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Financial frictions and climate policy in a small open economy☆

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ABSTRACT

To achieve the goals of the Paris Agreement, substantial investments in clean energy are needed in developing countries. We study the challenges faced by developing countries in accessing financial resources for clean energy investments during the low-carbon transition in a dynamic stochastic general equilibrium model calibrated to Brazil. We show that financial frictions exacerbate the costs of the low-carbon transition and reduce the competitiveness in international capital markets with adverse effects on the inflow of foreign funds. In a policy analysis, we explore different revenue recycling schemes and highlight the advantages of combining carbon taxation with clean energy subsidies to attract foreign funds and accelerate clean capital accumulation. These results underscore the importance of considering financial market responses and international capital market integration in designing efficient climate policies for developing countries and provide a roadmap for policymakers to balance climate ambitions with macroeconomic stability and international competitiveness in emerging economies.

1. Introduction

Decarbonizing global economic activity along the ambitious targets of the Paris Agreement requires an effort from all nations. Kreibiehl et al. (2022), for example, estimate that mitigation investments in developing economies need to increase by factor 4–7 compared to the 2015 levels. While mitigation costs are relatively low in many developing economies (Liu and Feng, 2018), mobilizing the necessary financial resources is challenging for mainly two reasons:

The first is financial development. The financial sector in lower-income countries is often only a relatively small part of the overall economy (Čihák et al., 2013), limiting the access to financial resources across all sectors with severe implications for economic activity. At the macro-level, a well-developed financial system is a prerequisite for direct investment to contribute positively to the a country's economic growth (Hermes and Lensink, 2000). At the micro-level, firms in developing economies are more frequently capital constrained compared to firms in developed economies with adverse consequences for their capital accumulation (Moll, 2014) and economic activity in general (De Soto, 2000). Financial market imperfections affect countries with low financial development more severely (Levine, 2005), causing sub-optimal allocation of funds and welfare losses. The transition to a green economy where fossil fuel-intensive capital is replaced by clean capital is therefore slowed, delayed, and more costly (Schuldt and Lessmann, 2022). In the presence of financial frictions, a sudden write-down of fossil fuel assets decreases the debt capacity of the non-financial sectors, challenging macroeconomic stability and investment capacities (Comerford and Spiganti, 2023). Frictions in the banking sector may not only reduce the efficiency of climate policies, but also increase the welfare costs of the transition (Diluiso et al., 2021; Benmir and Roman, 2020; Carattini et al., 2023; Lessmann and Kalkuhl, 2023).

Second, developing economies are more vulnerable to variations in foreign direct investments compared to advanced economies (International Monetary Fund (IMF), 2023). To attract foreign investors, developing economies need to offer a rate of return on investment that is competitive in international markets. But competitive returns are at risk when national climate policies increase the cost of energy. Carbon taxation, for instance, lowers the return on investment in fossil fuel and energy-intensive industries. Furthermore, due to the international flow of funds, open economies can experience impacts of climate policies that are different from those of a closed economy. Environmental policies generate cross-border spillovers leading to international coordination problems (Ganelli and Tervala, 2011), although the spillover effects of economic shocks depend on the carbon policy instrument in place (Annicchiarico and Diluiso, 2019). According to Grüning (2025)

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the most costly way to decarbonize an open economy is an international increase in the price of fossil fuel, while Xiao et al. (2022) finds that internationally linked emission trading systems lead to economic benefits for all parties involved.

Previous studies on the macroeconomic impact of financial market frictions and climate policies have predominantly focused on closed economies that neither account for the role of international flow of funds, variations in the real exchange rates, nor for the fact that the price of fossil fuels is (largely) set by international markets. Exceptions are Carattini et al. (2024) and Grüning (2025), which we review below. It is furthermore not clear to what extent findings from closed economy studies generalize to open economies. Climate policies that ignore financial market imperfections or openness of developing countries may fail to incentivize investments where they are most urgently needed or implement the transition in an unnecessarily costly way.

In this study we analyze the interactions between financial market frictions, financial openness and climate policy. We make three contributions to the literature. First, we are the first to combine borrower-side financial frictions (as in Bernanke et al., 1999) with an open-economy setting for climate policy analysis. This contrasts with existing open-economy studies that place frictions on financial intermediaries (Gertler and Kiyotaki, 2010; Gertler and Karadi, 2011), where losses in carbon-intensive assets spill over to all sectors via bank deleveraging. With borrower-side frictions, we show that the carbon tax remains effective in reducing emissions as frictions create sector-specific inertia that raises the cost of the transition without undermining its environmental effectiveness. Second, we demonstrate that financial openness interacts with borrower-side frictions in non-trivial ways. Shocks to the foreign borrowing rate do not affect the emission reduction path but significantly alter the macroeconomic costs of carbon taxation, to the point of reversing the sign of output and inflation responses. Furthermore, we show that the currency denomination of entrepreneurial debt matters: when entrepreneurs borrow in foreign currency while earning revenue in domestic currency, the resulting currency mismatch amplifies leverage dynamics through exchange rate movements driven by shocks to international borrowing conditions during the transition. Third, these structural insights have direct policy implications. Because the friction constrains the borrower, not the bank, the appropriate policy instrument operates on the borrower side: clean energy subsidies improve returns on clean capital, reduce entrepreneurial leverage, and thereby sustain the inflow of foreign funds, which addresses both the financial friction and the open-economy channel simultaneously. To this end, we incorporate financial frictions in a small, open-economy model, where foreign debt (and foreign goods) are denominated in foreign currency. Through this additional layer of analysis, we generate insights that are particularly relevant to developing countries.

The paper investigates the impact of financial market frictions on a low-carbon transition in a small open economy. We identify the potential short-term to medium-term impacts of introducing carbon pricing instruments that aim to reduce emissions in line with an exogenous climate target, with particular attention to the response of the flow of funds to the policy. We discuss the implications of the financial market imperfections and financial openness for the design of the climate policy, both in terms of carbon taxation level and tax revenue recycling.

As the basis of our analysis, we use a dynamic stochastic general equilibrium model of a small open economy with financial frictions. We calibrate the model to the Brazilian economy. Among developing countries, Brazil stands out with a large share of private investment in its cross-border financial flows, making Brazil's producing sectors highly connected to international capital markets. Furthermore, the spreads of commercial banks in Brazil are among the highest in the world (Torres and Zeidan, 2016), suggesting substantial financial market premiums. With a GDP per capita of 8717 USD (in 2019), Brazil is classified as an upper middle income country and as a developing country according to UN (2019). Brazil has implemented a number of policies to reduce emissions, including incentivizing renewable energy investments through support auctions and channeling funds through the Brazilian Development Bank (Isah et al., 2023). Direct carbon taxation is not yet among Brazilian policies (ICAP, 2022) but legislation has been passed to implement an emission permit trade system in the following years (ICAP, 2024).

In the model, investments are financed by a mix of domestic and foreign funds. Domestic funds are household savings, channeled through bank deposits, while foreign funds are borrowed on international credit markets at an internationally determined borrowing rate. Variations in the flow of foreign debt impact not only investment levels, but also the real exchange rate of the economy and the stock of debt denoted in foreign currency. Entrepreneurs are subject to default risk and, when taking out bank loans, they must pay a risk premium to cover expected losses. In this way, their equity positions (net worth) become collateralized. The resulting constraint to entrepreneurial debt leads to decelerated capital accumulation.

We study the response of the economy to a sudden introduction of a carbon tax applied to the usage of fossil fuels. A carbon tax increases the cost of using fossil fuels for production of energy goods, and hence promotes substitution of emission-intensive (dirty) energy with capital-intensive (clean) energy. However, the tax increases the cost of energy used as input to other production sectors, which drives up the costs of final goods, causing cost-push inflation and lowering aggregate investment, production, and consumption. Financial frictions amplify these effects by creating inertia in the clean energy investment response. Frictions drive up the cost of clean energy and reduce the availability of energy in production.

The model simulations show how the increased cost of energy reduce the return on capital and thus the competitiveness of the economy on international capital markets. As a consequence, the inflow of foreign funds declines and the domestic currency depreciates. Currency depreciation further increases the relative cost of fossil fuels, as well as the real debt burden of foreign debt denominated in foreign currency. We find that financial frictions and financial openness hardly influence the effectiveness of the carbon tax in terms of emission reductions. However, financial frictions strongly increase the social cost of the transition in an economy integrated with international financial markets.

In policy analyses we explore alternatives for carbon tax revenue recycling to cushion the slowdown of capital accumulation. We find that recycling the tax revenue to households in a lump-sum fashion leads to a significant drop in foreign lending, inflation and depreciation of domestic currency. This results in overall lower consumption despite the direct tax transfers to households. In contrast, combining the carbon tax with a subsidy to clean energy can ensure a faster build-up of clean capital. Subsidies reduce the cost of energy, keep inflation stable, increase the return on capital, and ultimately sustain the inflow of foreign funds.

We conclude that policy makers ought to account for the response of financial markets when designing climate policy. Our findings suggest that economies that are well integrated with international capital markets could benefit from combining carbon taxation with instruments designed specifically to attract clean energy investments.

Related literature

This paper contributes to a relatively recent but rapidly developing literature on the role of the financial sector and financial frictions for economies in transition to low CO_2 emissions. Most of the studies on this topic focus on a closed-economy setting. Studies that extend the analysis of financial frictions and the low-carbon transition beyond a closed economy to include cross-border financial flows as in our study are still scarce. We identified two notable contributions: Grüning (2025) develops an open-economy real business cycle model for Latvia with financial frictions that constrain bank lending as in Gertler and Karadi (2011) to study the effects of environmental, fiscal and bank

regulation policies, and combinations thereof. Grüning evaluates these policies in terms of their effectiveness in reducing emissions and the associated loss of GDP. In contrast, our analysis focuses on the financial implications of carbon pricing and the recycling of its revenues, and the subsequent dynamics of debt. Moreover, by introducing New Keynesian nominal frictions, we can discuss the amplifying inflationary effects of climate policy.

Carattini et al. (2024) investigate the implications of ambitious carbon taxes in a two country setting, calibrated to the EU as the "home" economy and the US as the "foreign" economy, finding that a financial friction as in Gertler and Kiyotaki (2010) has substantial effects: ambitious climate policy in the home economy amplifies transition risk, triggering a recession that spills over to the foreign economy via financial and trade channels. Our model setup differs from their two-country setting, as we study a small-open economy. But more importantly, we focus on a developing economy and its exposure to international market risks, reflected in the calibration to the Brazilian economy and in our analysis of capital inflows as a key determinant of policy costs. In short, we contribute to this literature by highlighting the effect of climate policy on foreign currency denoted debt and flows of international finance, using a calibration that focuses on developing countries that are particularly exposed to these risks.

Both of these studies place the financial friction on financial intermediation, which has more frequently been analyzed in closed economy settings. Examples are Benmir and Roman (2020), Carattini et al. (2023) and Ferrari and Nispi Landi (2023), who study transition dynamics subject to financial frictions as in Gertler and Kiyotaki (2010) and Gertler and Karadi (2011). Other approaches that capture frictions of financial intermediators are the default model of Clerc et al. (2015), used by Giovanardi and Kaldorf (2026) to explore the effects of capital regulation, or the industrial organization model of Monti et al. (1972) and Klein (1971), applied in Lessmann and Kalkuhl (2023).

This choice of friction placement has structural consequences: frictions placed on financial intermediators affect credit supply across sectors and can force recession also in the unregulated (green) sector (as in Carattini et al., 2023), whereas borrower-side frictions create sector-specific inertia that slows but does not block the reallocation from dirty to clean capital. By adopting this approach, we can furthermore isolate how currency denomination of financial contracts interacts with borrower-side leverage constraints, which is not possible in bank-side friction models where the binding constraint applies to aggregate intermediary net worth.

Fewer studies have studied the implications of financial frictions that constrain the borrower as in our study. Schuldt and Lessmann (2022) and Comerford and Spiganti (2023) implement financial frictions following Bernanke et al. (1999) where the borrowing rate is increasing in firm leverage, finding that financial frictions slow down the transition and necessitate higher carbon prices (Schuldt and Lessmann, 2022), and amplify the bursting of a "carbon bubble" in a fire-sale dynamic (Comerford and Spiganti, 2023). Our study differs by extending the scope of the model to international financial flows in an open-economy setting. Moreover, our policy analysis goes beyond carbon pricing and bank regulation, considering green subsidies as a revenue-recycling instrument.

The rest of the paper is organized in the following way. Section 2 outlines the modeling framework. Section 3 describes the model calibration. Section 4 presents the simulation results in two parts. First, we show the response of the main economic variables to the introduction of a carbon tax using a benchmark model with financial frictions. We compare the response to that of a model without frictions, and further discuss the role of financial openness (Section 4.1). Second, we explore scenarios that combine carbon taxation with a clean energy subsidy, and discuss the implications for the usage of foreign financial aid (Section 4.2). Section 5 concludes the paper.

2. Model

We develop a dynamic stochastic general equilibrium (DSGE) model tailored to analyzing the interaction between climate policy, financial frictions, and financial openness. The model economy is populated by a representative household, entrepreneurs in four sectors, aggregators, retailers, capital producers, a capital mutual fund (CMF), a central bank, and the government. The representative household maximizes welfare by choosing consumption, labor supply, and deposits. The entrepreneurs own and manage firms allocated to either of four sectors: non-tradable goods, tradable goods, clean energy, and dirty energy. All entrepreneurs own capital stock, borrow funds from the CMF, and use labor. Entrepreneurs in the dirty energy sector use a fossil resource in addition to capital and labor to produce energy, while clean energy entrepreneurs use only capital and labor, taking no fossil fuel as an input. Entrepreneurs in the non-tradable and tradable goods sectors use energy as an additional input to produce intermediate goods. Aggregators combine clean and dirty energy, and intermediate goods into the energy mix and wholesale goods respectively. Wholesale products are then purchased by retailers, who differentiate the goods and introduce nominal rigidities into the final goods market. Representative capital producers in each entrepreneurial sector manage investment and capital stocks, selling new capital to entrepreneurs and buying back depreciated capital. The CMF acts as a financial intermediary by pooling domestic household deposits and borrowing foreign currency debt from international markets to provide loans to entrepreneurs. The central bank sets the nominal interest rate through a Taylor rule, while the government implements the carbon tax and manages the resulting revenue. To analyze the exposure of the low-carbon transition to international financial markets, we introduced three non-standard features to the model economy:

1. Small Open Economy Setting: To capture the exposure of developing countries to international borrowing conditions, capital purchases can be funded both domestically and from abroad via the CMF. Foreign loans are denominated in foreign currency, and the model economy accounts for the real exchange rate by distinguishing between tradable and non-tradable goods as in Schmitt-Grohe and Uribe (2014).
2. Financial Frictions: Intermediation of capital via the CMF is subject to frictions that add rigidity to financing. Following the framework of Bernanke et al. (1999), the model implements a costly state verification problem where financing conditions depend on the net worth of the borrower, leading to sector-specific risk premiums.
3. Energy Sector Differentiation: The framework distinguishes between clean energy and dirty energy. The production of dirty energy requires fossil fuel as an additional input, the use of which generates carbon dioxide emissions and is subject to a carbon tax.

The model economy consists of a representative household, four entrepreneurial sectors producing clean and dirty energy goods, and tradable and non-tradable intermediate goods, aggregators of energy and wholesale goods, retailers, capital producers, a capital mutual fund, and a central bank. This section introduces the model assumptions and equations. Fig. 1 provides a schematic presentation of the model agents together with the main economic flows. All prices are in real terms, and the final good is the numeraire.

2.1. Households

The representative household maximizes its expected welfare (i.e. the discounted utility) by choosing consumption C_t, labor L_t and deposits D_{t+1} subject to budget constraint in Eq. (3). Welfare is a function of consumption and time worked

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

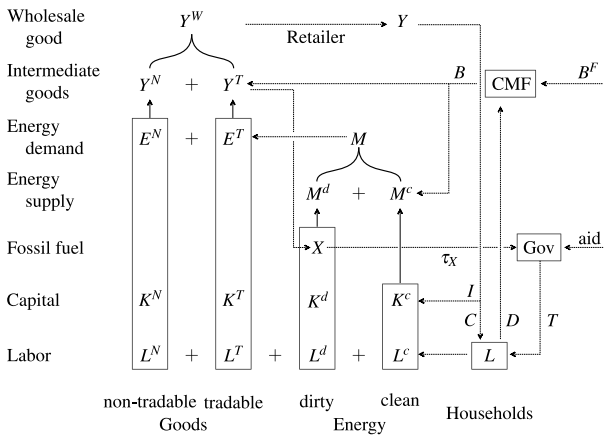


Fig. 1. Model overview. In the model economy, a representative household provides labor and deposits savings in the capital mutual fund (CMF). The CMF combines savings with foreign debt and lends it out to entrepreneurs. The entrepreneurs buy capital from capital producers. Clean and dirty energy is aggregated and used as input to production by tradable and non-tradable goods producer. Retailers differentiate final goods and maintain rigid prices.

where β is the discount factor. Instantaneous utility in each period is given by

$$u = \log\left(C_t\right) + \log\left(1 - L_t\right) \tag{2}$$

At time t, the representative household places deposits D_{t+1} in the capital mutual fund to earn an interest at the gross risk-free domestic interest rate R^H_{t+1}. They furthermore receive labor income $w_t L_t$ where w_t is the real wage, lump-sum transfer T_t from the government, a net transfer of wealth T^e_t from entrepreneurs who sell their businesses, and any profits Π^R_t made in the retail sector. The budget constraint reads:

$$C_t + D_{t+1} = w_t L_t + R^H_t D_t + T_t + T^e_t + \Pi^R_t \tag{3}$$

Maximization of $E[U_t]$ subject to the budget constraint yields the following first order conditions:

$$w_t = \frac{C_t}{1 - L_t} \tag{4}$$

$$\frac{1}{C_t} = \beta E_t\left[\frac{1}{C_{t+1}} R^H_{t+1}\right] \tag{5}$$

2.2. Capital producers

In the model economy, there are four representative, perfectly competitive capital goods producers, one for each entrepreneurial sector. The capital producer of sector i sells capital K^i_{t+1} at the real price Q^i_t to the entrepreneurs in the sector, who will use it to produce intermediate goods. At the end of the period t, capital producers buy depreciated capital $(1-\delta)K^i_t$ from entrepreneurs at price $\bar{Q}^i_t$ and decide the level of new investments I^i_t. Capital depreciates at rate δ and has a real quadratic adjustment cost (last term in (7)).

