thus continue to respond to risk, and government intervention generally affects this response. An interesting special case arises when $\tilde{\rho} = 0$, so government investment is free. In this case, the marginal cost of government ownership of capital is the same across sectors, and therefore it is optimal to equate premia across sectors. This is in sharp contrast to market neutrality which *maintains* differences in premia in the laissez-faire equilibrium. Here any differences in financial frictions across sectors should be undone by government.

Optimality of a collateral program vs a purchase program. The weights on the two funds in (32) reflect the relative costs of the public and private investment technologies. The optimal government portfolio is closer to the market portfolio when the private sector risk sensitivity is higher relative to that of the government, and the government share is lower. In fact, if $\tilde{\rho}$ and δ_t are sufficiently small, then we obtain a weight on the market neutral portfolio that is less than zero. In other words, it is optimal for the government to short a portfolio that is weighted towards safe assets. This may in general require not only an asset purchase program, but a collateral program as well since the optimal government portfolio is short in safe sectors.

For a concrete example, suppose that $\rho = \tilde{\rho}$ and there are two sectors that have the same weight one half in the market portfolio, but that sector 1 is much safer than the other so its weight κ_1^* is close to one. By (32), the weight on the safe sector 1 should be $\tilde{\kappa}_{t,1} = 1 - \frac{1}{2}\delta_t^{-1}$ which is negative whenever $\delta_t \leq \frac{1}{2}$. Optimal policy in this case consist of three operations. The government purchases the entire capital stock of the risky sector 2. It then enters a reverse repo agreement with private intermediaries for $\delta_t - \frac{1}{2}$ units against collateral of safe sector 1 capital. Finally, it issues δ_t units of government debt. Total assets consist of the loan and the sector 2 capital stock, whereas liabilities consist of debt. The private sector is on the other side: it buys δ_t units of debt and funds those by selling $\frac{1}{2}$ units of sector 2 capital and repoing $\delta_t - \frac{1}{2}$ units of sector 1 capital with the government.

The size of the government balance sheet δ_t follows from substituting the optimal weights into (31). Both government holding costs for capital and private intermediaries' holding cost for debt limit the scale of government. In particular, even if government holdings are free ($\tilde{\rho} = 0$), there is a finite share of debt

$$\delta_t = \frac{\sigma_b^{-2}}{\sigma_b^{-2} + \sum_{n=1}^{N} \sigma_n^{-2}}$$

that is larger the safer is government debt relative to capital. Positive government holding costs lower the optimal share below this benchmark, but a closed form solution is no longer available.

We now turn to a segmented financial system. Substituting premia into (29) we have

$$\rho\sigma_n^2 \frac{\kappa_{t,n} - \delta_t \tilde{\kappa}_{t,n}}{1-\delta_t} - \frac{1}{2}\rho \sum_{n=1}^{N} \frac{\left(\kappa_{t,n} - \delta_t \tilde{\kappa}_{t,n}\right)^2}{\left(1-\delta_t\right)^2}\sigma_n^2 - \frac{1}{2}\rho\sigma_b^2 = \tilde{\rho}\sigma_n^2 \tilde{\kappa}_{t,n} - \frac{1}{2}\tilde{\rho} \sum_{n=1}^{N} \tilde{\kappa}_{t,n}^2 \sigma_n^2.$$

The right-hand side is again the marginal government holding cost and the left-hand side is the excess premium of sector n capital relative to government debt. The key difference to (31) is that these assets are priced by two different intermediaries. In particular, in a segmented system there is always a constant positive premium on government debt that reflects the linear holding cost of the government bond fund.

The optimal portfolio is again a convex combination of the market portfolio and the market neutral portfolio:

$$\tilde{\kappa}_t = \frac{\rho}{\delta_t \rho + \left(1-\delta_t\right)\tilde{\rho}} \kappa_t + \left(1 - \frac{\rho}{\delta_t \rho + \left(1-\delta_t\right)\tilde{\rho}}\right) \kappa_t^*.$$

In the special case where risk sensitivity is the same for the government and the private sector $\rho = \tilde{\rho}$, then capital neutrality—which coincides with market neutrality in a segmented system—is optimal. Intuitively, in a segmented system, there is no interaction between debt and capital in the private sector. When costs are identical for the government bank and the private capital holding intermediary, it makes sense to just spread capital in the same proportions across both. When government holdings are cheaper, however, it is again optimal to overweigh relatively risky sectors and short safe sectors.

