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The role of emission disclosure for the low-carbon transition

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Non-technical summary

Research question

A growing strand of literature quantifies the transition costs of climate policies – like carbon taxes – in structural (DSGE) models. One policy measure that has not yet received attention in such models is disclosure mandates, i.e. prescribing firms to publish reliable information on their carbon emissions. This is in spite of a large empirical literature on the effects of disclosure, as well as policy initiatives to improve it. Which quantitative effects does an increase in disclosure have on macro-financial variables? How is the interplay with other climate policies, like carbon taxes?

Contribution

We build a structural DSGE model calibrated to the euro area to quantify the role of emissions disclosure. Our model contains energy as a factor of production besides labour and capital. Energy is produced by a fossil and a low-carbon energy sector, the former producing emissions that are subject to carbon taxation. Loans to each sector are provided by financial intermediaries with limited balance sheets due to a financial friction. Firms and intermediaries are perfectly informed about emissions. However, savers, who provide funds to the financial intermediaries, underestimate emissions by the fossil sector by 20% (a figure in line with the empirical literature). This leads to too much credit flowing to the fossil energy sector, to the detriment of the non-energy and the low-carbon sector. In this setup, we analyse the dynamic effects of increasing disclosure in isolation and in connection with more stringent climate policies (an exogenous increase in the carbon tax).

Results and policy implications

Disclosure alone has limited macro-financial effects – an increase of the disclosure rate from 80% to 100% increases low-carbon investments by 1.4% after six years and the gross domestic product (GDP) by 5.5 basis points. However, in connection with an increase in carbon taxes (calibrated so as to achieve the emission-reduction goals by the European Commission for 2030), improved disclosure considerably reduced the economic costs of higher carbon taxes. The 20 percentage-points increase in disclosure reduces GDP costs by 13%. This translates into GDP benefits of 47 bn euro over six years, or 2.4 bn euro per percentage point of additional disclosure on average. Hereby, the first disclosure improvements provide the largest GDP effects and benefits realize quickly, just when GDP costs are largest. However, we find ambiguous effects on bank capitalization and no appreciable further emissions reduction by improved disclosure.

Nichttechnische Zusammenfassung

Fragestellung

Eine wachsende Literatur quantifiziert die Übergangskosten klimapolitischer Maßnahmen – wie etwa CO2-Steuern – in strukturellen (DSGE-)Modellen. Eine politische Maßnahme, die in solchen Modellen bislang keine Beachtung gefunden hat, sind Offenlegungspflichten, d. h. die Verpflichtung von Unternehmen, verlässliche Informationen über ihre CO2-Emissionen zu veröffentlichen. Dabei gibt es eine umfangreiche empirische Literatur zu den Auswirkungen verbesserter Offenlegungspflichten sowie politische Initiativen zu ihrer Verbesserung. Welche quantitativen Auswirkungen hat eine Erhöhung der Offenlegung auf makrofinanzielle Größen? Wie ist das Zusammenspiel mit anderen Klimapolitik-Maßnahmen, wie CO2-Steuern?

Beitrag

Wir erarbeiten ein strukturelles DSGE-Modell und kalibrieren es auf den Euroraum, um die Rolle von Emissions-Offenlegung zu quantifizieren. Unser Modell beinhaltet Energie als Produktionsfaktor neben Arbeit und Kapital. Energie wird durch einen fossilen und einen karbonarmen Energiesektor erzeugt, wobei ersterer Emissionen erzeugt, die einer CO2-Steuer unterliegen. Kredite für alle Sektoren werden von Finanzintermediären bereitgestellt, deren Bilanzsumme aufgrund von Finanzfriktionen beschränkt ist. Firmen und Intermediäre sind vollständig über Emissionen informiert. Allerdings unterschätzen Sparer, die den Finanzintermediären Fremdkapital zur Verfügung stellen, die Emissionen des fossilen Sektors um 20 % (ein Wert, der mit der empirischen Literatur im Einklang steht). Dies führt dazu, dass zu viele Kredite in den fossilen Energiesektor fließen, zu Lasten des Nichtenergiesektors und des karbonarmen Energiesektors. In diesem Rahmenwerk analysieren wir die dynamischen Auswirkungen einer erhöhten Offenlegung von Emissionen sowohl isoliert als auch in Verbindung mit einer strengeren Klimapolitik (einer exogenen Erhöhung der CO2-Steuer).

Ergebnisse

Die Offenlegung allein hat nur begrenzte makrofinanzielle Auswirkungen – eine Erhöhung der Offenlegungsquote von 80 % auf 100 % erhöht die karbonarmen Energie-Investitionen nach sechs Jahren um 1,4 % und das Bruttoinlandsprodukt (BIP) um 5,5 Basispunkte. Im Zusammenhang mit einer Erhöhung der CO2-Steuer (kalibriert auf die Erreichung der Emissionsreduktionsziele der Europäischen Kommission für 2030) reduziert eine verbesserte Offenlegung jedoch die wirtschaftlichen Kosten höherer CO2-Steuern in erheblichem Maß. Die Erhöhung der Offenlegung um 20 Prozentpunkte reduziert die BIP-Kosten um 13 %. Dies bedeutet einen BIP-Vorteil von 47 Mrd. Euro über sechs Jahre oder durchschnittlich 2,4 Mrd. Euro pro Prozentpunkt zusätzlicher Offenlegung. Dabei sorgen die ersten Verbesserungen der Offenlegung für die größten BIP-Effekte und bieten dann Vorteile, wenn die BIP-Kosten der CO2-Steuer am größten sind. Allerdings bewirkt eine verbesserte Offenlegung keine eindeutige Auswirkung auf die Kapitalisierung der Banken und keine nennenswerte weitere Emissionsreduzierung.

Deutsche Bundesbank Discussion Paper No 33/2023

The Role of Emission Disclosure for the Low-Carbon Transition[*]

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Abstract

We show the importance of emission disclosure for climate policies in a DSGE model for the euro area. A low-carbon energy and a fossil energy sector contribute to production and are financed by balance-sheet constrained intermediaries. The underestimation of emissions from fossil energy firms (imperfect disclosure) provides them with too much funding. While improving disclosure in isolation has limited effects, it proves most beneficial in connection with higher carbon taxes: Improving disclosure by 20 percentage points reduces GDP costs of a carbon tax by 13%. For a carbon tax increase of 50 euro/ton CO_2, this implies an average GDP benefit of 47 bn euro over six years.

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

JEL classification: D82, E17, G11, G14, G18, H23, Q43, Q58.

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1 Introduction

If policy makers want to avoid the worst outcomes of climate change, immediate and forceful climate policies are needed to induce a transition to a low-carbon economy (see e.g. the latest report by the International Panel on Climate Change, IPCC, 2022). For the financial sector to assess risks and finance the transition, firms' disclosure of their carbon emissions has been named a key prerequisite, see FSB (2017) and UNEP-FI (2020). 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 as to which degree information on firms' carbon emissions is available in the first place. The existing approaches assume full information and thus the ability of financial actors to make efficient investment decisions. However, there is compelling evidence that financial actors seem to have difficulties at times to identify "green" companies as emission disclosure is far from complete (see e.g. Berg, Kölbel, and Rigobon, 2022). Firms or financial intermediaries 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 only incompletely disclosed information about the distribution of emissions in the economy is available. To do so, we build a structural DSGE model, thereby combining two strands of the literature: One on the transition dynamics of climate policies using DSGE models (see e.g. Diluiso, Annicchiarico, Kalkuhl, and Minx, 2021; Carattini, Heutel, and Melkadze, 2021; Giovanardi, Kaldorf, Radke, and Wicknig, 2022), and an empirical one on the effects of carbon-emission disclosure, which has mostly looked at financing costs (see e.g. Bolton and Kacperczyk, 2021b; Kacperczyk and Peydró, 2021). To the best of our knowledge, we are the first to address the interplay of disclosure and carbon taxes in a quantitative model.

Specifically, we develop a dynamic general-equilibrium model with financial frictions and carbon taxes as a policy tool to mitigate climate change. While climate policies come in various forms, from quotas over regulations to fiscal policies, a carbon tax that increases the relative price of fossil energy can capture most of these policies in a reduced form. The model economy, which is calibrated to the euro area, consists of a low-carbon energy and a fossil energy sector, both of which provide energy inputs to a non-energy production sector. Following Gertler and Karadi (2011), financial intermediaries allocate capital across these sectors but are subject to an endogenous balance-sheet constraint as they rely on the provision of deposits by savers.

This setup allows us to introduce imperfect disclosure via information asymmetries between financial intermediaries and depositors. We assume that firms and financial intermediaries (who allocate capital in the economy) are perfectly informed about emissions. However, entities funding the financial intermediaries – depositors in the model, but to be thought of as capturing savers more generally, also via pension or money-market funds etc – underestimate the emissions of the fossil energy sector as they form their beliefs about emissions based on an incomplete information set, namely emission disclosure by firms. Their decision on how many funds to supply to the intermediary depends on the expected return in each sector. When emissions and therefore the exposure to carbon taxes are underestimated, these returns appear higher and intermediaries have an incentive to allocate more funds to the fossil sector relative to full disclosure. In this case, intermediaries can attract more deposits if they allocate more funds to the fossil sector than under full disclosure. Due to limited balance sheets of financial intermediaries, this implies less lending at worse conditions to both the non-energy and the low-carbon energy sector and more as well as cheaper funding to fossil firms. While imperfect disclosure is usually assumed between financial intermediaries and firms, our modeling approach is sparser in assuming informational frictions. At the same time, it creates outcomes in line with an empirical finance literature quantifying the effects of disclosure.

Our results show that there are benefits from increasing disclosure in isolation, but these are small. We look at an increase in the rate of disclosure from 80% (as seems a good estimate of the share of total emissions currently disclosed, see Section 2) to 100%, i.e. by 20 percentage points (pp). This raises investment in the low-carbon sector – a proxy for the green transition – by around 1.4% after 6 years. Emissions are reduced by a mere 0.2%. The limited macro-financial effects of increasing disclosure in isolation in our model extends our understanding of findings from the empirical literature reviewed below, which consistently finds rather small effects on firms' financing costs and return on equity.

However, we highlight important interdependencies between emissions disclosure and climate policies. Such policies are simulated as an increase of carbon taxes from 75 to 125 euro/ton CO_2. The increase by 50 euro/ton is roughly in line with medium-term emission reduction targets by the European Commission, see Diluiso et al. (2021).[1] With imperfect disclosure, i.e. as long as information sets of financial actors in the economy are constrained, a carbon tax is not a fully efficient instrument to tackle climate change. Instead, when the carbon tax shock is accompanied by improved disclosure, the GDP costs of the transition are lowered by 13%. We show that improving disclosure to 100% is similarly powerful in reducing costs from climate policies as would be the elimination of financial frictions. In net present value terms, each percentage-point increase in disclosure yields an average GDP benefit of about 2.4 bn euro over six years. Hereby, the first percentage point of additional disclosure (from 80 to 81%) is around 60% more effective than the last (from 99 to 100%), making an argument for improving disclosure mandates quickly. From a political-economy perspective, another benefit of disclosure is that benefits in GDP costs avoided occur early during the green transition, just when the risk of a political backlash is largest. In contrast, we do not find that disclosure reduces financial stability risks, nor does it boost emission reductions from the carbon tax increase.

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[1] We use the unit euro/ton CO_2 ("per ton of carbon dioxide") throughout, not euro/ton C ("per ton of carbon").

Our model highlights the important dual role of the financial sector in a low-carbon transition: On the one hand, it is apparent that it needs to play a major role in enabling this transition, given the considerable need for additional investment in low-carbon energy. On the other hand, the financial sector is also subject to risks arising from the transition, see for example Bolton, da Silva, Després, Samama, and Svartzman (2020) or Van der Ploeg (2020). These risks may, mainly through unanticipated climate policies, lead to losses in the form of stranded assets, see Van der Ploeg and Rezai (2020a,b). This in turn could threaten financial stability, possibly undermining the enabler role of the financial sector for the transition. Disclosure affects both roles. It reduces risk by lowering the overall economic costs of climate policies. It also promotes the enabler role of the financial sector as it boosts asset reallocation across sectors and thereby allows for a quicker and more efficient transition.

Quantifying the interaction of a low-carbon transition and disclosure necessarily has to rely on assumptions about many unknowns. Here we believe our assumptions about disclosure to be conservative and, if anything, to lead to predictions that err on the low side. First, we assume that only entities funding investments are subject to imperfect disclosure, while firms and financial intermediaries making investment decisions are perfectly informed. Second, the erroneous attribution of emissions to non-fossil (i.e. low-carbon energy and non-energy) sectors is modeled in a way that does not much affect production in these sectors, reducing the benefits of improving disclosure in our model.[2] Third, our baseline steady-state disclosure rate of 80% is well in line with empirical estimates. Moreover, we provide many robustness and sensitivity checks to provide a credible range for our quantitative findings.