The maximization problem of the capital goods producers is given by:

$$\max_{I^i_t, K^i_t} Q^i_t K^i_{t+1} - I^i_t - \bar{Q}^i_t (1-\delta) K^i_t \tag{6}$$

subject to the capital accumulation equation:

$$K^i_{t+1} = I^i_t + (1-\delta) K^i_t - \frac{\chi}{2}\left(\frac{I^i_t}{K^i_t} - \delta\right)^2 K^i_t \tag{7}$$

where χ determines investment adjustment cost. The following first order conditions arise:

$$Q^i_t = \frac{1}{1 - \chi\left(\frac{I^i_t}{K^i_t} - \delta\right)} \tag{8}$$

$$\bar{Q}^i_t = Q^i_t\left(1 + \frac{1}{1-\delta}\frac{\chi}{2}\left(\frac{I^i_t}{K^i_t} - \delta\right)\left(\frac{I^i_t}{K^i_t} + \delta\right)\right) \tag{9}$$

2.3. Capital mutual fund

The representative, perfectly competitive CMF provides loans B_{t+1} to entrepreneurs on the basis of two types of liabilities: deposits D_{t+1} from households in domestic currency, and loans B^F_{t+1} from the international financial markets denominated in foreign currency. At the end of period t the CMF creates new loans B_{t+1}, issues new domestic deposits D_{t+1}, and borrows B^F_{t+1} from international financial markets to maximize profits:

$$\max_{D_{t+1}, B^F_{t+1}} R_{t+1} B_{t+1} - \left(R^H_{t+1} D_{t+1} + R^F_{t+1} S_{t+1} B^F_{t+1}\right) \tag{10}$$

where R_{t+1} corresponds to the risk-free interest rate, R^F_{t+1} to the foreign borrowing rate, and S_t to the real exchange rate. The maximization is subject to the following budget constraint:

$$B_{t+1} = D_{t+1} + S_t B^F_{t+1} \tag{11}$$

Under the assumptions of perfect competition and free entry, the CMF earns zero profits in equilibrium. In this model, there is no accumulation of foreign currency wealth, which means that the cross-border financial flow corresponds to the real flow of tradable goods. If the domestic economy demands more tradable goods than it produces itself, the demand can only be met through additional foreign debt obtained by the CMF.

The first order conditions provide the covered interest parity condition and pin down domestic interest rate:

$$R^H_{t+1} = R^F_{t+1} \frac{E_t\left[S_{t+1}\right]}{S_t} \tag{12}$$

$$R^H_{t+1} = R_{t+1} \tag{13}$$

On the international capital market, we assume that the foreign risk-free rate includes a premium that depends on the extent of foreign borrowing:

$$R^F_{t+1} = z_t \bar{R}^F + \kappa\left(e^{B^F_{t+1} - \eta} - 1\right) \tag{14}$$

$\bar{R}_F$ is the steady state foreign borrowing rate, z_t is a stochastic shock variable, taking the value of 1 in steady state, and the second term on the right hand side is the foreign borrowing premium. Eq. (14) closes the open economy model following Gertler et al. (2007) and Schmitt-Grohe and Uribe (2003) with a functional form of the foreign borrowing rate that penalizes surpassing the stationary level of indebtedness. The parameter η represents the country's debt capacity. The price of the tradable good in foreign currency is assumed to be exogenous and set as the numeraire. Consequently, the real price of tradable goods, p^T_t, is equal to the real exchange rate (multiplied by 1, the price of the numeraire).

$$p^T_t = S_t \tag{15}$$

2.4. Entrepreneurs

An entrepreneur j is an individual who owns and manages a productive firm. Heterogeneity between the firms is introduced through differentiated net worth positions. The economy has four entrepreneurial sectors: clean energy (c), dirty energy (d), tradable (T) and non-tradable (N) goods. Each sector consists of a continuum of entrepreneurs who take different types of inputs to their production. Clean and dirty energy goods become energy goods used for production by the other sectors. Tradable and non-tradable goods are aggregated into whole-sale goods.

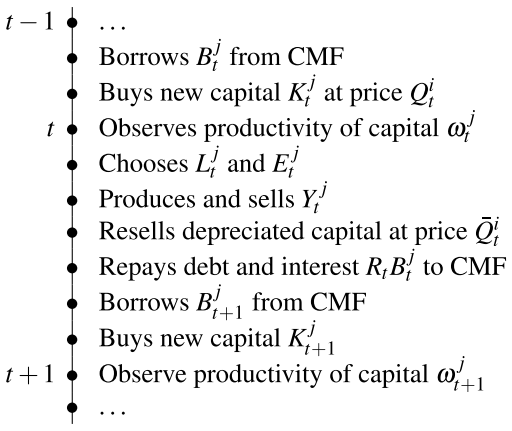


Fig. 2. Timeline of financial and operational decisions of entrepreneur j operating in sector i.

2.4.1. Technologies in entrepreneurial sectors

In the following superscript j denotes the individual entrepreneur, while the superscript $i \in \{T, N, c, d\}$ refers to the sector in which the entrepreneur j operates. Parameters and prices are common for all entrepreneurs in the same sector and therefore take index i, while variables are individual for each entrepreneur and are indexed with j until aggregation.

Entrepreneur j in the goods sectors, $i \in \{N, T\}$, produces output Y_t^j from the inputs of capital K_t^j, labor L_t^j, and energy E_t^j. The production function takes the form of a nested CES-function:

$$Y_t^j = \bar{A}_i \left(\phi_i \left((K_t^j)^{\alpha_i} (L_t^j)^{1-\alpha_i} \right)^{1-\varepsilon_i} + (1-\phi_i) \left(E_t^j \right)^{1-\varepsilon_i} \right)^{\frac{1}{1-\varepsilon_i}} \tag{16}$$

with share parameter ϕ_i, substitution parameters ε_i and output elasticity of capital in the nested function α_i. While the price of the non-tradable intermediate is determined by domestic supply and demand, the price of the tradable intermediate is determined on international markets and denominated in foreign currency (i.e. exogenous to the domestic economy), whereas the output of the non-tradable goods and the energy sectors is priced in domestic currency. Aggregate intermediate goods production is simply the sum, i.e. $Y_t^i = \sum_{j \in i} Y_t^j$ for $i \in \{N, T\}$.

The economy has two types of energy producers, clean c and dirty d. Like the goods production sectors, the output of entrepreneurs in the energy sectors, denoted M_t^{ij}, is given by a nested constant elasticity of substitution (CES) function taking labor and capital as input, but instead of energy the third input is fossil fuel X_t^j.

$$M_t^j = \bar{A}_i \left(\phi_i \left((K_t^j)^{\alpha_i} (L_t^j)^{1-\alpha_i} \right)^{1-\varepsilon_i} + (1-\phi_i) \left(X_t^j \right)^{1-\varepsilon_i} \right)^{\frac{1}{1-\varepsilon_i}} \tag{17}$$

We set the share parameter of the clean energy sector ϕ_c equal to one, which means that the clean energy production function simplifies to a Cobb–Douglas function with only capital and labor, and hence, the clean energy sector takes no fossil fuel as input. In this model, fossil fuel is part of the tradable intermediate goods.[1] Its price is therefore the same as the price of the tradable goods. Aggregate energy supply for sector $i \in \{c, d\}$ is $M_t^i = \sum_{j \in i} M_t^j$.

2.4.2. Entrepreneurs' labor, energy and fossil fuel choices

Consider an entrepreneur j belonging to sector i. Entrepreneur j maximizes her profit through a two-step process: First she obtains a loan B_t^j from the CMF to buy capital K_t^j from the capital producers at the sector specific price Q_t^i. Second, only a fraction ω_t^j of the capital turns out effective, $\bar{K}_t^j = \omega_t^j K_t^j$. Once the entrepreneur knows how much effective capital she has, she decides on the amount of other inputs to use in the production. The inputs depend on the sector (labor and energy or fossil fuels). The produced goods are then sold at the clearing price for sector i, p_t^i, and the depreciated capital is sold back to the capital producers at price $\bar{Q}_t^i$.

First, consider the second step of the maximization problem of entrepreneur j. The return on invested capital (ROI) is given by

$$ROI_t^j = OP_t^j + \bar{Q}_t^i (1-\delta) \bar{K}_t^j \tag{18}$$

where δ is the depreciation rate of capital, $\bar{Q}_t^i$ is the resell price obtained from the capital goods producers, Y_t^j is the output of entrepreneur j and OP_t^j are the operational profits, i.e. the total revenue minus the accumulated cost of inputs other than capital. The expression of operational profits depends on the production function. For tradable and non-tradable goods sectors the operational profits are

$$OP_t^j = p_t^i Y_t^j - w_t L_t^j - p_t^E E_t^j \tag{19}$$

Hence, maximization of ROI with respect to labor and energy gives the following first order conditions:

$$w_t = p_t^i \bar{A}_i^{(1-\varepsilon_i)} (1-\alpha_i) \phi_i \left(\hat{A}_i (K_t^j)^{\alpha_i} (L_t^j)^{(1-\alpha_i)} \right)^{(1-\varepsilon_i)} \frac{(Y_t^j)^{\varepsilon_i}}{L_t^j} \tag{20}$$

$$p_t^E = p_t^i (\bar{A}^i)^{(1-\varepsilon_i)} (1-\phi_i) \left(\frac{Y_t^j}{E_t^j} \right)^{\varepsilon_i} \tag{21}$$

Entrepreneurs in the dirty energy sector take labor and fossil fuel as input in addition to capital. Hence, the operational profits are given by

$$OP_t^j = p_t^d M_t^j - w_t L_t^j - (p_t^X + \tau_t^X) X_t^j \tag{22}$$

The cost of using fossil fuel is the price of p_t^X and a carbon tax τ_t^X. Maximization of the dirty energy entrepreneurs' ROI with respect to labor and fossil fuel input gives the first order conditions:

$$w_t = p_t^d \bar{A}_d^{(1-\varepsilon_d)} (1-\alpha_d) \phi_d \left(\hat{A}_d (K_t^j)^{\alpha_d} (L_t^j)^{(1-\alpha_d)} \right)^{(1-\varepsilon_d)} \frac{(M_t^j)^{\varepsilon_d}}{L_t^j} \tag{23}$$

$$p_t^X + \tau_t^X = p_t^d (\bar{A}^d)^{(1-\varepsilon_d)} (1-\phi_d) \left(\frac{M_t^j}{X_t^j} \right)^{\varepsilon_d} \tag{24}$$

Finally, the clean energy entrepreneurs take only labor as input in addition to capital. On top of the price on clean energy they receive a price subsidy τ_t^c on the output and hence, their operational profits and first order condition with respect to labor are given by:

$$OP_t^j = (p_t^c + \tau_t^c) M_t^j - w_t L_t^j \tag{25}$$

$$w_t = (p_t^c + \tau_t^c)(1-\alpha_c) \frac{M_t^j}{L_t^j} \tag{26}$$

Although the production function and operational profits depend on the sector in which the entrepreneur is operating, all functions exhibit constant-return-to-scale. Therefore, the ROI for optimal choices of labor and energy or fossil fuel for entrepreneur j (regardless of sector) can be expressed in terms of the gross return on capital $R_t^{k,j}$ of entrepreneur j:

$$ROI_t^j = \omega_t^j R_t^{k,j} Q_{t-1}^i K_t^j \tag{27}$$

It can be shown that due to the constant-return-to-scale properties the return to capital is independent of any j-specific values and hence equivalent for all entrepreneurs within the same sector, i.e. $R_t^{k,j} = R_t^{k,i}$ for $j \in i$. Eq. (27) provides a useful notation in the first step of the entrepreneur's problem, i.e. choosing the optimal amount of capital and debt.

[1] We follow the set-up of the single-good economy of Fischer and Springborn (2011), where the output of the production function can be used for consumption, investment, or as an energy input into the production function.

2.4.3. Financial contract

The first step of the entrepreneurs' problem is choosing the amount to be borrowed from the CMF and the capital to be used in the next period (see Fig. 2 for an overview of the timing). At the end of period t the entrepreneur uses its net worth N^j_{t+1} and a loan B^j_{t+1} to buy new capital to be used in next period, i.e.

$$Q^i_t K^j_{t+1} = B^j_{t+1} + N^j_{t+1} \tag{28}$$

Entrepreneurs agree to pay the CMF a Z^j_t interest rate for the loan. However, if the effective capital remains below a threshold, the entrepreneur will not generate sufficient ROI to repay their debt obligations and will default. In this case, only a fraction $1-\mu$ of the entrepreneur's value is recovered, the rest becomes frictional losses. Therefore, the equilibrium interest rate Z must take into account this default risk. For the CMF a loan to entrepreneur j has the following return, conditional on the realization of effective capital:

$$\Pi^{CFM,j}_t = \begin{cases} Z^j_t B^j_t & \text{in case of non-default, } \omega^j_t > \bar{\omega}^j_t \\ (1-\mu)(\omega^j_t R^{k,i}_t Q^i_{t-1} K^j_t) & \text{otherwise} \end{cases} \tag{29}$$

where $\bar{\omega}^j_t$ is the threshold value for the effective capital to lead to default. Here, the CMF anticipates the optimal ROI realized by the entrepreneur according to Eq. (27). The lending rate Z^j_t is given by the following condition:

$$R^{k,i}_{t+1} Q^i_t \bar{\omega}^j_{t+1} K^j_{t+1} = Z^j_{t+1} B^j_{t+1} \tag{30}$$

The expected return for the loan to entrepreneur j is given by

$$E\left[\Pi^{CFM,j}_t\right] = \left(1 - F(\bar{\omega}^j_{t+1})\right) Z^j_{t+1} B^j_{t+1} + \int_0^{\bar{\omega}^j_t} (1-\mu)\omega^j_{t+1} R^{k,i}_{t+1} Q^i_t K^j_{t+1} \, dF(\omega^j_{t+1}) \tag{31}$$

$$= R^{k,i}_{t+1} l^j_{t+1} N^j_{t+1} (\Gamma(\bar{\omega}^j_{t+1}) - \mu G(\bar{\omega}^j_{t+1})) \tag{32}$$

where $F\left(\omega^j_{t+1}\right)$ is the cumulative distribution function of ω^j_{t+1}. The gross share of profits that go to the lender is given by $\Gamma(\bar{\omega}^j_{t+1})$, and $\mu G(\bar{\omega}^j_{t+1})$ is the frictional loss.

$$\Gamma(\bar{\omega}^j_{t+1}) = \bar{\omega}^j_t (1 - F(\bar{\omega}^j_{t+1})) + \int_0^{\bar{\omega}^j_{t+1}} \omega^j_{t+1} \, dF(\omega^j_{t+1}) \tag{33}$$

$$G(\bar{\omega}^j_{t+1}) = \int_0^{\omega^j_{t+1}} \omega^j_{t+1} \, dF(\omega^j_{t+1}) \tag{34}$$

The zero profit condition of the CMF implies that the expected return on the loan is equal to its opportunity costs of funds (determined by the risk-free rate):

$$R_{t+1} B^j_{t+1} = R^k_{t+1} l^j_{t+1} N^j_{t+1} (\Gamma(\omega^j_{t+1}) - \mu G(\omega^j_{t+1})) \tag{35}$$

Using Eq. (28) we write the right hand side in terms of leverage:

$$R_{t+1} B^j_{t+1} = R_{t+1}(l^j_{t+1} - 1) N^j_{t+1} \tag{36}$$

where the entrepreneur's leverage ratio l^j_t is defined as the ratio between the real value of its capital and its net worth.

$$l^j_t = \frac{Q^i_{t-1} K^j_t}{N^j_t} \tag{37}$$

Substituting these equations into Eq. (35), we get the following zero profit condition of the CMF:

$$R_{t+1}(l^j_{t+1} - 1) N^j_{t+1} = R^{k,i}_{t+1} l^j_{t+1} N^j_{t+1} (\Gamma(\bar{\omega}^j_{t+1}) - \mu G(\bar{\omega}^j_{t+1})) \tag{38}$$

In case there exists aggregate risk, the threshold productivity of capital $\bar{\omega}^j_{t+1}$ will depend on the ex-post realization of $R^{k,i}_{t+1}$ (i.e. a realization of the aggregate state of the sector, see Section 3.2 in Bernanke et al. (1999) for more details). Entrepreneurs are risk-neutral and hence offer the lender "a (state-contingent) non-default payment that guarantees the lender a return equal in expected value to the riskless rate" (ibid.). Thus, the borrower chooses the leverage ratio l^j_{t+1} and the threshold productivity of capital $\bar{\omega}^j_{t+1}$ that are optimal for the expected return on capital, however, the borrowing rate and the actual threshold value are contingent on the aggregate realization of $R^{k,i}_{t+1}$.

2.4.4. Entrepreneurs' choice of capital

The entrepreneur's problem of choosing optimal capital stock and borrowing can then be expressed in the following way:

$$\max_{l^j_{t+1}, \bar{\omega}^j_{t+1}} E\left[R^k_{t+1} l^j_{t+1} N^j_{t+1} (1 - \Gamma(\bar{\omega}^j_{t+1}))\right] \tag{39}$$

subject to Eq. (38), i.e. the zero profit constraint of the CMF. It should be noted that since the borrowed amount is determined at the end of the previous period, the leverage ratio l^j_{t+1} is fixed at time t.

