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Climate Finance Intermediation: Interest Spread Effects in a Climate Policy Model

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Abstract: Interest rates are central determinants of saving and investment decisions. Costly financial intermediation distorts these price signals by creating a spread between deposit and loan rates. This study investigates how bank spreads affect climate policy in its ambition to redirect capital. We identify various channels through which interest spreads affect carbon emissions in a dynamic general equilibrium model. Interest rate spreads increase abatement costs due to the higher relative price for capital-intensive carbon-free energy, but they also tend to reduce emissions due to lower overall economic growth. For the global average interest rate spread of 5.1 percentage points, global warming increases by 0.2°C compared to the frictionless economy. For a given temperature target to be achieved, interest rate spreads necessitate substantially higher carbon taxes. When spreads arise from imperfect competition in the intermediation sector, the associated welfare costs can be reduced by clean energy subsidies or even eliminated by economy-wide investment subsidies.

JEL Codes: E43, G21, Q54, Q58

Keywords: financial friction, banking, greenhouse gas mitigation, investment subsidy

REDUCING GREENHOUSE GAS EMISSIONS to mitigate the adverse effects of global climate change requires shifting investment from emission-intensive economic activities toward low-carbon or carbon-free alternatives. The International Energy Agency in

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their sustainable development scenario, for example, estimates annual investment in renewable energy alone at USD 467 billion annually until 2025, rising thereafter (IEA 2018, 50).

Investment finance frequently includes capital from external sources; recent estimates put the share of external finance for private and public firms in the United Kingdom at 20% and 80%, respectively (Zetlin-Jones and Shourideh 2017). For renewable energy investments, Mazzucato and Semieniuk (2018, table 4) report an investment share close to 30% from institutional investors and banks—the latter frequently being the main source of renewable energy finance (Best 2017). Furthermore, Best (2017) finds that access to financial capital is particularly important for renewable energy investments, largely due to their relatively higher capital requirement compared to other energy sources. Access to external finance at low interest rates thus seems to be an important determinant for successful climate policy. In fact, Hirth and Steckel (2016) show that excessively high costs of capital prevent a switch to renewable energy otherwise triggered by a carbon tax.

Financial frictions raise the costs of external finance. Between the source of finance and the investment project, information asymmetries, agency problems, and transaction costs need to be overcome. In principle, financial intermediation provides the tools to address these issues. Hence for the investor, financial intermediation is a welcome solution. Yet it comes at the price of introducing a spread between the return realized in the investment project and the interest paid on the intermediated funds, with potentially adverse consequences for investment activities. Figure 1 shows investment versus interest spread data; lower investment coincides with higher interest rate spreads with a coefficient of correlation of −0.45. We take this as evidence that financial frictions reduce investment.[1]

This study focuses on investigating the effects of intermediation costs on the effectiveness and the design of climate policy. To this end we consider carbon-pricing policies in a dynamic general equilibrium model based on Kalkuhl et al. (2015). The model includes households, consumption goods production, three energy system sectors, and a regulator. For this study we extend the model to capture the effects of financial intermediation of investment flows on capital allocation and accumulation. As the saving and investment decisions are driven by the interest rate, we implement a simple approach to financial intermediation that determines the interest rate spread: financial

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Berlin), EAERE annual conference 2019 (Manchester), and the annual conference of the Global Research Alliance for Sustainable Finance and Investment (GRASFI) 2019 (Oxford). Bastian Grudde and Andrew McConnell supported this study with programming and data preparation. This study was supported by the German Federal Ministry of Education and Research (BMBF) as part of the FINFAIL project (grant no. 01LN1703A), which is gratefully acknowledged.

[1] Williamson (2018) shows a similar correlation based on bond spreads instead of bank spreads and kindly shared the technical details of his analysis with us.

