Carbon taxes, financial frictions and the role of climate-related disclosure[*]

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Abstract

How does carbon taxation interact with the financial sector of an economy? How does climate-related disclosure affect this interaction and which implications for financial stability do arise? To address these questions, we develop a DSGE model with a production sector, which uses capital, labor and energy as inputs, the latter provided by a low-carbon and a fossil energy sector. Financial intermediaries fund the capital in each sector, are constrained by financial frictions and subject to imperfect information regarding the emission intensity of firms. Introducing a carbon tax triggers a substitution towards low-carbon energy and causes balance sheet losses among financial intermediaries. Financial frictions amplify the impact of carbon taxes on the economy. We show that in the absence of full disclosure about the emission-intensity of economic activities, financial intermediaries face higher balance sheet losses and are impaired in their ability to finance the transition to a low-carbon economy.

Keywords: climate policy, carbon taxation, financial frictions, climate-related disclosure, emission disclosure

JEL classification: D82, H23, G11, G14, G18, Q43, Q58.

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Contents

1 Introduction

The latest report by the International Panel on Climate Change (IPCC, 2022) documents that immediate and forceful climate policies are needed to induce a transition to a low-carbon economy and thereby avoid the worst outcomes of climate change. In addition to the need for climate policies, it is apparent that the financial sector also needs to play a major role in realizing this transition, given the considerable need for additional investment in low-carbon energy. However, the financial sector is not only needed as an enabler of the low-carbon transition, it is also subject to risks arising from the transition, see for example Bolton, Despres, Da Silva, Samama, Svartzman, et al. (2020). Climate policies may lead to unexpected losses in the form of stranded assets or defaults on loans, which could threaten financial stability, possibly impairing the role of the financial sector in enabling the transition. Hence, in order to assess how the financial sector affects the transition to a low-carbon economy, we need to consider both roles of the financial sector, as enabler of the transition and subject of transition risk.

For the financial sector to assess risks and finance the transition, it is a key prerequisite that firms disclose emission-related information, see FSB (2017). While an emerging literature, reviewed below, has studied the impact of climate policy on the real economy and the financial sector, it has abstracted from the question to which degree emission-related information is available in the first place. The approaches assume the existence of full information and, thus, the ability of financial actors to make efficient investment decisions. However, there is evidence that financial actors seem to have difficulties at times to identify “green” companies as emission disclosure is far from complete, see Section 2. Firms might try to appear more climate-friendly than they actually are (a phenomenon labeled “greenwashing”), see Economist (2021). In this paper, we study the impact of carbon policies when the financial sector possesses only incompletely disclosed information about the emission intensities of the economic activities they fund.

To do so, we develop a dynamic general equilibrium model with financial frictions in the spirit of Gertler and Karadi (2011) and carbon taxes as a policy tool to mitigate climate change. While climate policies come in various forms, from quotas over regulation to fiscal policies, a carbon tax which increases the relative price of fossil energy can capture most of these policies in a reduced form for our structural model. The model economy consists of a low-carbon and a fossil energy sector, which provides energy inputs to a non-energy production sector, and is calibrated to the euro area economy.[1] Financial intermediaries allocate capital across these sectors subject to an endogenous balance-sheet constraint, giving rise to a financial accelerator. Most importantly, their expectations on the sectoral return on capital shape their decision about how much to invest in the various sectors. These expectations depend, however, on the emission-related disclosure by the corresponding firms. As a consequence, fossil energy firms will obtain more investment if they disclose a lower emission intensity. Intermediaries continue to form expectations based on disclosed information until full and correct disclosure is made available.

Our main results are as follows. Under imperfect disclosure financial intermediaries underestimate the carbon tax-induced emission costs of firms in the fossil energy sector. They thus charge lower costs of capital for fossil energy firms relative to the case when all emissions are disclosed. Hence an inefficiently high amount of fossil capital is allocated

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[1] Note that emissions in the model do not affect economic output, i.e. we abstract from physical risks of climate change. We do so since we are solely interested in the short-run impact of carbon prices and its amplification through the financial system.

and a too low amount in the low-carbon sector. The transition-inducing effect of carbon taxes is thus considerably hampered by imperfect disclosure. As a consequence of this capital misallocation under imperfect disclosure, the GDP loss induced by carbon taxes is lower when perfect disclosure prevails. Assuming that disclosed emissions are 20% below their full level, the GDP loss associated with a carbon tax increase of 50 Euro/ton is 1.1%, while it is 0.85% when all emissions are known. However, balance sheet losses of financial intermediares are only slightly lower under perfect disclosure. This is because imperfect disclosure sustains the valuation of capital assets in the fossil fuel sector, leading to a lower extent of stranded assets. Hence, perfect disclosure is beneficial for the reason that it allows the financial sector to play the role as an enabler of the transition and less so because it limits balance sheet losses of financial intermediaries in response to carbon tax shocks.

Interestingly, perfect disclosure only unfolds its full positive impact in the presence of financial frictions. When balance sheets of financial intermediaries are constrained, full disclosure prevents that scarce capital is allocated to the fossil energy sector and ensures that funding to other sectors is not reduced too strongly. In contrast, in the absence of financial frictions, the harm done by imperfect disclosure is limited since higher capital allocation in the fossil energy sector does not reduce funding elsewhere to the same extent.

We furthermore show, in line with previous literature, that a pre-announced and credible carbon tax path can limit the real-economic costs and financial fallout. However, we also demonstrate that the benefits of pre-announcement can only be reaped when emissions are fully disclosed. Given our base calibration of 20% undisclosed emissions, pre-annoucement in fact does not lead to any reduction in the extent of stranded assets relative to the unanticipated case. Even more strikingly, we find that imperfect disclosure can give rise to a phenomenon akin to the "Green Paradox" by Sinn (2012), in which fossil asset prices initially increase in response to pre-announced carbon taxes. However, the transmission channel is quite different from the one in Sinn (2012), where the anticipation of carbon taxes lead to faster extraction of fossil resources. In our model, it is the combination of bringing forward economic production in time to avoid future taxation and imperfect disclosure which leads to the paradox outcome that carbon taxes increase fossil sector valuations initially.

Our results demonstrate that reliable emission-related disclosure not only enables the financial industry to make appropriate investment decisions (thereby reducing transition risks to the financial sector), but more importantly ensures that the economic costs of carbon taxes are limited by channeling funds to where they are most efficient ("enabler role" of the financial sector). The introduction of emission pricing should thus be accompanied if not preceded by rules mandating the disclosure of emission-related information by firms. This is important for two reasons. First, the lack of disclosure increases transition costs the most during the initial phase of transition paths, where the risk of political backpedaling is largest. Second, while credible and pre-announced paths of carbon taxes have been shown to reduce the overall economic costs of the transition, these benefits can only be reaped when sufficiently many emissions are disclosed.

Our paper is related to an emerging literature on the macro-financial impact of carbon taxation. Closest in spirit are the contributions by Diluiso, Annicchiarico, Kalkuhl, and

Minx (2021), Carattini, Heutel, and Melkadze (2021) and Schuldt and Lessmann (2021), who develop multi-sector models with financial frictions and climate taxation. They show that carbon tax shocks are amplified by financial frictions and study the implications for the role of central banks and optimal macro-prudential policies. Related to our discussion of pre-announced carbon tax shocks, Peterman, Fried, and Novan (2021) study how beliefs over the likelihood that governments introduce carbon taxes can by themselves initiate a transition to a low-carbon economy. Similarly, Battiston, Monasterolo, Riahi, and van Ruijven (2021) explore the conditions under which the perception of risk by financial actors either enables or hampers the low-carbon transition. They link integrated assessment models with financial risk models, in which beliefs about the likelihood of carbon tax paths shape financing costs for low-carbon and fossil investments. Giovanardi, Kaldorf, Radke, and Wicknig (2021) study the emergence of green bond premiums in a model with financial frictions and the central banks' collateral framework tilted in favor of green bonds. Ferrari and Landi (2022) study the role of carbon taxes on inflation and the impact of imperfect information in this transmission. None of these contributions consider the role of imperfect disclosure in the transmission of carbon taxes. Our framework also contributes to the emerging empirical literature on disclosure, to be reviewed below.

The rest of the paper is structured as follows. Section 2 reviews the literature on emission-related disclosure and establishes a number of empirical facts about the impact of disclosure on firms. Section 3 presents our model, while Section 4 discusses the impact of disclosure on the financing decision by intermediaries in the model. Section 5 discusses the calibration of the model, before Section 6 presents simulation results. Finally, Section 7 concludes.

2 Evidence on the extent of emission disclosure and its impact on financing costs

This section discusses empirical evidence on the extent to which firms currently disclose information on their greenhouse gas emissions and the impact this disclosure has on these firms in terms of financing costs.

Carbone, Giuzio, Kapadia, Krämer, Nyholm, and Vozian (2021) develop a firm-level database on non-financial corporations from the S&P 500 and STOXX Europe 600 indices. They find that roughly 80% of firms in the sample disclosed emissions in 2019, of which about two thirds represent audited disclosures. A smaller share of firms (60-70%) chooses to disclose emission reduction targets. The share of disclosing firms is highest among the high-emitting firms (90%), likely reflecting that these firms are most exposed to scrutiny by financial actors and the general public. Similarly, TCFD (2022) notes in its status report find that 81% of the surveyed EU firms disclose emission-related information. In contrast, Bolton and Kacperczyk (2020) find much lower disclosing rates based on a large panel including 14,400 listed companies in 77 countries. In 2018, only 16% of companies in the panels disclosed emissions. Relative to the previous study, this much larger panel, however, includes many smaller firms, which less often disclose compared to larger companies.

Both studies find that disclosing firms, on average, face lower financing costs.[2] In addition, Carbone et al. (2021) show that disclosure of forward-looking emission targets have similarly positive effects on financing costs, and the scale of effects increase with more ambitious targets.[3] While this positive impact of disclosure holds on average in the studied samples, the disclosure of high levels of emission intensities among the high emitters has, however, a negative impact on financing costs.

While the above studies consider voluntary disclosure, Krueger, Sautner, Tang, and Zhong (2021) study a panel of 29 countries that introduced mandatory ESG disclosure. They show that the introduction of mandatory disclosure increased the likelihood and quality of ESG disclosure particularly among firms with lower ESG performance. This suggests that voluntary disclosure is avoided by firms that fear adverse financial impacts from disclosing low ESG performances.

In the ECB Financial Stability Review 2022, Emambakhsh, Giuzio, Mingarelli, Salakhova, and Spaggiari (2022) argue that given this impact of disclosure on financing costs, the risk of greenwashing remains high in the absence of mandatory reporting requirements. A potential remedy for greenwashing risks are independent third parties providing information on companies' emissions. However, the level of disagreement between such data providers is high. Berg, Koelbel, and Rigobon (2019) show that ESG-ratings diverge widely across the providers. The largest contributor to the divergence are differences in measurement of ESG-factors (rather than selection of indicators or weights attached to them), which reflects the absence of standards about the measurement and disclosure of emission-related information. Emambakhsh et al. (2022) find that the three main data providers for ESG-ratings agree in less than 20% of cases that a fund should be labelled as ESG. Rating agencies can even have opposite opinions on the same firms, see Billio, Costola, Hristova, Latino, and Pelizzon (2021). Finally, Elmalt, Kirti, and Igan (2021) show that there is at best a weak negative correlation between companies' ESG scores and their emission growth.

Overall, the empirical evidence suggests that the financial intermediaries are receptive to disclosed information about emissions by firms, but are unlikely to be fully informed about the emissions induced by the economic activities that they provide funding for. On average, disclosing emissions lowers the cost of financing for firms. In contrast, an increase in the disclosure of emissions among the most emitting companies increases the cost of financing for those companies. The transmission channels of disclosure to financing costs cannot be clearly identified from empirical results. It is likely, however, that the act of disclosing reduces uncertainty for financial agents, enabling them to price risks more effectively. Moreover, the level of disclosed emissions or emission targets are likely to affect financial agents' views on the expected profitability of firms in the presence or anticipation of climate policies. Hence, financing costs can increase if disclosed emission levels are relatively high or fall if companies disclose low emission levels. At the same time, disclosure of one firm can have spillover effects on other firms if the act of disclosure

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[2] Carbone et al. (2021) analyze how disclosure affects credit ratings of firms, while Bolton and Kacperczyk (2020) investigate the impact on risk premiums in equity markets.

[3] The fact that disclosure is nevertheless still far from comprehensive, even among low emitters, points to sizeable disclosure transaction costs, see Bolton and Kacperczyk (2020) for a discussion of potential channels.

redirects financing towards or away from disclosing firms.[4]

Our model, which is introduced in the next section, will analyse the impact of disclosure on financing costs in a theoretical framework. As we will show, the model can account for most of the empirical facts about the link between disclosure and financing costs outlined above. Additionally, the model can elucidate the implications of disclosure for how climate policies transmit through the economy and for potential financial stability risks arising from these policies.

3 Model

The model's representative household consumes final output, saves in the form of bank deposits, provides labor and earns wage income. The production side of the economy consists of three sectors. Two energy sectors, one of them using fossil resources, provide inputs to the aggregate non-energy sector, which creates the final good in the economy. Capital in each sector is funded by a financial sector, which is subject to financial frictions à la Gertler and Karadi (2011). The fiscal authority imposes a carbon tax on emission activities in the economy, while the central bank sets the nominal interest rate. In the following, we present the setup of the model in detail, while the derivations are discussed separately in Appendix A.