Our paper is related to an emerging literature on the macro-financial impact of carbon taxation. Closest in spirit are the contributions by Diluiso et al. (2021), Carattini et al. (2021), Giovanardi et al. (2022) and Schuldt and Lessmann (2022), who develop multi-sector models with financial frictions and climate taxation. They show that transition shocks are amplified by financial frictions and study the implications for the role of central banks and macroprudential policies. Similar to our setup, there are several models in which agents' beliefs play a role in the transmission of climate policies. For example, Fried, Novan, and Peterman (2022) study how beliefs over the likelihood that governments introduce carbon taxes have macroeconomic effects by themselves. Similarly, Khalil and Strobel (2023) investigate the implications of climate policy uncertainty. Campiglio, Lamperti, and Terranova (2023) look at the interaction of climate beliefs and policy makers' commitment to announced carbon taxes. Ferrari and Nispi Landi (2022) examine the role of carbon taxes on inflation and the impact of imperfect information in this transmission. Finally, one core finding of ours is that while the instrument of

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[2] The reason is that in our model, emissions 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- to medium-run impact of carbon prices and its amplification through the financial system. Examples of modeling frameworks that allow for the long-run trade-off with reduced physical risk are Heutel (2012) and Golosov, Hassler, Krusell, and Tsyvinski (2014).

disclosure improvements alone cannot induce a low-carbon transition (like a carbon tax can), it can considerably lower the economic cost of such a transition. The fact that carbon taxes remain indispensable is also mirrored in the results of Oehmke and Opp (2022) and Giovanardi and Kaldorf (2023), who show in model-based analyses that also green capital requirements, another policy option discussed at the moment, are relatively ineffective on their own. None of these contributions considers the role of imperfect disclosure in the transmission of carbon taxes. Our framework also contributes to the emerging empirical literature on disclosure, 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 and discusses the impact of disclosure on the financing decision by intermediaries in the model. Section 4 discusses the calibration of the model, before Section 5 presents simulation results. We look at an isolated increase in disclosure before studying the effects of higher disclosure during a "green transition" caused by a carbon tax increase and providing ample sensitivity analysis. Finally, Section 6 concludes.

2 Empirical evidence on disclosure and 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 has on their 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.[3] Similarly, FSB (2022) notes in its status report that 81% of the surveyed EU firms disclose emission-related information. In contrast, Bolton and Kacperczyk (2021a) 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 panel disclosed emissions. Relative to the previous study, this much larger panel, however, includes many firms that are smaller and from less developed countries, which less often disclose compared to larger companies in developed economies.[4]

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[3] Hereby, Carbone et al. (2021) use a wide definition of firm disclosure, counting all firms as disclosing that report *any* of Scope 1, 2 or 3 emissions. Here, firms' disclosed forward-looking emission targets are often ambitious, with a mean of emission reductions of 31.2%, a median of 25% and a standard deviation of 22.2%.

[4] Bolton, Halem, and Kacperczyk (2022), in a sample focusing on US and Europe from 2016-2020, highlight that disclosure rates increase in firm size. This also explains why disclosure rates are higher in North America than Europe, given larger firm size there.

Study	ΔCost variable (basis points p.a.)	Cost variable (capital or debt)	Sample	Method
Bolton and Kacperczyk (2023)	0.79 bps	Stock returns	Global, 2005-18	regression
Bolton and Kacperczyk (2021b)	1.97 bps	Stock returns	US, 2005-17	regression
Bolton and Kacperczyk (2021a)	4.73 bps	Stock returns	UK, 2012-13	diff-in-diff
Kleimeier and Viehs (2021)	2.74 bps	Loan spreads	Global, 2009-16	regression
Kacperczyk and Peydró (2021)	2.69 bps	Interest expenses	Global, 2013-18	diff-in-diff

Notes: Increase in cost of capital or borrowing in annualized basis points associated with a 1% increase in scope-1 CO_2 emissions. See Appendix A for details.

Table 1: Changes in disclosed carbon emissions and firms' cost of capital or debt

Both studies find that disclosing firms, on average, face lower financing costs.[5] In addition, Carbone et al. (2021) show that disclosure of forward-looking emission targets is similarly associated with a reduction of financing costs, and the scale of effects increases with more ambitious targets.[6,7]

However, while this positive impact of disclosure holds on average in the studied samples, the disclosure by high emitters has a negative impact on financing costs. Specifically, controlling for disclosure status, higher disclosed emissions increase financing costs. There are a number of empirical papers estimating the impact of disclosed carbon emission levels on the cost of capital or on financing cost of firms, which we summarize in Table 1 (see Appendix A for details). In general, the effects tend to become larger over time, i.e. for more current samples.[8] These results will also guide the calibration of our model.

In the ECB Financial Stability Review 2022, Emambakhsh, Giuzio, Mingarelli, Salakhova, and Spaggiari (2022) argue that given the potential negative impact of disclosure of high emission levels 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 et al. (2022) show that ESG ratings diverge widely across the providers. The largest contributor to the divergence are differences in measurement

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[5] Carbone et al. (2021) show that disclosure can reduce firms' loan rates, while Bolton and Kacperczyk (2021a) show that it tends to reduce risk premiums in equity markets.

[6] The fact that disclosure is nevertheless still far from comprehensive, even among low emitters, points to sizable disclosure transaction costs, see Bolton and Kacperczyk (2021a) for a discussion of potential channels.

[7] Note that disclosure may come in various forms, including information contained in texts from firms' publications. A new strand of literature has made progress in evaluating text-based publications by firms using text mining methods, see Moreno and Caminero (2022) and Sautner, Van Lent, Vilkov, and Zhang (2023). For example, Sautner et al. (2023) show that firms' use of climate-related vocabulary in their earning calls predicts green job creation and investment in green technologies. Moreover, they find evidence that the text-based information is priced in with financial assets related to the firm. Nonetheless, not all firms engage in the discussion of climate-related information, such that incomplete disclosure remains an issue.

[8] It should be noted that the largest estimate, from Bolton and Kacperczyk (2021a), stems from a quasi-natural experiment – the introduction of mandatory emissions-disclosure regulation in the UK in 2013 – and therefore provides a particularly convincing econometric setup.

of ESG factors (rather than selection of indicators or their weighting), 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 labeled as ESG. Rating agencies can even have opposite opinions on the same firms, see Billio, Costola, Hristova, Latino, and Pelizzon (2021). Finally, Elmalt, Igan, and Kirti (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 sector is receptive to disclosed information about emissions by firms, but is unlikely to be fully informed about the emissions induced by the economic activities that it provides funding for. On average, disclosing emissions lowers the cost of financing for firms. However, 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 redirects financing towards or away from disclosing firms.[9]

Our model, which is introduced in the next section, will analyze 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 from these policies.

3 Model

The model is structured as follows. A representative household consumes, provides labor, and saves via bank deposits. The production side of the economy consists of three sectors. Two energy sectors, one using fossil resources and the other being carbon-free, provide inputs to the aggregate non-energy sector, which creates the final good. 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.

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[9] 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.

3.1 The effect of incomplete disclosure in a nut shell

Before presenting our full model, we briefly outline the main mechanism by which incomplete disclosure affects the financial sector and the economy in our setup. Our main departure from established models lies in the information set of depositors, who provide financial intermediaries with funding. In the spirit of Adam and Marcet (2011), we assume that depositors are internally rational in the sense that they behave perfectly rationally given their information set. They are not externally rational as their information set is limited relative to the knowledge of intermediaries and firms. Specifically, depositors make their decisions based on disclosed emissions of firms, which capture only a subset of true emission levels. This leads them to overestimate profits in the fossil sector F and thus returns from funding it:

$$\mathbb{E}^D\text{profits}^F = \mathbb{E}^D\text{revenue}^F - \mathbb{E}^D\text{fossil resource cost}^F - \boldsymbol{D} \times \text{emissions}^F \times \text{carbon tax},$$

where D is the share of emissions disclosed and thus known to depositors and where $\mathbb{E}^D$ denotes internally rational expectations formed under the perception that $D < 1$.[10] At the same time, depositors underestimate returns from the low-carbon energy and non-energy sectors, as they wrongly attribute the “missing” emissions to these sectors.

The limited information set of depositors introduces a distortion in the incentive of intermediaries to allocate funding across sectors. In the Gertler and Karadi (2011, “GK”) setup, an agency problem limits the savings flowing to intermediaries to a share of their continuation value V, giving rise to an endogenous leverage constraint. This ensures that financial intermediaries have no incentive to abscond with the savings of depositors, but prefer to continue their business. The continuation value of intermediaries is an increasing function of returns R^i from all sectors i (fossil energy, low-carbon energy and non-energy). Thus, under imperfect disclosure, depositors grant funds to intermediaries based on their *perceived* continuation value – i.e. based on perceived returns from sectoral lending:[11]

$$\mathbb{E}^D V = \text{fct}\left(\underset{+}{\mathbb{E}^D R^i},\ \text{other variables}\right)$$

In the GK setup, an incentive constraint assures depositors that intermediaries’ returns are high enough that these will continue their operations. Intermediaries maximize their continuation value V subject to this incentive constraint. In the full information case ($D = 1$),

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[10] Compare this to equation (6) in the full model introduced below. Internal rationality also implies that depositors have model-consistent expectations about all other variables (like e.g. total energy demand and price).

[11] See equation (11) below.

optimality simply requires returns from all sectors to be equalized (as in GK):

$$\frac{\mathbb{E}\left\{\Omega(R^i - R)\right\}}{\mathbb{E}\left\{\Omega(R^k - R)\right\}} = \text{constant},$$

for all sectors i and k, where Ω denotes a discount factor and R the safe return on deposits. Note that the expectations operator $\mathbb{E}$ denotes fully rational expectations here. In contrast to the above, with imperfect disclosure, intermediaries optimally consider the effect that the divergence of true and perceived returns will have on the incentive constraint. Even though intermediaries have fully rational beliefs about sectoral returns, they know they can secure more funds by lending more to the fossil sector, where depositors (who are only internally rational) perceive higher returns:

$$\frac{\mathbb{E}\left\{\Omega(R^i - R)\right\} + \boldsymbol{\lambda^I}\left(\mathbb{E}^{\boldsymbol{D}}\left\{\boldsymbol{\Omega R^i}\right\} - \mathbb{E}\left\{\boldsymbol{\Omega R^i}\right\}\right)}{\mathbb{E}\left\{\Omega(R^k - R)\right\} + \boldsymbol{\lambda^I}\left(\mathbb{E}^{\boldsymbol{D}}\left\{\boldsymbol{\Omega R^k}\right\} - \mathbb{E}\left\{\boldsymbol{\Omega R^k}\right\}\right)} = \text{constant},$$

where $\lambda^I > 0$ denotes the Lagrange multiplier on the incentive constraint (equal to the shadow value of additional deposits for the intermediary and thus always positive).[12] Hence, when disclosure is imperfect and $\mathbb{E}^D$ and $\mathbb{E}$ do not align, returns will not be equalized across sectors. In particular, for the fossil sector ($i = F$), the right term in the numerator (after λ^I) will be positive as returns are perceived higher than under perfect disclosure. Holding the denominator constant, this means that returns R^F will be lower, implying more funding will flow to the fossil sector than in the perfect-disclosure optimality condition above (first part of the numerator). In other words, imperfect disclosure implies more and cheaper funding for the fossil sector, at the expense of less funding at worse conditions for other sectors. Again, note that all that is needed for this distortion is a wrong perception of disclosure by savers, but not by financial intermediaries or firms, i.e. by the entities making the actual investment decisions.

In the following, we present the setup of the full model in detail.

3.2 Households

A representative household consumes the final good of the economy, saves through bank deposits, provides labor and earns wage income. Specifically, the household's lifetime utility is a function of consumption C_t and labor supply L_t and given by

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

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[12] See equation (14) below.

where β is the discount factor, h_c the internal habit parameter and σ the inverse of the intertemporal elasticity of substitution. 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.[13] Deposits are given by B_t and the real interest rate on deposits by R_t. We define the household's stochastic 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 B.1.

3.3 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. 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.[14] The use of the latter causes 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 numéraire in the model. A perfectly competitive retailer buys the output of intermediate good firms and bundles them into a final good Y_t using the technology $Y_t = \left(\int_0^1 Y_{k,t}^{(\epsilon^I - 1)/\epsilon^I} dk \right)^{\epsilon^I/(\epsilon^I - 1)}$ where ϵ^I is the elasticity of substitution across intermediate goods. The retailer sells the final good to households, which consume it, and to capital producers, who convert it into capital.

Firm k produces by combining two composites, one consisting of capital and labor, $CD_{k,t}$, and one of low-carbon energy and fossil energy, $E_{k,t}$. The elasticity of substitution between the

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[13] Π_t is the sum of profits from banks $(\frac{1-\theta}{\theta} N_{e,t})$, retailers $(Y_t(1 - MC_t) - AC_t)$ and capital producers $((Q^Y_t - 1) I^Y_t + (Q^F_t - 1) I^F_t + (Q^L_t - 1) I^L_t - AC^{INV}_t)$, as well as the receipts from resource ownership $(F_t P^F_t)$.

[14] 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 to 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).

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

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

with K^Y and L^Y being capital and labor input.