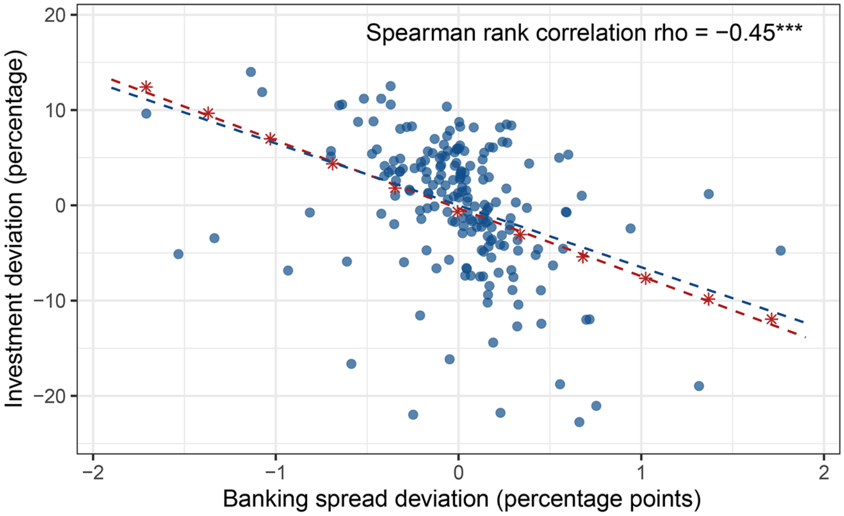

Figure 1. Large bank spreads coincide with periods of low investment. In gray we show private domestic investment for the United States, and the difference of prime loan rate and certificate of deposit as a proxy for the bank spread. The negative correlation is significant at a level of 0.001. All data are taken from Federal Reserve Economic Data (FRED). Asterisks show model calculations. Linear regression lines are provided as visual guides (*dashed lines*).

intermediaries determine the spread between the interest paid on consumers' savings and the rate charged on loans to firms in accordance with intermediation costs and their incentive to maximize profits. Intermediation costs capture the real resources required to operate the banking firm and manage intermediation risk. The supply of deposits and the demand for loans are determined by the preferences of consumers and firms in equilibrium. While one could also calibrate a general equilibrium model to consider intermediation costs in the form of higher costs of (capital-intensive) energy technologies, our approach allows us to explicitly shed light on different reasons for capital cost markups and their impacts on the overall economy. Importantly, our framework emphasizes that the high capital costs in the energy sector are endogenous to financial sector characteristics and could also decline when intermediation costs and market power decrease. From this we can derive optimal climate policy design in a consistent welfare-theoretic model framework.

Conceptually, our model set-up and the distortions in the capital market are also closely related to Barrage (2020). Her model focuses on the implication of labor and capital tax distortions for optimal carbon prices that work in a similar way to intermediation costs or oligopolistic mark-ups in financial markets. A key difference in our model is that interest rate wedges have asymmetric effects on energy sectors due to different capital intensities. This introduces an additional channel by which frictions in capital markets affect carbon emissions, potentially justifying sectoral investment policies as a second-best approach. Moreover, we put emphasis on a target-oriented approach where carbon prices are used to achieve a temperature or emission target politically set, for example, by the Paris Agreement.

Our main contribution is the analysis of the implications of financial intermediation costs and the interest rate spread for climate policy within a general-equilibrium setting. This is a first step toward integrating financial sector actors in the assessment of policies that redirect investment flows toward clean energy on a macroeconomic scale. We find that the resulting interest rate spread substantially affects the real economy. We identify eight channels through which capital market frictions affect the economy and carbon emissions. For all channels, savings and investments are reduced in response to a raised interest rate spread, much in accordance with the literature on growth and financial intermediation (recently in Hamada et al. 2018) and financial development (Fernández and Tamayo 2017). We identify emission-abating as well as emission-increasing channels; in equilibrium we find that the latter dominate the former for small to moderate interest spreads, such that emissions overshoot an intended climate policy target when this increases. Regulators who take this into account will set a considerably higher price on carbon.