3.1 Households

The representative household is modeled following the standard approach as in Gertler and Karadi (2011). Specifically, the household's lifetime utility is a function of consumption C_t and labor supply L_t and given by

$$U_0 = \mathbb{E}_0 \sum_t^{\infty} \beta^t \left[\xi_t^C \frac{(C_t - h_c C_{t-1})^{1-\sigma} - 1}{1-\sigma} - \chi \frac{L_t^{1+\psi}}{1+\psi} \right] \tag{1}$$

where β is the discount factor, h_c the internal habit parameter and σ the inverse of the intertemporal elasticity of substitution. The term ξ_t^C captures a consumption preference shock, which increases the household's preference for consumption. The parameter χ captures the relative weight on labor disutility, and ψ the inverse of the Frisch elasticity of labor supply.

The budget constraint is given by

$$C_t + B_t = W_t L_t - T_t + \Pi_t + R_{t-1} B_{t-1} \tag{2}$$

where W_t is the real wage rate in the economy, T_t lump-sum taxes, Π_t payouts from the ownership of financial intermediaries, firms and resource ownership.[5] Deposits are given by B_t and the real interest rate on deposits by R_t. We define the household's stochastic

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[4] This can be particularly harmful for low-carbon energy firms, as those have been shown to be more capital-intensive than other energy sources, see Best (2017) and Hirth and Steckel (2016). Low availability of capital thus tends to harm low-carbon energy production more than fossil one.

[5] XXX Require formula here, base on MAtalb Code

discount factor as $M_{t,t+1} = \beta \mathbb{E}_t(\frac{\lambda_{t+1}}{\lambda_t})$, where λ_t is the marginal utility of consumption. The optimality conditions of the household are stated in Appendix A.1.

3.2 Production

Production is organized in three sectors. The non-energy sector uses capital, labor and energy as inputs to produce the intermediate good, which is used by retailers to create the final good used for investment and consumption. Hence, besides the energy sector, the production side of the economy follows the NK-DSGE standard. Energy is supplied by the remaining two (perfectly competitive) sectors. The low-carbon energy sector employs only capital, while the fossil energy sector uses capital and fossil resources.[6] The use of the latter cause emissions, which are taxed by the government. Finally, a capital producer manufactures the capital stock for each sector by converting the final good in the economy into an investment good.

The non-energy sector and retailers. There is a continuum of monopolistically competitive non-energy firms, indexed as $k \in [0,1]$, producing intermediate goods $Y_{k,t}$ at the nominal price $P^N_{k,t}$ corresponding to the real price $P_{k,t} = \frac{P^N_{k,t}}{P_t}$, where P_t is the nominal price of the final good and the numeraire in the model. A perfectly competitive retailer buys the output of intermediate good firms and bundles them into a final good Y_t by using the technology $Y_t = \left(\int_0^1 Y_{k,t}^{(\epsilon_t^I - 1)/\epsilon_t^I} dk\right)^{\epsilon_t^I/(\epsilon_t^I - 1)}$ where ϵ_t^I is the elasticity of substitution across intermediate goods.[7] The retailer sells the final good to households, which consume it, and to capital producers, who convert it to capital.

Firm k produces by combining a composite good CD_k, made up of capital and labor, with a second composite good, energy E_k, made up of both low-carbon and fossil fuel energy. The elasticity of substitution between the two composites is given by ϵ_Y. Specifically, the production function is given by

$$Y_{k,t} = \left(w_{CD}^{1/\epsilon_Y} CD_{k,t}^{(\epsilon_Y - 1)/\epsilon_Y} + (1 - w_{CD})^{1/\epsilon_Y} E_{k,t}^{(\epsilon_Y - 1)/\epsilon_Y}\right)^{\epsilon_Y/(\epsilon_Y - 1)}$$

where the capital-labor composite is given by a Cobb-Douglas production function

$$CD_{k,t} = A_t^Y \left(\xi_t^Y (K_{k,t}^Y)^{\alpha_Y}\right) (L_{k,t}^Y)^{1-\alpha_Y}$$

with A_t^Y being productivity and K^Y and L^Y, capital and labor inputs, respectively. ξ_t^Y is an exogenously given measure of the quality of capital.

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[6] Since the energy sectors do not use inputs from the non-energy sector, our framework differs from general equilibrium models which take into account the full input-output structure of the economy, as in Atalay (2017) and Baqaee and Farhi (2019). These models are useful in disaggregating the impact of carbon taxes on a finer level as well as take into account the cross-border propagation of carbon taxes, see for example Devulder and Lisack (2020), Hinterlang, Martin, Röhe, Stähler, and Strobel (2021) and Frankovic (2022).

[7] The elasticity of substitution is subject to a price markup shock ξ^{ϵ^I}, where the equation $\log(\epsilon_t^I) = (1 - \rho_{\epsilon^I}) \log(\epsilon_{ss}^I) + \rho_{\epsilon^I} \log(\epsilon_{t-1}^I) + \sigma_{\epsilon^I} \xi_t^{\epsilon^I}$ holds.

When changing prices, firms in the non-energy sector face Rotemberg adjustment costs, given by $AC_{k,t} = \frac{\xi_P}{2}\left((P^N_{k,t}/P^N_{k,t-1})/(\pi_{t-1}^{w_p}\pi_{ss}^{1-w_p}) - 1\right)^2 Y_t$, where ξ_P is a parameter determining the magnitude of adjustment cost and w_p the degree of price indexation. Inflation is defined as $\pi_t = P_t/P_{t-1}$ with π_{ss} being steady-state inflation.

The non-energy sector can rely on low-carbon (E^L_t) or fossil energy (E^F_t) for its energy input. We assume that the two forms of energy can be imperfectly substituted following a CES technology given by

$$E_t = \left(w_{EL}^{1/\epsilon_E}(E^L_t)^{(\epsilon_E-1)/\epsilon_E} + (1-w_{EL})^{1/\epsilon_E}(E^F_t)^{(\epsilon_E-1)/\epsilon_E}\right)^{\epsilon_E/(\epsilon_E-1)}$$

where ϵ_E is the elasticity of substitution between low-carbon and fossil fuel energy and w_{EL} the initial weight of low-carbon technology. Since all firms from the non-energy sector face the same problem, the k-subscript was dropped. The relative price of low-carbon and fossil fuel energy is P^{EL}_t and P^{EF}_t, respectively.

Firms maximize the sum of their expected discounted profits by choosing the amount of labor and energy inputs and by setting the nominal price for their output. The amount of capital is taken as given as it is determined at the end of the previous period by financial intermediaries' willingness to supply funds, to be discussed later. Firms also choose the composition of energy inputs following the optimality conditions

$$E^L_t = w_{EL}\left(P^{EL}_t/P^E_t\right)^{-\epsilon_E}E_t$$
$$E^F_t = (1-w_{EL})\left(P^{EF}_t/P^E_t\right)^{-\epsilon_E}E_t$$

where $P^E_t = \left(w_{EL}(P^{EL}_t)^{1-\epsilon_E} + (1-w_{EL})(P^{EF}_t)^{1-\epsilon_E}\right)^{1/(1-\epsilon_E)}$ is the price of the composite energy good. Hence, an increase in the price of fossil energy P^{EF}_t, caused for example by the taxation of emissions from fossil resource use, will induce a shift in demand from fossil to low-carbon energy. The remaining optimality conditions for labor and prices are presented in Appendix A.2.

Low-carbon energy sector. The low-carbon energy sector consists of perfectly competitive firms and only uses capital as input. The production function is given by

$$E^L_t = A^L_t \xi^L_t K^L_t.$$

where K^L_t is low-carbon capital and ξ^L_t is a capital quality shock. Since the capital allocation is entirely determined by the financial sector, there is no decision problem for low-carbon firms.

Fossil energy sector. The fossil sector is perfectly competitive and uses capital and fossil resources F as inputs to production. The production function is given by

$$E^F_t = \left[w_{KF}^{1/\epsilon_F}\left(A^F_t\xi^F_tK^F_t\right)^{\frac{\epsilon_F-1}{\epsilon_F}} + (1-w_{KF})^{1/\epsilon_F}\left(F_t\right)^{\frac{\epsilon_F-1}{\epsilon_F}}\right]^{\frac{\epsilon_F}{\epsilon_F-1}},$$

where ϵ_F is the elasticity of substitution between capital and fossil inputs and w_{KF} the weight of capital in the production function. The term ξ_t^F captures sector-specific capital quality shocks. Fossil resources are inelastically supplied at the relative price $P_{F,t}$. However, a carbon tax τ_t is applied to each unit of emission Z_t, which in turn is given by

$$Z_t = eF_t \tag{3}$$

with e being the emission intensity. Profit maximization then implies that the optimal demand for fossil fuels is

$$F_t = (1 - w_{KF}) \left(\frac{P_t^F + e\tau_t}{P_t^{EF}} \right)^{-\epsilon_F} E_t^F . \tag{4}$$

Hence, an increase in the carbon tax rate will reduce the use of fossil resources and thus emissions. This will in turn lower the amount of fossil energy produced.

Note that there is a clear distinction between low-carbon and fossil energy in our model. In reality, a supposedly high-emissions firm, for example an electricity producer with existing coal plants, can undertake low-carbon investing, e.g. by building renewable energy power plants. Hence, investment in the fossil energy sector in our model is to be understood in the narrow sense. It captures only capital flowing into economic activities that convert fossil resources into energy.

Capital producers. Capital in each sector i evolves according to $K_{t+1}^i = \xi_t^i K_t^i (1 - \delta^i) + I_t^i$ where δ is the depreciation rate of capital in each sector $i \in \{Y, L, F\}$ and I_t^i is new investment. Perfectly competitive capital producers buy the existing capital stock at the end of each period, rebuild depreciated capital and possibly expand the capital stock through investment goods. They then sell the capital back to the sectors at a sector-specific price Q_t^i. We assume that the cost of refurbishing depreciated capital is unity. However, the price of producing new capital is subject to investment adjustment costs, which are given by $AC_t^{INV,i} = \frac{\gamma_I^i}{2} \left(I_t^i / I_{t-1}^i - 1 \right)^2 I_t^i$. The parameter γ_I^i captures the extent of adjustment costs and is sector-specific. Profit maximization by capital producers yields the following expression.

$$Q_t^i = 1 + \frac{\gamma_I^i}{2} \left(\frac{I_t^i}{I_{t-1}^i} - 1 \right)^2 + \gamma_I^i \left(\frac{I_t^i}{I_{t-1}^i} - 1 \right) \frac{I_t^i}{I_{t-1}^i} - \mathbb{E}_t M_{t,t+1} \gamma_I^i \left(\frac{I_{t+1}^i}{I_t^i} - 1 \right) \left(\frac{I_{t+1}^i}{I_t^i} \right)^2$$

Hence, the price of new capital depends endogenously on the level of investment required to obtain the desired new capital stock, which in turn depends on the expected sectoral return.

3.3 Financial sector

The financial sector consists of a continuum of financial intermediaries $j \in [0, 1]$. Intermediaries hold deposits by households in addition to their own accumulated net worth and finance capital expenditures in the real economy. In line with Gertler and Karadi (2011), financial intermediaries are constrained by an agency problem. This agency problem leads to an endogenous balance-sheet constraint for banks, which in turn gives rise to a financial accelerator in the model.

Let $S^i_{j,t}$ be a security that an financial intermediary j purchases from sector $i \in \{Y, L, F\}$ and Q^i_t the price of the security. The security portfolio $SP_{j,t} = \sum_i Q^i_t S^i_{j,t}$ is funded by the net worth of the financial intermediary $(N_{j,t})$ and deposits $(D_{j,t})$:

$$\sum_i Q^i_t S^i_{j,t} = D_{j,t} + N_{j,t}. \tag{5}$$

Let R^i_t be the realized gross rate of return on the purchased securities i. The net worth of the financial intermediary then evolves according to

$$\begin{aligned} N_{j,t+1} &= \sum_i Q^i_t S^i_{j,t} R^i_{t+1} - R_t D_{j,t} \\ &= \sum_i Q^i_t S^i_{j,t} (R^i_{t+1} - R_t) + R_t N_{j,t}. \end{aligned} \tag{6}$$

In equilibrium, the supply of shares must equal the purchase of new capital, hence

$$Q^i_t S^i_t = Q^i_t K^i_{t+1} \text{ for } i \in \{Y, L, F\}. \tag{7}$$

Following Gertler and Karadi (2011, 2013), we assume that financial intermediaries can run away with a fraction of total assets. Depositors recognize this and only lend funds to financial intermediaries if the value of continuing the financial business exceeds the benefit of running away with the divertable fraction of assets. However, the willingness to supply funds is a function of the asset, such that

$$V_{j,t} \geq \rho RWA_{j,t}, \tag{8}$$

where $RWA_{j,t} = Q^Y_t S^Y_t + \rho_L Q^L_t S^L_t + \rho_F Q^F_t S^F_t$ are risk-weighted assets, with ρ_S capturing the relative absconding rates for the sectors $S \in \{L, F\}$.[8] The term $V_{j,t}$ captures the continuation value of the financial intermediary and is given by

$$V_{j,t} = \max_{SP_{j,t}, s^L_{j,t}, s^F_{j,t}} \mathbb{E}^D_t \left((1-\gamma) M_{t,t+1} N_{j,t+1} + \gamma M_{t,t+1} V_{j,t+1} \right). \tag{9}$$

The parameter γ determines the likelihood that a financial intermediary will remain in the financial business in the next period. If the financial intermediary exits business, she will take the entire net worth to the household. Hence the value of the business j at time t is a probability weighted average of remaining or leaving the business in the next period. Note that financial intermediaries need to form expectations about the return on their investments. Since they form these expectation on the basis of emission-related disclosures by the energy sector, the expectation operator $\mathbb{E}^D_t$ might differ from expectations that would follow from full information. This will be discussed in greater detail in Section 4.