Schuldt and Lessmann (2022) show for the costly state verification problem that the choices of $\bar{\omega}^j_{t+1}$ and l^j_{t+1} are the same for all entrepreneurs in each sector i regardless of the individual capital stock, so we can drop the index j. Let Π^i_t be the aggregate entrepreneurial profit in sector i after repayment of debt:

$$\Pi^i_t = R^{k,i}_t Q^i_{t-1} K^i_t - \left(R_t + \mu \frac{G(\bar{\omega}^i_t) R^{k,i}_t Q^i_{t-1} K^i_t}{Q^i_{t-1} K^i_t - N^i_t}\right)\left(Q^i_{t-1} K^i_t - N^i_t\right) \tag{40}$$

The profit equals the return on capital minus the cost of debt. An expression for the external finance premium (defined as the margin on top of the risk-free rate paid on debt) is evident from the second term in Eq. (40).

In each period of time, a fraction $1-\nu$ of entrepreneurs close their business and transfer their net worth to households. At the same time, new entrepreneurs enter, endowed by households with initial seed finance SF^i. These assumptions ensure that the entrepreneurial net worth is stationary. The aggregation of net worth, borrowing and capital stock leads to the following set of aggregate first order conditions of the entrepreneurs in sector i:

$$N^i_{t+1} = \nu \Pi^i_t + SF^i \tag{41}$$

$$C^{e,i}_t = (1-\nu)\Pi^i_t \tag{42}$$

$$0 = \left(\Gamma(\bar{\omega}^i_{t+1}) - \mu G(\bar{\omega}^i_{t+1})\right) R^{k,i}_{t+1} l^i_{t+1} - R_{t+1}\left(l^i_{t+1} - 1\right) \tag{43}$$

$$0 = \frac{R^{k,i}_{t+1}}{R_{t+1}}\left(1 - \Gamma\left(\bar{\omega}^i_{t+1}\right)\right) + \frac{\Gamma'\left(\bar{\omega}^i_{t+1}\right)}{\Gamma'\left(\bar{\omega}^i_{t+1}\right) - \mu G'\left(\bar{\omega}^i_{t+1}\right)}\left(\left(\Gamma\left(\bar{\omega}^i_{t+1}\right) - \mu G\left(\bar{\omega}^i_{t+1}\right)\right)\frac{R^{k,i}_{t+1}}{R_{t+1}} - 1\right) \tag{44}$$

Eq. (41) gives the evolution of the sectoral net worth, Eq. (42) gives the period sectoral transfer of wealth to households, Eq. (43) is the zero profit constraint of the CMF and Eq. (44) defines the optimal debt contract by relating return on capital $R^{k,i}_{t+1}$ to the risk-free rate R_{t+1} and default productivity threshold ω^i_{t+1}. The total net transfer from entrepreneurs to households is then the entrepreneurial consumption less the seed finance:

$$T^e_t = \sum_i (C^{e,i}_t - SF^i) \tag{45}$$

2.5. Aggregators

Tradable and non-tradable goods are aggregated into a whole-sale good through a representative goods aggregator. The aggregator operates under perfect competition, makes no profits, and uses a standard CES function for aggregation:

$$Y^W_t = \left((\phi_W)^{\frac{1}{\varepsilon_W}} (Y^T_t)^{1-\frac{1}{\varepsilon_W}} + (1-\phi_W)^{\frac{1}{\varepsilon_W}} (Y^N_t)^{1-\frac{1}{\varepsilon_W}}\right)^{\frac{\varepsilon_W}{\varepsilon_W - 1}} \tag{46}$$

where ϕ_W is a share parameter and ε_W is a substitution parameter. Y_t^W is the whole-sale output, Y_t^N is the output of non-tradable goods entrepreneurs, and Y_t^T is the tradable goods available for the whole-sale goods market, i.e. the tradable goods entrepreneurial output plus net imports minus the fossil fuel used for production of energy.

The wholesale good aggregator maximizes its profit according to

$$\max_{Y_t^N, Y_t^T} p_t^W Y_t^W - p_t^T Y_t^T - p_t^N Y_t^N \tag{47}$$

subject to Eq. (46). The first order conditions give the following expressions of sectoral prices:

$$p_t^T = p_t^W \left((1-\phi_W) \frac{Y_t^W}{Y_t^T} \right)^{\frac{1}{\varepsilon_W}} \tag{48}$$

$$p_t^N = p_t^W \left((1-\phi_W) \frac{Y_t^W}{Y_t^N} \right)^{\frac{1}{\varepsilon_W}} \tag{49}$$

where p_t^T, p_t^N, p_t^W are the prices of the tradable good, non-tradable good and aggregated wholesale good, respectively.

Like the tradable and non-tradable goods, clean and dirty energies are aggregated into an energy product through a representative CES aggregator. The aggregation leads to the following model equations:

$$M_t = \left((\phi_E)^{\frac{1}{\varepsilon_E}} (M_t^d)^{1-\frac{1}{\varepsilon_E}} + (1-\phi_E)^{\frac{1}{\varepsilon_E}} (M_t^c)^{1-\frac{1}{\varepsilon_E}} \right)^{\frac{\varepsilon_E}{\varepsilon_E - 1}} \tag{50}$$

$$p_t^d = p_t^E \left((1-\phi_E) \frac{M_t}{M_t^d} \right)^{\frac{1}{\varepsilon_E}} \tag{51}$$

$$p_t^c = p_t^E \left((1-\phi_E) \frac{M_t}{M_t^c} \right)^{\frac{1}{\varepsilon_E}} \tag{52}$$

where M_t is the aggregated energy output, M_t^c and M_t^d are the output of the clean and dirty energy sectors. The price of energy is given by p_t^E, while p_t^c and p_t^d are the prices of clean and dirty energy.

2.6. Retailers

The wholesale goods aggregator sells its products in the fully competitive whole-sale market to a continuum of retailers, who then differentiate their products and sell them on the final goods market. By assuming that retailers j face monopolistic competition and have quadratic price adjustment costs à la Rotemberg (1982), we introduce nominal rigidity in the model. The final output is a composite of individual retailers' output:

$$Y_t = \left(\int_0^1 (Y_t^j)^{\frac{\theta-1}{\theta}} dj \right)^{\frac{\theta}{\theta-1}} \tag{53}$$

and we define the aggregate price level:

$$1 = \left(\int_0^1 (p_t^j)^{1-\theta} dj \right)^{\frac{1}{1-\theta}} \tag{54}$$

The left hand side of the equation above is the real price of the final good, which by definition is 1. For any level of output demand for the individual retailer's product is then given by:

$$Y_t^j = \left(p_t^j \right)^{-\theta} Y_t \tag{55}$$

Retailer j pays a marginal cost P_t^W for its input together with a quadratic price adjustment cost (i.e. menu costs), which depends on the cost parameter ψ and the size of the price adjustment. The profit of retailer j is:

$$\Pi_{t+1}^{R,j} = (p_{t+1}^j - p_{t+1}^W) Y_{t+1}^j - \frac{\psi}{2} \left(\frac{p_{t+1}^j}{p_t^j} - 1 \right)^2 Y_{t+1}^j \tag{56}$$

This leads to the following maximization problem of the retailers:

$$\max_{p_t^j} \sum_{k=0} \beta^k E \left[\Pi_{t+k}^{R,j} \right] \tag{57}$$

where β is the discount factor used to discount profits from period $t+k$ to period t. Taking the first order condition and recognizing that all retailers are symmetric (i.e. they face the same costs) and therefore set the same price, we obtain the New Keynesian Phillips Curve from the first order condition:

$$0 = \left(1 - \theta \left(1 - p_t^W\right) - \psi \left(1 + \pi_t\right) \pi_t \right) Y_t + \beta \psi \pi_{t+1} \left(\pi_{t+1} + 1\right) Y_{t+1} \tag{58}$$

where π_t is the price inflation of the final good from period $t-1$ to t.

2.7. Central bank

The central bank sets the nominal interest rate through a Taylor rule. For the specific form we adopt the rule given by Carvalho and Castro (2017) for their model of the Brazilian economy.

$$\frac{R_{t+1}^{H*}}{\bar{R}} = \left(\frac{R_t^{H*}}{\bar{R}} \right)^{\gamma_R} \left[\left(\frac{\pi_t}{\bar{\pi}} \right)^{\gamma_\pi} \left(\frac{GDP_t}{\overline{GDP}} \right)^{\gamma_y} \right]^{1-\gamma_R} \tag{59}$$

$\bar{R}$ is the equilibrium nominal interest rate given an inflation target $\bar{\pi}$, GDP_t is the gross national production at time t, γ_π and γ_y are the weighting parameters of the rule. This version of the Taylor rule balances considerations of previous periods' choice of interest rate (first factor on the right-hand side), preventing too large jumps in the rate, with the usual considerations for inflation and GDP gaps (second factor on the right-hand side).

$\overline{GDP}$ is a measure of domestic production smoothed over time through its moving average:

$$\overline{GDP}_t = \rho \overline{GDP}_{t-1} + (1-\rho) GDP_t \tag{60}$$

We calculate GDP through the expenditure method adjusting for the net cross border flow of funds, i.e.

$$GDP_t = I_t + C_t + \left(R_t^F B_t^F - B_{t+1}^F \right) S_t \tag{61}$$

The nominal rate defines the relation between the real risk-free rate of the economy and inflation and hence, by setting the nominal interest rate through the Taylor rule, the central bank indirectly controls inflation. However, because of price adjustment costs, real returns are also influenced by inflation. As the difference between foreign and domestic rates determines the real exchange rates, setting the nominal rate also affects the real exchange rate.

2.8. Government

The government implements the carbon tax, τ_t^X and distributes the tax revenues and the foreign aid. The government budget constraint is then given by:

$$T_t + \tau_t^c M_t^c = X_t \tau_t^X + S_t A_t \tag{62}$$

where T_t is the government transfers to households, the product $\tau_t^c M_t^c$ is the total expenses on clean energy subsidies, $X_t \tau_t^X$ is the total carbon tax collected, A_t is the foreign aid in foreign currency, and S_t is the exchange rate. We consider only two distinct cases of tax recycling: if the subsidy τ_t^c is non-zero, then the household transfer T_t is zero and vice-versa.

2.9. Market clearing conditions

2.9.1. Labor market

The labor market clears when labor supply by households equals the demand by the four entrepreneurial sectors:

$$L_t = \sum_i L_t^i \tag{63}$$

2.9.2. Energy market

The aggregated energy supply equals the energy demanded by the non-tradable and tradable goods sectors

$$M_t = E_t^N + E_t^T \tag{64}$$

where M_t is the aggregated energy output.

2.9.3. Final goods

Final goods (net of retailers' menu costs and frictional losses in the financial intermediation) are either consumed or invested. The market clearing condition for the final goods is given by the following equation:

$$\left(1 - \frac{\psi}{2}\left(\pi_t - 1\right)^2\right) Y_t^W - \sum_i \mu G(\bar{\omega}_t^i) R_t^{k,i} Q_{t-1}^i K_t^i = C_t + I_t \tag{65}$$

where the sum in the second term on the left-hand side is the total losses due to financial frictions in the four entrepreneurial sectors, and $I_t = I_t^N + I_t^T + I_t^c + I_t^d$ is the total investments. Capital adjustment costs are not included in this constraint, as in this model, adjustment costs affect the capital stock, not investments, according to Eq. (7).

2.9.4. Tradable and non-tradable goods

Non-tradable goods can only be produced and consumed domestically, hence the output of the non-tradable goods entrepreneur equals the goods available for aggregation. This is not the case for the tradable goods. The tradable goods available for aggregation (Y_t^T) are the output of the tradable goods entrepreneurial sector $Y_t^{T,\text{output}}$ less the fossil fuel consumed by the dirty energy sector, and then adjusted for the net cross border flow of funds. This results in the following market clearing condition:

$$Y_t^T = Y_t^{T,\text{output}} - X_t + B_{t+1}^F - R_t^F B_t^F \tag{66}$$

The market clearing conditions complete the set of model equations.

2.10. Policies

We model the low-carbon transition through a sudden introduction of a carbon tax τ_t^X applied to the use of fossil fuels and paid by the dirty energy producers. The carbon tax is constant in real terms (i.e. inflation adjusted), and once introduced, it remains in place. The carbon tax is a fundamental part of all climate policies analyzed in this paper. In the benchmark scenario, the carbon tax is recycled directly to households in terms of lump-sum transfers T_t. In the alternative tax recycling scenario, the proceeds of the carbon tax are awarded to the clean energy producers as a subsidy (τ_t^c). The level of subsidy depends on tax revenues and clean energy production for each period. In addition to the sudden introduction of the climate policy, we simulate the transition under variations to the international borrowing rate. We do this by analyzing the model response to the introduction of carbon tax coinciding with a shock to the foreign rate. The foreign borrowing rate is adjusted by z_t, which is determined by the following equation:

$$z_t = \rho_z z_{t-1} + \varepsilon_t^z \tag{67}$$

where ρ_z is a persistence parameter and ε_t^z is the shock variable. We set z_t to 1 in steady state.

3. Calibration

3.1. Benchmark calibration

As is common for DSGE studies that focus on identifying the mechanisms and channels through which policies operate (e.g. Giovanardi and Kaldorf, 2026), we calibrate the model to match observations, linking parameter values to the literature and data to ensure transparency and traceability of assumptions. Table 2 evaluates the fit of the calibrated model's steady state to empirical counterparts.

Table 1
Calibrated parameters (time unit of model: quarter).

Households		
β	Discount factor	0.9855
Capital good producers		
δ	Capital depreciation rate	0.02
χ	Investment adjustment cost parameter	0.59
Financial intermediation		
μ	Bankruptcy cost	0.873 (0)
σ	Success uncertainty	0.32
ν	Survival rate	0.92
SF	Seed finance	0.001
Foreign behavior		
η	Debt capacity	0.214 (0.395)
κ	Scaling parameter	0.212
Energy producers		
$\alpha_{c/d}$	Output elasticity of capital	0.3/0.3
$\bar{A}_{c/d}$	Productivity	1.0/2.15
ϕ_d	Share parameter	0.7
ϵ_d	INVERSE elasticity of substitution	3.333
Goods producers		
$\alpha_{T/N}$	Output elasticity of capital	0.497/0.372
$\bar{A}_{T/N}$	Productivity	1.035/0.996
$\phi_{T/N}$	Share parameter	0.645/0.811
$\epsilon_{T/N}$	INVERSE elasticity of substitution	2/2
Energy aggregators		
ϕ_E	Share parameter	0.75 (0.665)
ϵ_E	Elasticity of substitution	5
Goods aggregators		
ϕ_W	Share parameter	0.54
ϵ_W	Elasticity of substitution	2
Retailers		
ψ	Price adjustment cost	93.2
θ_R	Elasticity of substitution	9
Central bank		
$\bar{\pi}$	Annual Inflation target	0.045
$\bar{R}$	Quarterly equilibrium interest rate	0.0231
γ_R	Taylor rule parameter	0.825
γ_π	Taylor rule parameter	1.966
γ_y	Taylor rule parameter	0.185
ρ	Moving average parameter	0.9
Shock parameters		
ρ_z	Carbon tax persistence parameter	0.999999
ρ_k	Foreign-rate persistence parameter	0.99

For the calibration of the model to the Brazilian economy, we utilize literature estimates, data from the GTAP database (Narayanan and Walmsley, 2008), the World Bank (2022a) and the Banco Central do Brasil (2022). An overview of parameter values is provided in Table 1 and we evaluate the fit of the model's steady state to empirical counterparts in Table 2.

We choose a standard quarterly discount factor β equal to 0.9855 such that the model generates a steady state real risk-free rate of 6 percent.

We follow Carvalho and Castro (2017) by setting the quarterly depreciation rate of capital producers δ to 0.02 and, following Christensen and Dib (2008), we set the investment adjustment cost parameter χ to 0.59.

We calibrate the parameter of foreign debt capacity η to 0.214 such that the ratio of foreign debt to GDP is close to its empirical value in Table 2, row 6. The sensitivity parameter κ determines the response of foreign debt to variations in the foreign borrowing rate. We estimate a κ equal to 0.212 by fitting Eq. (14) to historical Brazilian foreign debt data during the period 1999–2018 (World Bank, 2022b). We use the US real interest rate as a proxy for the international borrowing rate (World Bank, 2022c).

Table 2
Steady state values and empirical counterparts. Ranges represent minimum and maximum values in years from 2015 to 2019 or ranges found in the literature. Data sources by rows: 1–5, 12–13: World Bank (2022c); 6–9: World Bank (2022b); 10: Bortoluzzo et al. (2022); 11: World Bank (2022a,b,c); 14: Banco Central do Brasil (2022).

#	Description	Symbol	Model	Data
1	Gross capital formation to GDP	I/GDP	0.097	0.155–0.174
2	Final consumption expenditure to GDP	C/GDP	0.895	0.837–0.851
3	Fossil energy ratio	$E^d/(E^d+E^c)$	0.578	0.565–0.591
4	Net trade in goods to GDP	$(R^F B^F - B^F)/GDP$	0.009	0.001–0.028
5	Real exchange rate	S	0.878	0.576–0.684
6	Foreign debt to GDP	SB^F/GDP	0.136	0.136–0.159
7	Bank deposits to GDP	D/GDP	0.4149	0.570–0.687
8	Bank credit to bank deposits	$\sum_i B^i/D$	1.329	0.904–1.173
9	Debt to equity	$\sum_i B^i/\sum_i N^i$	0.836	0.502–1.541
10	Annual bankruptcy rate	$F\left(\bar{\omega}_{T/N/d/c}\right)$	0.031–0.035	0.001–0.040
11	Total bankruptcy costs to GDP		0.015	0.016–0.019
12	Annual external finance premium	$Z_{T/N/d/c} - R$	0.025–0.028	0.053–0.096
13	Annual risk-free rate	R	0.060	0.053–0.148
14	Annual inflation rate	π	0.057	0.035–0.090

Estimates for the output elasticity of capital in the dirty and clean sector α_d and α_c, the share parameter for the capital labor composite in the production of dirty energy ϕ_d, and the elasticity of substitution between the capital labor composite and fossil fuel $1/\varepsilon_d$ are borrowed from Diluiso et al. (2021). The efficiency of dirty energy production $\bar{A}_d$ is set such that the steady state features the fossil energy ratio reported in Table 2, row 3.