3 Empirical results

Our empirical work compares the portfolio of the ECB with the market portfolio of capital holdings by sector in the euro area. We also compute the sector shares of bonds outstanding, which guide ECB asset purchases (because of its definition of market neutrality). Moreover, we measure the sector shares of eligible bonds. We then compare all these portfolios with emission shares by sector.

3.1 Data

For the empirical analysis, we combine sector level data with micro-data from multiple sources, covering the period from 2016 to 2018. We restrict the empirical analysis to this period because the Corporate Sector Purchase Program (CSPP) was initiated in March 2016 and data availability does not allow us to extend our analysis after the end of 2018. First, to accurately approximate the market sector shares in the euro area we use information from Eurostat national accounts. In particular, the variables used are gross value added, compensation of employees, and output by sector. These variables are reported at an annual frequency based on a NACE sector code classification.

We complement the sector data with firm level data from Orbis by Bureau van Dijk. We restrict the sample to active firms in the euro area and use information on the firms' total assets, total debt, revenues, and market capitalization. In total, we use information from more than 3 million firms that operate in the euro area and construct the sectoral shares of the total assets, total debt, revenues, and market capitalization. The advantage of using the Orbis firm level data is that the sector distribution is representative of all firms that have accurate financial statements, regardless of their size, and we utilize more variables at the firm level. At the same time, micro level data could be more affected by outliers. For that reason, we examine the distribution of the market shares using both the Eurostat macro variables and the Orbis micro data.

We estimate ECB portfolio sector shares with confidential micro level data from the ECB Securities Holdings Statistics (SHS). This database reports the exact amount of each security held by the Eurosystem. In total, bonds from 355 companies were purchased under the Corporate Bond Purchase Program until the end of 2018. Specific criteria are in place and define the eligibility of a bond that can purchased under the CSPP. These are related to the bond's original and remaining maturity, rating, and the issuing corporation.[1] We construct the sector shares of the ECB portfolio based on the amount held by the Eurosystem for each issuer sector.

Similarly, to estimate the sector shares of the bond market, we use information from the ECB Centralized Securities Database (CSDB) that contains information for all secu-

[1] To be eligible for purchase, securities must (a) have an investment grade rating, (b) be euro-denominated, (c) have minimum remaining maturity of six months and maximum remaining maturity of 30 years, and (d) be issued by a non-financial corporation established in the euro area.

rities held and transacted by euro area residents. We construct the sector shares of the bond market in the euro area using the amount outstanding at the end of each year of bonds issued by non-financial corporations incorporated in the euro area. In this construction, we exclude any privately placed bonds.

For our analysis, it is key that we match firms to their correct sector. A challenge with this match is that many large public companies issue bonds through a special purpose entity that is a financial company. For example, the oil manufacturer Royal Dutch Shell uses a subsidiary, Shell International Finance BV, to issue its bonds. The subsidiary is a finance company that belongs to the finance sector. If we used the raw sector classification of the bond issuer, we would find that the finance sector accounts for the largest share of the bond market. Moreover, we would find that finance has the largest sector weight in the ECB portfolio, accounting for approximately 55% of the portfolio. Obviously, this would be wrong—bonds issued by non-financial corporations are not even CSPP eligible, and so the ECB does not buy any bonds issued by financial corporations.

To obtain an accurate description of the bond market and the ECB portfolio, we research all financial companies individually and hand collect information about the right sector of their parent company. In particular, we hand collect the sectoral classification for all issuers that were characterized as financial companies in the ECB portfolio as well as for the 200 largest financial bond issuers in the euro area bond market. After we reassign these firms to their correct sector, we succeed to reduce the financial sector share in the ECB portfolio from 56% to 11%. For the remaining 11% we are unable to correctly identify the parent company as the issuer name was not informative enough and in most of the cases is a special purpose entity. Following a similar procedure for all bond issuers, we are able to reduce the share of the finance sector from 87% to 73%. It is not surprising that the bond share of the finance sector is so large, because banks are the largest issuers of corporate bonds in the euro area. In our core analysis we only consider firms that are correctly classified as non-financial.