In the following section, we discuss related literature. The model is described in sections 2 and 3. Section 4 presents results, and section 5 concludes.

1. LITERATURE

The interest rate has a profound impact in the assessment of climate policy due to the long time scales under consideration. When consumption is forgone today, more consumption becomes possible in the future—either because climate change damages are avoided or because more emissions are still permissible. Investment decisions are made against this intertemporal backdrop by discounting future income at the interest rate, making both the economic dynamics and the policy recommendations sensitive to the interest rate (Gollier 2013). For example, an interest rate that is consistent with observed interest rates (see Nordhaus 2008) may be substantially higher than an interest rate based on normative reasoning (e.g., Stern et al. 2006). The considerably different policy recommendations from the studies cited show their high sensitivity to discounting (Kelleher 2017).

In an undistorted economy, markets will clear at equilibrium prices. The interest rate, in particular, clears the (intertemporal) markets for capital. From a very general perspective, distortions (or frictions) drive a wedge between the valuations on the supply and demand sides. Chari et al. (2007) formalize this notion by showing the equivalence of models where frictions are either explicitly represented by agency problems or parameterized as a price spread. In their business cycle accounting approach, this allows them to estimate the severity of frictions from price spreads, including mapping financial frictions to interest rate spreads. Hall (2011) builds on this but takes interest rate spreads as a modeling input to estimate the associated real effects. For a 6% shock to the spread between the interest rate paid by private businesses and the rate received by consumers, Hall estimates a 4.2% decline in output and a 12.6%–14.7% decline in investment. For investments specifically into renewable energy sources, Hirth and Steckel (2016) model that energy system portfolios are subject to increasingly high costs of capital. They find that very high costs of capital (of 25%) undo the effects of a CO_2 tax in switching the energy system from fossil to renewable energy sources. A key driver of this result is the high capital intensity of renewable energy technologies, which is empirically supported by Best (2017). Andersen (2016) also studies the link between financing conditions and emissions but focuses on the effect of credit constraints on the firm's ability to update to cleaner technology. In Andersen's model, credit constraints take effect via four distinct channels to create an ambiguous overall effect on pollution levels; empirically, relaxing credit constraints is shown to reduce production-generated pollution. Similarly, Andersen (2017) shows that collateral requirements for external finance create a bias toward tangible assets and hence higher emission intensity when the two are positively correlated. These insights on the effect of financing conditions on emissions have, in recent research, been complemented by studies that conversely explore the effect of climate policy on financing conditions. By stranding emission-intensive assets, abrupt and ambitious climate policy can limit bank lending to all sectors, leaving "green" sectors without sufficient access to finance (Carattini et al. 2021). Similarly, climate policy can cause a rise in financing costs, when the rapid capacity expansion in "green" sectors is financed at higher leverage ratios and thus greater default risk (Schuldt and Lessmann 2023).

The financial frictions that find expression in interest rate spreads can be traced back to asymmetric information and agency problems at the microeconomic level. In his financial friction literature survey, Quadrini (2011) traces back frictions to agency problems that give rise to costly state verification (as in Bernanke and Gertler 1989) or collateral constraints (as in Kiyotaki and Moore 1997), which impose a limit on the supply of credit. Quadrini's survey is complemented by Brunnermeier et al. (2013), who in their survey focus on the macroeconomic implications of financial frictions such as more amplified and more persistent downturns. Furthermore, Brunnermeier et al. (2013) focus specifically on the role of financial intermediation in eliminating or reducing frictions. Despite the measurable success of financial intermediation, the introduction of intermediary agents comes with new problems, for example, agency and system fragility.

The literature on financial intermediation is vast (see Gorton and Winton 2003), with more recent research often inspired by asymmetric information and agency problems (Thakor and Boot 2008). This literature provides the underpinnings of the effects that financial frictions, moderated by financial intermediation, have on macroeconomic dynamics—see, for example, Brzoza-Brzezina et al. (2013) for an introduction to the modeling approach and Christiano et al. (2011) for an application—we, however, take a bird's eye approach of focusing specifically on the intermediation costs that arise.