We utilize the GTAP database to determine parameter estimates in the tradable and non-tradable goods producing sectors.[2] The equations used for calibration are described in Appendix C and the parameter values are reported in Table 1. Estimates of the inverse elasticity of substitution $\varepsilon_{T/N}$ are borrowed from Diluiso et al. (2021).

All types of entrepreneurs in this model obtain debt through financial intermediaries that are subject to financial friction. The strength of frictions is determined primarily through the parameters bankruptcy costs μ, the uncertainty of the success of entrepreneurs σ, and the survival probability of entrepreneurs ν. The World Bank (2022a) reports recovery rates for Brazil ranging from 12.7 to 18.3 percent for the period 2015 to 2019. Therefore, we set the share of realized profits lost in bankruptcy to $\mu = 0.873$. The standard deviation of $log(\omega)$, expressing the uncertainty of the success of entrepreneurs, is fixed at $\sigma = 0.32$ and the survival probability of entrepreneurs at $\nu = 0.92$ to match the debt equity ratios and bankruptcy rates reported in Table 2, rows 9 and 10. Values for bankruptcy cost μ, entrepreneurial success uncertainty σ, and entrepreneurial default rates $1-\nu$ are above the conventional ranges used in the literature (e.g. Bernanke et al. (1999), Gertler et al. (2007) and Christiano et al. (2014)) and are expressions of the relative challenging economic conditions in Brazil when compared to the rather developed economies in the model regions for mentioned publications. For the transfer of funds from households to entrepreneurs SF, we choose an infinitesimally small value below the estimate of Christiano et al. (2010) to not generate an additional significant source of entrepreneurial net worth.

For energy aggregators, the values for the share parameter for dirty energy ϕ_E, and the elasticity of substitution between dirty and clean energy ε_E are taken from Diluiso et al. (2021) and reported in Table 1.

The share parameter of tradable goods ϕ_W with the goods aggregator is calculated using GTAP data, following the procedure described in Appendix C. The elasticity of substitution between tradable and non-tradable goods is borrowed from Cavalcanti and Vereda (2016).

Retailers are subject to price rigidities à la Rotemberg (1982) and we adopt the price adjustment cost parameter ψ and the elasticity of substitution between goods varieties θ from Diluiso et al. (2021).

The Taylor rule parameters γ_R, γ_π, and γ_y are borrowed from Carvalho and Castro (2017) who apply a similar rule to describe the Brazilian central bank. Inflation targets for the period from 2015 to 2019 are obtained from Banco Central do Brasil (2022) and averaged to calculate $\bar{\pi}$. The equilibrium interest rate $\bar{R}$ is set such that observed inflation is achieved (cf. Table 2).

3.2. Climate policy and foreign aid scenarios

Though lately in decline, Brazilian emissions from land-use related activities have historically been substantial, while energy-related per capita greenhouse gas emissions are low (La Rovere, 2017). In this paper, we focus on energy-related emissions only. To calibrate the climate policy, we use Brazil's "fair share" contribution that is compatible with the global warming target of 1.5 degree. Brazil's fair share contribution amounts to 856 Mt CO_2 (excl. LULUCF) in 2030 according to Climate Tracker (2022). The absolute emission level was 1110 MtCO_2e in 2019 (Climate Transparency, 2022), which gives approx. 23 percent fair share reduction until 2030. The current Brazilian government intends to implement carbon pricing as a climate policy and has recently passed legislation to establish an emissions trading system, the *Sistema Brasileiro de Comércio de Emissões de Gases de Efeito Estufa* (SBCE) (as reported, for example, in ICAP, 2024). We set the carbon tax levels such that the model economy's response to the introduction of this unannounced and flat carbon tax schedule yields emission reductions of 23 percent in the new equilibrium of the benchmark economy that is assumed to be reached after 200 quarters.

The model considers only one generic fossil fuel. Translating model prices into real world prices requires calculating a weighted price and weighted emission index of one unit of fuel equivalent, i.e. the average fuel in the primary energy mix. We use primary energy supply data (IEA, 2022), fuel price data (World Bank, 2023) and carbon intensity for each fuel type (United States Environmental Protection Agency (EPA), 2021) to do so. The calculation is based on oil (assumed crude oil) and natural gas only, since the Brazilian coal consumption is insignificant. The resulting carbon tax level is 14.9 USD per tCO_2.

International aid could potentially incentivize the introduction of strict climate policy in developing countries by compensating for some of the associated cost. To date, Brazil has received 394.8 million USD in support from the Green Climate Fund, which is approximately 3.3 percent of the total funds (12 billion USD as of 2023) (Green Climate Fund, 2023). If the fund were to fulfill its target of 100 billion USD per year, and Brazil continued to receive the same share, then it would

[2] Within the GTAP database, we aggregate data as follows: regions are Brazil and the rest of the world; sectors are energy (oil, gas, coal, petroleum, coal products and electricity), non-tradable (construction, trade, transport, communication, financial services, insurance, business services, recreation, administration, health, defense, education and dwellings) and tradable (all other); factors of production are capital (capital, land, natural resources) and labor (skilled and unskilled). For the calibration we consider agents' prices instead of market prices to also include tax liabilities (and subsidies) associated with the factors of production and intermediate goods.

receive 3.3 billion USD per year. We calibrate the aid introduced in the model to this level. Brazil received on average 797 million USD in Official Development Assistance (Gross ODA) in 2019–2020 and 28 percent of the bilateral ODA went to infrastructure investments (OECD, 2022), hence 3.3 billion USD is a fairly large figure.

For policy comparisons of the net present value of GDP changes, we follow Moore et al. (2020) and set the social discount rate to 4.36 percent, fairly close to the risk-free rate (cf. Table 2, row 13).

3.3. Counterfactual frictionless calibration

The response of the economy with financial frictions is compared with that of a frictionless economy. To model the frictionless economy, we set the bankruptcy cost parameter μ to zero, which implies there are no costs related to defaults. To ensure that the steady state emission intensity is comparable to the model with friction, we slightly adjust the share parameter ϕ_e of the energy aggregator. In addition, the debt capacity parameter η of the foreign borrowing constraint is updated to 0.395 for the model to produce a similar foreign debt to GDP ratio for the frictionless model. The parameters are reported in parentheses in Table 1.

3.4. Counterfactual more open and less open calibrations

The sensitivity of the foreign debt level to fluctuations in the foreign borrowing rate is expressed through the parameter κ in Eq. (12), calibrated in the benchmark model as described above. To study the sensitivity of the model response to the degree of openness, we vary the value of κ. A high value implies little or no variation in the foreign debt level in response to changes in the lending rates, which is expected for an economy that is poorly integrated with the global financial system. We shall refer to such an economy as *less open*. In contrast, a low value implies large variations, implying a more pronounced reaction to changes in the global financial system. We call this economy *more open*. For the counterfactual modeling we set κ to 2 orders of magnitude smaller or larger than the benchmark value, respectively.

3.5. Model fit

Table 2 reports steady state values of the model and corresponding empirical counterparts. Most values are within the range of empirical counterparts, or close to it. Data for GDP shares of investment and consumption, for the fossil energy ratio, and net trade in goods (rows 1–4) are taken from the World Development Indicators (World Bank, 2022c). From the same source, we use the *Price level ratio of PPP conversion factor (GDP) to market exchange rate* as a measure for the real exchange rate (row 5). Values on foreign debt (international debt issues), bank deposits, bank credit and debt to equity (rows 6–9) are reported in the Global Financial Development database (World Bank, 2022b). The debt-to-equity ratio is calculated as the ratio of gross portfolio debt liabilities to gross portfolio equity liabilities. The annual bankruptcy rate (row 10) is borrowed from Bortoluzzo et al. (2022) who report rates for small, medium and large companies. Total bankruptcy costs (row 11) are calculated as one minus the recovery rate reported in the Doing Business data set (World Bank, 2022a) weighted by the ratio of non-performing bank loans to GDP from the Global Financial Development database (World Bank, 2022b). The World Development Indicators (World Bank, 2022c) also provide data on real interest rates, risk premiums on lending, and inflation rates. Risk premiums on lending are recorded as the difference between the lending rate and the treasury bill interest rate. Such mark-ups on the lending rate finance operating costs, tax expenditures, profits, and loan-loss provisions on the banks' income statements. In the model, external finance premiums finance loan-loss provisions only and we therefore apply the share of loan-loss provisions of net interest income for Brazil from Calice and Zhou (2018, Table 3) as a factor to the risk premium obtained from World Bank (2022c). The resulting nominal external finance premiums are divided by inflation to yield real annual external finance premiums (row 12) for Brazil. The real risk-free rate (row 13) is calculated by subtracting the real risk premium on lending from the real interest rate.

4. Results

We report results in two parts. In the first part, we examine the role of financial frictions and financial openness in a small open economy when the low-carbon transition is driven by a carbon tax. The tax is paid by the dirty energy producers for the use of fossil fuels and the tax revenues are recycled to households as lump-sum transfers. In the benchmark version of the model, the economy is open and financial frictions are calibrated as described in Section 3.1. We compare the model response to a *no frictions* scenario, in which there are no costs associated with defaults (cf. Section 3.3) and show that the frictions only have a relatively small effect on the emission path, but greatly increase the costs of the transition by reducing the inflow of foreign funds. We then explore the role of openness by varying the degree to which foreign debt responds to the introduction of a carbon tax and combine the carbon tax with variations in the foreign borrowing rate. We find that, just like financial frictions, the degree of openness does not affect the emission path, but alters the impact of the policy on consumption and output.

In the second part, we discuss the impact of policy design on the low-carbon transition trajectories in the open economy with financial frictions. We introduce a targeted industrial support to the clean energy sector (clean energy subsidies) as an alternative use of the carbon tax revenues and analyze the response of the economy to such a policy scheme. We show that subsidies allow for a much faster scale-up of clean energy, and by keeping the cost of energy low, a subsidy policy can significantly reduce the short-term welfare losses implied by the carbon tax. Finally, we model the effects of foreign aid on the low-carbon transition and show that foreign aid can counteract some of the negative welfare implications from the climate policy.

4.1. Financial frictions in the open economy

Financial frictions act like an adjustment cost that creates inertia in the adjustment of the capital structures. As such, they affect the steering effect of the policy during the transition, but have little impact on the post-transition steady states.[3]

The basic transmission mechanism of an unannounced and flat carbon tax schedule remains intact throughout all model variations studied in this paper. We thus summarize its mechanics before we discuss specific scenarios. We use the benchmark model simulation in Fig. 3 to illustrate the explanation. The same forces are at play in the other scenarios below.

Fig. 3 shows the response of the benchmark model of selected economic variables following the introduction of a climate policy, modeled as a permanent carbon tax shock (τ^X in Eq. (22)).[4] The carbon tax increases the cost of using fossil fuels in energy production, making fossil fuel-based (dirty) energy more expensive, and hence, promoting substitution towards fossil fuel free (clean) energy (Fig. 3A). The declining profitability of dirty energy entrepreneurs is reflected in

[3] Figs. 3–7 focus on the next decades. Variables that have not converged to their new steady state levels by 2030 do so soon after.

[4] We opt for an immediate implementation of the carbon tax at its new level for its simplicity and clean results. A gradual phase-in, while more realistic, introduces a more complex model response where it levels off to its final value. We check the robustness of our findings to the timing of policy implementation in a sensitivity analysis and find that a gradual phase-in of the carbon tax over five years produces qualitatively similar results, with smaller absolute impacts but preserved relative rankings across policy designs and model variants. This analysis is reported in Appendix E.

the corresponding reductions in investment and capital stock in this sector (Fig. 3B). By the end of year 2030 the dirty energy capital stock is reduced 18 percent, while the clean energy stock has increased 12 percent. The increasing cost of fossil fuel increases the price of energy with approximately 3 percent, leading to a decrease in overall energy consumption.

As energy is an input to the goods producing sectors, the higher price of energy drives up the input costs, leading to less energy consumption. Less energy as input to production lowers the marginal return on capital and labor. In this way, carbon taxes lead to lower production (Fig. 3G). The lower return on capital implies a reduction in the overall level of investment and domestic savings (Fig. 3H). It also impedes the inflow of foreign funds, leading to a drop in the level of foreign debt (Fig. 3J). With the decelerating inflow of foreign funds, less tradable goods are available in the economy, driving up the price of the tradable good and, hence, the real exchange rate. At the same time, higher production costs and lower domestic production increase inflation (Fig. 3F), leading to losses (menu costs) that add to the contractionary pressure on the economy. The estimated impact on inflation is an increase from 5.7 percent per year in steady state to 6.1 percent upon the introduction of the carbon tax.

Since this model does not consider economic damages from climate change, the carbon tax appears distortionary. As the benefits of emission reductions are long-term and depend on global emission, this reflects the lack of incentives for a small economy. The following sections show how financial frictions and financial openness may aggravate these distortions. As the benefits do make a difference for the welfare assessment of policies, we include avoided climate damages in Section 4.2.

4.1.1. The role of frictions in the open economy

The debt of the dirty energy sector decreases, while the growth of the clean energy sector is accompanied by an expansion in its debt level. However, the net worth of the clean energy sector increases only slowly with the accumulating capital stocks. As a result, the leverage ratio peaks (Fig. 3C) followed by a higher risk of default. In the presence of financial frictions, the external finance premium of the clean sector increases, resulting in higher costs for clean energy.

At the same time, the finance premium in the dirty sector is falling. Despite the adverse effect of climate policy on the net worth of the dirty energy sector, its low demand for new investments drives down the leverage ratio (Fig. 3C) and therefore the finance premium.

The question of aggregate leverage across the entire economy is also relevant for assessing financial stability during the transition. While the leverage ratio increases substantially in the clean sector, the effect on aggregate leverage is small for two reasons. First, as the dirty sector shrinks during the transition, it deleverages, which counteracts the increasing leverage in the clean sector. Second, the energy sectors are small by comparison to the rest of the economy, so their impact on aggregate leverage is negligible. In our simulations, aggregate weighted leverage increases only slightly in the first period post-shock (as net worth and debt are pre-determined), then drops below steady state. The maximum deviation is just 0.06 percent above the steady state of 1.836, while the minimum reaches −0.16 percent. This indicates that the transition does not put stress on the financial system as a whole; any frictions are purely sectoral. The clean energy sector is the only increasing force for leverage as it scales up capital, but the dirty sector counteracts this, and for overall capital the effect hardly matters.

Fig. 3 also indicates the role of financial frictions during the transition by highlighting the differences from the model without frictions. In an economy without frictions, there is no cost related to defaults, and hence external finance premiums are zero throughout. Entrepreneurs are not restricted when borrowing from banks and are nearly completely financed through debt. For this reason, the leverage ratio plays no role in the frictionless economy and is not shown in the figure.

A comparison between the economy with frictions and the counterfactual frictionless indicates that frictions and the growing external finance premiums on clean energy loans have a clear impact on the speed with which clean energy capital is scaled up (Fig. 3B). For instance, we estimate that clean energy capital would increase by 10 percent by 2025 in the presence of financial frictions, compared to a 14 percent increase if there were no financial frictions. Due to the decelerated clean energy investments, frictions slow the substitution of dirty energy and thus, a larger share of the energy is subject to the carbon tax. This implies slightly higher energy prices, which further reduces the return on capital in the goods sectors, leading to an overall lower level of investment. The additional pressure on the energy costs under frictions results in a stronger decline in foreign debt, indicating that financial frictions make it harder to stay competitive in international capital markets. The drop in the inflow of foreign funds (Fig. 3J) in turn has adverse effects on consumption (Fig. 3I), which clearly suffer more under frictions.

The adjustment speed of sectoral capital stocks can be quantified by computing the time required to complete 90% of the adjustment to the new steady state following the carbon tax introduction. In the benchmark economy with financial frictions, clean energy capital requires 8.25 years to reach this threshold, whereas in the frictionless counterfactual, the transition is completed in just 1.75 years. This delay by 6.5 years reflects the banking system's limited capacity to supply credit during the transition: without financial frictions, entrepreneurs face no borrowing constraints and can scale up investments immediately. The effect is asymmetric across sectors. Dirty energy capital takes 9 years to adjust with frictions and 7.25 years without, implying only a delay of 1.75 years. Scaling up clean capital is more severely affected than scaling down dirty capital because expansion requires borrowing, which is directly constrained by financial frictions. This asymmetry highlights that financial intermediation capacity is a critical bottleneck for the pace of low-carbon transition.

This interplay of carbon tax and financial frictions contrasts with the "financial accelerator" effect of a productivity shock, as frequently explored in business cycle models. A positive productivity shock raises asset prices, leading to an increase in net worth, which then lowers the leverage and reduces the external finance premium (see e.g. Bernanke et al. (1999)). Frictions amplify productivity shocks because leverage is counter-cyclical. However, the leverage response is ultimately the result of the shock's impact on net worth relative to the demand for capital. The carbon tax shock affects prices not productivity, and has a stronger impact on the demand for capital than on the net worth—opposite to productivity shocks.

The simulation results indicate that the relative change in fossil fuel consumption is almost identical in the two models (Fig. 3D). Financial frictions slow down the decarbonization slightly in the short term but by 2030 the difference has all but vanished. However, frictions result in a 3 percent increase in emissions that accumulate during the transition period.