To measure the environmental impact of corporate bond purchases, we study emissions. The data on emissions come from two sources. First, the annual greenhouse gas Scope 1 air emissions by sector are reported in Eurostat national accounts. Scope 1 emissions capture the direct emissions associated with the production by the sector (for example, the emissions associated with car production in the automobile sector.) Our second source of emissions data is firm level information from Urgentem. The data provides measures of direct Scope 1 emissions and also indirect emissions of greenhouse gases by each firm. The firm's Scope 2 emissions include those generated by the production of energy that is used in the production (for example, Scope 2 emissions for Volkswagen include the emissions generated by the utility company that produces the electricity used by Volkswagen in its car production.) The difference between Scope 1 and 2 emissions is often small. Scope 3 emissions include emissions that occur when the products of the company are used by their customers (such as the emissions associated with the driving of Volkswagen cars.) Scope 3 emissions are usually the largest component of total emissions.

3.2 ECB portfolio holdings and other sector shares

We compare the ECB portfolio with various other sector shares. Importantly, we want a comprehensive measure of capital holdings, including holdings of intangible capital, by sector—the market portfolio. The ideal measure of a sector's capital would therefore be the sum of the market value of equity plus debt in the sector. Since the market value of equity is not available for private firms, we present results for several alternative measures of capital holdings. Our main result is based on the share of capital income by sector. If returns on capital and depreciation rates of capital are the same across sectors, the share of capital income of a sector equals its market share. We measure capital income as value added subtracting wages by sector, using data from Eurostat. Further below, we compare our main result with two additional measures of market shares and show that our findings are consistent across these different measures. The first measure sums up book assets from Orbis within each sector, while the second measures aggregates the market value of equity plus debt for only public firms in a sector.

Figure 2 presents our main empirical result. The red horizontal bars are the sector shares in the market portfolio, measured with data on capital income shares from Eurostat. The largest sector of the euro area economy is services. The other large sector, manufacturing, consists of many subsectors that greatly differ in their emissions. We therefore group these subsectors according to their emissions into dirty manufacturing (oil and coke, chemicals, basic metals, and nonmetallic manufacturing) and other manufacturing (food, beverages, tobacco, textiles, leather, wood, paper, pharmaceuticals, electronics, electrical equipment, machinery, furniture, construction, and other manufacturing.) The other sectors like agriculture, automobile, dirty manufacturing, utilities, and transport are small shares of the economy.

The blue bars in Figure 2 correspond to the ECB holdings portfolio. Relative to the market portfolio, the ECB holds a larger share of the automobile, dirty manufacturing, utilities, transport, and other manufacturing sectors and holds a smaller share of ser-