The financial intermediary chooses the amount of securities bought from each sector to maximize its current value. As shown in Appendix A.3, the financial intermediary's

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[8] While we interpret the assets as risk-weighted, note that there is no actual default risk in the model.

value is a linear function of net worth:

$$V_{j,t} = \nu_t N_{j,t}$$

We define the ratio between the net worth of the intermediary and its risk-weighted assets as $\kappa_t = N_{t,j}/RWA_{j,t}$. We show in the appendix that ν_t and κ_t are identical across all intermediaries. By appropriate calibration we ensure that the incentive constraint always binds, such that

$$\nu_t N_t = \rho RWA_t \Leftrightarrow \kappa_t = \rho/\nu_t. \tag{10}$$

In reality, even if the constraint does not hold with equality, total funding by financial intermediaries might still be limited by net worth. This can be the case if intermediaries anticipated that the constraint may be binding in the future, which gives rise for a precautionary motive to limit funding already today, see Brunnermeier and Sannikov (2014) and He and Krishnamurthy (2014).

Solving the financial intermediary's problem (see Appendix A.3), one obtains the following optimality conditions:

$$\mathbb{E}_t^D \Omega_{t+1}(R_{t+1}^L - R_t) = \rho_L \mathbb{E}_t^D \Omega_{t+1}\left(R_{t+1}^Y - R_t\right) \tag{11}$$

$$\mathbb{E}_t^D \Omega_{t+1}(R_{t+1}^F - R_t) = \rho_F \mathbb{E}_t^D \Omega_{t+1}\left(R_{t+1}^Y - R_t\right) \tag{12}$$

Since all financial intermediaries face the same problem the subscript j has been dropped. The financial intermediary's effective stochastic discount factor is given by

$$\Omega_{t+1} = M_{t,t+1}(1 - \gamma + \gamma\nu_{t+1}). \tag{13}$$

Hence, the financial sector allocates stocks in such a way that the expected return (net of portfolio adjustment costs) in the sectors are equal to each other after adjusting for the relative absconding rates, corrected for the perceived riskiness of sector-specific assets.

Total net worth in the financial sector consists of the net worth of existing financial intermediaries surviving to this period and that of new intermediaries, such that $N_t = N_{e,t} + N_{n,t}$. New intermediaries are equipped with a share $\omega/(1-\gamma)$ of assets by exiting intermediaries. Hence, net worth of new intermediaries is given by $N_{n,t} = \omega \sum_i Q_t^i S_{t-1}^i$. The net worth of financial intermediaries that continue to exist is given by

$$N_{e,t} = \gamma\Big[\sum_i Q_t^i S_{t-1}^i (R_t^i - R_{t-1}) + R_{t-1} N_{t-1}\Big].$$

3.4 Government and central bank

Government spending G_t is exogenous and given by

$$G_t = (1 - \rho_g) G_{ss} + \rho_g G_{t-1} + \xi_t^g \tag{14}$$

The governments budget constraint is

$$G_t = T_t + \tau_t Z_t, \tag{15}$$

The aggregate market clearing is given by

$$Y = C_t + G_t + \sum_{i \in \{Y,L,F\}} \left(I_t^i + AC_t^{INV,i} \right) + AC_t.$$

Monetary policy is conducted following a Taylor interest rate rule as follows

$$\frac{R_t^N}{R_N} = \left(\frac{R_{t-1}^N}{R_t^N} \right)^{\rho_R} \left[\left(\frac{\pi_t}{\pi_{ss}} \right)^{\rho_\pi} \left(\frac{Y_t}{Y_{t-1}} \right)^{\rho_Y} \right]^{1-\rho_R},$$

where R_t^N is the nominal interest rate, ρ_R a smoothing parameter and ρ_π as well as ρ_Y are parameters governing the responsiveness of the nominal interest rate to deviations in inflation and output. The real interest rate is then given by $R_t = R_t^N / \pi_{t+1}$.

4 Capital allocation under imperfect emissions disclosure

To understand financial intermediaries' capital allocation decision across the three real-economic sectors, we first note that the gross return to capital R_t^i in each sector $i \in \{Y, L, F\}$ is given by

$$R_t^i = \frac{\xi_t^i (Q_t^i - \delta_i) K_t^i + \Pi_t^i}{Q_{t-1}^i K_t^i} \tag{16}$$

where Π_t^i are sectoral revenues minus costs, defined below. Hence, in period $t-1$ financial intermediaries purchase stocks S_{t-1}^i at price Q_{t-1}^i, financing the purchase of K_t^i units of capital to be used in production in the next period t. This investment generates returns through asset price appreciation (adjusted for physical depreciation) and through revenues net of costs, given by

$$\begin{aligned}
\Pi_t^Y &= MC_t Y_t - W_t L_t - P_t^E E_t \\
\Pi_t^L &= P_t^{EL} E_t^L \\
\Pi_t^F &= P_t^{EF} E_t^F - F_t P_t^F - Z_t \tau_t
\end{aligned}$$

The non-energy sector has revenues given by the product of its sales price (to retailers) and output, and faces costs for labor and energy inputs. The low-carbon energy sector only uses capital in its production processes and thus exhibits no costs, while the fossil energy sector pays for fossil fuel costs and emission taxes.

Financial intermediaries form expectations about the sectoral returns in the next period when making their investment decisions. Considering the forward-looking version of equation (16) and solving for the capital stock we obtain:

$$K^i_{t+1} = \frac{\mathbb{E}^D_t \Pi^i_{t+1}}{\mathbb{E}^D_t (R^i_{t+1} - R_t) Q^i_t + R_t Q^X it - \mathbb{E}^D_t \xi^i_{t+1} (Q^i_{t+1} - \delta_i)}, \tag{17}$$

where $\mathbb{E}^D$ is the expectation operator for financial intermediaries at time t and is described further below. We can infer two important observations from this. First, the amount of capital allocated to each sector increases with the expected revenue as given in the numerator of the right-hand side term. Remember that in the case of the fossil sector the emission costs are deducted from the revenue, such that higher carbon taxes will reduce investing in the fossil energy sector. Second, capital allocation falls with the size of the expected sectoral spread $\mathbb{E}^D_t (R^i_{t+1} - R_t)$. Note that the optimality conditions in equations (11)-(12) govern these risk spreads. In particular, since relative absconding rates in the low-carbon and fossil energy sector exceed unity ($\rho_L, \rho_F > 1$), spreads are larger relative to the non-energy sector, which reduces, ceteris paribus, investment in these sectors.

Hence, the expectations which financial intermediaries form of sectoral profits are key for the capital allocation decision. We assume that these expectations are based on the disclosure of the future level of emission intensity, given by $D_{t+1}e$, rather than the actual emission intensity e. The variable D thus measures the degree of disclosure. The case $D_{t+1} = 1$ captures the full disclosure or full information case, in which financial intermediaries are aware of the true emission intensity of fossil energy firms. In that case, expectations are based on full emissions and model consistent. If instead $D_{t+1} < 1$, holds, financial intermediaries will base their expectations of the profitability of the fossil energy sector on the belief that the emission intensity is lower than e.[9] In reality, emission-related disclosure might not be available in the form of forward-looking emission (intensity) targets. Instead, financial intermediaries might use information about historical emissions to form expectations about the future emission intensities. In this case, we can view D as measuring the share of current or historical emissions that are publicly known.[10] We abstract from any emission disclosure in the low-carbon energy and the non-energy sector. Instead, the implicit assumption in our setup is that financial intermediaries are aware that these sectors cause zero emissions. Besides, it is unlikely that firms would disclose higher emissions than actually the case. Low-carbon firms are nevertheless affected by imperfect disclosure, as investment otherwise flowing to the low-carbon sector is deployed in the fossil energy sector as a consequence of disclosed emission intensities being lower than actually the case.

The disclosed emission intensity affects the financial sector's forecast on emissions in the fossil energy sector in the following way. First, the expected fossil resource use is now a function of the disclosed emission intensity, rather than actual emission intensity as in

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[9] Ferrari and Landi (2022) follow a similar approach when studying the impact of carbon taxes under imperfect information. In their case households have incorrect expectations about the duration of the carbon tax increase, while we assume incorrect beliefs by intermediaries about the emission intensity of firms.

[10] Expectations about the emission intensity of a firm can in theory relate to both the mix of fossil resources employed (e.g. gas vs. coal) or the technological efficiency of the production methods.

equation (4):

$$\mathbb{E}_t^D(F_{t+1}) = (1 - w_{KF}) \left(\frac{P_{t+1}^F + D_{t+1} e \tau_{t+1}}{\mathbb{E}_t^D P_{t+1}^{EF}} \right)^{-\epsilon_F} \mathbb{E}_t^D E_{t+1}^F. \tag{18}$$

The future price of fossil resources (P_{t+1}^F), the tax rate (τ_{t+1}) as well as disclosure is known to intermediaries.[11] However, intermediaries also need to form expectations about the expected price ($\mathbb{E}_t^D P_{t+1}^{EF}$) and demand ($\mathbb{E}_t^D E_{t+1}^F$) for fossil energy consistent with the degree of disclosure. These expectations follow from variations of the corresponding equations from Section 3.2:

$$\begin{aligned} \mathbb{E}_t^D E_{t+1}^F &= \left[w_{KF}^{1/\epsilon_F} \left(A_{t+1}^F \xi_{t+1}^F K_{t+1}^F \right)^{\frac{\epsilon_F - 1}{\epsilon_F}} + (1 - w_{KF})^{1/\epsilon_F} \left(\mathbb{E}_t^D (F_{t+1}) \right)^{\frac{\epsilon_F - 1}{\epsilon_F}} \right]^{\frac{\epsilon_F}{\epsilon_F - 1}}, \\ \mathbb{E}_t^D E_{t+1}^F &= (1 - w_{EL}) \left(\mathbb{E}_t^D P_{t+1}^{EF} / \mathbb{E}_t P_{t+1}^E \right)^{-\epsilon_E} \mathbb{E}_t E_{t+1} \end{aligned}$$

The future level of capital productivity ($A_{t+1}^F \xi_{t+1}^F$) is known, while the amount of capital invested (K_{t+1}^F) is a decision variable of the intermediary at time t. With respect to the remaining variables in the equations, note that financial intermediaries form expectations about the price and demand for fossil energy. They also form expectations about the use of fossil resources, which are consistent with the disclosed emission intensity. However, intermediaries form model-consistent expectations about the price of energy ($\mathbb{E}_t P_{t+1}^E$) and the demand for it ($\mathbb{E}_t E_{t+1}$), as well as about all other variables in the model (i.e. these expectations are based on the true emission intensity). This reflects that the emission-intensity for the economy as whole is known to all agents. Hence, financial intermediaries can predict the aggregate impact on energy demand, energy prices, total output and so on, which are consistent with the true emission intensity. Imperfect disclosure, thus, only affects fossil energy firm-specific variables.[12]
Since from a given disclosed emission intensity the resulting amount of emissions can be calculated (and vice versa), we use "disclosure of emissions" and "disclosure of the emission intensity" interchangeably.

The degree of disclosure D is exogenous in our setup.[13] However, it is clear from equation (17) that disclosing a lower emission intensity than the true one is beneficial to the fossil energy firms in terms of attracting capital funding. This is because the profitability of these firms will be assessed to be higher due to emission costs being underestimated relative to the full disclosure case. Conversely, any increase in the disclosure degree towards 100% will reduce capital allocated to the fossil energy sector and promote investment in the non-energy and low-carbon sector. Hence, on the basis of equation (17) we can rationalize some of the empirical facts outlined in Section 2. However, questions about how

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[11] In fact, we hold the price of fossil resources fixed throughout all simulations.

[12] Model-consistent expectations in this case actually imply expectations based on knowing the true emission-intensity as well as knowing that intermediaries will have expectations shaped by imperfect disclosure for a set of variables. However, as will be discussed in Appendix **??**, the model-consistent expectations about macroeconomic outcomes under imperfect disclosure are quite close to those obtained under full disclosure. Hence, this difference matters little in quantitative terms.

[13] Hence our framework cannot speak to empirical results showing that disclosing firms tend to reduce emissions faster and to a higher degree than non-disclosing firms.

much imperfect disclosure matters quantitatively for fossil energy firms and how large the effect on other sectors and the overall economy is can only be answered through numerical simulations. The next two sections seek to do exactly that. Section 5 presents how the model is calibrated to reflect the euro area economy, while Section 6 presents simulation results for how carbon tax shocks impact the economy under different degrees of emission disclosure.