In the short term, the policy's ability to foster replacement of dirty energy capital with clean energy capital greatly depends on the level of frictions. Without a cheap, clean substitute for fossil fuel-based energy, the transition becomes costly. In conclusion, the main impact of frictions on the low-carbon transition is not on the effectiveness of the carbon tax but rather in the economic cost of the policy: frictions lead to a much stronger decline in the inflow of foreign funds, higher incentive for savings, and therefore less consumption.

4.1.2. The role of openness in the frictions economy

The section above discussed the role of financial frictions in a small open economy and showed that financial frictions interact with the inflow of foreign funds. Frictions reduce the return on capital making the economy less competitive on international markets. In this section, we explore this property further — we turn the question around, and discuss the role of financial openness in an economy with frictions. We

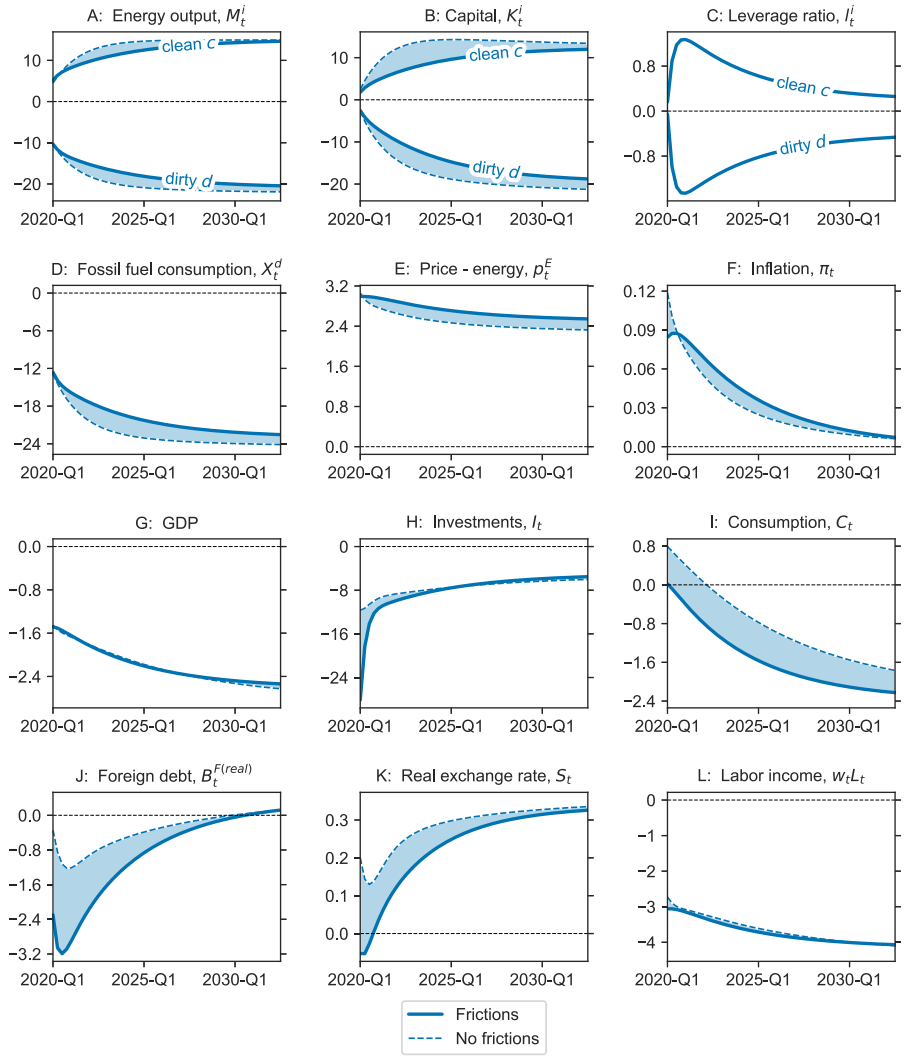


Fig. 3. The benchmark model response to the introduction of a carbon tax. Response values are reported as percentage deviation from steady state values, except inflation that is reported in percentage points. The shaded area indicates the difference to the same model without frictions. The leverage ratio is not shown for the frictionless model, as the lack of frictions implies fully debt-financed investments.

show that the emission path remains largely unaffected by the degree of financial openness, however, output and consumption are affected.

Note that fossil fuel is assumed to be a good available for international trade. Therefore, it is valued and priced as a tradable good with a price equivalent to the real exchange rate. Consequently, variations in the level of foreign debt, which affect the exchange rate, also have implications for the cost of fossil fuels.

Fig. 4 shows the response of the benchmark model to the sudden introduction of a carbon tax together with the response of the model where the sensitivity parameter κ is 2 orders of magnitude smaller or greater than the benchmark value, respectively.[5]

The tax increases the cost of fossil fuels and induces a reduction in its use (Fig. 4D). This reduction in the use of fossil fuels leaves more tradable goods for consumption and investments. However, the carbon tax lowers the return on capital by increasing the cost of energy, and hence, in the open economy, the supply of foreign funds declines (foreign debt, Fig. 4J), reducing the availability of goods in the economy. This effect increases with the level of openness: Fig. 4J shows how a decline in foreign debt is far greater in the more open economy than in the benchmark model. The steep reduction in the supply of tradable goods raises the real exchange rate (Fig. 4K) and thus the price of fossil fuel. That is, in the open economy the rise in the cost of fossil fuel from the carbon tax is exacerbated by the reaction of the real exchange rate. This is in contrast to closed-economy settings, where the increased price of fossil fuel implies a drop in demand which cushions the upward pressure on fuel prices.

In the less open version of the economy, the foreign debt level does not adjust, and therefore the lack of demand for fossil fuel leads to a short-term excess supply of tradable goods, which in turn causes a currency appreciation and lower energy prices in the first periods.

Despite the differences in the impact on the model economies, Fig. 4A–D indicate that the level of financial openness only has a minor impact on the transition path. Emissions (Fig. 4D) are almost identical in the three cases shown. Additionally, capital stocks in the energy sectors (Fig. 4B) evolve almost identically following the introduction of a carbon tax. The reason behind this result is the difference in output: The drop in foreign debt in the more open economy reduces the number of goods available in the economy, and creates an incentive for domestic production. Hence, the more open economy may experience higher output compared to the benchmark. More output leads to

[5] The steady state level of foreign debt is the same as in the benchmark model. The focus of the section lies on the role of the degree of sensitivity towards variation in international markets, not the steady state debt size, although in real life, these two properties may be connected.

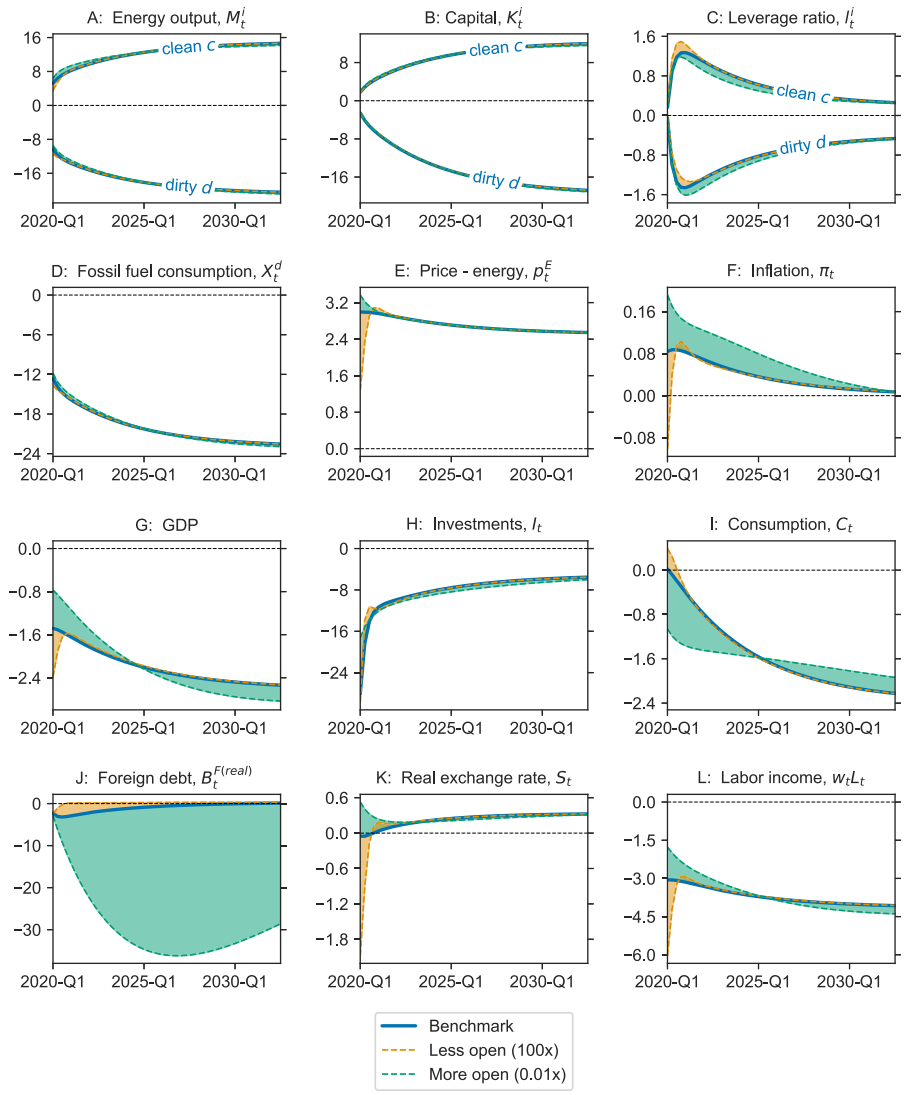


Fig. 4. The benchmark model response to the introduction of a carbon tax. Response values are reported as percentage deviation from steady state values, except inflation that is reported in percentage points. The shaded areas show the response for variations in the κ parameter that determines the sensitivity of foreign debt level to variations in the foreign borrowing rate.

higher demand for inputs, including energy, which implies an increased demand for fossil fuels despite higher prices. Domestic production cannot offset the drop in inflow of foreign funds, and therefore high sensitivity to international borrowing conditions has adverse effects on consumption (Fig. 4I), inflation (Fig. 4F), and price adjustment costs during the transition.

The analysis of the impact of financial frictions on foreign debt presented in Section 4.1.1 indicates that frictions exaggerate the decline in foreign debt following the introduction of a carbon tax. Here, we find that the degree of openness interacts with the frictions. A more open economy experiences higher prices that increase the net worth of entrepreneurs. Higher net worth implies lower leverage ratios (Fig. 4C) and therefore lower frictional losses. It should be noted that the leverage ratios of both the clean and dirty energy sectors are lower in the more open economy, whereas they are higher for both sectors in the less open economy. Because the degree of openness pushes the leverage ratio of the two sectors in the same direction, openness does not offer any relative advantage for either sector. Consequently, there is no effect on the substitution dynamics of the two capital stocks during the transition.

4.1.3. *Variations in the foreign borrowing rate*

Financial openness implies that the economy is sensitive to variations in the foreign borrowing rate, and hence any changes in the borrowing conditions in the international capital markets will carry over to the domestic economy. We find that such variations have only minor effects on the effectiveness of climate policy and its ability to facilitate clean energy investment, but they dominate short-term effects on consumption, output, inflation and foreign debt. In this section, we discuss the response of the economy to a carbon tax under variations of the foreign borrowing rate, i.e. at the same time the tax is introduced, a shock to the borrowing rate on the international market materializes (z_t in Eq. (14)). Fig. 5 shows the response to foreign rate shocks corresponding to ± 1 and ± 2 standard deviations, where the positive and negative one-standard-deviation shocks change the annualized foreign rate on impact by approximately +1.13 and −1.97 percentage points, respectively.

Variations in the level of the foreign borrowing rate have a substantial impact on the foreign debt level. When the cost of foreign debt declines (for a negative shock to the foreign borrowing rate), the level of debt increases substantially (Fig. 5J). The intensified inflow of foreign funds depresses the real exchange rate in the short term (currency appreciation, cf. Fig. 5K), making fossil fuels and, subsequently, energy

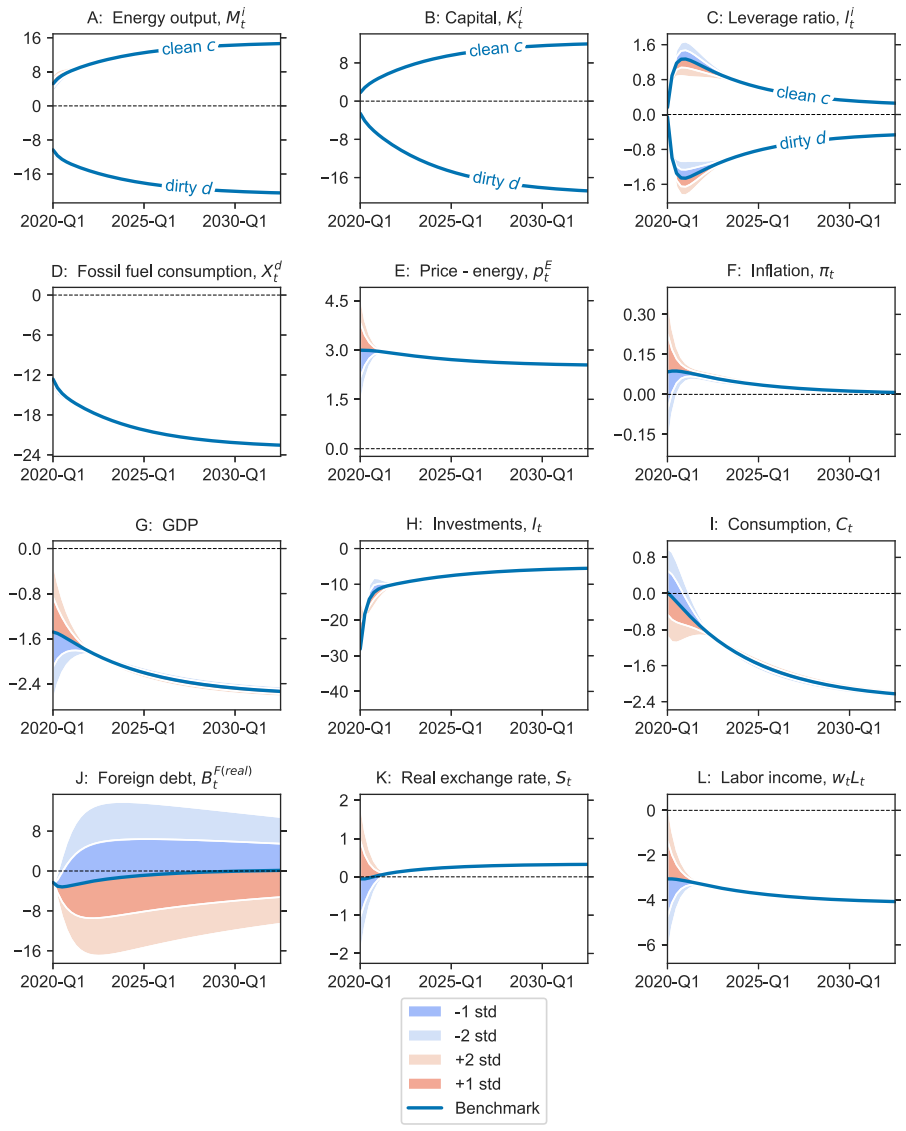


Fig. 5. The model response to the introduction to a carbon tax under variations of the foreign borrowing rate, i.e. at the same time the tax is introduced, shocks happen to the borrowing rate at the international market. Response values are reported as percentage deviation from steady state values, except inflation that is reported in percentage points.

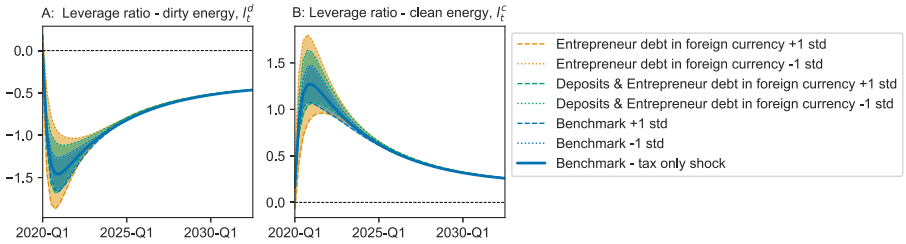


Fig. 6. The leverage ratio in response to the introduction to a carbon tax under variations of the foreign borrowing rate, i.e. at the same time the tax is introduced, shocks happen to the borrowing rate at the international market. The three models differ in terms of currency of the activities of the financial intermediator.

cheaper. The deflationary pressure (Fig. 5F) following a negative shock to the foreign borrowing rate exacerbates the drop in output (Fig. 5G). The increased levels of foreign debt lead to higher consumption levels (Fig. 5I), despite lower labor income.

The opposite is true if the borrowing rate in international markets increases while the carbon tax is introduced. The increased costs of foreign funds lead to higher prices and higher output.

The simulations of the economic response to a positive shock to the foreign borrowing rate point to the importance of foreign debt for the value of firms. Higher borrowing rates imply higher prices for all goods, which cause a short-term increase in net worth for both the clean and the dirty energy sectors. With higher net worth, leverage ratios are lower and investments can be made at lower cost (Fig. 5C).

In conclusion, financial openness towards international markets does not matter much for the effectiveness of the carbon tax to reduce

emissions but the effects of foreign rate shocks alter the economic effects of the carbon tax in the short term. Increased foreign rates create inflation, which is good for those with debt: our model suggests that a higher foreign rate lowers foreign debt level and boosts domestic production, leading to higher energy consumption and more use of fossil fuels. But while GDP (Fig. 5G) increases with the foreign borrowing rate, a larger share of GDP goes to foreign lenders to service debt, leaving less for domestic consumption.