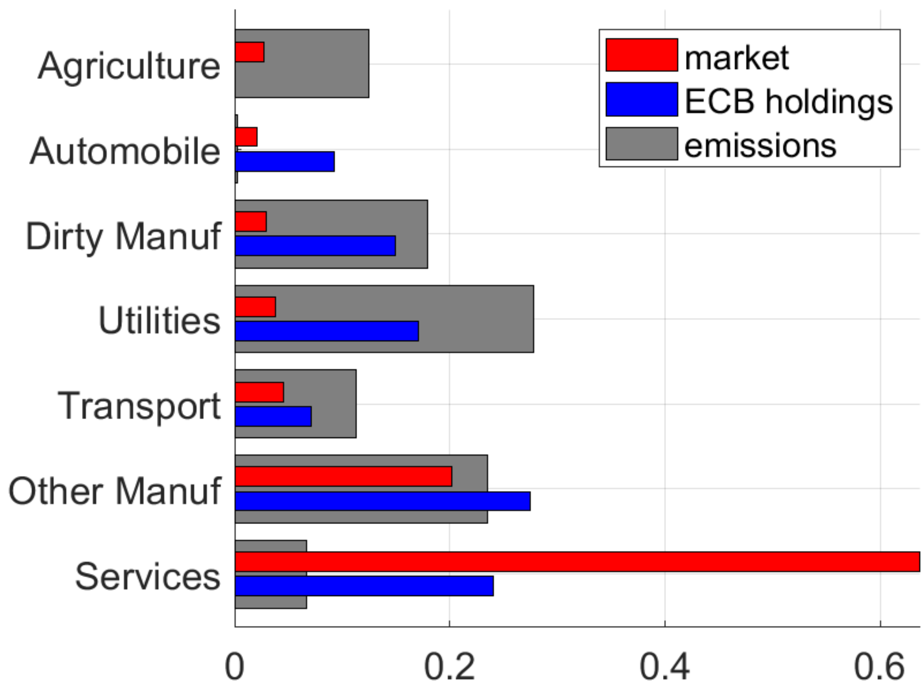
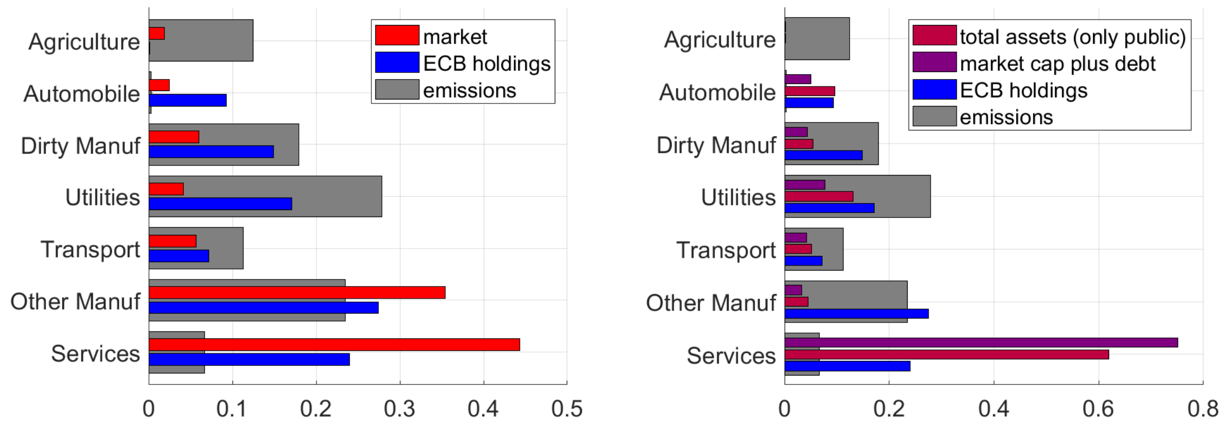


Figure 2: Sector shares of the market portfolio, ECB holdings, and emissions

This figure is constructed based on the year-end 2017 data. Market shares are measured as capital income by sector (capital income = value added - wages). Emission intensity is measured by Scope 1 air emissions by sector. The ECB portfolio includes only securities held under the corporate sector purchase program (CSPP) that was initiated in March 2016. By construction, all sector shares sum up to one. Data sources: SHS (ECB), Orbis, and Eurostat. Definition of sectors: Dirty Manufacturing includes: oil and coke, chemicals, basic metals, nonmetallic minerals manufacturing; Other Manufacturing includes: food, beverages, tobacco, textiles, leather, wood, paper, pharmaceuticals, electronics, electrical equipment, machinery, furniture, construction, and other manufacturing.



(a) Market portfolio based on book assets

(b) Market value of assets for public firms

Figure 3: Sector shares of the market portfolio, ECB holdings, and emissions

This figure is constructed based on the year-end 2017 data. Panel 3(a) measures market shares as output from Eurostat times the ratio of total assets to revenues from Orbis by sector. Panel 3(b) measures market shares as total market value of public firms (market capitalization plus debt) from Orbis. Total asset shares are book assets from Orbis only of public firms. Emission intensity is measured by Scope 1 air emissions by sector. The ECB portfolio includes only securities held under the corporate sector purchase programme (CSPP) that was initiated in March 2016. By construction, all sector shares sum up to one. Data sources: SHS (ECB), Orbis, and Eurostat. Definition of sectors as in Figure 2.

vices. The emissions shares by sector are the grey bars in Figure 2. The sectoral emission shares are constructed using the ratio of Scope 1 air emissions over output of each sector. A simple comparison of these shares suggests that the ECB overweighs sectors with more emissions (such as dirty manufacturing and utilities), while it underweighs sectors with low emissions (such as services). This finding suggests that there is a strong positive correlation between emissions and ECB holdings by sector.