5 Calibration

We calibrate the model to reflect the economy of the euro area. In doing so we follow closely the estimated parameters from Diluiso et al. (2021). An overview of all parameters is provided in Table 1.

We use standard values for the capital share and discount factor. The latter implies a steady-state annual real interest rate of 1.9%. With inflation set to 1.9%, the nominal interest rate evaluates to approx. 3.8% annually. We take the sector-specific depreciation rates as well as elasticities of substitution directly from Diluiso et al. (2021). However, we choose a lower baseline elasticity of substitution between low-carbon and fossil energy inputs to be in line with the macro substitutability of green and brown energy inputs in Papageorgiou, Saam, and Schulte (2017). Appendix B discusses how our results are affected by other parameterizations of the elasticities parameters.

We adopt the estimated utility parameters σ, h_c and ψ from Diluiso et al. (2021), with the weight on labor disutility being determined by steady-state targets. The survival rate of financial intermediaries as well as the absconding rates are set to match the risk-weighted capital ratio of 9% (reflecting Basel III capital requirement) as well as the empirical sectoral spreads. Finally, the parameters relating to adjustment costs as well as the Taylor rule are directly taken from the estimation in Diluiso et al. (2021). The size of the various sectors in the model is shown in the second column of Table 1. These also imply the weighting parameters w in the CES-functions and we thus obtain the following values to $w_{CD} = 0.9$, $w_{EL} = 0.2$ and $w_{KF} = 0.7$.

Table 1: Calibrating the model to the euro area economy

parameters					
capital share	α	0.36	AC inv. fossil sect.	χ_F	13.3921
discount factor	β	0.9954	AC prices	χ_p	54.5121
depreciation rate Y	δ	0.025	retailer inflation indexation	w_p	0.6018
depreciation rate L	δ_L	0.02	Taylor rule persistence	ι_R	0.6571
depreciation rate F	δ_F	0.0125	Taylor rule coeff. output gap	ι_Y	0.0684
elast. of sub. factor inputs	ϵ_Y	0.5	Taylor rule coeff. inflation	ι_π	2.9985
elast. of sub. energy inputs	ϵ_E	2			
elast. of sub. fossil resources	ϵ_F	0.3			
elast. of sub. interm. goods	ϵ^I_{ss}	6			
intertemp. elast. of subst.	σ	1.5365	steady state		
habit parameter	h_c	0.6326	gov. spending share	G/Y	20.51%
Frisch labour elasticity	ψ	0.7223	energy cost shares	$P^E E/Y$	5%
weight on labor disutility	ξ	19.5	share low-carbon sector	$P^{EL}E^L/(P^E E)$	20%
transfers to new bankers	ω	0.00058	fossil spending share	$P^X X/Y$	1.8%
survival prob. bankers	γ	0.9554	CO_2 price per tonne	τ	30 Eur/t
absconding rate Y	ρ	0.3853	risk-weighted cap. ratio	κ	9%
rel. absconding rate L	ρ_L	1.25	spread Y	$R_Y - R$	0.0032
rel. absconding rate F	ρ_F	1.0938	spread L	$R_F - R$	0.004
AC investment	χ_I	9.4913	spread F	$R_L - R$	0.0035
AC inv. low-carbon sect.	χ_L	14.5498	inflation rate	π	1.0047

Note: Y = intermediate sector, L = Low-carbon energy sector, F = Fossil energy sector, HH = household, elast. of sub. = elasticity of substitution, AC = adjustment costs.

6 Results

In this section we simulate the impact of carbon taxes on the economy and the financial system under different conditions. Section 6.1 discusses how the carbon tax propagation differs under full and imperfect disclosure. Section 6.2 shows that financial frictions and disclosure interact and the benefits of the latter are strongest in a constrained financial system. Section 6.3 discusses the role disclosure plays in the period after announcement of carbon taxes but before its implementation. Finally, Section 6.4 shows how mandatory disclosing requirements impact the economic and financial system when previously only voluntary and imperfect disclosure was available.

6.1 The impact of disclosure on the propagation of carbon taxes

We begin by studying a one-off, unanticipated increase in carbon taxes by 50 Euro per ton.[14] Regarding the availability of information to the financial sector, we distinguish between two cases: i) All agents in the economy are fully informed. In particular, financial intermediaries know the true emission intensity of economic activities they fund and thus make efficient investment decisions. ii) Each financial intermediary bases its investment decisions on the belief that the emission intensity among fossil sector firms in its portfolio is 20% lower than what is actually the case (corresponding to $D = 0.8$). Case ii) implies

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[14] Starting from a steady-state carbon tax of 30 Euro per ton, this is a considerable increase. As shown in Diluiso et al. (2021), an increase of approximately this size is required in order to gradually reach a 24% cumulative emissions reduction within 10 years, in line with the targets by the European Commission.

that while the financial sector perfectly understands the aggregate effects of the carbon tax increase, each atomistic financial intermediary underestimate the emission costs of the fossil companies funded by itself.

Setting the degree of disclosure to 80% can be loosely linked to the empirical evidence on the current extent of disclosure from Section 2. Carbone et al. (2021) report that 90% of high-emitters among large, public US and EU companies disclose information. However, only 60% of high-emitters disclose externally verified information. Moreover, the quality of disclosure data is generally poor – even that of third parties – since estimates of emission levels differ greatly across data providers. Furthermore, larger firms tend to disclose more often, such that economy-wide disclosure rates are likely to be substantially lower. Since firms often face some uncertainty about their emission levels but have an incentive to underreport them, the share of emissions revealed among disclosing firms is likely to be below 100%. Given these estimates and considerations, we have chosen a disclosure degree of 80% as our baseline. We believe this to be a conservative choice, since on the basis of the above estimates the true extent of coverage of disclosure might be even lower.[15] To test the robustness of our results, below we show how our results depend on the exact assumption about the degree of disclosure.

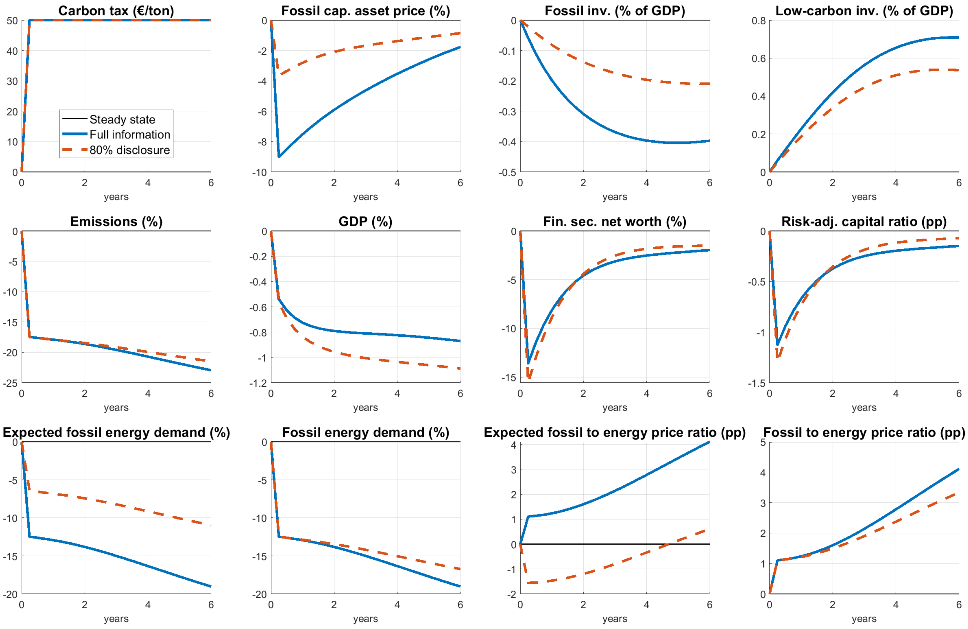

Figure 1: The impact of a 50 Euro/ton carbon tax shock when disclosure is full or imperfect

The blue solid line in Figure 1 illustrates the dynamic effect of a carbon tax shock under full information. Emission costs thereby increase, which reduces the profitability of the fossil-energy sector and thus lowers the net present value of the return to fossil capital. The asset price of fossil capital thus drops sharply on impact, by full 9%, which is

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[15] As an illustration, following the cited numbers from Carbone et al. (2021), our figure of $D = 0.8$ would be obtained if we assume that external verification leads to a disclosure of 90% of the true emissions, disclosure without external verification will be 70% of the true emissions and no disclosure will allow financial intermediaries to recognize 50% of the true emissions $(0.6 * 0.9 + 0.3 * 0.7 + 0.1 * 0.5 = 0.8)$.

synonymous with a surplus of capital in that sector (think of stranded assets). Investment in the fossil-energy sector therefore are reduced by 0.4% of GDP after four years. Instead, capital flows to the low-carbon sector, which sees its asset prices increase by more than 6% (not shown) and investment rise by 0.7% of GDP. This transition to low-carbon energy reduces emissions by roughly 20% after six years. Since the substitution is imperfect, energy prices increase by around 20% (not shown), increasing the input costs for the non-energy sector and reducing GDP by about 0.85% after six years. The impact of the carbon tax shock, in particular the movements in asset prices, also affect the balance sheets of financial intermediaries. The shock reduces the net worth of intermediaries by roughly 13%, which corresponds to a reduction in the risk-adjusted capital ratio by around 1.1 percentage points. The loss in net worth forces the financial sector to reduce its balance sheets, limiting the funding available to the real economy.

When the disclosure of the emission intensity is imperfect, the carbon tax shock, despite being of the same size, has quantitatively different implications, as illustrated by the orange, dotted line in Figure 1. To understand the difference in results, we need to compare the intermediaries' expectations about fossil energy demand with its actual realization, see the bottom row in the figure. When full information are available, these two perfectly coincide. In contrast, when disclosure is imperfect, financial intermediaries make overly optimistic assumptions about the demand that funded fossil investment projects will generate. The reason for this lies in our assumption that financial intermediaries make correct estimates about the macroeconomic impact of the carbon tax shock (i.e. in line with the true emission intensity) since the aggregate economy's emission intensity is well-known. Hence, even under imperfect disclosure, intermediaries expect the price for energy to increase roughly in line with the full disclosure case. However, expected fossil energy prices increase in line with the belief that the funded fossil energy firms' emissions are 20% lower than aggregate emissions would suggest.[16] A financial intermediary financing the entire fossil energy industry would naturally notice the discrepancy between aggregate and disclosed emissions. However, we have assumed a continuum of intermediaries, none of which can verify the firm-level disclosure by aggregation. The relative low increase in expected fossil energy prices due to imperfect disclosure yields in fact a fall in the expectation of the relative price of fossil to energy prices. As a consequence, the expected demand for fossil energy in the imperfect disclosure case is much greater than in the perfect disclosure case. This result can also be interpreted as financial intermediaries believing that other fossil energy firms exist which are not funded by them and which account for the remaining 20% aggregate emissions. These other fossil energy firms must thus charge higher prices on their fossil energy output. The funded fossil energy firms that disclose lower emissions thus appear to have a competitive edge and to be able to expand their share in the fossil energy market.

As a consequence of this misjudgment about the profitability of the fossil sector, intermediaries allocate more investment to this sector relative to the full information case. Fossil-sector investment now falls only by 0.2% of GDP (as opposed to 0.4% under full disclosure). Due to the limits to available funds in the financial sector, the parallel increase in low-carbon investment is less pronounced under imperfect disclosure and shrinks by less

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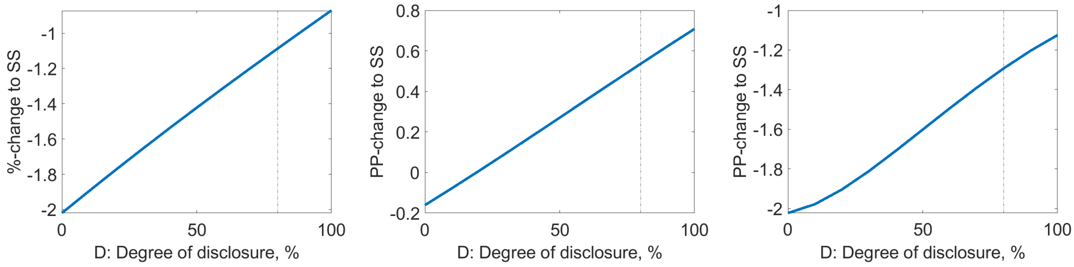
[16] In fact, the expected price for fossil energy in the imperfect disclosure case increases roughly in the same way as in the case of a 40 Euro/ton carbon tax shock, i.e. 80% of 50 Euro/ton, under full disclosure.

than 0.5% of GDP (rather than by 0.7%). Hence, the low-carbon transition is significantly hampered. As the changes in demand for low-carbon and fossil capital become smaller, the respective asset prices also react less strongly to the carbon tax shock. The level of emissions differs very little across the full and imperfect disclosure scenario. This is because the actual decision for the use of fossil resources is made in knowledge of the true emission intensity. Hence the degree of disclosure to financial intermediaries matters little in that respect. However, the funding decisions made by financial intermediaries under the assumption of a lower emission intensity lead to an inefficient capital allocation. In particular, there is less capital allocated to the low-carbon and non-energy sectors, which lowers GDP. The effect of imperfect disclosure is sizeable. Our model suggests that an underestimation of emissions by 20% leads to GDP losses larger by 17% relative to the full disclosure case. Imperfect disclosure also affects the balance sheet of financial intermediaries negatively. The impact on the risk-adjusted capital ratio increases by about 15 bp relative to the full information benchmark. Overall, however, the results indicate that the impact of imperfect disclosure on the real economy is much more severe than on the balance sheet of financial intermediaries. This is because imperfect disclosure also limits the extent of stranded assets since markets are not correctly pricing fossil energy assets. Hence, imperfect disclosure is costly mostly due to the impairment of the financial sector's role as enabler of the transition and less so because it increases the balance sheet losses of financial intermediaries in response to carbon tax shocks. The losses might be larger once mandatory disclosure standards are implemented, which is the subject of Subsection 6.4.