When changing prices, firms in the non-energy sector face Rotemberg (1982) adjustment costs, given by

$$AC_{k,t} = \frac{\chi_p}{2} \left[(P_{k,t}^N / P_{k,t-1}^N) / (\pi_{t-1}^{w_p} \pi_{ss}^{1-w_p}) - 1 \right]^2 Y_t,$$

where χ_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 uses low-carbon (E_t^L) or fossil energy (E_t^F) for its energy needs. We assume that the two forms of energy are imperfect substitutes following a constant elasticity of substitution (CES) technology given by

$$E_t = \left[w_{EL}^{1/\epsilon_E} (E_t^L)^{(\epsilon_E-1)/\epsilon_E} + (1-w_{EL})^{1/\epsilon_E} (E_t^F)^{(\epsilon_E-1)/\epsilon_E} \right]^{\epsilon_E/(\epsilon_E-1)},$$

where ϵ_E is the elasticity of substitution between low-carbon energy and fossil energy and w_{EL} the initial weight of low-carbon technology.[15] Since all firms from the non-energy sector face the same problem, the k-subscript was dropped. The relative price of low-carbon energy and fossil energy is P_t^{EL} and P_t^{EF}, 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

$$\begin{aligned} E_t^L &= w_{EL} \left(P_t^{EL} / P_t^E \right)^{-\epsilon_E} E_t \\ E_t^F &= (1-w_{EL}) \left(P_t^{EF} / P_t^E \right)^{-\epsilon_E} E_t, \end{aligned}$$

where $P_t^E = \left(w_{EL} (P_t^{EL})^{1-\epsilon_E} + (1-w_{EL}) (P_t^{EF})^{1-\epsilon_E} \right)^{1/(1-\epsilon_E)}$ is the price of the composite

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[15] See Yanovski and Lessmann (2021) for a version with an endogenous ϵ_E that firms can improve through investment over time.

energy good. Hence, an increase in the price of fossil energy P_t^{EF}, caused for example by a carbon tax, will induce a shift in demand from fossil to low-carbon energy. The remaining optimality conditions for labor and prices are standard and presented in Appendix B.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

$$E_t^L = K_t^L,$$

where K_t^L is low-carbon capital. 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

$$E_t^F = \left[w_{KF}^{1/\epsilon_F}\left(K_t^F\right)^{(\epsilon_F-1)/\epsilon_F} + (1-w_{KF})^{1/\epsilon_F} F_t^{(\epsilon_F-1)/\epsilon_F}\right]^{\epsilon_F/(\epsilon_F-1)},$$

where ϵ_F is the elasticity of substitution between capital and fossil inputs and w_{KF} the weight of capital in the production function. Fossil resources are inelastically supplied at the relative price $P_{F,t}$. 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 gives the demand for fossil resources:

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

Hence, an increase in the carbon tax rate will reduce the use of fossil resources and thus emissions.

Capital producers. Capital in each sector i evolves according to $K_{t+1}^i = K_t^i(1-\delta^i) + I_t^i$, 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. The cost of refurbishing depreciated capital is assumed to be unity. The price of producing new capital is subject to investment adjustment costs, which are given by $AC_t^{INV,i} = \frac{\chi_i}{2}\left(I_t^i/I_{t-1}^i - 1\right)^2 I_t^i$. The parameter χ_i captures the extent of adjustment costs and is sector-specific. Profit maximization by capital producers yields the expression

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

Hence, the price of new capital Q_t^i for each sector i endogenously depends on the level of investment required to obtain the desired new capital stock, which in turn depends on the expected sectoral return.[16]

Return on capital. In period $t-1$, financial intermediaries purchase capital K_t^i at price Q_{t-1}^i. This investment generates returns through asset price appreciation (adjusted for physical depreciation) and through revenues net of costs (Π_t^i), such that the gross return to capital R_t^i in each sector $i \in \{Y, L, F\}$ is given by

$$R_t^i = \frac{(Q_t^i - \delta_i)K_t^i + \Pi_t^i}{Q_{t-1}^i K_t^i}, \tag{5}$$

where

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

The non-energy sector (Y) earns revenues by selling its output to retailers at marginal cost, and faces costs for both 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 needs to account for fossil-resources costs and emission taxes.

3.4 The role of disclosure

Agents in the model form expectations about returns in all three sectors. We allow for these expectations to deviate from the full information benchmark. Specifically, we assume that households' willingness to provide savings to intermediaries is shaped by a limited information set, namely by disclosed emissions rather than true ones. The latter are known, however, to intermediaries and firms.

Depositors are unaware of the true emission intensity e of fossil energy firms and instead rely on their disclosed emission intensity (for future production), given by $e_{t+1}^D = D_{t+1}e$. D_t is an exogenous process, with $D_{t+1} = 1$ capturing the full disclosure case. If instead $D_{t+1} < 1$

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[16] The constant returns to scale in production of all three sectors and in the production of capital imply that the average Q_t^i equals the marginal Q_t^i for each sector in our model, see Hayashi (1982).

holds, the agents will base their expectations of the profitability of the fossil energy sector on the belief that the emission intensity is at $e^D_{t+1} < e$.[17,18]

We abstract from any emission disclosure in the low-carbon energy and the non-energy sector. Instead, we assume that depositors know the aggregate amount of emissions in the economy and assign the amount of undisclosed emissions to these two remaining sectors: A share ζ is assigned to the non-energy sector and a share $1-\zeta$ to the low-carbon sector. In our baseline, we set ζ to the relative size of the non-energy sector, but perform robustness checks with other parameter values below.

Disclosure-based expectations about revenues from fossil energy firms are then given by

$$\mathbb{E}^D_t \Pi^F_{t+1} = \mathbb{E}^D_t P^{EF}_{t+1} E^F_{t+1} - P^F_{t+1} \mathbb{E}^D_t F_{t+1} - e D_{t+1} \tau_{t+1} \mathbb{E}^D_t F_{t+1} \tag{6}$$

where $\mathbb{E}^D_t$ is the disclosure-based expectation operator at time t. Hence, when forming expectations about fossil-sector profitability, depositors also assume output prices, demand and fossil energy use that are all consistent with the disclosed emissions. These expectations follow from variations of the corresponding equations from Subsection 3.3:

$$\begin{aligned}
\mathbb{E}^D_t F_{t+1} &= (1-w_{KF}) \left(\frac{P^F_{t+1} + e D_{t+1} \tau_{t+1}}{\mathbb{E}^D_t P^{EF}_{t+1}} \right)^{-\epsilon_F} \mathbb{E}^D_t E^F_{t+1}, \\
\mathbb{E}^D_t E^F_{t+1} &= \left[w_{KF}^{1/\epsilon_F} \left(K^F_{t+1} \right)^{(\epsilon_F-1)/\epsilon_F} + (1-w_{KF})^{1/\epsilon_F} \left(\mathbb{E}^D_t F_{t+1} \right)^{(\epsilon_F-1)/\epsilon_F} \right]^{\epsilon_F/(\epsilon_F-1)}, \\
\mathbb{E}^D_t E^F_{t+1} &= (1-w_{EL}) \left(\mathbb{E}^D_t P^{EF}_{t+1} / \mathbb{E}_t P^E_{t+1} \right)^{-\epsilon_E} \mathbb{E}_t E_{t+1}
\end{aligned}$$

Note that when forming these disclosure-based expectations about profits, turnover and fossil resource use, depositors still have model-consistent expectations about the total energy demand (E), its price (P^E) and the amount of capital invested in fossil energy (K^F). As the emission intensity for the economy as a whole is known to all depositors, they can predict the aggregate impact on energy demand, energy prices, and total output. Furthermore, depositors know the investment plans of the financial intermediaries, who in turn take into account the limited information among depositors.

As can be seen in equation (6), imperfect disclosure ($D < 1$) reduces the perceived emission cost faced by the fossil sector. This holds in spite of an increase in the perceived fossil resource use and other changes in the perception about the fossil sector turnover, as will be shown

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[17] Ferrari and Nispi Landi (2022) follow a similar approach when studying the impact of carbon taxes under imperfect information about the duration of the carbon tax shock.

[18] In reality, emission-related disclosure might not be available in the form of forward-looking emission (intensity) targets. Instead, depositors 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. 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.

numerically later on. While the degree of disclosure D is exogenous in our setup, disclosing a lower emission intensity than the true one is thus beneficial to the fossil energy firms in terms of perceived sectoral returns.[19] Conversely, any increase in the disclosure degree towards 100% will lower expectations of fossil-energy sector returns.

Perceived profits in the remaining two sectors are based on model-consistent expectations about turnover and costs. However, emission costs from undisclosed emissions are attributed to the remaining sectors as follows:

$$\begin{aligned}
\mathbb{E}_t^D \Pi_{t+1}^Y &= \mathbb{E}_t MC_{t+1} Y_{t+1} - \mathbb{E}_t W_{t+1} L_{t+1} - \mathbb{E}_t P_{t+1}^E E_{t+1} - \zeta \tau_{t+1} Z_{t+1}^{nD}, \\
\mathbb{E}_t^D \Pi_{t+1}^Y &= \mathbb{E}_t P_{t+1}^{EL} E_{t+1}^L - (1-\zeta) \tau_{t+1} Z_{t+1}^{nD},
\end{aligned}$$

where $Z_{t+1}^{nD} = e(\mathbb{E}_t F_{t+1} - D_{t+1} \mathbb{E}_t^D F_{t+1})$ is the gap between disclosed and total emissions.

As the next section will show, this impact of disclosure on depositors' expectations of sectoral returns and profits affects the capital allocation decision of banks.

3.5 Financial sector

Intermediaries hold deposits by the household in addition to their own accumulated net worth. With these funds they finance capital expenditures in the real economy. In line with Gertler and Karadi (2011), financial intermediaries are constrained by an agency problem. This leads to an endogenous balance-sheet constraint for banks, giving rise to a financial accelerator.

Note that while financial intermediaries receive funding from depositors in the model, depositors should be interpreted more widely as any funding entities. Our modeling approach thus relies on the existence of an informational divergence between entities investing directly in firms (banks in our setup), who possess detailed knowledge about firms' business model and thus their emissions, and funding entities like households, money-market or pension funds with incomplete information on firms' carbon footprint.

The financial sector consists of a continuum of financial intermediaries $j \in [0, 1]$. Let $S_{j,t}^i$ be funding that intermediary j provides to sector $i \in \{Y, L, F\}$ at price Q_t^i. The total security

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[19] Modeling disclosure as an exogenous variable abstracts from firms' potential ability to engage in efforts to appear to have fewer emissions than in reality, i.e. in "greenwashing". One could allow for greenwashing in the model by assuming a cost for firms for appearing less polluting to savers and letting them choose their greenwashing effort endogenously. We do not pursue this, as we are first and foremost interested in aggregate and average effects. However, note that if greenwashing led to asymmetric degrees of imperfect disclosure across fossil-energy firms, the resulting asymmetric provision of credit in that sector would increase the economic damage due to decreasing returns to capital in its production function. This, and a reduction in potentially costly rent-seeking (think expensive lobbying efforts) would create another benefit of increasing disclosure – and thereby reducing greenwashing – on top of those shown below.

portfolio $SP_{j,t}$ is funded by the intermediary's net worth ($N_{j,t}$) and deposits ($D_{j,t}$):

$$SP_{j,t} = \sum_i Q_t^i S_{j,t}^i = D_{j,t} + N_{j,t} \tag{7}$$

The supply of funds equals the purchase of new capital, hence $S_t^i = K_{t+1}^i$ for $i \in \{Y, L, F\}$. The net worth of the financial intermediary evolves according to

$$N_{j,t+1} = \sum_i Q_t^i S_{j,t}^i R_{t+1}^i - R_t D_{j,t} = \sum_i Q_t^i S_{j,t}^i (R_{t+1}^i - R_t) + R_t N_{j,t}, \tag{8}$$

where R_t^i are the sectoral, state-contingent returns defined above. Intermediaries have a constant survival probability, γ. Hence, $1 - \gamma$ intermediaries cease to exist each period and their net worth is transferred to the household. As in Gertler and Karadi (2011), this prevents intermediaries to ever amass sufficient net worth as to become independent of deposits.

Following the agency problem in Gertler and Karadi (2011), 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 absconding with the fraction of assets that can be diverted. However, here we assume that it is the *perceived* value of financial intermediaries (and thus their assets) that matters for their ability to attract funding. This perceived value of banks is based on disclosed rather than true emissions. Since depositors assess the return on fossil energy assets to be higher if emissions disclosure is imperfect, they are willing to extend more funds to intermediaries for investment in emission-intensive activities. To see this, let us first define the *true* value of financial intermediaries at time t, which is given by

$$V_{j,t} = \max_{SP_{j,t}, s_{j,t}^L, s_{j,t}^F} \mathbb{E}_t \left[(1-\gamma) M_{t,t+1} N_{j,t+1} + \gamma M_{t,t+1} V_{j,t+1} \right], \tag{9}$$

where $s_{j,t}^i = \frac{Q_t^i S_{j,t}^i}{SP_{j,t}}$ are the sectoral portfolio weights and $M_{t,t+1}$ is the household's stochastic discount factor defined above. Hence, intermediaries choose the size of the total portfolio as well as the sectoral weights to maximize their value. This value is given as a weighted sum of the value in case of leaving business, with probability $(1 - \gamma)$, and the value of continuing business beyond the next period, with probability γ.

As shown in Appendix B.3, the intermediary's value is a linear function of its net worth:

$$V_{j,t} = \nu_t N_{j,t} \tag{10}$$

The value of intermediaries can then be rewritten using equation (10) to yield

$$\begin{aligned} V_{j,t} &= \max \mathbb{E}_t \left[(1-\gamma) M_{t,t+1} N_{j,t+1} + \gamma M_{t,t+1} \nu_{t+1} N_{j,t+1} \right] \\ &= \max \mathbb{E}_t \Omega_{t+1} \left[\sum_i (R^i_{t+1} - R_t) s^i_{j,t} SP_{j,t} + R_t N_{j,t} \right], \end{aligned}$$

where $\Omega_{t+1} = M_{t,t+1}(1 - \gamma + \gamma \nu_{t+1})$ is the effective discount factor of intermediaries.

We can now define the *perceived* value of the financial intermediaries. It is defined analogously to the real value, but is based on disclosure-based expectations of sectoral returns rather than those based on the actual emission intensity:

$$V^D_{j,t} = \mathbb{E}_t \Omega_{t+1} \left[\sum_i (\mathbb{E}^D_t R^i_{t+1} - R_t) s^i_{j,t} SP_{j,t} + R_t N_{j,t} \right]. \tag{11}$$

Hence, depositors are aware of the sectoral weights in banks' balance sheets, but form expectations about the sectoral returns in line with disclosed emissions. We can now define the difference between perceived and real value as

$$\Delta V^D_{j,t} = V^D_{j,t} - V_{j,t} = \sum_i \left(\mathbb{E}^D_t \Omega_{t+1} R^i_{t+1} - \mathbb{E}_t \Omega_{t+1} R^i_{t+1} \right) s^i_{j,t} SP_{j,t}. \tag{12}$$

As was shown in the previous section, the imperfect-disclosure expectation of the return in the fossil energy sector exceeds the expectation based on full information when emissions are under-disclosed, i.e. when $D < 1$. In contrast, the expected return in the remaining two sectors is underestimated by depositors as undisclosed emissions are attributed to these sectors. Thus, with imperfect disclosure the value of banks might be perceived to be lower or higher than the true value, depending on whether the overestimation of fossil-sector return or the underestimation of the other two sectors dominate.