In the benchmark model, foreign debt is in foreign currency, while deposits and debt to entrepreneurs are in domestic currency. The choice of currency affects the sensitivity towards foreign rate shocks. Fig. 6 shows the effect of two model variations on sectoral leverage ratios (as in Fig. 5C). The two variations are: (1) entrepreneurial debt contracts are in foreign currency, and (2) both entrepreneurial debt and household deposits are in foreign currency. The variations move the exposure to currency risk to entrepreneurs and households, respectively. The figure shows that leverage is more affected by the foreign rate shock in (1), when entrepreneurial debt is denominated in foreign currency, but deposits are not. This effect is a sign of currency mismatch of the entrepreneur, i.e. due to the use of different currencies, there is a discrepancy between changes in the value of the liabilities (debt) and in the value of the produced output. The currency risk is borne by the entrepreneur. With a decline in the foreign borrowing rate, the leverage ratio of entrepreneurs increases because their net worth, which depends mainly on domestic prices, does not increase as much. In case (2) where household deposits are also in foreign currency, the households are also exposed to currency risk. However, this means that their purchasing power and hence the net worth of the entrepreneur depend on the foreign borrowing conditions. As a result, the currency mismatch of the entrepreneurs is reduced. It should be noted, however, that the choice of currency in the financial contract has no effect on the emission path induced by the carbon tax. This is because the effect on leverage takes the same direction for both clean and dirty energy producers, offering no relative advantage.

4.2. Policy design in the open economy with frictions

In the previous sections, the carbon tax revenue is recycled directly to households as transfers (tax-and-transfer for short). Our simulations of the response of an open economy with financial frictions indicate that introducing a carbon tax increases the cost of energy, lowers the return on capital, and makes the economy internationally less competitive. Frictions makes this problem worse by preventing a fast, cheap scale-up of clean capital. In this section we will discuss alternative policy designs that can address this issue. We first explore an alternative method for recycling the tax revenue, i.e. a clean energy subsidy (tax-and-subsidy), then we discuss how foreign aid is best suited to promote the low-carbon transition.

4.2.1. Clean energy subsidy

Fig. 7 illustrates the impact of a carbon tax on the key economic variables when the tax revenue is either recycled as transfers to households or as a clean energy subsidy. The simulations indicate that for the same tax level, the tax-and-subsidy policy leads to emissions falling faster (and remaining lower) (Fig. 7G) while much of the negative impacts of carbon taxation can be avoided, including the increase in inflation (Fig. 7I) and the drop in consumption (Fig. 7L) and output (Fig. 7J). The subsidy policy substantially mitigates the macroeconomic costs of carbon taxation while achieving larger emission reductions than the transfer policy. Whether the policy mix is welfare-improving once environmental benefits are accounted for is assessed below. The combined tax and subsidy addresses distortions in the economy, i.e. features where our model departs from the standard idealized assumptions of welfare economics, that a tax alone cannot address. Before providing an analysis of the impact of the specific model features, we discuss the result of the policy response simulations.

The reason for the difference in the response between the transfer policy and the subsidy policy is the price of energy: by subsidizing clean energy, the price of energy increases only slightly upon the introduction of a carbon tax, and the price goes back to steady state level relatively fast. On the contrary, if tax revenues are returned to the household as transfers, the price of energy remains high above steady state levels.

The lower cost of energy also implies that the return on capital remains high and hence, the rate on debt stays competitive in international markets. For this reason, the tax-and-subsidy policy does not lead to a reduction in foreign debt as much as the tax-and-transfer policy (Fig. 7M).

Fig. 7 also highlights the role of financial market frictions under the two policies (the shaded areas indicate the difference between the economy with and without frictions). The difference between the fossil fuel consumption in the economy with and without frictions is larger under the subsidy policy (Fig. 7G). This is a consequence of the stronger steering effect of the subsidy policy. The clean energy capital undergoes a larger adjustment in a short period of time and therefore the leverage ratio during the transition is higher. Due to the constraints imposed by the leverage ratio on borrowing possibilities, the effectiveness of the tax-and-subsidy policy is more sensitive to financial frictions than the benchmark case where the tax revenue is recycled as transfers to households.

While the subsidy policy appears as the most effective policy independent of the level of frictions, the simulations indicate that policy makers considering the introduction of a subsidy ought to recognize the impact on financial market frictions on the policy response. The results are robust to variations in bankruptcy costs (see Table D.7).

Transfers of the tax revenue to households is a non-distortive policy, while the subsidy policy is not. Hence, in a standard model the transfer policy is expected to be the policy with the lowest welfare cost, but our model simulations indicates otherwise. This result originates from a combination of model assumptions that are different from standard neo-classical climate-economy models without market distortions. To investigate the importance of the different assumptions we remove model features one by one, and estimate the emission reductions and welfare costs in terms of consumption equivalents under the two policies.

Model variation *M0* corresponds to the benchmark model as presented in Section 2 and calibrated according to Section 3.1. We have identified in total five distinct features of the benchmark model that effects the ranking of the policy instruments in terms of welfare. Each model variation removes one feature.

In *M1*, there are no financial market frictions: the default cost μ is set to 0. In *M2*, we remove the price rigidity in the retail sector by setting the price adjustment cost parameter ψ to 0. In addition, to eliminate the profits from the final goods sector from the household budget, we introduce near-perfect competition by increasing the substitution elasticity θ_R to a large number (10 000). In *M3*, there is no foreign debt, i.e. B_t^F is 0 for all periods t. In *M4*, transfers from entrepreneurs are excluded from the household budget constraint.[6] In *M5*, fossil fuel is no longer a tradable good, but instead it is an endowed resource that every period enters into the budget constraint of the household.[7] The endowment is equal to the steady state fossil

[6] Compared to the benchmark model, where households consume a share of the entrepreneurial wealth each period, excluding the transfers imply that the equity positions of the entrepreneurs only affects the household income indirectly through the labor demand from the firms and return on deposits. To maintain market balance, the entrepreneurial transfers instead become a part of the final good market clearing constraint.

[7] The resource can either be used for production of energy or be wasted. That is, unlike in the benchmark model fossil fuel cannot be exchanged with other tradable goods and used for consumption and investment. While the fixed resource endowment is not the most realistic way to model fossil fuel production, this alternative is the simplest way to remove the tradable goods assumption, and hence, it offers the most straight forward comparison to the benchmark model.

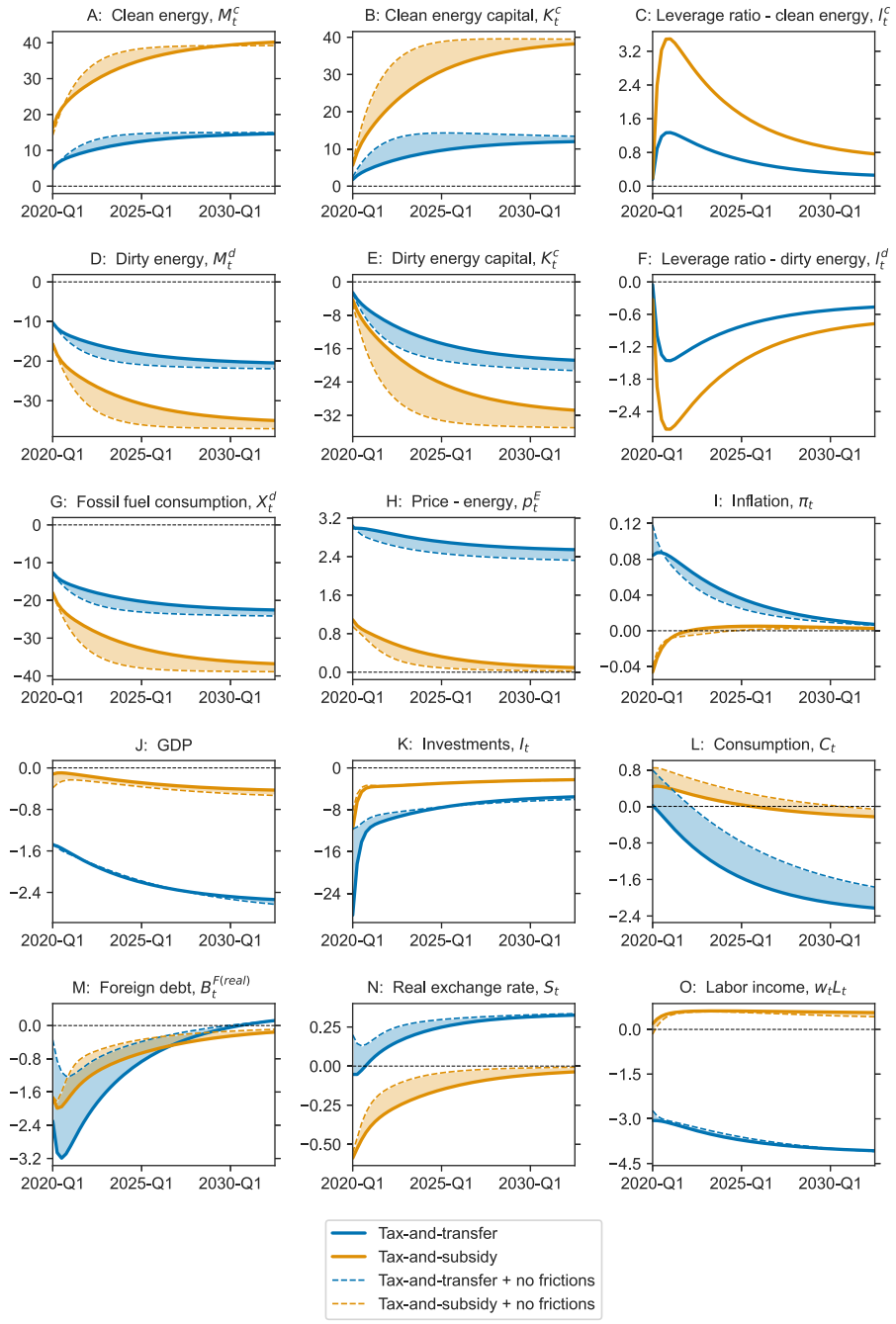


Fig. 7. The model response to the introduction of a carbon tax when the tax revenue is recycled as transfers to households or as a clean energy subsidy. Response values are reported as percentage deviation from steady state values, except inflation that is reported in percentage points.

fuel usage in the benchmark model. The fixed resource assumption has implications for the modeling of the climate policy: since it will always be optimal to use the entire resource endowment, a carbon tax cannot reduce the consumption of fossil fuel. Hence, to reduce the fossil fuel consumption the carbon tax is combined with a reduction in the endowment, representing an emission cap. In the case where tax revenue is recycled as transfers to households, the tax level makes no difference as the tax will be offset by the fossil fuel price. However, the tax level is important in case the tax revenue is recycled as a subsidy, because its size determines the level of the subsidy.

Finally, we also provide estimates for the welfare implications when all the features are removed at the same time. $M6a$ includes all the corrections as in $M1$ to $M4$ in combination, and $M6b$ also includes $M5$ on top of $M1$ to $M4$.

Table 4 provides an overview of the model variations. Fig. 8 summarizes the differences in the economic impact of the policy in place — represented in the figure in terms of the impact on emission reductions (Fig. 8A), discounted GDP change (Fig. 8B) and the welfare effect in consumption equivalents (Fig. 8C). The consumption equivalents measure the policy schemes' implications for household welfare in units of 2019-consumption. A detailed derivation can be found in Appendix A.

While recycling tax revenues as transfers to households has a relatively large negative impact on GDP in the benchmark model (1.70 percent), the subsidy policy has only little effect on the output (0.21

Table 3
Decomposition of consumption effects by economic group. Values show the discounted average annual impact on income components over the first 10 years as percent deviation from steady state. P1: carbon tax with household transfers; P2: carbon tax with clean energy subsidies.

Group	Category	P1: tax-and-transfer	P2: tax-and-subsidy
Workers	Labor income	−2.7%	0.44%
	Tax transfers	2.4%	0.0%
Equity holders		−2.5%	−0.89%
Retailers		−2.2%	−0.04%

percent). The consumption equivalents tell a similar story: Household welfare reductions are equivalent to 1.10 percent of 2019-consumption in the benchmark model under the transfer policy, while only 0.36 percent under the tax-and-subsidy policy despite the significantly higher emission reductions.

Our consumption-equivalent welfare measures capture only private consumption and leisure and abstract from climate damages within the model (cf. the discussion in Section 4.1). To assess whether the simulated emission reductions offset the GDP costs, we value annual emission reductions at an exogenous marginal damage estimate, discount them using the same interest rate as for GDP (Section 3), and compare the resulting environmental benefits to the discounted GDP losses reported above. Under this accounting, environmental benefits as low as 13.95 USD per tCO_2 would suffice to outweigh the negative GDP impact of the subsidy policy, whereas the tax-and-transfer policy would require environmental benefits of 182.95 USD per tCO_2 or higher. For reference, Ricke et al. (2018) estimate the national social cost of carbon for Brazil at 24 USD per tCO_2 (95% confidence interval: 14–41 USD per tCO_2), while the global social cost of carbon is 417 USD per tCO_2. Notably, the breakeven value for the tax-and-transfer policy exceeds the carbon tax level used in the simulations (14.9 USD per tCO_2; Section 3). If the tax is interpreted as reflecting marginal climate damages, the simulated GDP losses under the transfer policy would exceed the environmental benefits from the additional emission reductions, whereas the subsidy policy would remain net beneficial at the same damage valuation.

In model versions where financial frictions are excluded (*M1*), the impact on household welfare is much lower. This is a consequence of the short term increase in consumption combined with a large drop in supplied labor. The comparison between the model economies with and without frictions indicates that models without financial frictions greatly underestimate the welfare effects of carbon taxes.

Fig. 8 shows that the ranking of the two policies in terms of welfare impact remains robust to removal of financial frictions (*M1*) and price rigidity in the retail sector (*M2*). The openness alone also cannot explain the difference in welfare outcomes between the two policies (*M3*). At the same time, the estimate reveals that household welfare is affected by the climate policies mainly through transfers from the entrepreneurial sectors. While removing entrepreneurial transfers from the household budget constraint (*M4*) reduces welfare impacts, it does not change the ranking of the policies. More details on the impact of transfers on the household budget constraint can be found in Appendix B.

We further check the robustness of our findings to the timing of policy implementation: a gradual phase-in of the carbon tax over five years produces qualitatively similar results, with smaller absolute impacts but preserved relative rankings across policy designs and model variants. This analysis is reported in Appendix E.

The decomposition in Table 3 reveals how the two policy regimes distribute costs and benefits across different economic groups. Under the tax-and-transfer policy, workers experience a substantial decline in labor income (−2.727 percent) due to the increase in energy prices that reduces production and labor demand. Although this is largely offset by tax transfers (+2.415 percent), the net effect on household income is a decline by 0.312 percentage points. In contrast, under the subsidy policy, workers' labor income actually increases by 0.437 percent, as subsidies prevent the rise in energy prices and maintain production levels.

The key difference between the two policies lies in their treatment of energy prices: subsidies stabilize energy costs, which preserves the return on capital and maintains competitiveness in international markets. This explains why equity holders and retailers experience smaller welfare losses under the subsidy policy (−0.888 and −0.039 percent, respectively) compared to the tax-and-transfer policy (−2.455 and −2.204 percent). By preventing the vicious cycle of rising energy prices, inflation, and currency depreciation, the subsidy policy protects all economic groups from the more severe impacts of the transition. The assumption that fossil fuel is a tradable good also appears important for the welfare implication of climate policies: if instead fossil fuel is a fixed resource endowment awarded to households every period, the costs of climate policy becomes high (*M5*). Under the endowment assumption, the fossil fuel resource is lost if unused, whereas under the tradable goods assumption, any saved fossil fuels can be exchanged with other tradable goods. Despite the importance of the endowment assumption for welfare costs, it does not change the ranking of the two policies — the subsidy policy remains the one with the lowest welfare costs. The ranking remains the same for all variations. Only when all the variations are applied simultaneously and, therefore, the model variant differs strongly from the original setup, Panel C shows a (very slight) advantage for the transfer policy in *M6b*. This result implies that it is the totality of the modeling choices including the combination of various market frictions that leads to lower welfare cost of the subsidy policy compared to the transfer policy.

The benefit of green subsidies implied by our model simulations aligns with the findings of Grüning (2025), who argue that in a small open economy GDP is almost unaffected when carbon tax revenues are distributed to the green sector. Likewise, Diluiso et al. (2021), who study the role on capital taxes in a closed economy with financial friction, find that tax on fossil fuel debt combined with a subsidy on clean energy debt significantly reduces inflationary pressure and output losses. However, Diluiso et al. (2021) point out that this policy scheme leads to a greater risk of financial instability due to a stronger devaluation of fossil fuel assets on the banks' balance sheets. In contrast, by focusing on the role of default risks of the entrepreneurs, we do not observe any reason for the clean energy output subsidies to challenge macro-stability: Although the net worth of dirty energy producers surely decreases faster under the subsidy scheme, dirty energy firms simultaneously reduce their debt. In sum, their leverage is reduced, falling faster and making them less likely to default in the subsidy scenario.

4.2.2. Foreign aid

The effects of foreign aid worth 3.3 billion USD introduced at the same time as the carbon policy, would hardly be visible in the response functions in Fig. 7, and are therefore not plotted. The limited impact can be attributed to the relatively modest scale of aid in relation to the overall size of the economy. However, the simulation results indicate that aid introduced simultaneously with a carbon tax and given directly to households may offset some of the short-term negative impacts on consumption caused by the carbon tax, however, in the long run, this effect will be outweighed by the decline in output. Aid given directly to households mainly creates inflation and lowers the incentive for domestic savings and production. As a result, it has only little effect on the fossil fuel consumption and the scale up of clean energy capital.

If instead the aid and tax revenues are used as a clean energy subsidy, the response of the model economy is very different. In this case, the aid increases the level of investments in clean energy, causing a stronger decline in the use of fossil fuel, which in combination leads to a lower price of energy. This boosts production and investments.