6.1.1 Impact under different degrees of disclosure


(a) GDP, after 6y

(b) Low-carbon investment, as share of GDP, after 6y

(c) Risk-adj. capital ratio, after 1q

Figure 2: Impact of carbon taxes for different degrees of disclosure; Vertical line shows benchmark calibration

As discussed in Section 2, emission-related disclosure is currently far from being complete. Furthermore, due to the absence of reliable disclosure frameworks and mandatory disclosure requirements, the risks of greenwashing are considerable. To our knowledge, there are no reliable estimates of the extent to which emissions are underreported. For this reason, we explore how our results change for different assumptions about the degree of disclosure.

Figure 2 shows how the response of various variables to the carbon tax shock depends on the degree of emission-related disclosure. The loss in GDP after 6 years following the carbon tax shock declines with the degree of emissions disclosed, while the boost to low-carbon investment increases with it. Hence, the more complete the information about emissions is, the less adverse is the impact of the tax shock on the economy and the more pronounced the transition. Furthermore, the drop in banks' risk-adjusted capital ratios caused by the carbon tax shock is lower when the degree of disclosed emissions is higher. Improvements in emission-related disclosure have sizeable effects. Moving from a state of 20% underreporting of emissions to perfect emission disclosure reduces carbon-tax induced GDP losses by 17% and losses in the capital ratio by 5%. The increase in low-carbon investments is 23% higher under perfect disclosure than under the baseline disclosure of $D = 0.8$ (0.43% of GDP instead of 0.35% in the baseline). The results thus underline that emissions-related disclosure can play a substantial role in limiting costs from climate change mitigation, particularly through boosting the financial intermediaries' role as an enabler of the transition.

6.1.2 Impact of carbon taxes on sectoral financing costs

In the following, we explore the impact of carbon tax shocks on financing costs at different levels of disclosure. When providing capital to sectors, financial intermediaries demand a certain return on their investment in excess of the risk-free return. We refer to that excess return as the sectoral spread. We can measure spreads from the perspective of financial intermediaries ($\mathbb{E}_t^D R_{t+1}^X - R_t$ for $X \in \{Y, L, F\}$) or of firms ($\mathbb{E}_t R_{t+1}^X - R_t$). The difference lies solely in the expectation operator, where financial intermediaries' expectations are based on beliefs about the profitability of these sectors in the carbon tax regime, which in turn are influenced by the degree of emission disclosure. In contrast, firms are aware of their true emission levels.

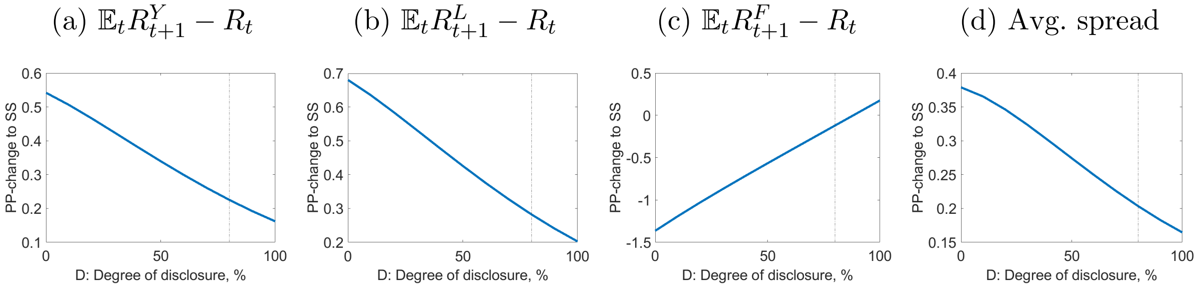

(a) $\mathbb{E}_t R_{t+1}^Y - R_t$ (b) $\mathbb{E}_t R_{t+1}^L - R_t$ (c) $\mathbb{E}_t R_{t+1}^F - R_t$ (d) Avg. spread

Figure 3: Impact of carbon taxes on spreads (after 1 quarter) for different degrees of disclosure; Vertical line shows benchmark calibration

Figure 3 illustrates how actual sectoral spreads, i.e. viewed from the perspective of firms, respond to the carbon tax shock and how that response differs across different degrees of disclosure. Spreads tend to increase across all sectors when the tax shock occurs. This simply reflects the fact that financial intermediaries face balance sheet losses due to the carbon tax shock, which requires them to limit funding in subsequent periods, pushing up required returns. However, the higher the degree of emissions disclosed, the lower is the increase in spreads in the non-energy and low-carbon energy sector in response to the carbon tax shock. In contrast, the increase in the spread for fossil energy firms rises with the extent of emission disclosure. This is because imperfect disclosure leads to an underestimation of the emission cost in the fossil energy sector and thus an overestimation of returns. This enables fossil energy firms to obtain more investment than under full information. From the perspective of fossil energy firms, who are aware of their true emission levels, the return (after emission costs) required to obtain that level of capital funding is thus lower than if disclosure were perfect. The opposite is true for the clean and the non-energy sector. Since the fossil energy sector attracts more investment than under full disclosure, there is, due to constrained balance sheets, less capital flowing towards the remaining sectors. This in turn implies that these sectors face implicitly a higher required return. We can also determine the average response of spreads in the economy to the carbon tax shock by calculating the sum of these spread responses weighted by the share of securities held in each sector. The increase in the average spread is negatively related to the level of emissions disclosed, just as in the case for the non-energy and the low-carbon energy sector.

Hence, disclosure affects financing costs as measured by credit spreads differently across sectors. Fossil energy firms benefit from incomplete disclosure, while the financing costs of the remaining sectors are higher under incomplete disclosure. Overall, a higher degree of disclosure lowers financing costs for the economy as a whole. The model can thus account well for the empirical evidence presented in Section 2 and provides theoretical explanations for the observed cross-sector heterogeneity of credit spreads.

6.1.3 Robustness

Appendix B discusses the robustness of the results with respect to the elasticity of substitution parameters between different inputs for production.[17] We discuss both the full-information results as well as the role of disclosure. Generally, the results remain qualitatively unchanged. For empirically relevant ranges of elasticity values the quantitative changes are rather limited.

Furthermore, in Appendix C we present a number of alternative simulations to shed further light on the transmission of carbon taxes under imperfect disclosure. Specifically, in Appendix C.1, we show that an alternative investment strategy of financial intermediaries, which is to simply preserve their initial sectoral investment shares in light of imperfect disclosure, is generally inferior to acting on the incomplete information. However, if the degree of disclosure drops below a critical threshold, acting on the imperfect information actually decreases economic performance and increases losses to financial intermediaries' net worth.

Finally, Appendix C.2 shows that imposing monetary costs on portfolio adjustments of financial intermediaries yields similar responses to the carbon shock as does our imperfect disclosure framework. The latter can thus be interpreted as offering a micro-foundation for why portfolio adjustments might occur gradually.

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[17] In particular, these are ϵ_Y, ϵ_E and ϵ_F, where ϵ_Y is the elasticity of substitution between labor as well as capital and energy in the non-energy sector, ϵ_E that between low-carbon and fossil-fuel energy and ϵ_F that between capital and fossil inputs in the fossil sector.

6.2 The interaction between imperfect disclosure and financial frictions

In this section we investigate how financial frictions affect our results from Section 6.1. For this purpose we add two simulations, in which we remove financial frictions from the model while assuming that the carbon tax shock propagates under either full or imperfect disclosure. The absence of financial frictions implies that financial intermediaries are no longer bound by the incentive constraint given by equation (8). Instead, they are free in expanding their balance sheet as long as they provide the risk-free return to depositors.[18] Figure 4 compares the results in the presence and absence of financial frictions.

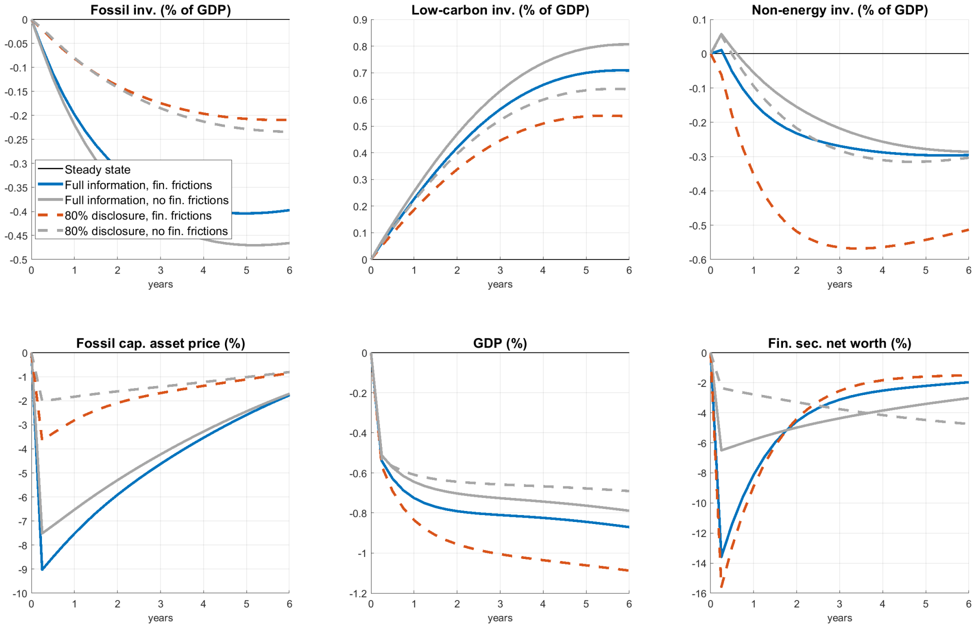

Figure 4: The impact of a 50 Euro/ton carbon tax shock when disclosure is full or imperfect, with and without financial frictions present

The blue solid as well as the orange dashed line show the simulations with financial frictions active and are thus identical to Figure 2. The gray lines correspond to the new simulations of carbon tax shocks under full and imperfect disclosure in the absence of financial frictions. Comparing the blue with the gray solid line (full disclosure, with and without financial frictions), we observe that the absence of financial frictions reduces GDP losses caused by carbon prices. This is because the net worth losses that accrue for financial intermediaries do not limit the funding for the real economy in this case. The transition to low-carbon investment is also more pronounced given the absence of this constraint. Comparing the orange line (imperfect disclosure, financial frictions) with the gray dotted line (imperfect disclosure, no financial frictions) we see that this is also true when imposing imperfect disclosure. Again, GDP losses are smaller and the transition occurs to a larger extent when financial frictions are absent.

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[18] The derivation of the financial sector problem in case of the absence of financial frictions is provided in Appendix A.3, see last paragraph.

However, we can identify a sizable complementarity between financial frictions and imperfect disclosure by comparing the two gray lines with each other. The difference between them show how imperfect disclosure acts on an economy which is not subject to financial frictions. Contrary to the financial friction case, imperfect disclosure in fact reduces the GDP losses from a carbon tax shock. To see why, note that with financial frictions in place, intermediaries reduce non-energy investment strongly when disclosure is imperfect to channel relatively more funds to the fossil energy sector. Without financial frictions it is optimal for financial intermediaries to keep financing the non-energy investment while still channeling more funds to the fossil energy sector in the light of imperfect disclosure. The sustained non-energy investment then reduces the GDP loss associated with the carbon tax. Hence, in the absence of financial frictions, the imperfect disclosure prompts intermediaries to provide more funding to the economy than optimally the case. This supports the economy, but only so at the cost of increasing balance sheet losses over time for financial intermediaries.

Financial frictions and disclosure thus interact in an important way, since perfect disclosure only unfolds its full positive impact in the presence of financial frictions. With financial friction, balance sheets of financial intermediaries are constrained. In this environment full disclosure prevents that scarce capital funding resources are allocated to the fossil energy sector. In doing so the full disclosure ensures that capital funding to other sectors is not reduced too strongly. In contrast, in the absence of financial frictions, the harm done by imperfect disclosure is limited since higher capital allocation in the fossil energy sector does not reduce funding elsewhere to the same extent. This effect is quantitatively significant. Financial frictions alone increase the impact of carbon taxes on GDP by XXX percent, while imperfect disclosure alone even slightly lowers the GDP losses. Together, however, they increase GDP losses associated by the carbon tax by YYY percent. Obtaining high-quality emission disclosure is thus most urgent for economies with a constrained financial system.