Given the perceptions of funding entities, the incentive constraint is given by

$$V^D_{j,t} \geq \rho RWA_{j,t}, \tag{13}$$

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 $S \in \{L, F\}$.[20] Most importantly, financial intermediaries can influence the incentive constraint by allocating funds towards sectors that households deem more profitable. By appropriate calibration, we ensure that the incentive constraint always binds.[21]

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[20] Here we follow Diluiso et al. (2021). While we interpret the assets as risk-weighted, note that there is no actual default risk in the model.

[21] Note that the true value of the intermediary might lie below the perceived value. In fact, for our calibration,

The financial intermediary chooses the amount of funds granted to each sector to maximize its current value. Solving the financial intermediary's problem (see Appendix B.3), one obtains the following optimality conditions:

$$\begin{aligned} &\mathbb{E}_t\Omega_{t+1}(R^i_{t+1}-R_t)+\lambda^I_t\left(\mathbb{E}^D_t\Omega_{t+1}R^i_{t+1}-\mathbb{E}_t\Omega_{t+1}R^i_{t+1}\right)\\ =&\rho_i\left(\mathbb{E}_t\Omega_{t+1}(R^Y_{t+1}-R_t)+\lambda^I_t\left(\mathbb{E}^D_t\Omega_{t+1}R^Y_{t+1}-\mathbb{E}_t\Omega_{t+1}R^Y_{t+1}\right)\right)\text{ for } i\in\{L,F\}, \end{aligned} \tag{14}$$

where λ^I is the Lagrange multiplier on the incentive constraint and thus captures the shadow value of deposits for banks. Since all financial intermediaries face the same problem, the subscript j has been dropped. The equations show how imperfect disclosure distorts the sector allocation problem. Under perfect disclosure, banks simply equate required returns ($R^i_{t+1}-R_t$) across sectors (adjusted for the relative absconding rate ρ_i), as the disclosure-based wedge between perceived and real returns ($\mathbb{E}^D_t\Omega_{t+1}R^i_{t+1}-\mathbb{E}_t\Omega_{t+1}R^i_{t+1}$) evaluates to zero in this case.

With imperfect disclosure, banks additionally take into account that depositors' perceived returns of sectors affect their incentive constraint. For the fossil sector, perceived returns in the sector are higher than true ones. Hence, the disclosure-based wedge is a positive term (as is the shadow value λ^I), which, ceteris paribus, lowers the return in the fossil sector required by banks ($R^F_{t+1}-R_t$), see the left hand side of equation (14) for $i=F$. Due to decreasing marginal returns to capital, the reduction of these required returns leads to an increase in investment in that sector, relative to the efficient allocation outcome under full information. This effect is stronger, the larger λ^I is, i.e. the more valuable deposits for banks are.

In contrast, the disclosure-based wedge for the non-energy and low-carbon sector is negative as depositors underestimate returns. Hence, in these sectors banks will require a higher return than under full disclosure, leading to a reduction in investment in these sectors.

Finally and in line with the standard framework, total net worth in the financial sector consists of the net worth of existing financial intermediaries surviving to this period and that

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we have numerically verified that $V^D>V$ if $D<1$. Given the incentive constraint from above, this implies that intermediaries have a lower continuation value (V) than the value of the assets in case of absconding (ρRWA). This could potentially imply that intermediaries have an incentive to run away with depositors' funds. However, we assume that the secondary market (where absconded assets would be sold at) is populated with sophisticated, perfectly informed agents, who would buy the funds only at the fair value V. Absconding does therefore not occur. This can also be seen by reformulating the incentive constraint under imperfect disclosure to an incentive constraint as known in Gertler and Karadi (2011), but with adjusted absconding rates on sectoral assets:

$$\begin{aligned} &\mathbb{E}^D_tV_{j,t}\geq\rho RWA_{j,t}\Leftrightarrow V_{j,t}\geq\rho RWA_{j,t}-\Delta V^D_{j,t}\\ &\Leftrightarrow V_{j,t}\geq\rho\sum_i\left(\left(\rho_i-\frac{1}{\rho}\left(\mathbb{E}^D_t\Omega_{t+1}R^i_{t+1}-\mathbb{E}_t\Omega_{t+1}R^i_{t+1}\right)\right)Q^i_tS^i_{j,t}\right)\\ &\Leftrightarrow V_{j,t}\geq\rho\widetilde{RWA}_{j,t}, \end{aligned}$$

where $\widetilde{RWA}_{j,t}=\sum_i\widetilde{\rho}_{i,t}Q^i_tS^i_{j,t}$ and $\widetilde{\rho}_{i,t}=\rho_i-\frac{1}{\rho}\left(\mathbb{E}^D_t\Omega_{t+1}R^i_{t+1}-\mathbb{E}_t\Omega_{t+1}R^i_{t+1}\right)$. Hence, the effective absconding rates adjust in a way that intermediaries have no incentive to run away with the funds.

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 surviving financial intermediaries is given by

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

We define the financial-sector capital ratio κ_t as the ratio between the net worth of the representative intermediary and its risk-weighted asset, i.e. $\kappa_t = N_t / RWA_t$.

3.6 Government and central bank

Government spending G_t equals (constant) taxes T plus the receipts of the carbon tax:

$$G_t = T + \tau_t Z_t \tag{15}$$

The aggregate market clearing is given by

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

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 Calibration

In this section we discuss the parameterization of the model. We first provide a full list of all parameters. We then motivate our choice of the initial disclosure rate and carbon price in more detail, as those are key for our quantitative results.

4.1 Parameters of the model

We calibrate the model to reflect the euro area economy, closely following the estimated parameters from Diluiso et al. (2021). An overview of all parameters is provided in Table 2. We deviate from Diluiso et al. (2021) with respect to a few selected parameters. First, we lower the

Parameters					
capital share	α	0.36	AC inv. fossil sector	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	0.6	Taylor rule coeff. inflation	ι_π	2.9985
elast. of sub. energy inputs	ϵ_E	3.0	Initial disclosure level	D_{ss}	80%
elast. of sub. fossil resources	ϵ_F	0.15	Share undisclosed emissions Y	ζ	0.99
elast. of sub. interm. goods	ϵ^I_{ss}	6			
intertemporal elast. of subst.	σ	1.5365	Steady states		
habit parameter	h_c	0.6326	government spending share	G/Y	20.51%
Frisch labor elasticity	ψ	0.7223	energy cost shares	$P^E E/Y$	5%
weight on labor disutility	ξ	25.9	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 probability bankers	γ	0.9554	CO_2 price / ton	τ	75 €/ton
absconding rate Y	ρ	0.3853	risk-weighted capital ratio	κ	9%
relative absconding rate L	ρ_L	1.25	spread Y	$R_Y - R$	0.0032
relative 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 sector	χ_L	14.5498	inflation rate	π	1.0047

Note: Y = non-energy sector, L = low-carbon energy sector, F = fossil energy sector, elast. of sub. = elasticity of substitution, interm. = intermediate, coeff. = coefficient, AC = adjustment costs.

Table 2: Calibrating the model to the euro area economy

elasticity of substitution between low-carbon energy and fossil energy inputs (ϵ_E) from a value of 5 to 3. This value is at the upper end of the band of estimates provided by Papageorgiou, Saam, and Schulte (2017). Furthermore, we lower the elasticity of substitution between fossil capital and resource use (ϵ_E) from 0.3 to 0.15. In doing so, we lie between the specification of Diluiso et al. (2021) and many other papers that do not allow for any substitution of fossil capital and resource use, as in Carattini et al. (2021). In Subsection 5.3, we discuss how our results are affected by other choices of the elasticity parameters to account for the uncertainty in the empirical literature. Table 2 also includes the steady-state sector sizes resulting from our calibration.[22]

4.2 Calibration of the initial carbon price

We investigate the current carbon prices implemented in euro area countries using the World Bank's Carbon Pricing Dashboard.[23] According to this data set, the EU emission trading scheme (ETS) covers roughly 40% of the union's emissions, with the price having averaged about 80 euro/ton in 2022 with peak values of above 100 euro/ton. Numerous national carbon pric-

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[22] These also imply the weighting parameters w in the CES-functions: $w_{CD} = 0.9$, $w_{EL} = 0.2$ and $w_{KF} = 0.7$. These result in an energy-share in GDP of 5%, of which 4% are accounted for by the fossil energy sector and the remaining 1% by the low-carbon energy sector.

[23] The dashboard can be accessed at https://carbonpricingdashboard.worldbank.org/.

ing schemes complement the EU scheme, usually covering the sectors not included in the EU ETS. Germany has implemented an ETS pricing CO_2 emissions at currently 30 euro/ton with this price scheduled to increase to 60 euro/ton during the next five years. France, Spain, and Netherlands have introduced carbon taxes currently at 45, 15, and 42 euro/ton. More generally, Brand, Coenen, Hutchinson, and Saint Guilhem (2023) state that on the basis of the latest available data (for 2021) and including also other environmental taxes, the average effective carbon tax rate in the euro area is 85 euro/ton CO_2. To be conservative, we choose a slightly lower steady-state value of 75 euro/ton.

4.3 Calibration of the disclosure rate

We set the initial degree of disclosure to $D = 80\%$, which 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 under-report 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 easily be lower.[24]

Validation of our calibration. Our choice of steady-state carbon tax and disclosure rate is also supported by comparing the effects of improving disclosure on required returns in the empirical literature and our model. As suggested by equation (6), the required return in the fossil energy sector increases in the degree of disclosure. Figure 1 reveals that this steady-state relationship is highly dependent on the carbon price: A higher carbon price increases the benefit of appearing less emission-intensive and thus the increase in fossil-sector refinancing rates R^F when disclosure improves. At a carbon price of 50 euro/ton and an initial disclosure rate of 80%, a 1 pp reduction in disclosed emissions implies a reduction in required returns by 1.03 bp. This impact is more than doubled to 2.36 bps at a carbon price of 100 euro/ton. For our benchmark choice of 75 euro/ton, the impact is 1.66 bps for each pp disclosure increase.

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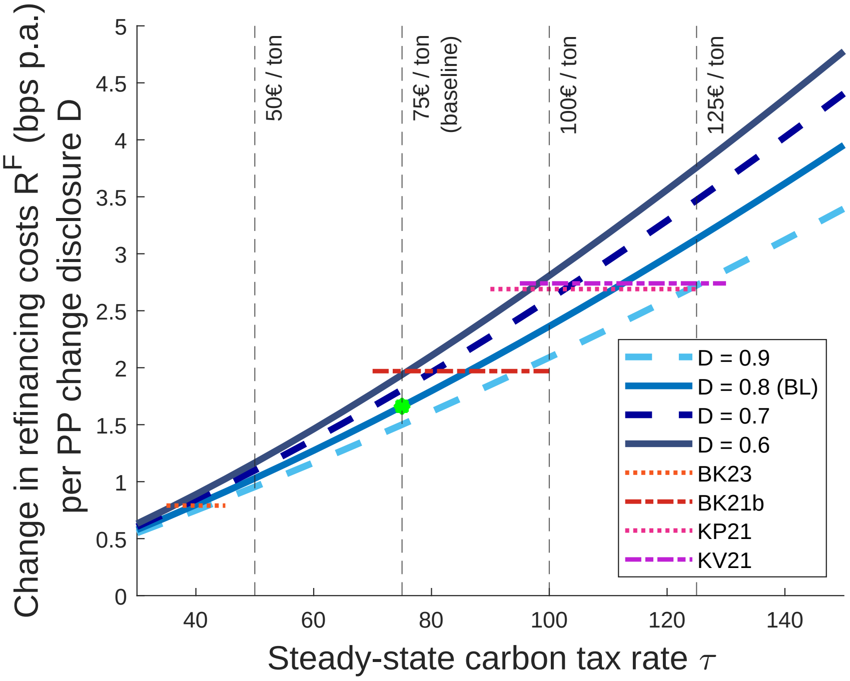
[24] As an illustration, following the cited numbers from Carbone et al. (2021), our figure of $D = 0.8$ would be obtained if we assume that external verification leads to a disclosure of 90% of the true emissions, disclosure without external verification will be 70% of the true emissions and no disclosure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



Note: Change in required returns in the fossil sector when improving disclosure to 100% in our model, per percentage point of disclosure change (i.e., $\frac{\Delta R^F}{\Delta D}$, from average values). Values are given for different levels of the steady-state carbon tax rate τ (x-axis) and for four levels of initial disclosure D (blue lines). Horizontal lines compare these to the values from the empirical literature, cf. Table 1 above. Vertical lines highlight some steady-state carbon tax rates (in €/ton CO_2). The green dot denotes our baseline ("BL") calibration choice.

Figure 1: Effects of improved disclosure on fossil-sector refinancing costs (different τ and D).

At the same time lowering the initial level of disclosure also tends to increase the benefits of a 1 pp increase in disclosure. For example, at a disclosure rate of only 60% and a carbon tax rate of 75 euro/ton the impact of a 1 pp disclosure increase is at approx. 2 bps.