Our results indicate that aid may help alleviate negative effects on consumption caused by taxes but if not targeted directly towards clean

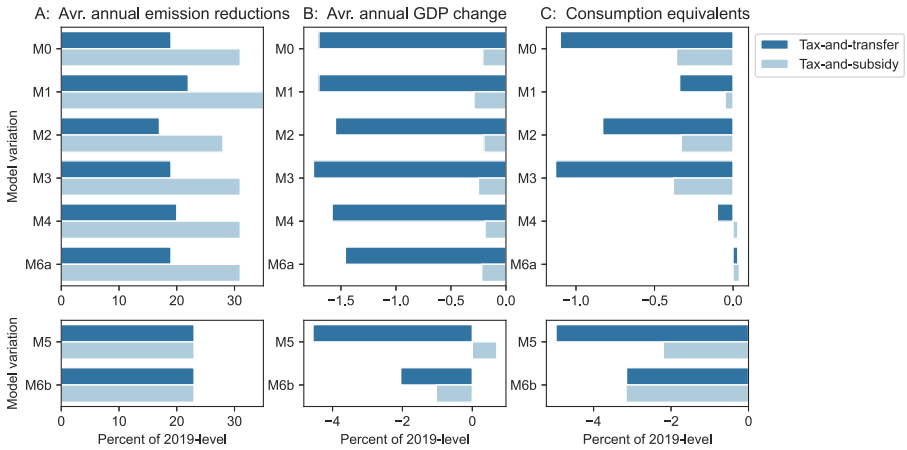


Fig. 8. Comparison of the model response to the introduction of a carbon tax under different tax revenue recycling schemes and variations of the modeling assumptions. Panel A shows the simple arithmetic mean of annual emission reductions over 10 years. Panel B shows the discounted average of annual GDP changes, where future values are discounted using the market interest rate. Panel C shows consumption equivalents, which are derived from the discounted sum of welfare changes. Note that the model variations have different steady states and, thus, comparisons are only valid within one model variant.

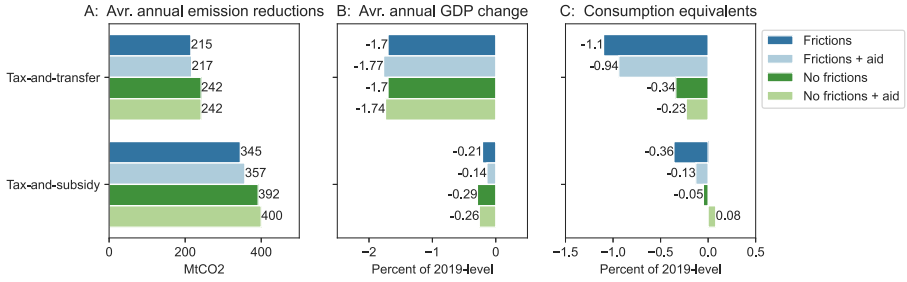


Fig. 9. Comparison of the model response to the introduction of a carbon tax under different tax revenue recycling schemes, presence of financial frictions and availability of foreign aid. See Fig. 8 for details on the metrics.

Table 4
Model variations are made to the benchmark model, which is described in Section 2 and calibrated according to Section 3.1. Variation 4 implies that the transfers to and from the entrepreneurial sector are separated from the households' budget constraint. Hence, the households cannot derive utility from consumption of entrepreneurial net worth. In variation 5 fossil fuel is no longer a tradable good, but instead a resource endowed to households in each period. In this case, the emission target is reached by limiting the endowment each period.

	Variation	*M1*	*M2*	*M3*	*M4*	*M5*	*M6a*	*M6b*
1	No financial frictions ($\mu = 0$)	X					X	X
2	No menu costs, perfect competition in the retail sector		X				X	X
3	No foreign debt ($B_t^F = 0$)			X			X	X
4	No entrepreneurial transfers (T_t^e) to households				X		X	X
5	Fossil fuel as an endowment					X		X

investment, it creates additional inflationary pressure on the economy without any direct impact on emissions. Targeted industry policies can help keep the cost of energy low by alleviating adverse effects on exchange rates and inflation.

Fig. 9 summarizes the economic impact of foreign aid under the two tax revenue policies, and with and without financial frictions. Panel A shows the yearly average emission reductions until 2030. Since using tax revenues as a clean energy subsidy is a more effective strategy than lump-sum transfers to households, the emission reductions are significantly higher. This result holds regardless of the presence of financial frictions and foreign aid. Fig. 9 also shows that foreign aid may not have a large impact on the emission reductions, especially not when used as direct household transfers, but if used differently, it may have strong implication for the welfare costs of transition. According to the model simulations, if the foreign aid is used as a subsidy for clean energy, it can remove approximately two thirds of the consumption equivalent impact of the climate policy (from −0.36 to −0.13 percent).

5. Conclusion

Constrained availability of financial resources decelerates the green transition and increases its cost. Financial markets' ability to foster sufficient clean energy investments is in particular causing concern to developing economies, where the clean energy financing gap is large and financial resources are scarce. In this paper, we investigate the role of financial market failures in the green transition and their implications for climate policy in an open economy. To this end, we introduce financial frictions in a dynamic, stochastic model of a small open economy calibrated to Brazil. Through simulations of the economic response to policies designed to mitigate climate change, we explore the role of frictions and financial openness for the effectiveness and efficiency of the interventions.

The analyses presented in this paper highlight that frictions interact with the financial openness of the economy. Both frictions and openness have implications for the economic costs of carbon policies. In our benchmark model, the carbon tax leads to higher cost of fossil fuel

usage, which drives up the energy prices. Energy is an input to the tradable and non-tradable goods producing sectors, and the higher cost of usage lowers the return on capital. In an open economy, the lower return on capital reduces the competitiveness of the economy on international capital markets, which in return reduces the inflow of foreign funds, driving prices even further up. Frictions slow down the investment in clean capital and increase the cost of the clean energy substitute for dirty energy. In this way, replacing fossil fuels with clean energy becomes difficult.

Mitigating the damages caused by climate change through a reduction of fossil fuel consumption will undoubtedly have positive welfare effects in the long run, however, we find that introducing a carbon tax has strong short-term negative effects on the economy and household welfare under the presence of financial frictions. With the lack of a low-cost green substitute, the only way to scale down fossil fuel usage is through scaling down economic activity. We find that a carbon tax is an effective policy instrument for reducing emissions, however, it causes cost-push inflation and a reduction in inflow of foreign funds, which implies a large welfare cost.

Using carbon tax revenues to lower the costs of clean energy can help alleviate some of the negative effects caused by the carbon tax. Clean energy subsidies increase the net worth of clean energy companies and allow for a faster scale-up of clean energy capital, keeping the price of energy low and the inflow of foreign funds high. If combined with foreign aid, our model simulations indicate that all short term negative impacts of introducing climate policy can be removed.

The low-carbon transition requires significant new investments in clean energy infrastructure, especially in developing countries. However, financial frictions may restrict the flow of funds toward clean energy investments. When the borrowing conditions of clean energy investors depend on their net worth, the economic environment matters for the cost of the transition. Financial openness is a requirement for attracting foreign funds, but it also puts the economy at the mercy of foreign investors. Interventions aiming to address the issue of climate change need to be carefully designed so that they attract, rather than appall, investors.

The scale of this challenge is substantial: global climate finance flows remain far below the levels needed for the low-carbon transition, with developing countries facing the largest gaps relative to investment needs (Climate Policy Initiative, 2025). A key challenge is the mobilization of private capital, which requires public interventions that reduce investment risk and improve returns (Bowen, 2011). Our model provides a structural rationale for such interventions: clean energy subsidies operate as a de-risking instrument by improving the return on clean capital, reducing entrepreneurial leverage, and thereby sustaining foreign capital inflows. This mechanism mirrors the policy and financial de-risking strategies discussed by Steckel and Jakob (2018), who argue that carbon pricing alone is insufficient to attract clean energy investment in countries with high financing costs and that complementary measures to reduce the cost of capital are essential. In a similar vein, multilateral development banks have increasingly directed financing toward renewable energy in developing countries (Steffen and Schmidt, 2019), acting on the same logic of using public funds to improve the risk-return profile of clean investments for private investors. Our results formalize this intuition in a general equilibrium framework, showing that the interaction between borrower-side frictions, financial openness, and policy design determines whether public support crowds in or fails to attract private capital.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work, the authors used Anthropic's Claude Opus to update the literature review and check language for consistency and correctness, and OpenAI's GPT-6 Astra for code review. The authors reviewed and edited the output as needed and take full responsibility for the content of the published article.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Kai Lessmann reports financial support was provided by Federal Ministry of Education and Research (BMBF). The other authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Consumption equivalents

Consumption equivalents capture the welfare implications for households of a policy intervention p compared to the alternative, no policy np. Consumption equivalents measure how much of consumption in the no policy scenario the households would have to give up in order to obtain the same change in discounted utility as the change implied by the policy.

The total expected utility is given by the discounted sum of each period's utility:

$$E\left[U_t\right] = E\left[\sum_{t=0}^{\infty} \beta^t u(C_t, L_t)\right] \tag{A.1}$$

with $u(C_t, L_t) = \log(C_t) + \log(1 - L_t)$

Then define the ε as the consumption equivalent of p as a fraction of consumption of np such that policy p and np gives the same expected discounted utility:

$$E\left[U_t^p\right] = E\left[U_t^{np}(\varepsilon)\right] = E\left[\sum \beta^t u(C_t^{np}(1+\varepsilon), L_t^{np})\right] \tag{A.2}$$

If ε is greater than 0, the policy results in greater welfare than the no policy case, and if it takes a negative value the policy implies a welfare loss compared to the no policy case. Inserting the expression for the period utility and rearranging Eq. (A.2) gives:

$$E\left[U_t^p\right] = \frac{\log(1+\varepsilon)}{1-\beta} + E\left[U_t^{np}\right] \tag{A.3}$$

and hence, the consumption equivalents take the following form:

$$\varepsilon = e^{\left(E\left[U_t^p\right] - E\left[U_t^{np}\right]\right)(1-\beta)} - 1 \tag{A.4}$$

Appendix B. Details on the household budget under the transition

In this section we describe in detail what happens to the household budget constraint under the introduction of the two climate policy schemes. In the first (benchmark) policy, a carbon tax is combined with a lump-sum transfer of tax revenues to the households. In the second, the tax revenue is recycled as a subsidy to clean energy.

Fig. B.10 shows the evolution of the budget constraint in the two cases. With the benchmark policy, the labor income declines sharply. At the same time the transfers from the entrepreneurial sectors drop. The transfers from entrepreneurial sectors decline because the carbon tax slowly diminishes the net worth of the sectors. In addition, with increasing inflation, the profits from the retail sector drop. The drop in income is partly compensated by the large tax transfer, but the transfer is not large enough to cover all income losses. As a result, the household must reduce consumption to keep a balanced budget.

In case the carbon tax revenue is used to subsidize clean energy investments, there is hardly any effect on the household budget. Because the cost of energy remains low, the marginal productivity of labor and capital remains at steady state levels. This means there is no decline in labor income, neither in the net worth of the entrepreneurial sector.

Appendix C. Calibration with GTAP data

This appendix describes the methods and equations used for calibrating parameters through the GTAP data.

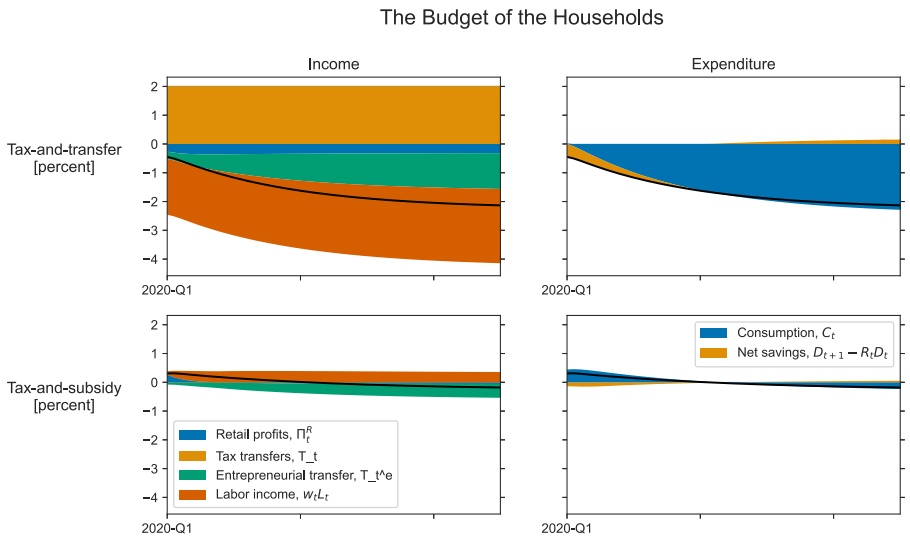


Fig. B.10. The budget constraint of the households under policy intervention. The figure shows income (left panels) and expenditures (right panels) for the two policies.

C.1. Final goods aggregation

Aggregators have the following production function

$$Y_t^W = A_t \left(\phi_W^{\frac{1}{\varepsilon_W}} Y_t^T \frac{\varepsilon_W - 1}{\varepsilon_W} + (1 - \phi_W)^{\frac{1}{\varepsilon_W}} Y_t^N \frac{\varepsilon_W - 1}{\varepsilon_W} \right)^{\frac{\varepsilon_W}{\varepsilon_W - 1}}$$

The parameter that governs the substitution elasticity will be extracted from the literature. To get the share parameter ϕ_W solve

$$\min p_t^T Y_t^T + p_t^N Y_t^N$$
$$s.t.$$
$$Y_t^W \leq A_t \left(\phi_W^{\frac{1}{\varepsilon_W}} Y_t^T \frac{\varepsilon_W - 1}{\varepsilon_W} + (1 - \phi_W)^{\frac{1}{\varepsilon_W}} Y_t^N \frac{\varepsilon_W - 1}{\varepsilon_W} \right)^{\frac{\varepsilon_W}{\varepsilon_W - 1}}$$

$$L = p_t^T Y_t^T + p_t^N Y_t^N + \lambda \left(Y_t^W - A_t \left(\phi_W^{\frac{1}{\varepsilon_W}} Y_t^T \frac{\varepsilon_W - 1}{\varepsilon_W} + (1 - \phi_W)^{\frac{1}{\varepsilon_W}} Y_t^N \frac{\varepsilon_W - 1}{\varepsilon_W} \right)^{\frac{\varepsilon_W}{\varepsilon_W - 1}} \right)$$

The first order condition with respect to Y_t^T is

$$p_t^T = \lambda \left(A_t \left(\phi_W^{\frac{1}{\varepsilon_W}} Y_t^T \frac{\varepsilon_W - 1}{\varepsilon_W} + (1 - \phi_W)^{\frac{1}{\varepsilon_W}} Y_t^N \frac{\varepsilon_W - 1}{\varepsilon_W} \right)^{\frac{\varepsilon_W}{\varepsilon_W - 1} - 1} \phi_W^{\frac{1}{\varepsilon_W}} Y_t^T \frac{\varepsilon_W - 1}{\varepsilon_W} - 1 \right)$$

$$p_t^T = \lambda \left(A_t^{\frac{\varepsilon_W - 1}{\varepsilon_W}} \frac{Y_t^W}{\left(Y_t^W\right)^{\frac{\varepsilon_W - 1}{\varepsilon_W}}} \phi_W^{\frac{1}{\varepsilon_W}} Y_t^T \frac{\varepsilon_W - 1}{\varepsilon_W} - 1 \right)$$

$$p_t^T = \lambda \left(A_t^{\varepsilon_W - 1} \phi_W \frac{Y_t^W}{Y_t^T} \right)^{\frac{1}{\varepsilon_W}}$$

and

$$p_t^N = \lambda \left(A_t^{\varepsilon_W - 1} (1 - \phi_W) \frac{Y_t^W}{Y_t^N} \right)^{\frac{1}{\varepsilon_W}}$$

$$\frac{p_t^N}{p_t^T} = \left(\frac{(1 - \phi_W)}{\phi_W} \frac{Y_t^T}{Y_t^N} \right)^{\frac{1}{\varepsilon_W}}$$

By an appropriate choice of units for final, tradable and non-tradable goods, prices can be set equal to one, i.e. $p_t^N = p_t^T = p_t = 1$ and the equation becomes

$$1 = \left(\frac{(1 - \phi_W)}{\phi_W} \frac{Y_t^T}{Y_t^N} \right)^{\frac{1}{\varepsilon_W}}$$
$$\phi_W Y_t^N = Y_t^T - \phi_W Y_t^T$$

Table C.5
Calibration to GTAP data (goods).

Variable	Data	Calibration
Tradable goods	$\widehat{p_t^T Y_t^T}$	Y_t^T (by setting $p_t^T = 1$)
Non-tradable goods	$\widehat{p_t^N Y_t^N}$	Y_t^N (by setting $p_t^N = 1$)

and

$$\phi_W = \frac{Y_t^T}{Y_t^N + Y_t^T} \tag{C.1}$$

$$1 - \phi_W = \frac{Y_t^N}{Y_t^N + Y_t^T} \tag{C.2}$$

We also need to calibrate productivity A.

$$A = \frac{Y_t^W}{\left(\phi_W^{\frac{1}{\varepsilon_W}} Y_t^T \frac{\varepsilon_W - 1}{\varepsilon_W} + (1 - \phi_W)^{\frac{1}{\varepsilon_W}} Y_t^N \frac{\varepsilon_W - 1}{\varepsilon_W} \right)^{\frac{\varepsilon_W}{\varepsilon_W - 1}}}$$

According to Euler's theorem with perfect competition and prices equal to one (assumption from above still holds) we have

$$Y_t^T + Y_t^N = Y_t$$

such that

$$A = \frac{Y_t^T + Y_t^N}{\left(\left(\frac{Y_t^T}{Y_t^N + Y_t^T} \right)^{\frac{1}{\varepsilon_W}} Y_t^T \frac{\varepsilon_W - 1}{\varepsilon_W} + \left(\frac{Y_t^N}{Y_t^N + Y_t^T} \right)^{\frac{1}{\varepsilon_W}} Y_t^N \frac{\varepsilon_W - 1}{\varepsilon_W} \right)^{\frac{\varepsilon_W}{\varepsilon_W - 1}}}$$

$$A = \frac{Y_t^T + Y_t^N}{\left(\frac{Y_t^T + Y_t^N}{\left(Y_t^N + Y_t^T\right)^{\frac{1}{\varepsilon_W}}} \right)^{\frac{\varepsilon_W}{\varepsilon_W - 1}}}$$

$$A = 1 \tag{C.3}$$

C.1.1. Data table

We can now calculate ϕ_W (Eqs. (C.1) and (C.2)) and A (Eq. (C.3)) through Y_t^N and Y_t^T. With our assumptions on prices we can use GTAP data as shown in Table C.5.