Figure 3 presents results based on alternative measures of market shares. Panel 3(a) uses book asset from Orbis. More specifically, we combine output by sector from Eurostat with the ratio of book assets to revenues from Orbis. The market portfolio and the overall result are similar to those in our main Figure 2. Panel 3(b) aggregates the market value of equity plus debt of only the public companies in Orbis by sector to compute market shares. The sectoral distribution of public companies is similar to the market shares in the other figures. In particular, the service sector has the largest total book assets and the largest market value. The fact that the sectoral bond shares are not similar to the market shares of public companies is driven by the fact that not all public companies issue bonds. This highlights the underdevelopment of the European corporate bond market. The basic finding that the ECB portfolio underweighs the services sector is not explained by the sectoral distribution of the public firms' market capitalization.

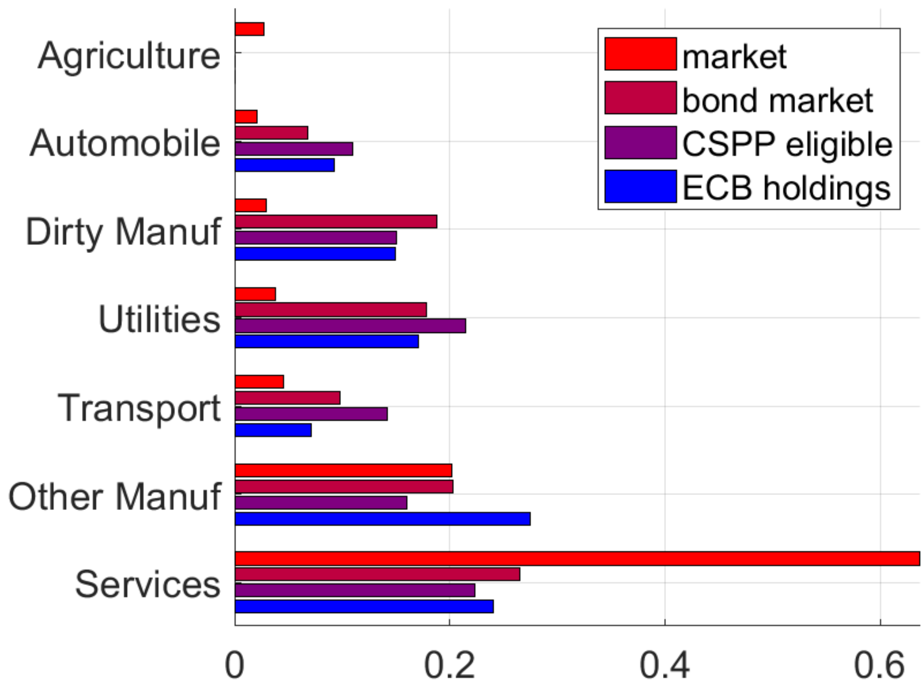


Figure 4: Sector shares of the market portfolio, bond market, CSPP eligible, and ECB holdings

This figure is constructed based on the year-end 2017 data. Market shares are measured as capital income by sector (capital income = value added − wages). The bond market shares are constructed based on the total amount of bonds outstanding by sector relative to the total. The CSPP eligible shares are constructed based on the total amount of eligible bonds by sector relative to the total. The ECB portfolio includes only securities held under the corporate sector purchase programme (CSPP) that was initiated in March 2016. By construction, all sector shares sum up to one. Data sources: SHS and CSDB (from the ECB), and Eurostat. Definition of sectors as in Figure 2.

To understand what explains the difference between the market portfolio and the ECB holdings, we compare the market share by sector to the bonds outstanding by sector, the bonds in the sector that are eligible for the CSPP, and the ECB holdings by sector. Figure 4 shows the four types of shares as horizontal bars. As bond market, we define the shares based on the total amount of bonds outstanding by sector and, similarly, as CSPP eligible we define the shares based on the total amount of eligible bonds by sector. The figure shows that firms in the automobile, dirty manufacturing, utilities, transport, and other manufacturing issue a relatively higher share of bonds, while firms in the service sctor (and agriculture) do not issue many bonds. This striking difference is driven by the fact that large firms in carbon-intensive sectors have large holdings of fixed assets that can serve as collateral. These differences in bond issuance across sectors account for the low weight on the service sector in the ECB portfolio. Importantly, the CSPP eligibility criteria do not change this finding. CSPP eligible shares are similar to the bond market shares and to the ECB portfolio. Thus, the eligibility criteria are not distorting the ECB portfolio. The bottom line is that the ECB's definition of market neutrality conducts asset purchases in proportion to the market value of outstanding bonds. As a consequence, assets purchases are biased towards carbon-intensive sectors, which issue more bonds.