Our baseline calibration of 75 euro/ton and 80% disclosure squares well with the empirical evidence from Table 1 on the relationship between the level of emissions disclosed by firms and their financing costs: There, a 1 pp increase in disclosed emissions is associated with an increase in costs of capital or debt between 0.79 and 4.73 bps, well in line with our calibration-implied 1.66 bps. Even a carbon tax of 100 euro/ton or a lower disclosure rate would produce results well within the range of empirical estimates (2.36 bps per % of disclosed emission). In that case, disclosure would become an even more powerful tool than suggested by our results. We conclude that our calibration choices for carbon tax and disclosure rate are conservative.

5 Results

In this section, we evaluate the quantitative impact of emissions disclosure by simulating various exogenous shocks. We first consider an increase in disclosure from the initial level of 80%

to 100% in isolation. Second, we study the transmission of a carbon tax shock when disclosure is imperfect or perfect. We focus on a medium-term impact of six years.

Our quantitative results depend on several parameters about whose size there is naturally some uncertainty. To lay open how our results vary with different calibrations, we finally show a number of sensitivity analyses which vary the values of core parameters. These parameters are related to how technology allows to substitute several factors of production, as well as where undisclosed emissions are mis-attributed. The sensitivity analyses are interesting in themselves, as they show how disclosure effects may vary across economies and time.

5.1 Disclosure shock

Our simulation design is as follows. We impose an unanticipated and permanent shock on our disclosure variable D in the first simulation period – think of a sudden introduction of disclosure mandates. Specifically, we raise D from 80% to 100%, such that depositors are informed about the source of the previously undisclosed emissions (20% of all emissions). We simulate the disclosure shock from different initial levels of carbon tax rates (as in Figure 1), thereby covering a range of empirical estimates of the response of financing costs.

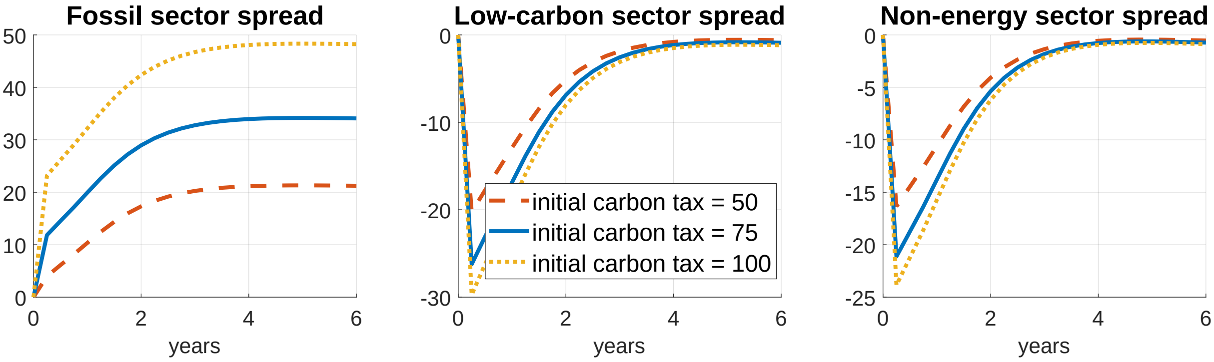


Figure 2: Dynamic response of sectoral spreads (in bps p.a.) after an exogenous increase in disclosure from $D = 0.8$ (initial steady state) to $D = 1$, for different carbon tax rates

Figure 2 shows that the higher disclosure level increases the returns that financial intermediaries require from the fossil sector. As depositors now correctly recognize fossil firms' true emission intensity, they are less willing to provide savings to fund fossil activities, prompting intermediaries to increase the spread in the fossil sector. The increase in this spread is larger, the higher the steady-state carbon tax rate and emission costs. Due to our calibration discussed above, the increase in the spread of fossil-energy firms is around 34 bps – or around 1.7 bps per pp of disclosed emissions – and therefore in line with the empirical estimates given in Table 1.[25] Conversely, the spreads in the other two sectors fall, as before the shock, depositors

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[25] Note that the empirical estimates would rather speak for quantitative spread effects as shown by the yellow line (48 bps, or 2.4 bps per pp of emissions). Hence, we take a conservative stance by focusing on the blue line.

falsely assigned undisclosed emissions to these sectors.

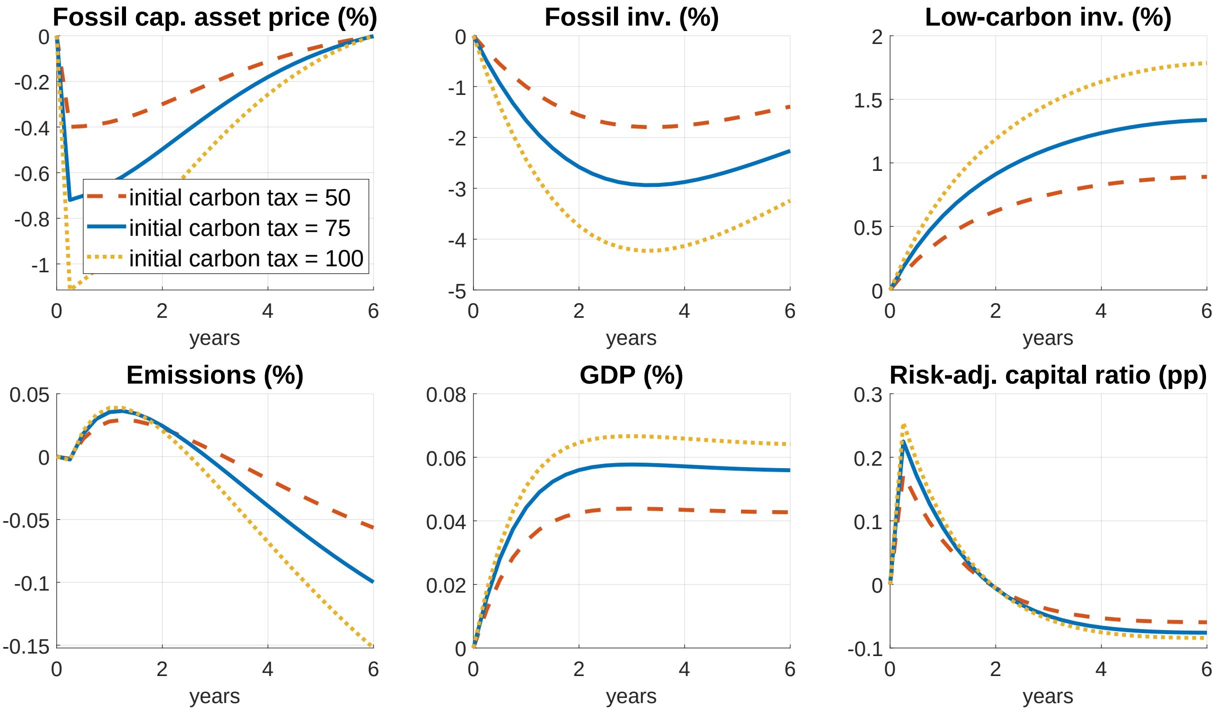

Figure 3: Dynamic response of key variables after an exogenous increase in disclosure from $D = 0.8$ (initial steady state) to $D = 1$, for different carbon tax rates

Turning to Figure 3, the capital asset price of the fossil sector drops slightly on impact, amounting to a modest stranded asset effect of up to 1.1% of the total value. Asset prices in the other sectors increase slightly. Investment in the fossil energy sector falls by up to 4%, while the two other sectors increase their capital stock.Low-carbon investments increase by around 1.4% after 6 years. This in turn leads to a reduction in emissions, which is, however, only modest in size. The reason for this is that fossil firms consider the true costs of using fossil resources throughout. While the improvement in disclosure cancels their funding advantage, they used fossil resources already before efficiently, being perfectly aware of carbon taxes and emissions. In the long run, emissions fall by only 0.2%.

GDP rises as the resource allocation across sectors is more efficient under full information. Overall, the 20 pp increase in disclosure raises GDP by about 0.04% to 0.07%. The capitalization of banks is affected differently in the short and medium term. Initially, the positive reassessment of non-energy and low-carbon assets boosts the net worth of intermediaries, thereby reducing their leverage. Once asset prices converge back to the long-run steady state, however, the capitalization of banks is governed solely by the incentive constraint. Since disclosure is perfect after the shock occurs, depositors value the banks correctly. Banks have thus no more incentive to deviate from the efficient sectoral allocation of capital, which boosts their value. This in turn allows them to attract more deposits and to extend their balance sheet, both of which increase their leverage.[26]

Overall, we conclude that an isolated disclosure shock has a rather small quantitative impact on the real and financial sector in the model. Nor does it cause a reduction in emissions that would significantly contribute to reaching climate goals. Hence, other policies like carbon pricing remain the main tool to reduce emissions. We next show that disclosure does play an important role in how costly such carbon taxes prove for the economy.

5.2 A carbon tax increase with imperfect and full disclosure

Here we study a one-off, unanticipated and permanent increase in carbon taxes by 50 euro/ton CO_2.[27] We distinguish between two cases with respect to the availability of emission disclosure: First, the carbon tax shock does not lead to an improvement in the level of disclosure provided to funding entities, hence $D = 0.8$ throughout. Second, the carbon tax shock comes along with a full public accounting of emissions, such that funding entities are fully informed about the correct distribution of emissions in the economy upon the arrival of the tax shock, i.e. D increases from 80% to 100% when the carbon tax is introduced.[28]

Without an improvement in disclosure (red, solid line in Figure 4), the carbon tax shock 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 22.6%. Investments in the fossil-energy sector are strongly reduced and fall by about 70% after six years. Capital flows instead to the low-carbon sector, which sees its asset price increase by about 12% (not shown) and low-carbon investment more than double. This transition to low-carbon energy reduces emissions by roughly 25% after six years. Since the substitution is imperfect, energy prices increase (by more than 25%, not shown), increasing the input costs for the non-energy sector and reducing GDP by 0.72% after six years. Via the movements in asset prices, the carbon tax shock also affects the balance sheets of financial intermediaries, leading to a modest reduction in bank capitalization by 20 to 30 basis points.

When instead the carbon tax shock is accompanied by a full public accounting of emissions (blue-dotted line in Figure 4), the impact on the real economy is considerably changed. The extent of stranded assets in the fossil energy sector is reduced to 20.6% (a decrease by about 10%). This occurs despite a much quicker reduction in fossil energy investment and a quicker

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[26] One might wonder why banks do not provide full disclosure in the first place if the absence of it reduces their value. This is because only the banking sector as a whole benefits from full disclosure. Single intermediaries can still benefit from appearing greener as they are in the absence of mandatory rules on disclosure.

[27] As shown in Diluiso et al. (2021), an increase of roughly this size is required in order to reach a 24% cumulative emissions reduction within 10 years, equivalent to the target set by the European Commission for 2030.

[28] While we model the increase in carbon tax and disclosure as two separate shocks, in practice the latter might follow from the former as the introduction of carbon taxes improves the availability of publicly available emission information. For example, the introduction of the EU ETS led to collection and release of plant-level emission data for those firms covered by the pricing system.

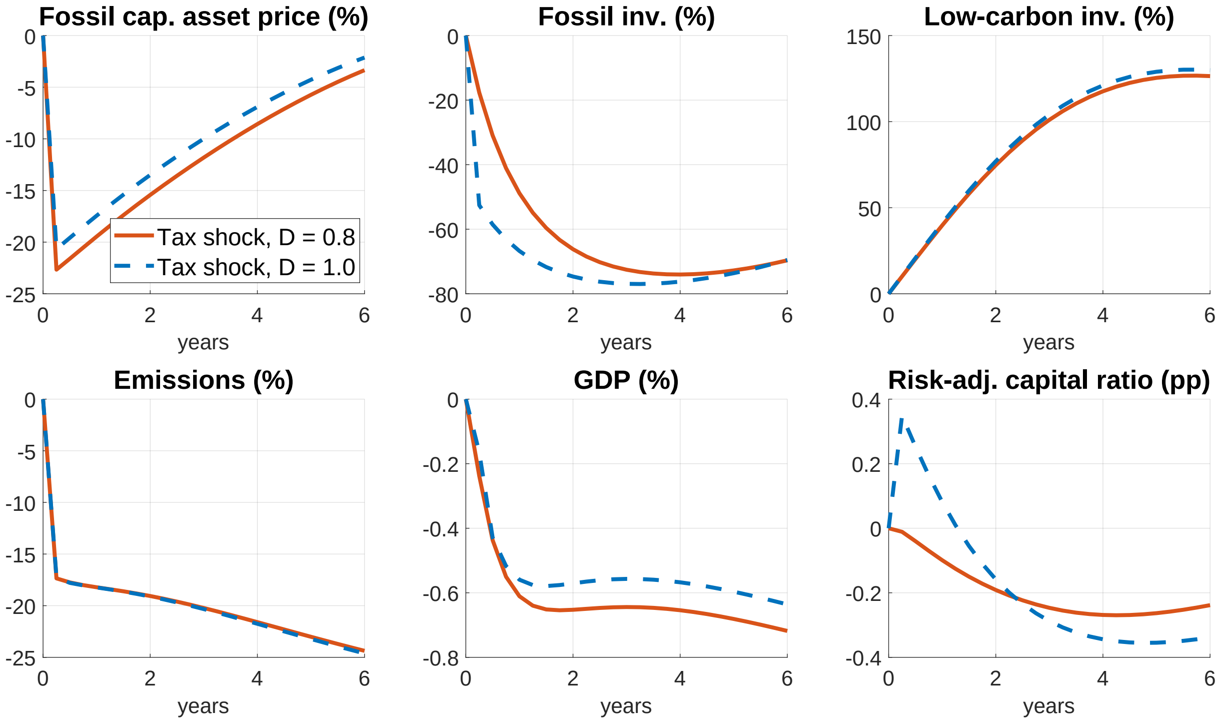

Figure 4: A 50 euro/ton carbon tax shock under imperfect ($D = 0.8$) and full disclosure ($D = 1$)

boost to low-carbon investment. Asset value losses in the fossil energy sector are reduced due to general-equilibrium effects: GDP losses associated with the carbon tax shock are significantly lower when disclosure becomes perfect. The tax now causes a reduction by only 0.63% in GDP, compared to 0.72% under imperfect disclosure, reducing the adverse GDP impact of carbon taxes by 13%, see Table 3.[29] Hence, the disclosure shock allows the economy to transition to a less emission-intensive production faster and more efficiently, boosting low-carbon at the cost of fossil activities, and thereby reducing the strain from emission costs. This in turn allows the remaining fossil sector capital to be used more profitably. In contrast, in the absence of full disclosure, fossil capital is maintained at a higher and thus less profitable level.