Tradable and non-tradable goods are both calculated as the sum of the GTAP variables *intermediates, firms' purchases at agents' prices* and *intermediates, firms' imports at agents' prices*.

C.2. Tradable and non-tradable goods entrepreneurs

For this calibration we extract the firms from the entrepreneurs to ease calculations and make the rental rate of capital explicit. Firms' production functions are

$$Y_t^i = \bar{A}_i \left(\phi_i \left(K_t^{i\alpha_i} L_t^{i\,1-\alpha_i} \right)^{\frac{\epsilon_i - 1}{\epsilon_i}} + (1-\phi_i) E_t^{i\,\frac{\epsilon_i - 1}{\epsilon_i}} \right)^{\frac{\epsilon_i}{\epsilon_i - 1}} \tag{C.4}$$

where $i \in \{T, N\}$ indicates sector affiliation but will be omitted for the remainder to increase readability. All equations equally apply for both sectors.

C.2.1. Capital-labor composite

First, we extract the capital-labor composite and calibrate α then move to the CES and calibrate ϕ. We define

$$Z_t = K_t^{\alpha} L_t^{1-\alpha}$$

With perfect competition, profit maximization implies

$$\begin{aligned} w_t &= p_t^Z \frac{\delta Z_t}{\delta L_t} = p_t^Z (1-\alpha) \frac{Z_t}{L_t} \\ &\rightarrow 1 - \alpha = \frac{w_t L_t}{p_t^Z Z_t} \\ r_t &= p_t^Z \frac{\delta Z_t}{\delta K_t} = p_t^Z \alpha \frac{Z_t}{K_t} \\ &\rightarrow \alpha = \frac{r_t K_t}{p_t^Z Z_t} \end{aligned}$$

Combining first order conditions with Euler's Equality

$$\begin{aligned} p_t^Z Z_t &= p_t^Z \frac{\delta Z_t}{\delta K_t} K_t + p_t^Z \frac{\delta Z_t}{\delta L_t} L_t \\ p_t^Z Z_t &= r_t K_t + w_t L_t \end{aligned}$$

such that

$$\alpha = \frac{r_t K_t}{r_t K_t + w_t L_t} \tag{C.5}$$

$$1 - \alpha = \frac{w_t L_t}{r_t K_t + w_t L_t} \tag{C.6}$$

We get $r_t K_t$, $w_t L_t$ from GTAP (remuneration of endowments are included in input–output tables) and calculate factor shares. See data table below C.6.

C.2.2. Upper layer

We now move to the upper layer of the CES and calibrate ϕ.

$$Y_t^i = \bar{A}_i \left(\phi_i Z_t^{i\,\frac{\epsilon_i - 1}{\epsilon_i}} + (1-\phi_i) E_t^{i\,\frac{\epsilon_i - 1}{\epsilon_i}} \right)^{\frac{\epsilon_i}{\epsilon_i - 1}}$$

Cost minimization yields

$$\begin{aligned} &\min p_t^Z Z_t^i + p_{Et} E_t^i \\ &s.t. \\ &Y_t^i \leq \bar{A}_i \left(\phi_i Z_t^{i\,\frac{\epsilon_i - 1}{\epsilon_i}} + (1-\phi_i) E_t^{i\,\frac{\epsilon_i - 1}{\epsilon_i}} \right)^{\frac{\epsilon_i}{\epsilon_i - 1}} \end{aligned}$$

$$L = p_t^Z Z_t^i + p_{Et} E_t^i + \lambda_t^i \left(Y_t^i - \bar{A}_i \left(\phi_i Z_t^{i\,\frac{\epsilon_i - 1}{\epsilon_i}} + (1-\phi_i) E_t^{i\,\frac{\epsilon_i - 1}{\epsilon_i}} \right)^{\frac{\epsilon_i}{\epsilon_i - 1}} \right)$$

The first order conditions with respect to Z_t^i and E_t^i are:

$$p_t^Z = \lambda_t^i \left(\bar{A}_i \left(\phi_i Z_t^{i\,\frac{\epsilon_i - 1}{\epsilon_i}} + (1-\phi_i) E_t^{i\,\frac{\epsilon_i - 1}{\epsilon_i}} \right)^{\frac{\epsilon_i}{\epsilon_i - 1} - 1} \phi_i Z_t^{i\,\frac{\epsilon_i - 1}{\epsilon_i} - 1} \right)$$

Table C.6
Calibration to GTAP data (input factors).

GTAP variable	Data	Calibration
Labor	$\widehat{w_t L_t}$	L_t (by setting $w_t = 1$)
Capital	$\widehat{r_t K_t}$	$r_t K_t \Rightarrow K_t = \frac{\widehat{r_t K_t}}{r_t}$
Energy	$p_t^E E_t$	E_t (by setting $p_{Et} = 1$)

$$p_t^E = \lambda_t^i \left(\bar{A}_i \left(\phi_i Z_t^{i\,\frac{\epsilon_i - 1}{\epsilon_i}} + (1-\phi_i) E_t^{i\,\frac{\epsilon_i - 1}{\epsilon_i}} \right)^{\frac{\epsilon_i}{\epsilon_i - 1} - 1} (1-\phi_i) E_t^{i\,\frac{\epsilon_i - 1}{\epsilon_i} - 1} \right)$$

Dividing first order conditions yield

$$\frac{p_t^Z}{p_t^E} = \frac{\phi_i}{1-\phi_i} \left(\frac{E_t^i}{Z_t^i} \right)^{\frac{1}{\epsilon_i}}$$

By setting prices equal to one, $p_{Et} = 1$ (above assumption holds), the equation becomes

$$\begin{aligned} p_t^Z &= \frac{\phi_i}{1-\phi_i} \left(\frac{E_t^i}{Z_t^i} \right)^{\frac{1}{\epsilon_i}} \\ p_t^Z (1-\phi_i) Z_t^{i\,\frac{1}{\epsilon_i}} &= \phi_i \left(E_t^i \right)^{\frac{1}{\epsilon_i}} \\ p_t^Z Z_t^{i\,\frac{1}{\epsilon_i}} &= \phi_i \left(E_t^i \right)^{\frac{1}{\epsilon_i}} + \phi_i p_t^Z Z_t^{i\,\frac{1}{\epsilon_i}} \end{aligned}$$

$$\phi_i = \frac{p_t^Z Z_t^{i\,\frac{1}{\epsilon_i}}}{\left(E_t^i \right)^{\frac{1}{\epsilon_i}} + p_t^Z Z_t^{i\,\frac{1}{\epsilon_i}}} \tag{C.7}$$

We get estimates for E_t^i from GTAP and, through GTAP, Eqs. (C.9) and (C.10), calculate Z_t^i and p_t^Z (see table below).

We also need to calibrate productivity $\bar{A}_i$.

$$\bar{A}_i = \frac{Y_t^i}{\left(\phi_i Z_t^{i\,\frac{\epsilon_i - 1}{\epsilon_i}} + (1-\phi_i) E_t^{i\,\frac{\epsilon_i - 1}{\epsilon_i}} \right)^{\frac{\epsilon_i}{\epsilon_i - 1}}}$$

According to Euler's theorem with perfect competition and $p_t = p_t^E = 1$ (assumption from above still holds) we have

$$p_t^Z Z_t^i + E_t^i = Y_t^i$$

such that

$$\begin{aligned} \bar{A}_i &= \frac{p_t^Z Z_t^i + E_t^i}{\left(\left(\frac{p_t^Z Z_t^{i\,\frac{1}{\epsilon_i}}}{\left(E_t^i \right)^{\frac{1}{\epsilon_i}} + p_t^Z Z_t^{i\,\frac{1}{\epsilon_i}}} \right) Z_t^{i\,\frac{\epsilon_i - 1}{\epsilon_i}} + \left(\frac{\left(E_t^i \right)^{\frac{1}{\epsilon_i}}}{\left(E_t^i \right)^{\frac{1}{\epsilon_i}} + p_t^Z Z_t^{i\,\frac{1}{\epsilon_i}}} \right) E_t^{i\,\frac{\epsilon_i - 1}{\epsilon_i}} \right)^{\frac{\epsilon_i}{\epsilon_i - 1}}} \\ \bar{A}_i &= \frac{p_t^Z Z_t^i + E_t^i}{\left(\frac{p_t^Z Z_t^i + E_t^i}{\left(E_t^i \right)^{\frac{1}{\epsilon_i}} + p_t^Z Z_t^{i\,\frac{1}{\epsilon_i}}} \right)^{\frac{\epsilon_i}{\epsilon_i - 1}}} \\ \bar{A}_i &= \left(\frac{\left(\left(E_t^i \right)^{\frac{1}{\epsilon_i}} + p_t^Z Z_t^{i\,\frac{1}{\epsilon_i}} \right)^{\epsilon_i}}{p_t^Z Z_t^i + E_t^i} \right)^{\frac{1}{\epsilon_i - 1}} \end{aligned} \tag{C.8}$$

C.2.3. Data table

By an appropriate choice of units for labor and energy, wages w_t and prices p_{Et} can be set equal to one. The rental price of capital $\frac{r_t}{p_t^Z} = 0.06$. Here, we assume a value that is ultimately identical to the endogenously generated model variable R.

Labor and capital are reported in GTAP as variables *endowments, firms' purchases at agents' prices*' (we consider the tradable and non-tradable goods sectors). For energy, the corresponding GTAP variable

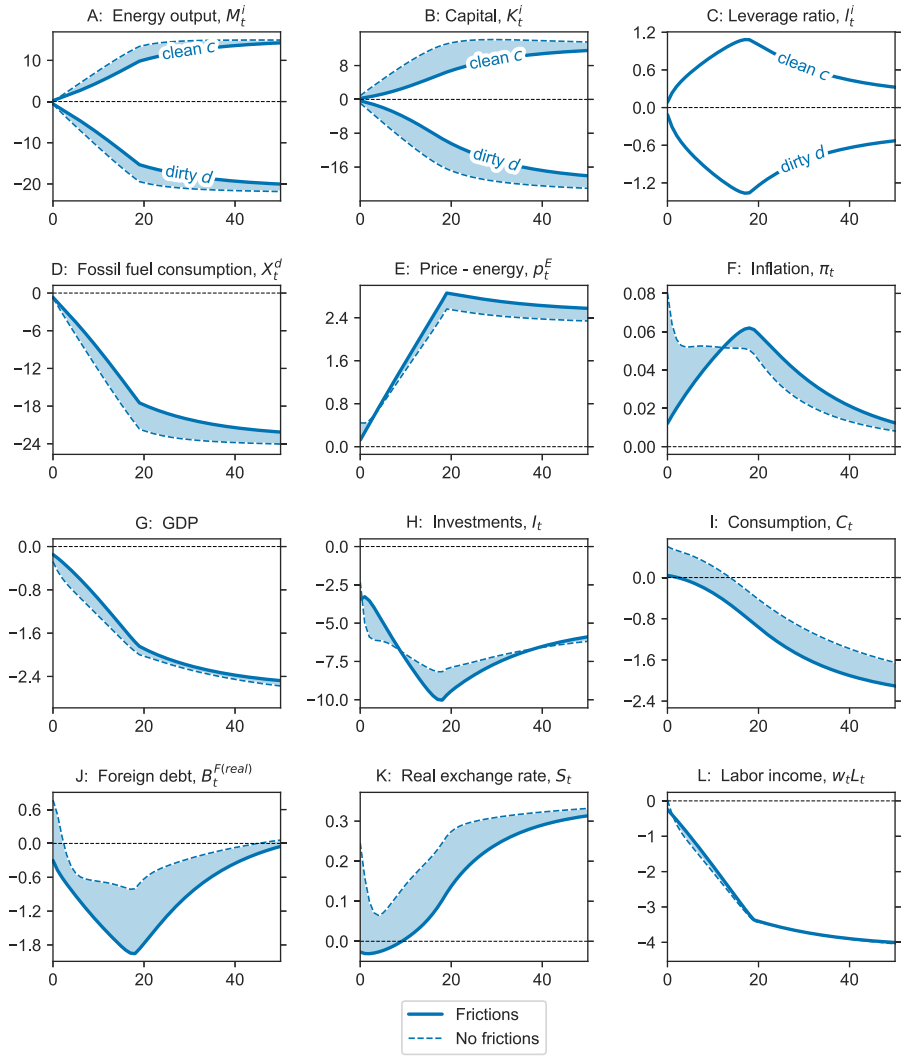


Fig. E.11. Policy phase-in, impulse response functions (cf. Fig. 3).

Table D.7
Sensitivity analysis: Impact of varying bankruptcy costs μ.

	$\mu_{ss} - 10\%$	$\mu_{ss} + 10\%$
Average annual emissions reductions (MtCO2)	218.0	213.0
Average annual GDP impact (% of 2019-level)	−1.67	−1.73
Consumption equivalent impact (% of 2019-level)	−1.07	−1.12

is the sum of *intermediates, firms' purchases at agents' prices* and *'intermediates, firms' imports at agents' prices* (we consider the energy sector), see Table C.6 for a summary.

For Y_t^T and Y_t^N refer to Table C.5. The capital-labor nest

$$Z_t = K_t^{\alpha} L_t^{1-\alpha}$$
$$Z_t = \left(\frac{\widehat{r_t K_t}}{r_t}\right)^{\alpha} \left(\widehat{w_t L_t}\right)^{1-\alpha} \tag{C.9}$$

and prices from the Euler condition

$$p_t^Z = \frac{\widehat{r_t K_t} + \widehat{w_t L_t}}{Z_t} \tag{C.10}$$

Appendix D. Sensitivity analysis: Bankruptcy costs

Table D.7 reports the average annual impacts on emissions, GDP, and welfare for $\mu_{ss} \pm 10\% \cdot \mu_{ss}$. The variations in μ have negligible effects on the main outcomes, confirming the robustness of our findings.

Appendix E. Policy phase-in

In the main analysis, we model the climate policy as a permanent carbon tax shock that takes effect immediately. In practice, however, climate policies are often introduced gradually to allow firms and households time to adjust. This section examines how a five year, smooth phased-in implementation affects the transition dynamics relative to the permanent shock analyzed in the main text. Fig. E.11 compares the impulse response functions under both scenarios, Fig. E.12.

The impulse response functions of the phased-in climate policy (Fig. E.11) are qualitatively similar to those of the permanent tax shock (Fig. 3). In both cases, the economy converges to the same long-run steady state, and the difference between the model with financial frictions and the frictionless benchmark remains largely unchanged. However, the transition dynamics differ in important ways. Under the phased-in policy, energy prices rise gradually rather than jumping on impact, which delays and attenuates the reallocation of capital across sectors: clean-sector capital accumulates more slowly and the leverage ratio adjusts at a more moderate pace. This is expected, since the policy signal is initially muted by the gradual implementation schedule. Moreover,

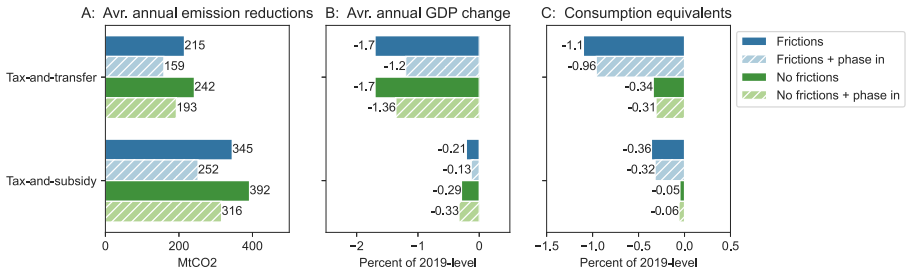


Fig. E.12. Policy phase-in, policy design analysis (cf. Fig. 9).

the point at which the tax rate reaches its permanent level introduces visible kinks in the impulse responses, reflecting the discrete change in the policy's rate of increase. Overall, the phased-in design smooths the macroeconomic adjustment without altering the economy's eventual destination.

The policy design comparisons yield similar qualitative conclusions under both the permanent shock and phased-in scenarios (Figs. 8 and E.12). The phased-in policy produces slightly muted effects across all outcomes, which is plausible given the reduced policy stringency during the phase-in period. However, the reductions do not alter the key comparative results. First, the differences between the tax-and-transfer and tax-and-subsidy variants remain substantial and robust: the relative ranking of policy designs is preserved, and while absolute impacts are somewhat smaller under phase-in, both scenarios are affected in a similar manner such that the policy design differences dominate the phase-in effect. Second, the distinction between the model with financial frictions and the frictionless benchmark is largely unaffected by the phase-in schedule. The frictions continue to amplify the macroeconomic costs and dampen the emissions reductions in a comparable way under both implementation schedules. These results show that the main conclusions about policy design trade-offs are robust to the timing of policy implementation.

Data availability

All data used for this research is available as part of the replication package except for proprietary data.

Replication package: Financial Frictions and Climate Policy in a Small Open Economy (Original data) (Mendeley Data)

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