6.3 The role of disclosure in the transmission of pre-announced carbon tax increases

The introduction or increase in carbon taxation might in reality not come as a complete surprise, as implicitly assumed in the simulation design in the previous sections. Instead agents might learn about an upcoming carbon tax increase earlier. Also beliefs and expectations formed about whether carbon tax are introduced can affect economic behavior even today, see Peterman et al. (2021).

In this section we want to investigate what role disclosure plays in such an anticipatory period before a carbon tax is increased. Specifically, we simulate a scenario in which economic agents learn about a future carbon tax increase by 50 Euro/ton three years before its implementation. In doing so, we distinguish between two cases: i) the emission intensity of the fossil energy sector is fully known by the financial sector at the point of the announcement of the future carbon tax increase, ii) the true emission intensity is only known once the carbon taxes rates are increased, with the disclosed emission intensity being 20% lower than the true one during the anticipatory phase. Such a situation could come about if financial markets expect an increase in carbon taxes in the future, but during the anticipatory phase, disclosure is imperfect.

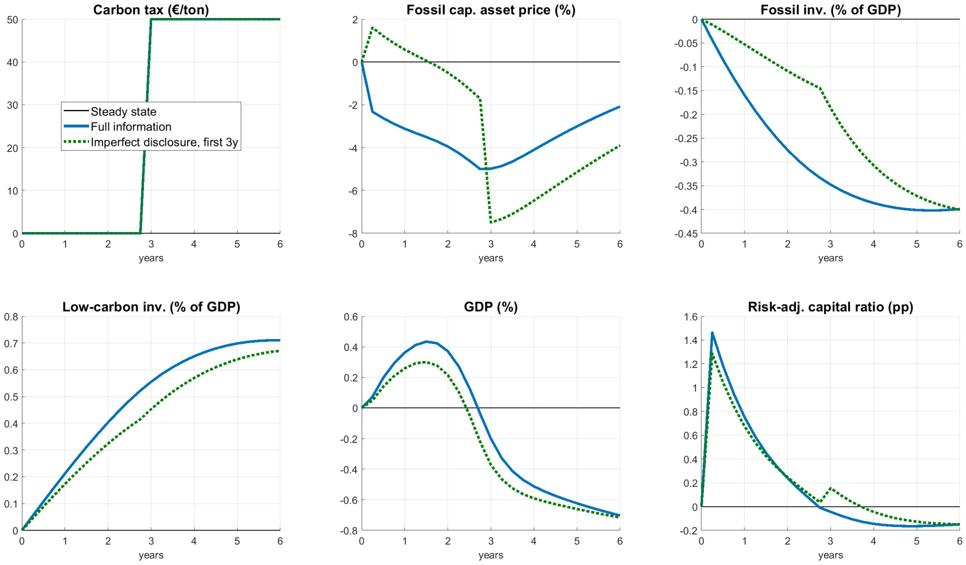

Figure 5: The impact of a pre-announced 50 Euro/ton carbon tax shock under different assumptions about the availability of information to the financial sector.

Figure 5 illustrates the response of the economy to the pre-announced increase in carbon taxation. The blue solid line captures the full information case. Since financial actors immediately recognize the decreased future profitability of the fossil energy sector, they reduce investment. Fossil energy asset prices fall since the demand for fossil capital is strongly reduced. In contrast, low-carbon investment and investment in the non-energy sector (not shown) strongly increase. The pre-announcement of the carbon tax increase leads to an initial boost in GDP. This is because it is optimal to shift some of the production forward in time given the carbon tax increase in the future.[19] Because of this short-lived economic boom, the risk-adjusted capital ratio in the financial sector increases on impact and only falls below its initial level once carbon taxes start to impose costs on the economy.

The green, dotted line in Figure 5 shows the response to the pre-announced carbon tax increase when the true emission intensity is only learned on impact of the tax shock. Now, the fall in fossil-energy investment is much less pronounced. Fossil capital-asset prices even increase slightly upon arrival of the information shock, giving rise to a "Green Paradox" in the spirit of Sinn (2012). This is because fossil-sector investment decisions are shaped by an underestimation of the true emission intensity and thus future emission cost, as discussed in Section 6.1. Additionally, fossil investments do not fall as much due to the economic boom caused by the rush to increase economic production while the carbon tax is still low. This transmission channel is distinct from Sinn (2012), where the anticipation of carbon taxes lead to faster extraction of fossil resources. In our model, it is the combination of bringing forward economic production in time and imperfect

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[19] Mertens and Ravn (2012) show that pre-announced (non-carbon) tax cuts in the US (the mirror case to the anticipation of a tax increase considered in our simulation) cause a contraction in output during the anticipatory period and a boost to output on impact of the tax shock, in line with our simulation result.

disclosure, which together lead to the paradox outcome that carbon taxes increase fossil capital asset prices initially. Note that each channel on its own, i.e. the advancement in time and imperfect disclosure, cannot produce that increase. Also, once the information about the true emission intensity arrives after three years, investment decisions are optimal again and the variables converge slowly to the path obtained under full information.

Note that under full information, the stranding of fossil assets is weaker when pre-announcing the carbon tax increase. Asset prices only fall by at most 4% compared to 9% when the carbon tax was not pre-announced (see previous section). This is because the adjustment period of three years is used by the financial sector to reduce exposure to the fossil energy sector. This has important implications for policy makers. A pre-announced and credible carbon tax path can limit the real-economic costs and financial fallout of such climate policies. However, if the financial sector does not possess the information necessary to make good forecasts on the profitability of investment projects under the new tax regime, this advantage of pre-announcement disappears. Given our calibration of 20% undisclosed emissions, pre-announcement in fact does not lead to any reduction in the extent of stranded assets relative to the unanticipated case. In both cases fossil assets lose more than 7% of their value once the true emission intensity is known.

6.4 The impact of mandatory disclosure requirements

The assumption that financial intermediaries have permanently wrong beliefs about the emission intensity of the fossil fuel sector is, of course, a strong one. For this reason we simulate another scenario, in which the disclosed emission intensity is only initially inaccurate and below the true emission intensity (again by 20%). After some time the government passes mandatory disclosure requirements regarding emissions and financial intermediaries thus obtain the correct information about the emission intensity of the fossil firms they fund. We implement the mandatory disclosure requirement as an unanticipated information shock occurring in the first quarter of the fourth year after the carbon tax increase. The corresponding simulation is shown by the green dashed line in Figure 6, while the blue solid and red dotted line represent, as in previous figures, the case when full and imperfect disclosure prevail permanently.

By construction, the response to the tax shock is identical across the imperfect and the mandatory disclosure scenario during the first three years, since also in the latter scenario only 80% of emissions in the fossil fuel sector are disclosed during those initial years. After disclosure is made mandatory, however, we observe that real economy variables converge slowly to the path of the full information disclosure. Specifically, investment in fossil and low-carbon energy as well as GDP adjust smoothly to their efficient levels.

In contrast, adjustments in the financial sector in response to the mandatory disclosing requirements passed in year four are not equally smooth. Asset prices in the fossil energy sector fall strongly, even below the level of the full disclosure case. This reflects that after obtaining the correct emission information financial intermediaries realize the surplus of capital in the fossil capital. As a consequence assets lose immediately in value and thus become stranded. The opposite picture emerges among the low-carbon capital assets which appreciate upon the arrival of the new information provided by mandatory disclosure.

Note also that even though disclosure is imperfect until year four, the transition to low-carbon energy has been already under way to some extent. This reduces the exposure of the

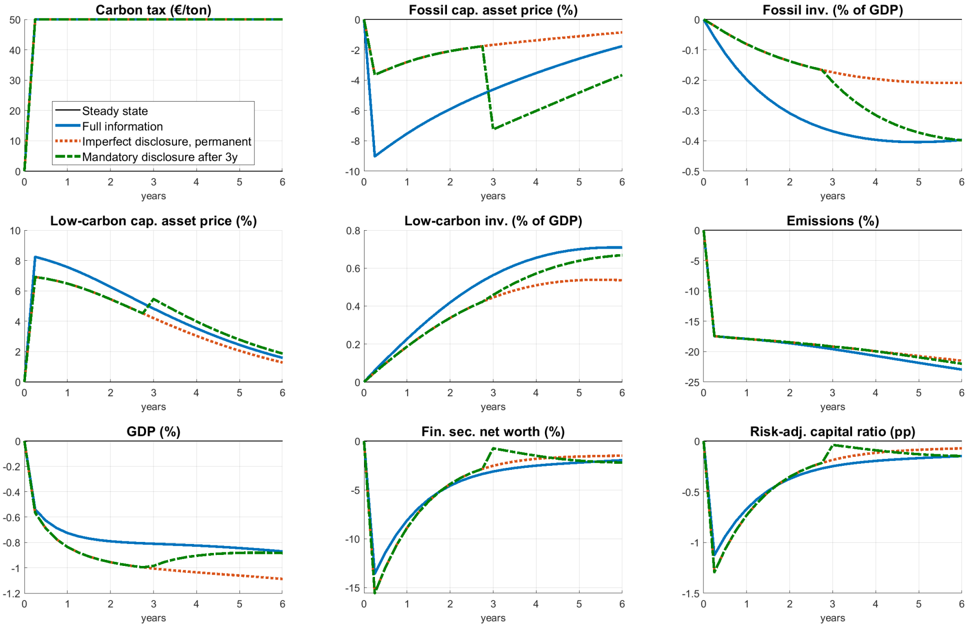

Figure 6: The impact of a 50 Euro/ton carbon tax shock when disclosure is full, permanently imperfect and when mandatory disclosure is passed

financial system to fossil capital asset price changes when disclosure is made mandatory. That and the appreciation of low-carbon and non-energy assets leads even to a slight improvement in the profits and thus net worth of financial intermediaries. Hence, passing mandatory disclosing requirements is beneficial to both the real economy as well as the financial system. We have considered here a scenario in which full disclosure is made mandatory after the carbon tax shock. Of course, mandating full disclosure before or upon carbon taxes are increased, a situation which corresponds to our full information simulation, is best suited to minimize the negative impact of carbon taxes on economic performance.

7 Conclusion

In this paper we have analyzed how imperfect disclosure affects the transmission of a carbon tax to the financial sector and the real economy. We have shown that imperfect disclosure aggravates the losses in GDP and financial values caused by the introduction of a carbon tax. The additional losses scale with the degree to which disclosed emissions fall short of true emission levels.

Imperfect disclosure impacts the two roles that the financial sector plays in the climate transition. First, it increases balance sheet losses and thus the impact of transition risk shocks on the financial sector. Second, imperfect disclosure significantly impairs the ability of the financial sector to enable the transition by allocating funds toward low-carbon activities. The latter effect is much more pronounced than the former one, since disclosure also mutes the response in asset prices which limit balance sheet losses.

Our model can rationalize previous empirical findings on the impact of disclosure on financing costs. High emitters face lower credit spreads under imperfect disclosure and thus have an incentive to underreport emissions. As a consequence and when funding is constrained, greenwashing not only benefits high-emission firms, but also lowers capital funding available to low-carbon companies in absolute terms.
We furthermore demonstrate that disclosure of emissions is also essential for the financial system to prepare for anticipated, future increases in carbon tax. Only when sufficient information about emission intensities is available, can the anticipatory period be used effectively to limit the extent of stranded assets caused by the carbon tax shock. Finally, we show that disclosure not only matters in the context of a sudden carbon tax shock, but also in the case of an orderly, gradual increase in carbon.

As many empirical studies have shown, disclosure alone is not a potent tool to reduce emissions substantially. In the absence of mandatory disclosure requirements, the risk of greenwashing remains high. However, we show that disclosure of emission is an important condition for carbon taxes to have their desired effects. The absence of disclosure both increases costs to the financial sector and impairs it ability to fund the transition.

An important caveat of our analysis is the assumption of perfect foresight. In our framework disclosure thus only plays a role if carbon taxes are already in place or pre-announced. However, disclosure is likely to play a role also when there is uncertainty about whether and when carbon taxes are introduced. It would thus be interesting to extend our framework to study the role of disclosure in the context of such policy uncertainty. We leave this to future work.