We can also express these GDP cost reductions in absolute euro terms. To do so, we calculate the net present value of GDP over six years in each of the two simulations.[30] Taking the difference, we obtain the net present value of tax-induced GDP costs avoided by the 20 pp disclosure improvement. Our calculations yield a net present value of disclosure in connection with an increase in carbon taxes of 47 bn euro over six years. Hence, each percentage-point increase in the disclosure rate yields an average benefit of about 2.4 bn euro over six years.[31]

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[29] So in combination with the tax shock, disclosure boosts GDP by 0.09%, while disclosure in isolation improves GDP by a mere 0.05% (Figure 3). This highlights the strong complementarity of disclosure and climate policies.

[30] Specifically, we calculate $NPV = \sum_{q=0}^{24}(\prod_{s=1}^{q} 1/R_s)Y_q$ for each of the two simulations, where Y_0 is set to 3.4 tn euro, roughly equal to the euro area GDP in Q4 2022.

[31] In Appendix C we show that the relevance of disclosure for the transmission of carbon taxes is upheld for alternative carbon tax pathways. Specifically, we consider an exponential increase in carbon taxes following a Hotelling rule. Also in this case, disclosure leads to reduction in carbon-tax related GDP costs. The magnitude in

Table 3 summarizes our findings. Comparing the first and second pair of rows in the table, we observe that under perfect disclosure the costs to GDP of a given carbon tax shock are smaller. The benefits of perfect disclosure become larger with a higher carbon tax shock. The third pair of rows indicate the isolated benefit of disclosure (i.e. the difference between pair one and two). We can see that disclosure yields a benefit of 0.05-0.08% of GDP. While this seems small, it needs to be considered in absolute euro terms (amounting to 8.3 to 13.3 bn euro), or in relation to the actual impact of carbon taxes. As stated above, perfect disclosure lowers GDP costs from carbon taxes by 13% (0.63% relative to 0.72%). For the smaller carbon tax shock of 25 Euro/ton this amounts to 17%. The benefit of disclosure also appears substantial if expressed relative to the gain in tax revenue from the carbon tax increase. Costs saved by disclosure amount to 15 to 23% of additional tax revenue.

Carbon tax	75€/tonCO$_2$	100€/tonCO$_2$	125€/tonCO$_2$
GDP, imperfect disclosure (bn €)	13,427 bn €	-55.1 bn €	-96.7 bn €
GDP, imperfect disclosure (% GDP)	100%	-0.41%	-0.72%
GDP, perfect disclosure (bn €)	+6.7 bn €	-45.7 bn €	-84.6 bn €
GDP, perfect disclosure (% GDP)	+0.05%	-0.34%	-0.63%
GDP, effect $D = 0.8 \to D = 1.0$ (bn €)	+6.7 bn €	+9.4 bn €	+10.7 bn €
GDP, effect $D = 0.8 \to D = 1.0$ (% GDP)	+0.05%	+0.07%	+0.08%
Carbon tax revenue (bn €)	263.2 bn €	+41.6 bn €	+69.8 bn €
Carbon tax revenue (% GDP)	1.96%	+0.31%	+0.52%

Note: The first two rows state the EA GDP under different carbon prices. The first column reflects the EA GDP in 2022, to which our steady state is calibrated. All percent values are deviations from that steady state. Rows 3 and 4 give the GDP impact if disclosure is improved from 80 to 100%. (At the steady state, disclosure is at 80%.) Rows 5 and 6 show the net effect of improving disclosure from 80 to 100% (e.g. the difference of row 1 and 3 and row 2 and 4). The last two rows show the carbon-tax revenue in the model at different carbon tax rates. Empirically, energy-tax revenue in the EU27 in 2021 (latest available) was 255 bn €.

Table 3: Summary of our quantitative results

It is also noteworthy that the marginal impact of improved disclosure is largest at lower disclosure levels. Increasing D from 80% to 81% reduces GDP costs of carbon taxes more strongly than increasing D from 99% to 100%, by a factor of 60%.[32,33] This implies that low-hanging fruits should be picked early, rather than postponing disclosure rules until a comprehensive

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GDP costs saved is comparable to those presented here in the main text for the sudden carbon tax shock.

[32] The non-linearity derives from the decreasing marginal returns to capital. To see this intuitively, consider an extreme scenario in which wrong information would induce the economy to hold no low-carbon capital at all and invest all energy capital in fossil assets. Then any small bit of information raising low-carbon investment to a positive value would at the margin boost energy output by an infinite quantity.

[33] This means we fit the empirical estimates in Table 1, which evaluate marginal effects at the current state of imperfect disclosure, even better. As discussed in Section 4, a 1 pp. increase in D will increase refinancing rates R^F by 1.66 bps p.a. *on average*. But as this effect is 60% larger at the margin, an empirical investigator in our model world would obtain an effect of 2.66 bps p.a., quite at the center of the estimate range in Table 1.

method accounting for all emissions in the economy has been established. In other words, in order to avoid unnecessary transition costs by climate policies like a carbon tax, increasing the disclosure level quickly is more important than eventually lifting it to near 100%.

Contrary to improving the GDP outcome, better disclosure does not necessarily help the economy to save more emissions – the path of emissions is virtually the same with $D = 0.8$ and $D = 1$ after a carbon tax shock. This is not surprising since the disclosure shock by itself had virtually no effect on emissions (see previous subsection).

Finally, the impact of carbon taxes on bank capitalization is also affected by higher disclosure. Now, banks experience a boost to their net worth since the gains in asset prices of the low-carbon energy and non-energy sector more than compensate the losses from the fossil-energy sector. In the medium and longer term, however, the increase in the value of banks' assets following the improved disclosure lowers their capital ratio, see previous section.[34] Hence, improved disclosure does not necessarily alleviate financial stability risks from carbon taxes by itself. The transitional effects of improved disclosure might thus call for close scrutiny by macroprudential regulators.

Overall, while disclosure in isolation is unlikely to trigger a substantial shift from fossil to low-carbon energy production, it plays a much larger role in alleviating the economic stress caused by a carbon tax shock. In our baseline simulation, full disclosure decreases the GDP cost of a carbon tax by a substantial 13%. The first steps in improving disclosure have the largest GDP effects and their benefit will show quickly, right when GDP costs are largest. We find, however, only ambiguous effects on bank capitalization and virtually no further emission reductions by disclosure.

The importance of disclosure relative to financial frictions. Here, we briefly compare the importance of disclosure for the carbon tax impact to that of financial frictions, the latter having been studied in Carattini et al. (2021) and Diluiso et al. (2021).

In Figure 5a, we simulate a carbon tax shock in our baseline model as above, with and without the introduction of full disclosure upon the arrival of the carbon tax shock (this figure is in fact identical to "GDP" panel in Figure 4). In both simulations, financial frictions exist (without them, disclosure would play no role in our model).

In Figure 5b, we instead simulate a carbon tax increase under full disclosure ($D = 1$), with and without financial frictions.[35] In line with the literature, the presence of financial frictions increases the GDP costs of carbon taxes.

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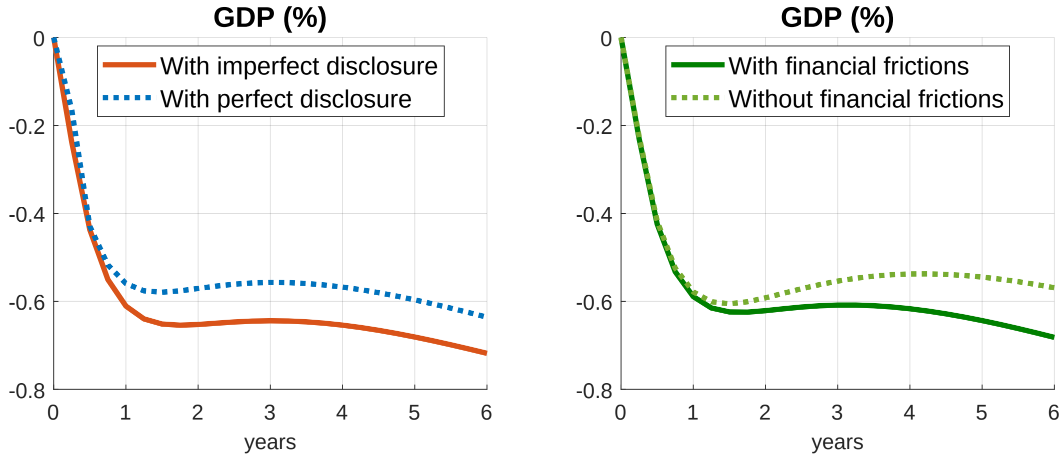
[34] The variations in net worth also affect the demand for deposits and might thus be one example of liquidity risks arising from climate mitigation policies (see Acharya, Berner, Engle, Jung, Stroebel, Zeng, and Zhao, 2023).

[35] Note that the dashed blue line in Figure 5a and the solid dark green one in 5b are not identical. This is because in 5a we assume that the initial steady state is characterized by imperfect disclosure, whereas in 5b perfect disclosure holds throughout.

Comparing these experiments reveals that improving disclosure from 80% to 100% reduces the costs of carbon taxes to a similar extent as the removal of financial frictions would, by approximately 13% and 17%, respectively. While the literature has so far focused very much on frictions arising from agency problems in financial markets, our result points to a similarly important role that informational frictions play in determining the extent of economic costs caused by climate policies.



(a) Role of imperfect disclosure

(b) Role of financial frictions

Figure 5: The role of financial frictions and of disclosure for the GDP impact of carbon taxes

5.3 The role of technology and mis-attribution of emissions

This subsection serves a dual purpose: First, it provides sensitivity analysis on some core parameters affecting the dynamics of disclosure, both in isolation and in connection with a carbon tax shock. Overall, the previous results appear quantitatively robust. Second, the parameters most important for the dynamic effects of disclosure have an intuitive economic interpretation, such that varying them is an interesting exercise in itself. Three of these parameters (ϵ_Y, ϵ_E and ϵ_F) govern substitutability between different factors of production and therefore describe technological limitations. The fourth parameter, ζ, determines to which zero-emission sector(s) depositors mis-attribute the $(1-D)$ undisclosed emissions.

Here, these parameters are varied for both a pure disclosure shock (Figure 6) and one in connection with a carbon tax shock: Table 4 shows the sensitivity of key variables to the impact of the carbon tax shock as well as the incremental effect of the disclosure shock (after 6 years).

The substitutability of labor and capital relative to energy inputs, ϵ_Y, plays only a marginal role for the transmission of the disclosure shock (Figure 6a).[36] Emission reductions are slightly larger for the pure disclosure shock when it is easier for firms to substitute energy with labor

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[36] Here, we consider $0.4 \leq \epsilon_Y \leq 0.8$, in line with the estimates from Atalay (2017).

and capital (larger ϵ_Y). In the case of a carbon tax shock (Table 4, second and third line), a higher ϵ_Y increases the ability of the economy to substitute away from energy. Hence a lower boost to low-carbon investment is required to maintain GDP (which itself is barely affected by the higher elasticity). Energy demand and emissions fall by a larger amount in this case.

If it is easier for firms to substitute fossil by low-carbon energy (higher ϵ_E), the impact of disclosure is significantly larger (Figure 6b).[37] With a high degree of substitutability between the energy types, the funding costs become more important in guiding investment decisions relative to technological constraints. Hence, full disclosure is more powerful in redirecting investments to low-carbon energy, reducing carbon tax costs and thus also boosting GDP by more. Moreover, a higher ϵ_E increases the complementarity between carbon tax and disclosure shock (Table 4): With $\epsilon_E = 3$ (baseline), the disclosure shock alone boosts GDP by 0.055%, and by 0.08% with a contemporaneous carbon tax shock. However, if energy sources are highly substitutable ($\epsilon_E = 5$), the respective values are 0.065% and 0.13%. Hence, the quantitative effects of disclosure improvements should be expected to be palpably larger than for our baseline euro area calibration in regions with conditions allowing for easier adoption of renewable energy.

	GDP		Low-carbon investment		Emissions	
Variable	Tax shock	Discl. shock	Tax shock	Discl. shock	Tax shock	Discl. shock
Baseline	-0.72	0.08	126.45	3.45	-24.37	-0.25
$\epsilon_Y = 0.4$	-0.65	0.09	142.28	3.08	-20.63	-0.09
$\epsilon_Y = 0.8$	-0.78	0.09	111.81	2.55	-27.88	-0.05
$\epsilon_E = 1.5$	-1.12	0.07	43.85	0.80	-19.87	-0.01
$\epsilon_E = 5$	-0.05	0.13	244.16	5.62	-29.80	-0.10
$\epsilon_F = 0.075$	-0.72	0.14	126.43	3.87	-24.00	-0.08
$\epsilon_F = 0.3$	-0.72	0.03	126.93	1.51	-24.86	-0.06
$\zeta = 1$	-0.72	0.08	126.42	3.43	-24.37	-0.25
$\zeta = 0$	-0.72	0.09	129.84	4.71	-24.43	-0.28

Note: Impact on GDP, low-carbon investment and emissions after six years in % of initial steady state.