The emission shares used in the figures discussed above rely only on the direct emissions produced by each sector (Scope 1 air emissions as characterized in the greenhouse gas protocol). We extend this measure by looking also on indirect emissions produced by firms (Scope 2 and 3 emissions based on the GHG protocol). To do so, we use firm level data from Urgentem on emission intensities by firm. Here, as intensity is defined the level of emissions per revenue. Scope 1 emissions correspond to the emissions produced directly by the firm while it operates, while Scope 2 and 3 emissions include indirect emissions linked to the firm's usage of electricity and the use of the end product, respectively. We are confident that the data from Urgentem are accurate as the sum of Scope 1 emissions by sector from Urgentem are close to the direct emissions by sector in the Eurostat data.

Figure 5 shows the result including the broader measures of carbon footprint. Scope 2 emission intensities by sector are similar to Scope 1 intensities, suggesting that the use of electricity is not changing the sectoral distribution of emissions. However, Scope 3 emissions play a significant role as these are significantly higher for automobile, dirty manufacturing, utilities, and transport, while there is only a small increase for services. Overall, Figure 5 implies that the ECB portfolio appears to overweigh carbon-intensive sectors even more when we include indirect emissions.

Table 1 documents more formally the relations shown in the plots. Specifically, we

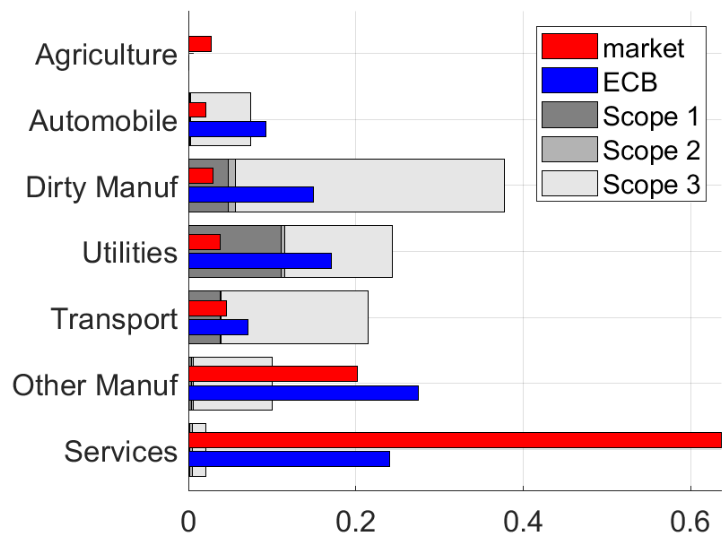


Figure 5: Market portfolio, ECB holdings and Scope 1, 2 and 3 emission intensities

This figure is constructed based on the year-end 2017 data. Market shares are measured as capital income by sector. The ECB portfolio includes only securities held under the corporate sector purchase programme (CSPP) that was initiated in March 2016. Emission intensities are defined as tons of CO2 emissions per 10bn Euro revenue. Scope 1, 2, and 3 emission intensities as characterized in the greenhouse gas protocol (GHG) are included. The sector shares of emission intensities are constructed as before. By construction, all sector shares sum up to one. Data sources: SHS (from the ECB), Urgentem, and Eurostat. Definition of sectors: Dirty Manufacturing includes: oil and coke, chemicals, basic metals, nonmetallic minerals manufacturing; Other Manufacturing includes: food, beverages, tobacco, textiles, leather, wood, paper, pharmaceuticals, electronics, electrical equipment, machinery, furniture, construction, and other manufacturing.

estimate the correlations between all variables of interest and we include data from three years (2016-2018). The table shows a strong correlation – very close to one – between the different measures of the market portfolio. Moreover, the correlation between the ECB holdings, the bond market, and the CSPP eligible sector shares is also very strong and close to one. Two interesting observations arise though from the table. First, the correlation between the ECB holdings and the several measures of market portfolio is significant and positive but not as strong as it is with the bond market – varies from 0.49 to 0.82 depending on the measure of the market portfolio. Second, even though emissions do not appear to be significantly correlated with the market measures, they are positively and significantly correlated with the ECB holdings and the bond market. These observations confirm the conclusions derived from the plots that the ECB's current bond holdings reflect sectoral bond issuance patterns and not the market portfolio sectoral shares. Bond issuance shares are also correlated with sectoral emission intensity.