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A Model derivations

A.1 Optimization problem of household

Maximizing the household's lifetime utility subject to the budget constraint yields the following standard first order conditions:

$$\lambda_t = \xi_t^C (C_t - h_c C_{t-1})^{-\sigma} - \beta h_c (\mathbb{E}_t \xi_{t+1}^C (C_{t+1}) - h_c C_t)^{-\sigma}, \tag{19}$$

$$\mathbb{E}_t (M_{t,t+1} R_t) = 1, \tag{20}$$

$$\chi L_t^{\psi} = \lambda_t W_t. \tag{21}$$

A.2 Optimization problem of firms

The retailer k aims to maximize output of the final good for a given cost of inputs $\int_0^1 P_{k,t} Y_{k,t} dk$, which yields the demand functions

$$Y_{k,t} = \left(\frac{P_{k,t}^N}{P_t} \right)^{-\epsilon_t^I} Y_t$$

with the aggregate price index of the intermediate good given by

$$P_t = \left(\int_0^1 (P_{k,t}^N)^{(1-\epsilon_t^I)} dk \right)^{1/(1-\epsilon_t^I)} .$$

First-order conditions for optimal labor and energy demand as well for the optimal price setting are as follows. The k-subscript was dropped since all firms face the same optimization problem.

$$W_t = MC_t w_{CD}^{1/\epsilon_Y} Y_t^{1/\epsilon_Y} CD_t^{(\epsilon_Y - 1)/\epsilon_Y} (1 - \alpha_Y) \frac{1}{L_t^Y} \tag{22}$$

$$P_t^E = MC_t (1 - w_{CD})^{1/\epsilon_Y} Y_t^{1/\epsilon_Y} E_t^{1/-\epsilon_Y} \tag{23}$$

$$0 = 1 - \epsilon_t^I + MC_t \epsilon_t^I - DAC_t + \mathbb{E}_t \left(M_{t,t+1} DAC_{t+1} \frac{Y_{t+1}}{Y_t} \pi_{t+1} \right), \tag{24}$$

where W_t and P_t^E are the (real) prices for one unit of labor and energy, respectively, and MC_t is the marginal cost of one unit of output. The term DAC_t reflects the derivative of adjustment costs and is given by $DAC_t = \xi_P \left(\frac{\pi_t}{\pi_{t-1}^{wp} \pi_{ss}^{1-wp}} - 1 \right) \left(\frac{\pi_t}{\pi_{t-1}^{wp} \pi_{ss}^{1-wp}} \right)$.

A.3 Optimization problem of financial intermediaries

We derive the problem of financial intermediaries for the more general case with portfolio adjustment costs as features in Appendix C.2. Hence, we impose as portfolio adjustment costs $\Gamma_{j,t} = \frac{\xi_S}{2} \sum_i \left(s_{j,t}^i - s_{j,t-1}^i \right)^2 SP_{j,t}$ levied on changes in sectoral portfolio weights $s_{j,t}^i = \frac{Q_t^i S_{j,t}^i}{SP_{j,t}}$. However the special case from the main text without portfolio adjustment costs is obtained by setting ξ_S to zero.

Intermediaries value as given by equation (9) can be rewritten using the incentive constraint (10) to yield

$$\begin{aligned}
V_{j,t} &= \max \mathbb{E}_t^D \left((1-\gamma)M_{t,t+1}N_{j,t+1} + \gamma M_{t,t+1}V_{j,t+1}\right) \\
&= \max \mathbb{E}_t^D \left((1-\gamma)M_{t,t+1}N_{j,t+1} + \gamma M_{t,t+1}\nu_{t+1}N_{j,t+1}\right) \\
&= \max \mathbb{E}_t^D \Omega_{t+1} \left(\sum_i (R_{t+1}^i - R_t)s_{j,t}^i SP_{j,t} - \Gamma_{j,t}R_t + R_t N_{j,t}\right) \\
&= \max \mathbb{E}_t^D \Omega_{t+1} \left(TR_{j,t}SP_{j,t} + R_t N_{j,t}\right)
\end{aligned}$$

where $\Omega_{t+1} = M_{t,t+1}(1-\gamma+\gamma\nu_{t+1})$ is the effective discount factor of intermediaries and $TR_{j,t} = \left(\sum_i (R_{t+1}^i - R_t)s_{j,t}^i - \frac{\xi_S}{2}\sum_i \left(s_{j,t}^i - s_{j,t-1}^i\right)^2 R_t\right)$ the total return on the intermediaries stock portfolio. Maximizing the intermediaries value subject to the incentive constraint (8) gives rise to the following Lagrangian:

$$\mathcal{L} = \mathbb{E}_t^D \Omega_{t+1} \left(TR_{j,t}SP_{j,t} + R_t N_{j,t}\right) + \lambda_t^I \left(\nu_t N_t - \rho RWA_{j,t},\right)$$

where λ_t^I is the Lagrange multiplier on the incentive constraint. Note that the relationship between risk-weighted assets and total assets is given by $RWA_{j,t} = (s_{j,t}^Y + \rho_L s_{j,t}^L + \rho_F s_{j,t}^F)SP_{j,t}$.

Taking the first-order derivative with respect to the total portfolio $SP_{j,t}$, we obtain

$$\mathbb{E}_t^D \Omega_{t+1} TR_{j,t} = \lambda_t^I \rho (s_{j,t}^Y + \rho_L s_{j,t}^L + \rho_F s_{j,t}^F). \tag{25}$$

Taking the first-order derivative with respect to the sector shares $s_{j,t}^i$, we obtain

$$\mathbb{E}_t^D \Omega_{t+1} \left(R_{t+1}^i - R_t - \xi_S (s_{j,t}^i - s_{j,t-1}^i) R_t\right) = \lambda_t^I \rho_i \rho \text{ for } i \in \{Y, L, F\},$$

where $\rho_Y = 1$. Equating the first-order conditions for sector Y, L and F gives rise to equations (11) and (12) in the main text. Since the derived first-order conditions do not depend on the size of the intermediary, each intermediary will obtain the same optimal investment shares s_t^i and we can drop the subscript j. For the same reason the total return TR_t is also independent of the intermediary.

Inserting equation (25) in the value function yields

$$\begin{aligned}
\nu_t N_{j,t} = V_{j,t} &= \Omega_{t+1} TR_t SP_{j,t} + \Omega_{t+1} R_t N_{j,t} \\
&= \lambda_t^I \rho (s_t^Y + \rho_L s_t^L + \rho_F s_t^F) SP_{j,t} + \Omega_{t+1} R_t N_{j,t} \\
&= \lambda_t^I \rho RWA_{j,t} + \Omega_{t+1} R_t N_{j,t} \\
\Leftrightarrow \nu_t N_{j,t} &= \left(\lambda_t^I \nu_t + \Omega_{t+1} R_t\right) N_{j,t} \\
\Leftrightarrow \nu_t (1 - \lambda_t^I) &= \Omega_{t+1} R_t \\
\Leftrightarrow \nu_t &= \frac{\rho \Omega_{t+1} R_t}{\rho - \rho \lambda_t^I},
\end{aligned}$$

where $\rho\lambda_t^I$ is given by equation (25). Hence, we have confirmed that ν_t does not depend on intermediary-specific characteristics. Consequently, the ratio of risk-weighted assets and net worth κ_t is identical across all banks (since $\kappa_t = \rho/\nu_t$) and aggregation is straightforward.

The problem of the financial intermediary simplifies if financial frictions are assumed to be absent. In this case the incentive constraint (8) does not enter the Lagrangian, since intermediaries are completely free in expanding their balance sheets as long as they provide the risk-free return to depositors. The first-order conditions simplify to

$$\begin{gathered} \mathbb{E}_t^D \Omega_{t+1} TR_{j,t} = 0 \\ \mathbb{E}_t^D \Omega_{t+1} \left(R^i_{t+1} - R_t - \xi_S (s^i_{j,t} - s^i_{j,t-1}) R_t \right) = 0 \text{ for } i \in \{Y, L, F\}, \end{gathered}$$

with $\nu_t = \Omega_{t+1} R_t$ since $\nu_t N_{j,t} = V_{j,t} = \Omega_{t+1} TR_t SP_{j,t} + \Omega_{t+1} R_t N_{j,t} = \Omega_{t+1} R_t N_{j,t}$.

B Robustness

Robustness with respect to ϵ_E

Figure 7 shows that the impact of the carbon tax shock on emissions and fossil fuel investment is larger if ϵ_E, the elasticity of substitution between low-carbon and fossil energy, is higher. At the same time the impact on GDP and the risk-adjusted capital ratio is less pronounced. This reflects that with a higher elasticity, it is less costly for the economy to switch to low-carbon energy.

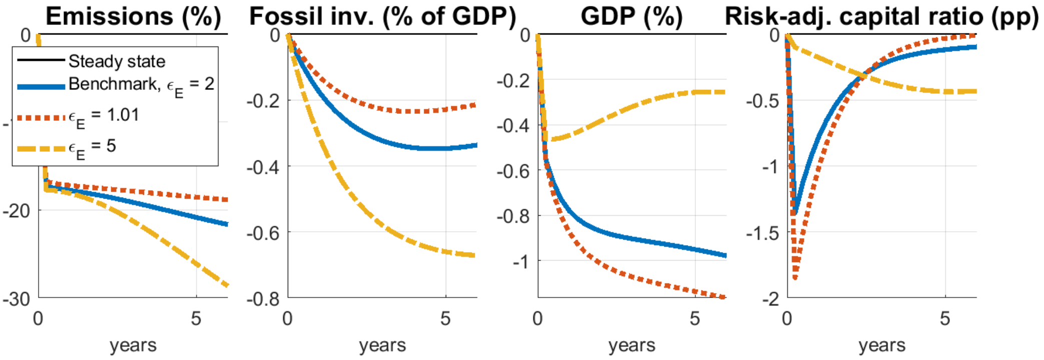
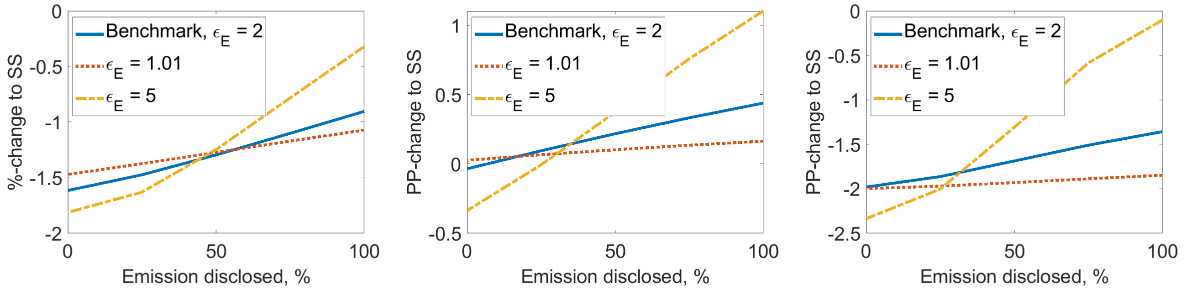


Figure 7: Impact of a 50 Euro/ton carbon tax shock

Figure 8 reveals that with a higher elasticity of substitution between low-carbon and fossil energy, the degree of emission disclosure is even more important in determining economic outcomes. This is because with high elasticity of substitution, disclosing rather than substitution possibilities become the main impediment to the transition. Conversely, lower levels of the elasticity reduce the importance of disclosure.



(a) GDP, after 3y

(b) Low-carbon inv., as share of GDP, after 3y

(c) Risk-adjusted capital ratio, after 1q

Figure 8: Impact of carbon taxes for different degrees of disclosure

Robustness with respect to ϵ_F

Figure 9 shows that the impact of the carbon tax shock on emissions is larger if ϵ_F, the elasticity of substitution between fossil capital and fossil resources is higher. This is because it is then easier for fossil firms to reduce emissions by substituting fossil resources with capital. This in turn increases demand for fossil investment relative to the benchmark calibration. The losses in financial intermediaries' balance sheets are smaller since fossil capital is in higher demand and the corresponding assets fall less in value.

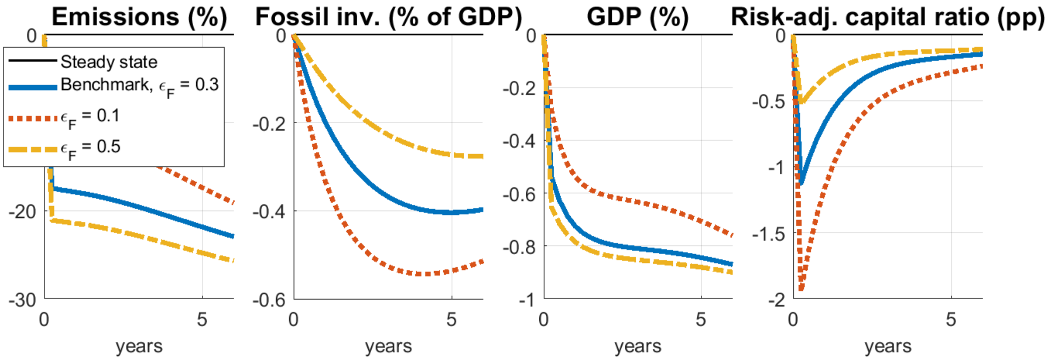
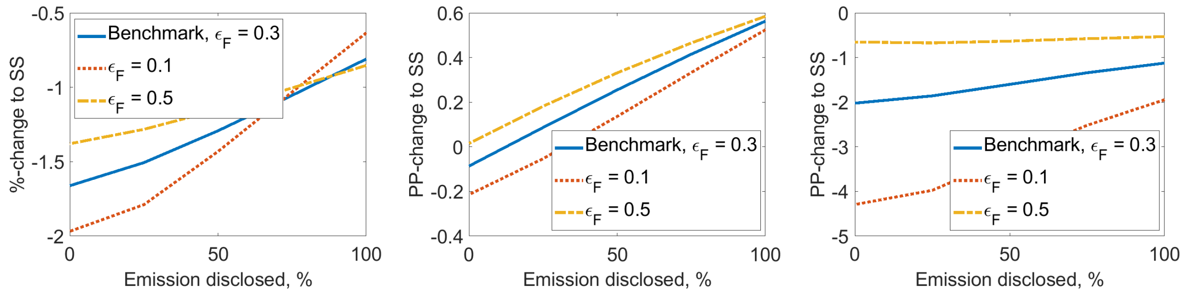


Figure 9: Impact of a 50 Euro/ton carbon tax shock

Figure 10 reveals that with a higher elasticity of substitution between fossil capital and fossil resources, disclosure matters slightly less for GDP losses. However, the importance of disclosure for low-carbon investment and for the risk-adjusted capital ratio (as measured by the slope of the curves) is relatively little affected by different values of this elasticity parameter.