Table 4: Sensitivity analysis for the tax shock and incremental disclosure shock impact.

When it is more difficult for fossil firms to substitute fossil resources with capital (lower ϵ_F), fossil firms' funding costs play a more important role in determining the size of the fossil sector (Figure 6c). Hence, imperfect disclosure distorts the allocation of fossil investment to a stronger degree. As a consequence, introducing full disclosure from a steady state in which fossil firms are very capital-dependent (i.e. with a low ϵ_F) will shrink that sector more. Accordingly, this will increase low-carbon investment and emission savings more strongly, and ultimately boost

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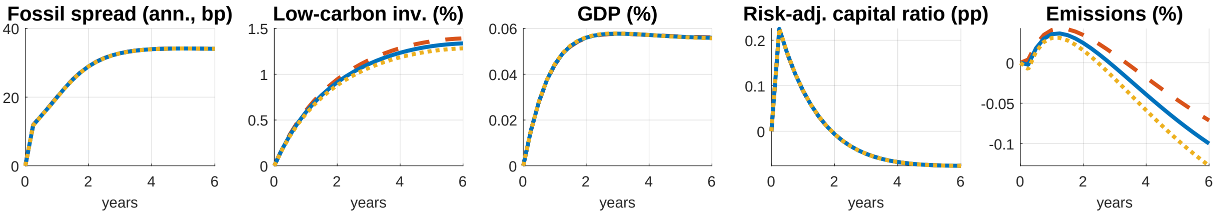
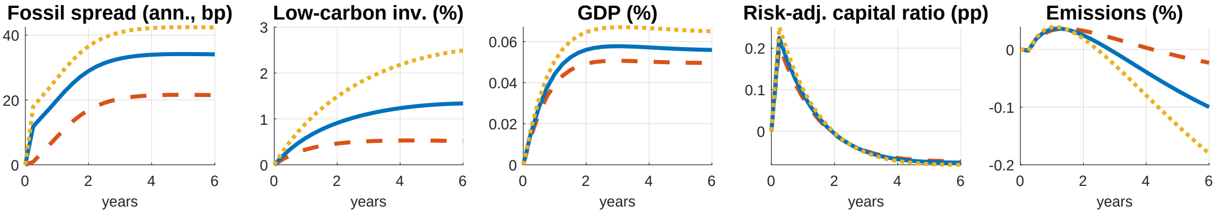
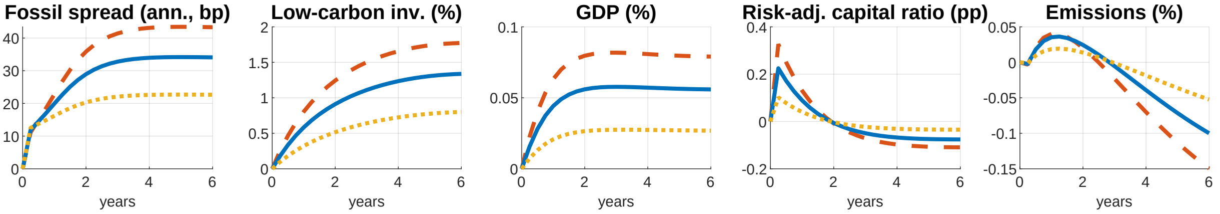
[37] We look at $1.5 \leq \epsilon_E \leq 5$, fully encompassing the band of estimates from Papageorgiou et al. (2017), but also allowing for larger values as in Diluiso et al. (2021).



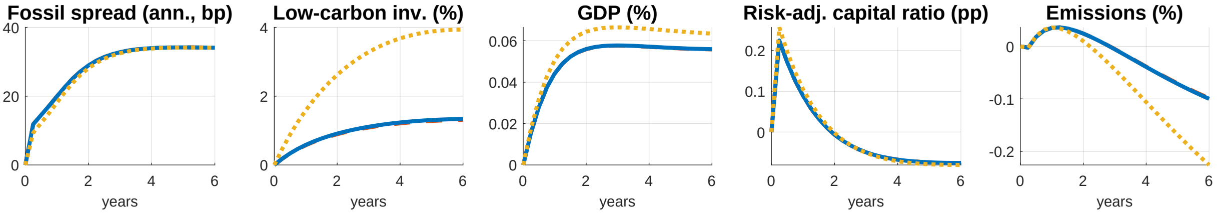
(a) $\epsilon_Y = 0.4$ (red dashes), $\epsilon_Y = 0.6$ (blue; baseline), $\epsilon_Y = 0.8$ (yellow dots)



(b) $\epsilon_E = 1.5$ (red dashes), $\epsilon_E = 3$ (blue; baseline), $\epsilon_E = 5$ (yellow dots)



(c) $\epsilon_F = 0.075$ (red dashes), $\epsilon_F = 0.15$ (blue; baseline), $\epsilon_F = 0.3$ (yellow dots)



(d) ζ: All to non-energy (red dashed), Proportional (blue; baseline), All to low-carbon (yellow dots)

Figure 6: Sensitivity analysis for the disclosure shock

GDP by more. As Table 4 shows, changes in ϵ_F do not significantly change the impact of the tax shock on the three variables we consider.[38] However, when it is more difficult for fossil firms to substitute resource use with fossil capital (ϵ_F reduced from 0.15 to 0.075), the disclosure shock becomes significantly more powerful: Higher disclosure rates make it more expensive for fossil firms to obtain funding and a lower ϵ_F impedes substitution with fossil resources, thus shrinking the fossil sector more. Thus, similarly to ϵ_E, the complementarity between tax and disclosure shock also increases strongly in ϵ_F.

Figure 6d considers alternative assumptions about the parameter ζ, which measures how

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[38] The reason is that ϵ_F merely affects the capital-intensity of the fossil sector and not its overall size, which is determined by carbon taxation. A higher ϵ_F simplifies substitution of fossil resource use with fossil capital, leading a somewhat higher capital intensity, which in turn reduces emissions slightly.

much of the undisclosed emissions from the fossil energy sector is perceived by depositors to be caused by the non-energy sector. In our baseline, we assume that undisclosed emissions are attributed to the low-carbon energy and non-energy sector according to their relative size. If we instead assume that all undisclosed emissions are perceived to occur in the non-energy sectors ($\zeta = 1$), the results barely change (the dashed-red and blue line overlap), since already in our baseline the non-energy sector is much larger than the low-carbon sector. However, if we assume that the entirety of undisclosed emissions is attributed to the low-carbon sector ($\zeta = 0$), this sector benefits a lot more from full disclosure and low-carbon activity increases strongly in response to the disclosure shock (see also the last two rows of Table 4). Yet overall, the complementarity of the two shocks is not affected greatly by emission mis-attribution.

In summary, the disclosure shock impact is fairly robust to a wide range of parameter values.[39] Disclosure becomes more powerful when technological constraints to substitute fossil with low-carbon energy are low (high ϵ_E), when fossil firms cannot easily become less capital-intensive (low ϵ_F), or when depositors initially attribute a large share of undisclosed emissions to the low-carbon sector. Conversely, in economies where technological constraints impede shifting between sources of energy, or where capital access matters little for fossil firms, disclosure becomes a rather weak tool in promoting a low-carbon transition.

6 Conclusion

In this paper, we have investigated the effects of imperfect disclosure about carbon emissions. To do so, we have constructed a structural DSGE model, calibrated to the euro area, with a role for fossil and low-carbon energy in production and with balance-sheet constrained financial intermediaries providing funding. Imperfect disclosure implies that returns in the fossil-sector are overestimated in the presence of carbon taxes. This implies financial advantages for emission-intensive fossil energy firms, while due to constrained bank lending, the remaining sectors in the economy receive less financing at higher costs.

Improving disclosure increases investments in the low-carbon sector and stimulates the economy as inefficiencies are reduced. However, the largest benefits of improved disclosure are reaped in connection with additional climate policies: Better disclosure palpably reduces the macroeconomic cost of a green transition initiated by higher carbon taxes. For an increase in carbon taxes in line with the EU climate goals, we find that GDP costs can be reduced by around 13%. Even small improvements in disclosure will pay off handsomely: The net present value of avoided GDP costs for each percent of disclosed emissions amounts to 2.4 bn euro.

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[39] The value of disclosure in terms of the net present value (NPV) of GDP is affected as follows: It varies considerably with ϵ_E. For $\epsilon_E = 5$, it amounts to 64 bn euro over six years, or 3.2 bn euro per pp of total emissions disclosed. Conversely, with $\epsilon_E = 1.5$ the NPV is 0.9 bn euro per pp of emission. In contrast, varying ϵ_F does not affect the NPV metric much.

In contrast, there are almost no additional emission decreases with higher disclosure in our setup, nor does improved disclosure reduce financial stability risks.

This implies some clear policy recommendations. First, policy initiatives to improve carbon-emission disclosure – like the one by FSB (2017) – should aim to increase disclosure rates as quickly and thoroughly as possible. By doing so the economic costs of climate policies are significantly reduced and the likelihood that governments will implement them rises accordingly. Importantly, the economic benefits of disclosure manifest particularly during the early stage of the low-carbon transition, at a time when the risk of political backpedaling is greatest.

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 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 Empirical estimates for the relationship between emissions and financing costs or return on equity

Here we provide some background for Table 1 in our main text. In particular, we document how we obtain the estimates of the relationship between emissions and financing costs or equity returns from the individual studies cited there. Most studies look at scope-1 emissions in tons of CO_2, i.e. emissions from sources that are controlled or owned by a firm. In the following, all changes in cost of capital (stock returns) or cost of financing are given in bps p.a. associated with a 1% increase in disclosed scope-1 CO_2 emissions.

Bolton and Kacperczyk (2023): 0.792 bps. The paper finds a widespread carbon premium in a sample of firms spanning three continents, i.e. firms with higher emissions exhibit higher stock returns. For their full sample of 77 countries, the authors report the relationship between firms' stock returns and their emission level (log of scope-1 emissions). The authors focus on within-industry effects, as developments in the energy sector could otherwise drive results. For their specification with industry fixed effects, see Table 6, Panel A, column (4). The dependent variable of monthly returns is in % per month, so the coefficient (0.066) times 12 gives the effect in bps p.a. for a 1% increase in the scope-1 CO_2 emissions.

Bolton and Kacperczyk (2021b): 1.968 bps. The paper gives associations of monthly stock returns and changes in CO_2 emissions from large US firm panel. We focus on the specification with industry fixed effects, following the reasoning in Bolton and Kacperczyk (2023). Table 8, Panel A, column (4) provides the coefficient (0.164) for monthly returns. So a 1% increase in a firm's scope-1 CO_2 emissions is associated with an increase in its stock returns of $0.164 \times 12 = 1.968$ bps p.a. Without industry fixed effects, the coefficient is still significant, but much smaller in size – 0.043, see column (1) –, reducing the association with stock returns to 0.516 bps p.a.

Bolton and Kacperczyk (2021a): 4.728 bps. This paper investigates a quasi-natural experiment, which is the introduction of mandatory emissions-disclosure regulation for publicly listed firms in the UK in 2013. Those firms which did not previously disclose emissions but began to do so in 2013 are considered as treated. Table 11, Panel B, column (2) presents results with firm fixed effects. We evaluate marginal effects for treated firms at the sample mean: We set the variable TREATMENT to 1 throughout (we look at firms that started disclosing with the new regulation in 2013). The variable of a time dummy, GBSHOCK (which is zero in 2012m11-2013m10 and one in 2013m11-2014m10), is set to its sample mean of 0.5. This yields an effect on stock returns of 4.73 bps after a 1% increase in disclosed CO_2 emissions. If instead we were to set GBSHOCK$= 1$ (looking at the treatment effect only after the introduction of the regulation), we would obtain a slightly larger estimate of 5.54 bps.[40]

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[40] With GBSHOCK $= 0.5$, we get an increase in monthly returns for a 100% change in CO_2 emissions of $-0.007 + 0.333 \times 1 - 0.109 \times \mathbf{0.5} + 0.245 \times 1 \times \mathbf{0.5} = 0.394$ bps Multiplied by 100×12 (for returns in bps p.a.)

Kleimeier and Viehs (2021): 2.738 bps. The authors regress the natural logarithm of a loan spread of a firm (in bps) onto the (level of) scope-1 CO_2 emissions, see their Table 1, column (3) for the results.[41] Due to the semi-log specification, we need to transform the coefficient (0.28) to get the approximate relative effect of a one-unit change in CO_2 emissions on the spread: $e^{0.28} - 1 = 0.3231$. Given the sample mean of the loan spread of 169.46 bps, this translates into an absolute increase of in the loan spread of 54.76 bps.[42] To obtain the absolute increase in the loan spread after a relative increase in CO_2 emissions by 1%, we need to multiply with the sample mean of emissions, which is 0.05 (see Table A2 in their appendix). This yields the value of 2.738 bps p.a.[43]

Kacperczyk and Peydró (2021): 2.689 bps. For the empirical identification, the paper uses a commitment by banks to reduce brown lending under the so-called "Science Based Targets Initiative". The authors look at firms with a pre-existing lending relationship to at least one bank that commits to reduce brown lending (variable Committed_f). There is also a time dummy $\widetilde{\text{Post}}_t$ which equals one after 2015Q2, when the first banks started to commit under the initiative. Table 6, column (2) looks at the firm-level effects on financing costs, here given by interest expenses per total debt (winsorized at 2.5% at both ends). We evaluate the effect on annualized interest expenses of a commitment of one of the banks lending to the firm ($\text{Committed}_f = 1$), as well as $\widetilde{\text{Post}}_t$ and $\text{Post}_{f,t} \times \text{Committed}_f$ at their sample means (of 0.625 and 0.383, respectively)[44]. This yields an effect on interest expenses of 2.689 bps p.a.[45] Similarly, if we were to set $\text{Post}_{f,t} \times \text{Committed}_f = 1$ (evaluating the effect for a firm all of whose lenders are committing) and $\widetilde{\text{Post}}_t = 1$ (considering only the sample from 2015Q2 onward), we would obtain an effect of 6.970 bps p.a.[46]

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and divided by 100 (for a 1% ΔCO_2 emissions), we obtain 4.728 bps p.a. For GBSHOCK $= 1$, the respective value is $12 \times (-0.007 + 0.333 \times 1 - 0.109 \times \mathbf{1} + 0.245 \times 1 \times \mathbf{1}) = 5.544$ bps p.a.