3.3 How important is the ECB in the corporate bond market?

To investigate whether the ECB is an important investor in the market for corporate bonds, we measure the amount of bonds that each sector newly issues as a percent of bonds outstanding. The percentage for each sector is plotted as red horizontal bar in Figure 6 and ranges from close to zero for agriculture to above 6 percent for services. The blue-shaded portions of these horizontal bars represent the newly issued bonds bought by the ECB. The figure shows that the ECB buys between 20 and 40 percent of the newly issued bonds of each sector. We conclude that the ECB is a big player in the market for corporate bonds.

Table 1: Correlations of sector shares

	market (capital)	market (Orbis)	total assets	total assets (public)	market cap.	ECB holdings	bond market	CSPP eligible	emissions
market (capital income)	1								
market (Orbis)	0.919***	1							
total assets	0.964***	0.792***	1						
total assets (public firms)	0.939***	0.760***	0.990***	1					
market cap. plus debt	0.955***	0.773***	0.999***	0.993***	1				
ECB holdings	0.629***	0.824***	0.500**	0.521**	0.478*	1			
bond market	0.690***	0.782***	0.642***	0.668***	0.627***	0.923***	1		
CSPP eligible	0.544**	0.614***	0.534**	0.591**	0.519**	0.863***	0.935***	1	
emissions	0.0236	0.242	-0.0599	-0.0430	-0.0918	0.624***	0.588**	0.618***	1

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

This table presents correlations between the variables of interest. The data is annual for the sample period 2016–2018. All the variables are constructed as sector shares and sum up to one. Market shares are measured as capital income by sector. Market (Orbis) shares are measured as output from Eurostat times the ratio of total assets to revenues from Orbis. Total assets correspond to the shares by sector of the total assets of all firms included in Orbis. Market capitalization plus debt as reported in Orbis only for public firms. The ECB portfolio includes only securities held under the corporate sector purchase program (CSPP). The bond market shares are constructed based on the total amount of bonds outstanding by sector relative to the total. The CSPP eligible shares are constructed based on the total amount of eligible bonds by sector relative to the total. Emission intensity is measured by scope 1 air emissions by sector from Eurostat.

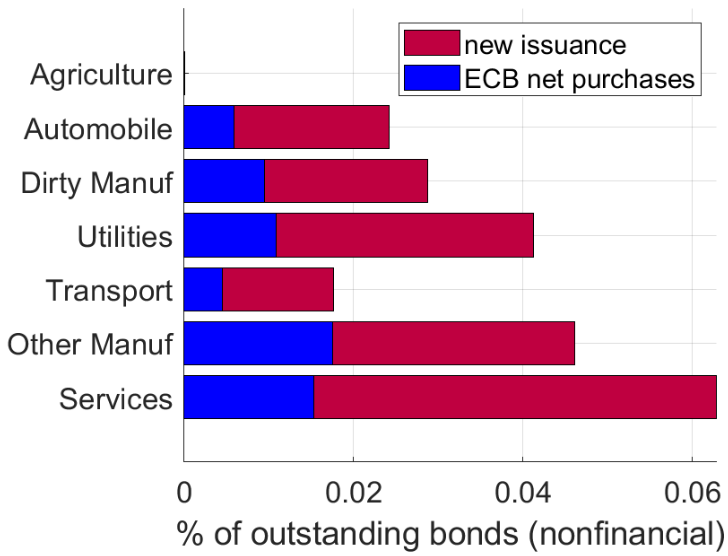


Figure 6: ECB holdings and new issuance

This figure is constructed based on the year-end 2017 data. The ECB net purchases include only securities held under the corporate sector purchase programme (CSPP) that was initiated in March 2016. The percent of new issuance relative to total bonds outstanding is estimated using the year-end 2017 data from the CSDB. Data sources: SHS and CSDB (from the ECB). Definition of sectors: Dirty Manufacturing includes: oil and coke, chemicals, basic metals, nonmetallic minerals manufacturing; Other Manufacturing includes: food, beverages, tobacco, textiles, leather, wood, paper, pharmaceuticals, electronics, electrical equipment, machinery, furniture, construction, and other manufacturing.