(a) GDP, after 3y

(b) Low-carbon inv., as share of GDP, after 3y

(c) Risk-adjusted capital ratio, after 1q

Figure 10: Impact of carbon taxes for different degrees of disclosure

Robustness with respect to ϵ_Y

Figure 11 demonstrates how our results differ with a higher elasticity of substitution between energy and the capital-labor composite in the non-energy sector. A higher elasticity enables firms to more easily switch away from energy inputs, so that a given tax cut reduces emissions and investment in fossil investment more strongly. Losses in the banking sector become higher the more forcefully the transition occurs and thus the larger the extent of stranded assets is, which is the case at higher elasticity values. The GDP response is relatively unaffected by this parameter.

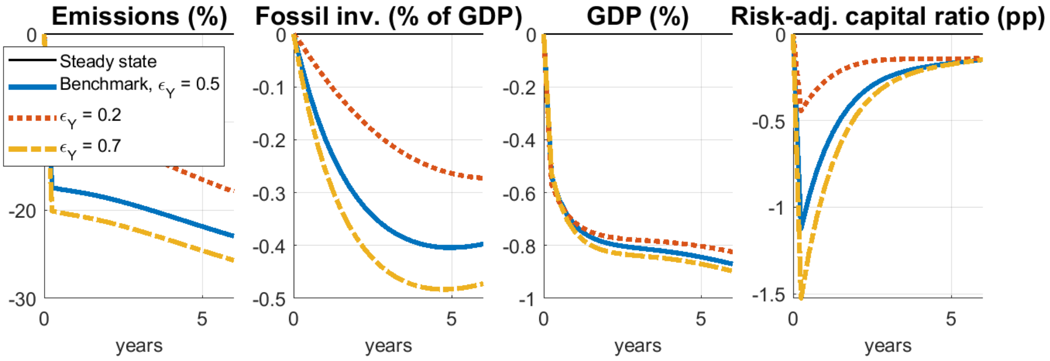
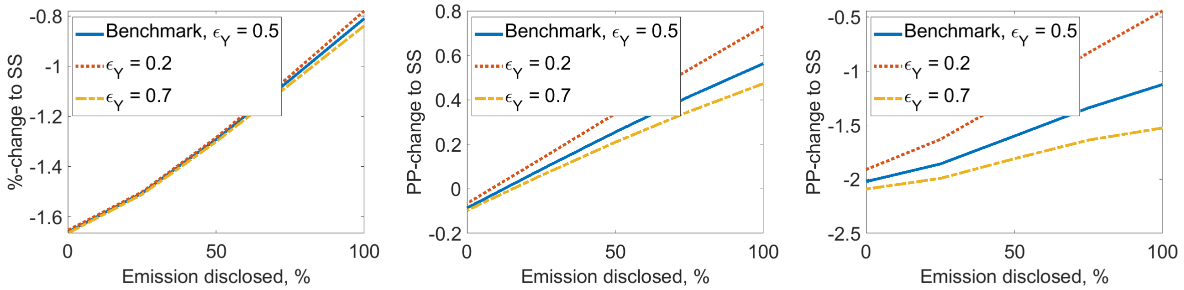


Figure 11: Impact of a 50 Euro/ton carbon tax shock

Figure 12 shows that the significance of disclosure is not changed much by different choices of this elasticity parameters. The slopes of the curves, which measure how sensitive outcomes are to the degree of disclosure, do not change considerably relative to the benchmark.



(a) GDP, after 3y

(b) Low-carbon inv., as share of GDP, after 3y

(c) Risk-adjusted capital ratio, after 1q

Figure 12: Impact of carbon taxes for different degrees of disclosure

C Alternative simulations

C.1 Fixed sectoral shares

As an alternative to expectation formation of financial intermediaries based on disclosed emissions, we consider a situation in which financial intermediaries do not adjust their sector-specific investment shares in response to the carbon tax shock. The rationale for this simulation is that financial intermediaries could conclude from lack of full disclosure that they lack a solid foundation for any portfolio rebalancing. Hence, instead they resort to simply continue the sectoral allocation of their funds. This provides us with a useful point of comparison for the imperfect disclosure case from the main text.

Specifically, we now modify the banking problem, such that

$$V_{j,t} = \max_{SP_{j,t}} \mathbb{E}_t \left((1-\gamma) M_{t,t+1} N_{j,t+1} + \gamma M_{t,t+1} V_{j,t+1} \right).$$

Hence, financial intermediaries do not chose any longer the number of stocks bought in each sector ($S^Y_{j,t}, S^L_{j,t}, S^F_{j,t}$), but only determine optimally the size of their total assets, i.e. $SP_{j,t} = \sum_i Q^i_t S^i_{j,t}$. The share of assets bought in each sector reflects the initial allocation, i.e.

$$s^i_t = s^i_{SS} \text{ for } i \in \{L, F\}.$$

As can be seen in Figure 13, the simulation of fixed sectoral investment shares yields a scenario in which the transition to low-carbon energy is much more hampered than in the case of imperfect disclosure. This demonstrates that even under imperfect disclosure financial intermediaries do better, both in terms of their own profits but also in terms of supporting overall economic performance, than if they made no adjustment to their sectoral investment shares. However, if we reduce the degree of disclosed emissions all the way to zero (i.e. the financial sector assumes fossil firms cause zero emissions), the resulting sectoral investment decisions lead to worse outcomes than if sector shares are held constant. This is because in the extreme scenario of zero disclosed emissions, the fossil fuel sector would in fact see their investment share increase.

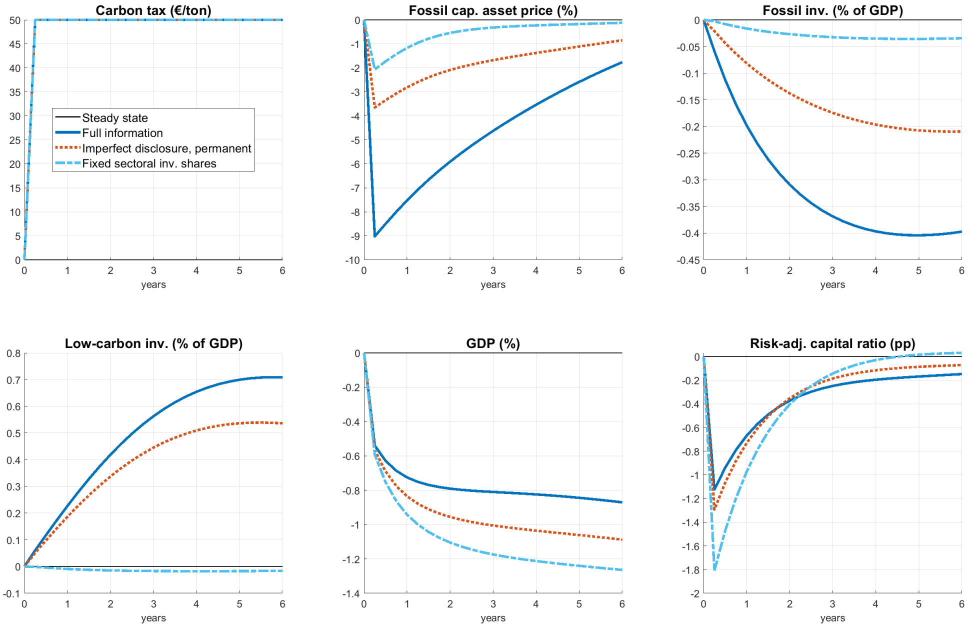


Figure 13: The impact of a 50 Euro/ton carbon tax shock when sectoral investment shares are fixed

C.2 Portfolio adjustment costs

In this section we test whether imperfect disclosure can alternatively be modeled as a cost to portfolio rebalancing, since similar to the lack of disclosed information these costs will slow down the changes in the portfolio of financial intermediaries necessary to achieve a low-carbon transition.

To do so, we change the balance sheet equation of financial intermediaries to

$$\sum_i Q_t^i S_{j,t}^i + \Gamma_{j,t} = D_{j,t} + N_{j,t},$$

where $\Gamma_{j,t} = \frac{\xi_S}{2} \sum_i \left(s_{j,t}^i - s_{j,t-1}^i \right)^2 SP_{j,t}$ are portfolio adjustment costs levied on changes in sectoral portfolio weights $s_{j,t}^i = \frac{Q_t^i S_{j,t}^i}{SP_{j,t}}$. The net worth of the financial intermediary then evolves according to

$$N_{j,t+1} = \sum_i Q_t^i S_{j,t}^i (R_{t+1}^i - R_t) - \Gamma_{j,t} R_t + R_t N_{j,t}.$$

Solving the financial intermediary's problem, one now obtains the following optimality conditions.

$$\mathbb{E}_t\Omega_{t+1}\frac{R^L_{t+1} - R_t - \xi_S(s^L_{j,t} - s^L_{j,t-1})R_t}{\rho_L} = \mathbb{E}_t\Omega_{t+1}\left(R^Y_{t+1} - R_t - \xi_S(s^Y_{j,t} - s^Y_{j,t-1})R_t\right)$$

$$\mathbb{E}_t\Omega_{t+1}\frac{R^L_{t+1} - R_t - \xi_S(s^L_{j,t} - s^L_{j,t-1})R_t}{\rho_L} = \mathbb{E}_t\Omega_{t+1}\left(R^Y_{t+1} - R_t - \xi_S(s^Y_{j,t} - s^Y_{j,t-1})R_t\right)$$

Figure 14 illustrates the response to a carbon tax when portfolio rebalancing is costly, but full information prevail. We compare this simulation to the full information and imperfect disclosure simulations from the main part of the paper, both of which feature no portfolio adjustment costs. The adjustment cost parameter was chosen to obtain roughly the same initial GDP response as in the case of imperfect disclosure. Portfolio adjustment costs lead to similar effects compared to the imperfect disclosure case. The transition to low-carbon investment is hampered, increasing overall losses in GDP and in the balance sheets of the financial sector. However, low-carbon investment increase much less initially under adjustment costs. This is because under full disclosure the transition to the low-carbon economy is only hampered because of less funding resources available from the fossil energy sector, while under adjustment costs the scaling up of investment in the low-carbon sector itself is costly and thus reduced in magnitude.

Nevertheless, portfolio adjustment costs appear to be yield broadly similar dynamics as the imperfect disclosure case. In fact, the modeling of imperfect disclosure can be viewed as a way to build a micro-foundation for portfolio adjustment costs, since the restructuring of the portfolio is not slowed down due to some unexplained monetary cost, but due to the lack of disclosed information which make intermediaries adjust portfolios slower than they would otherwise do. Also note that in our imperfect disclosure framework, the speed of adjustment is not pinned down by an arbitrary adjustment cost parameter but by parameters that have a clear economic meaning, namely the degree of emissions disclosed to the financial sector (and possibly the rate at which full disclosure is being approached).

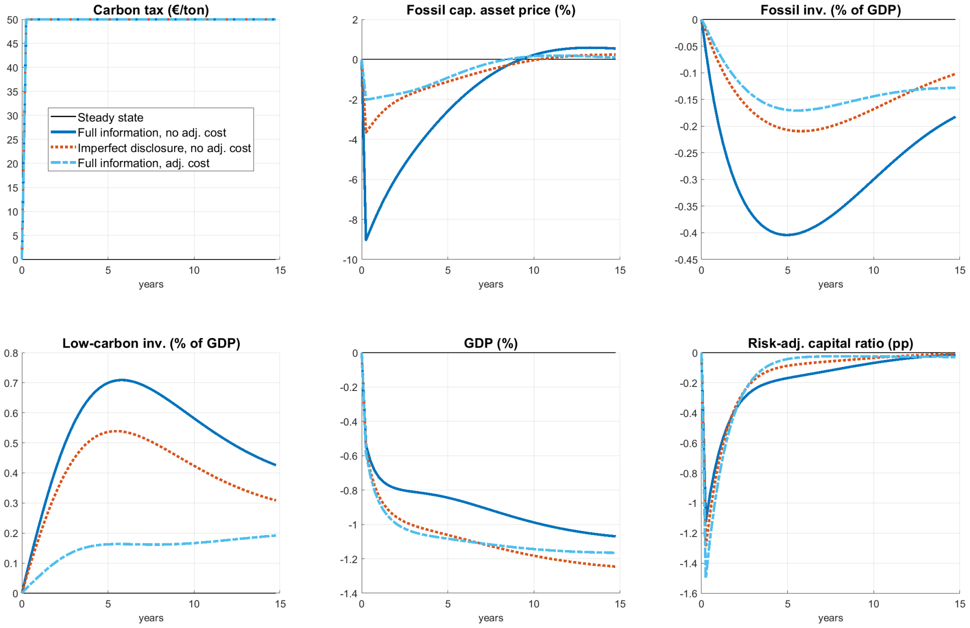


Figure 14: The impact of a 50 Euro/ton carbon tax shock under portfolio adjustment costs