[41] Note that in this regression, the dependent variable is "tons of scope 1 CO_2 emissions per 1 US dollar of assets of borrower relative to industry median emissions and divided by 100" (see their appendix). We interpret a change in this variable as a change of scope 1 CO_2 emissions for a fixed amount of firm assets, which does not affect the median.

[42] See also Tables A2 and A10 in the appendix to their paper.

[43] In particular, we use

$$\begin{aligned} \frac{\partial \log(Y)}{\partial X_k} &\approx e^{\hat{\beta}_k} - 1 \\ \partial \log(Y) &\approx \frac{\partial Y}{Y} \text{ and } \partial X_k \approx \partial \log(X_k) \times X_k \\ \rightarrow \frac{\partial Y}{\partial \log(X_k)} &\approx (e^{\hat{\beta}_k} - 1) \times Y \times X_k \\ &= (e^{0.28} - 1) \times 169.46 \text{ bps p.a.} \times 0.05 = 2.738 \text{ bps p.a.} \end{aligned}$$

[44] The time dummy $\widetilde{\text{Post}}_t$ has a sample mean of 15/24 (it is zero in 2013Q1-2015Q1 and one in 2015Q2-2018Q4).

[45] $(0.000688 \times 0.383 + 0.000009 \times 0.625) \times 100\% \times 100$ (bps per %) = 2.689 bps p.a.

[46] $(0.000688 \times 1 + 0.000009 \times 1) \times 100\% \times 100$ (bps per %) = 6.970 bps p.a.

B Model derivations

B.1 Optimization problem of household

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

$$\lambda_t = (C_t - h_c C_{t-1})^{-\sigma} - \beta h_c (\mathbb{E}_t \xi^C_{t+1}(C_{t+1}) - h_c C_t)^{-\sigma}, \tag{16}$$

$$\mathbb{E}_t(M_{t,t+1} R_t) = 1, \tag{17}$$

$$\chi L_t^{\psi} = \lambda_t W_t. \tag{18}$$

B.2 Optimization problem of firms

Retailer k maximizes final-goods output for given input costs $\int_0^1 P_{k,t} Y_{k,t} dk$, yielding the demand function and aggregate price index of the intermediate good

$$Y_{k,t} = \left(P^N_{k,t}/P_t\right)^{-\epsilon^I} Y_t$$

$$P_t = \left(\int_0^1 (P^N_{k,t})^{(1-\epsilon^I)} dk\right)^{1/(1-\epsilon^I)}.$$

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 problem.

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

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

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

where W_t and P_t^E are the (real) price 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 $DAC_t = \chi_p \left(\frac{\pi_t}{\pi_{t-1}^{w_p} \pi_{ss}^{1-w_p}} - 1 \right) \left(\frac{\pi_t}{\pi_{t-1}^{w_p} \pi_{ss}^{1-w_p}} \right)$.

B.3 Optimization problem of financial intermediaries

We derive the problem of financial intermediaries for the more general case with portfolio adjustment costs. Hence, we impose as portfolio adjustment costs $\Gamma_{j,t} = \frac{\chi_S}{2} \sum_i \left(s^i_{j,t} - s^i_{j,t-1} \right)^2 SP_{j,t}$ levied on changes in sectoral portfolio weights $s^i_{j,t} = \frac{Q^i_t S^i_{j,t}}{SP_{j,t}}$. The special case from the main text without portfolio adjustment costs is obtained by setting χ_S to zero.

Intermediaries' value, (9), can be rewritten using the incentive constraint (10) to yield

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

where $\Omega_{t+1} = M_{t,t+1}(1-\gamma+\gamma\nu_{t+1})$ is the effective discount factor of intermediaries and $TR_{j,t} = \left(\sum_i (R^i_{t+1} - R_t)s^i_{j,t} - \frac{\chi_S}{2}\sum_i \left(s^i_{j,t} - s^i_{j,t-1}\right)^2 R_t\right)$ the total return on the stock portfolio. Maximizing $V_{j,t}$ subject to the incentive constraint (13) gives the following Lagrangian:

$$\mathcal{L} = \mathbb{E}_t\Omega_{t+1}\left(TR_{j,t}SP_{j,t} + R_tN_{j,t}\right) + \lambda^I_t \left(\nu_tN_t + \Delta V^D_{j,t} - \rho RWA_{j,t}\right),$$

where $\Delta V^D_{j,t} = \sum_i \left(\mathbb{E}^D_t\Omega_{t+1}R^i_{t+1} - \mathbb{E}_t\Omega_{t+1}R^i_{t+1}\right)s^i_{j,t}SP_{j,t}$ and λ^I_t is the Lagrange multiplier on the incentive constraint. Remember that the relationship between risk-weighted assets and total assets is given by $RWA_{j,t} = (s^Y_{j,t} + \rho_L s^L_{j,t} + \rho_F s^F_{j,t})SP_{j,t}$.

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

$$\mathbb{E}_t\Omega_{t+1}TR_{j,t} = \lambda^I_t\rho(s^Y_{j,t} + \rho_L s^L_{j,t} + \rho_F s^F_{j,t}) - \lambda^I_t \sum_i \left(\mathbb{E}^D_t\Omega_{t+1}R^i_{t+1} - \mathbb{E}_t\Omega_{t+1}R^i_{t+1}\right)s^i_{j,t}. \quad (19)$$

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

$$\begin{aligned}
\mathbb{E}_t\Omega_{t+1}\left(R^Y_{t+1} - R_t - \chi_S(s^Y_{j,t} - s^Y_{j,t-1})R_t\right) &= \lambda^I_t\rho - \lambda^I_t\left(\mathbb{E}^D_t\Omega_{t+1}R^Y_{t+1} - \mathbb{E}_t\Omega_{t+1}R^Y_{t+1}\right), \\
\mathbb{E}_t\Omega_{t+1}\left(R^L_{t+1} - R_t - \chi_S(s^L_{j,t} - s^L_{j,t-1})R_t\right) &= \lambda^I_t\rho_L\rho - \lambda^I_t\left(\mathbb{E}^D_t\Omega_{t+1}R^L_{t+1} - \mathbb{E}_t\Omega_{t+1}R^L_{t+1}\right), \\
\mathbb{E}_t\Omega_{t+1}\left(R^F_{t+1} - R_t - \chi_S(s^F_{j,t} - s^F_{j,t-1})R_t\right) &= \lambda^I_t\rho_F\rho - \lambda^I_t\left(\mathbb{E}^D_t\Omega_{t+1}R^F_{t+1} - \mathbb{E}_t\Omega_{t+1}R^F_{t+1}\right).
\end{aligned}$$

Equating the first-order conditions for sector Y with those for L and F gives rise to equation (14) in the main text. Since the derived first-order conditions do not depend on the size of the intermediary, each intermediary obtains the same optimal investment shares s^i_t and we drop the subscript j. The same applies for total return TR_t.

Inserting equation (19) in the value function yields

$$\begin{aligned}
\nu_t N_{j,t} = V_{j,t} &= \Omega_{t+1} TR_t SP_{j,t} + \Omega_{t+1} R_t N_{j,t} \\
&= \lambda_t^I \rho RWA_{j,t} - \lambda_t^I \sum_i \left(\mathbb{E}_t^D \Omega_{t+1} R^i_{t+1} - \mathbb{E}_t \Omega_{t+1} R^i_{t+1} \right) s^i_{j,t} SP_{j,t} + \Omega_{t+1} R_t N_{j,t} \\
&= \lambda_t^I (V^D_{j,t} - \sum_i \left(\mathbb{E}_t^D \Omega_{t+1} R^i_{t+1} - \mathbb{E}_t \Omega_{t+1} R^i_{t+1} \right) s^i_{j,t} SP_{j,t}) + \Omega_{t+1} R_t N_{j,t} \\
&= \lambda_t^I V_{j,t} + \Omega_{t+1} R_t N_{j,t} \\
\Leftrightarrow \nu_t N_{j,t} &= \left(\lambda_t^I \nu_t + \Omega_{t+1} R_t \right) N_{j,t} \\
\Leftrightarrow \nu_t (1 - \lambda_t^I) &= \Omega_{t+1} R_t \\
\Leftrightarrow \nu_t &= \frac{\rho \Omega_{t+1} R_t}{\rho - \rho \lambda_t^I},
\end{aligned}$$

where $\rho\lambda_t^I$ is given by equation (19). 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 (13) 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 funding entities (depositors). The first-order conditions simplify to

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

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

C A rising carbon tax path with imperfect and full disclosure

In the following, we consider an exponentially rising carbon price path reaching a cumulative increase of 50 Euro/tonCO_2 after 6 years. The scenario is thus comparable in the medium run with the tax-shock scenario from the main text. However, rather than rising at once, carbon prices grow following a Hotelling rule. Specifically, we set the carbon tax growth rate to 8.5%. Hotelling-type carbon tax paths were also considered by Diluiso et al. (2021).

Our main conclusions about the role of disclosure in the transmission of carbon taxes are upheld in this variation as well. Figure 7 shows the simulation results for the exponentially rising carbon price. Focusing first on the GDP impact, we observe that the rising carbon tax path gives rise to a front-loading of economic output to periods with lower carbon taxation. This response to announced increases in taxation has been observed elsewhere in the literature, see for example Diluiso et al. (2021). More importantly for our research question, the presence of full disclosure significantly boosts GDP relative to the scenario without disclosure. Again, the reallocation towards low-carbon capital at the cost of fossil investment accounts for this diverging GDP responses. Expressed quantitatively, GDP losses after 6 years are by about 20% lower with full disclosure, which even exceeds the magnitude of the impact of disclosure in the main text.

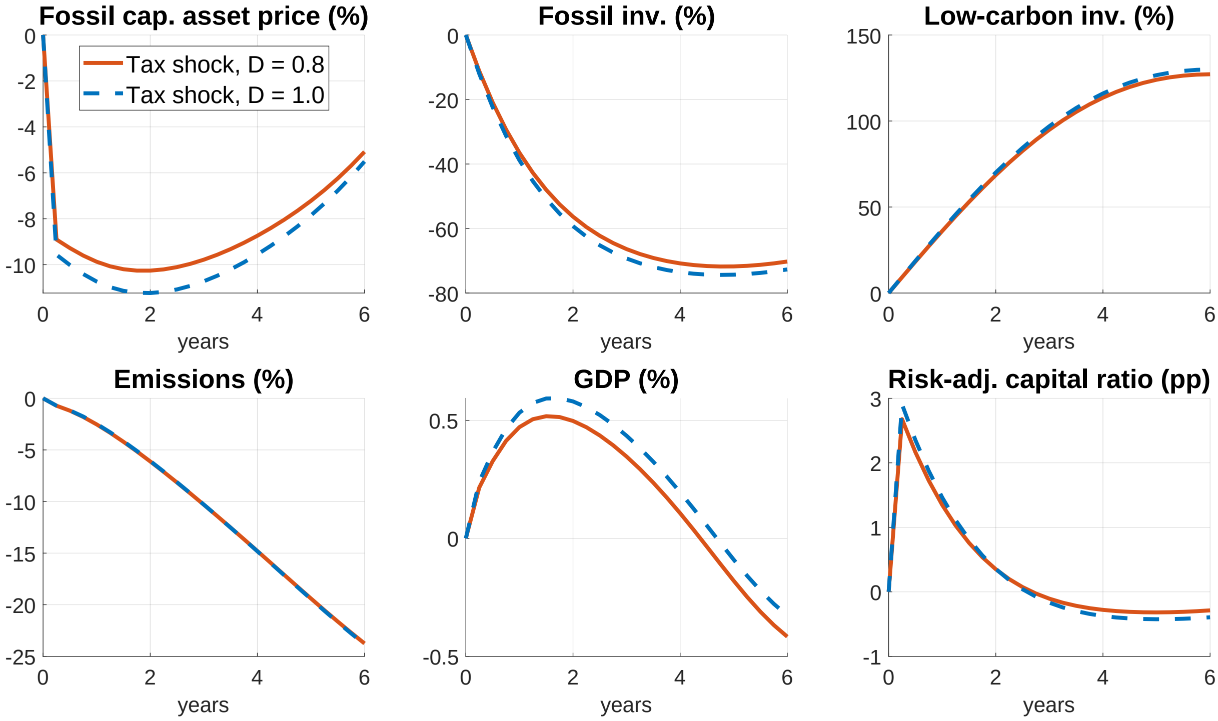

Figure 7: Simulation of an exponentially rising carbon price, reaching a total increase of 50 euro/tonCO$_2$ after 6 years, under imperfect ($D = 0.8$) and full disclosure ($D = 1$)