References

Baker, Malcolm, Daniel Bergstresser, George Serafeim, and Jeffrey Wurgler, "Financing the Response to Climate Change: The Pricing and Ownership of U.S. Green Bonds," Working Paper 25194, National Bureau of Economic Research October 2018.

Baldauf, Markus, Lorenzo Garlappi, and Constantine Yannelis, "Does Climate Change Affect Real Estate Prices? Only If You Believe In It," *Review of Financial Studies*, 2020, *33* (3), 1256–1295.

Bolton, Patrick and Marcin T. Kacperczyk, "Do investors care about carbon risk?," *Forthcoming Journal of Financial Economics*, 2021a.

__ **and** __ , "Global Pricing of Carbon-Transition Risk," 2021b. Working Paper, Imperial College.

Boyarchenko, Nina, Anna Kovner, and Or Shachar, "It's What You Say and What You Buy: A Holistic Evaluation of the Corporate Credit Facilities," 2020. CEPR Discussion Paper No. DP15432.

Choi, Darwin, Zhenyu Gao, and Wenxi Jiang, "Attention to Global Warming," *Review of Financial Studies*, 2020, *33* (3), 1112–1143.

Cúrdia, Vasco and Michael Woodford, "The Central-Bank Balance Sheet as an Instrument of Monetary Policy," *Journal of Monetary Economics*, 2011, *58* (1), 54–79.

D'Amico, Stefania and Thomas King, "Flow and Stock Effects of Large-Scale Treasury Purchases: Evidence on the Importance of Local Supply," *Journal of Financial Economics*, 2013, *108* (2), 425–448.

Engle, Robert F., Stefano Giglio, Bryan Kelly, Heebum Lee, and Johannes Stroebel, "Hedging Climate Change News," *Review of Financial Studies*, 2020, *33* (3), 1184–1216.

Gagnon, Joseph, Matthew Raskin, Julie Remache, and Brian Sack, "The financial market effects of the Federal Reserves large-scale asset purchases," *International Journal of Central Banking*, 2011, *7* (1), 3–43.

Gertler, Mark and Peter Karadi, "A Model of Unconventional Monetary Policy," *Journal of Monetary Economics*, 2011, *58* (1), 17–34.

Giglio, Stefano, Bryan Kelly, and Johannes Stroebel, "Climate Finance," *Forthcoming Annual Review of Financial Economics*, 2021.

Hambel, Christoph, Holger Kraft, and Rick van der Ploeg, "Asset Diversification versus Climate Action," 2021. Working Paper, University of Oxford.

Hassler, John, Per Krusell, and Tony Smith, "Environmental Macroeconomics," *Handbook of Macroeconomics*, 2016, *2*, 1893–2008.

Hong, Harrison and Marcin T. Kacperczyk, "The price of sin: The effects of social norms on markets," *Journal of Financial Economics*, 2009, *93* (1), 15–36.

Hsu, Po-Hsuan, Kai Li, and Chi-Yang Tsou, "The Pollution Premium," 2021. Working Paper, HKUST Business School.

Koijen, Ralph, François Koulischer, Benoît Nguyen, and Motohiro Yogo, "Inspecting the Mechanism of Quantitative Easing in the Euro Area," *Journal of Financial Economics*, 2021, *140* (1).

Krishnamurthy, Arvind and Annette Vissing-Jorgensen, "The Effects of Quantitative Easing on Interest Rates: Channels and Implications for Policy," *Brookings Papers on Economic Activity*, 2011, p. 215–265.

__ , Stefan Nagel, and Annette Vissing-Jorgensen, "ECB Policies Involving Government Bond Purchases: Impact and Channels," *Review of Finance*, 2018, *22* (1), 1–44.

Mota, Lira and Melina Papoutsi, "Understanding the Effects of Unconventional Monetary Policy on Corporate Bond Market in the Euro Area," 2020. Working Paper, ECB.

Piazzesi, Monika and Martin Schneider, "Payments, Credit and Asset Prices," 2018. Working Paper, Stanford.

__ , Ciaran Rogers, and Martin Schneider, "Money and Banking in a New Keynesian Model," 2020. Working Paper, Stanford.

Zerbib, Olivier David, "The effect of pro-environmental preferences on bond prices: Evidence from green bonds," *Journal of Banking and Finance*, 2019, *98*, 39–60.