Woodford (2010) develops a model where intermediation costs create diverging interest rates for savers and borrowers of funds and then applies the model in a general equilibrium study (Curdia and Woodford 2010). Similarly in the industrial organization approach to modeling the banking firm as a financial intermediary, intermediation costs are the driver of the interest rate spread between loan rate and deposit rate (Freixas and Rochet 2008; VanHoose 2017). In this approach, intermediation costs represent the costs of providing financial services, including underlying agency costs or inefficiency costs of imperfect competition. A substantial share of intermediation costs arise from real resource costs such as the labor and capital necessary for the intermediaries' operation. According to VanHoose (2017, fig. 1.5) the share of real resource costs in bank expenditure exceeds 80%. Similarly, Dia and Menna (2016) find that resource costs explain between 33% and 66% of a banks' interest margin. That is, resource costs may dominate intermediation costs, hence reducing the link between endogenous risk and intermediation. Recent studies using industrial organization approaches, integrate financial intermediation by banking sectors into models of overlapping generations (Hamada et al. 2018) and endogenous growth (Diallo and Koch 2018). They find higher growth (Hamada et al. 2018) and a higher probability of innovation (Diallo and Koch 2018) when interest spreads shrink due to a higher degree of competition.

Empirical literature attributes observed interest rate spreads to properties of financial intermediation, for example, to characteristics of the financial intermediaries (such as size, liquidity, and equity), regulatory environment (Demirguc-Kunt et al. 2004), and competitiveness (Degryse and Ongena 2008); see Calice and Zhou (2018) and Dwumfour (2019) for analyses of recent data. Further empirical support for the link between financial frictions and financial intermediation (or lack thereof) to capital accumulation and allocation is found in the financial development literature (Levine 2005). See Fernández and Tamayo (2017) for a review stressing the links to financial frictions and Cihak et al. (2013) and Grechyna (2018) for recent analyses including the role of financial intermediation with empirical and theoretical focus.

The potential implications of the financial sector for climate economics have been emphasized in recent literature. The list of shortcomings of current climate economy models includes monetary economics, financing issues, and financial intermediation (Farmer et al. 2015) as well as financial networks and instabilities (Battiston et al. 2016). Campiglio (2016) specifically discusses the central role of banking but in contrast to this study puts emphasis on creation of credit by banks (rather than financial intermediation), arguing that additional market failures in the banking sector call for a portfolio of policy instruments beyond carbon pricing. Recent modeling studies have explored the implications of such "green monetary policies" (Benmir and Roman 2020; Abiry et al. 2022; McConnell et al. 2022; Ferrari and Nispi Landi 2023). A first attempt to separate financial sector dynamics from the real economy in an integrated assessment model is found in de Fosse et al. (2018), who investigate the effect of climate change damages on the financial sector. Also in an integrated assessment context, Paroussos et al.

(2019) explore options to improve access to finance by introducing a country-specific risk premium on top of cost of capital, which is reduced for countries within "climate clubs."

2. THE MODEL

In this study, we investigate the effects of interest rate spreads on climate policy. To do this, we extend an established climate policy model (Kalkuhl et al. 2012, 2013, 2015) by costly financial intermediation following Freixas and Rochet (2008) and Woodford (2010). For a concise presentation of the model, we first discuss our modeling approach to financial intermediation and how it translates into equations to be used in the climate policy model. Next, we describe the basics of the climate policy model and how the financial intermediaries are embedded in its general equilibrium.

2.1. An Industrial Organizations Approach to Financial Intermediation

To investigate the effect of financial intermediation on the implementation of climate policy, it is essential that we capture how it affects capital allocation during the transition to a low-carbon economy. Financial intermediation facilitates the flow of capital from investors to the productive sectors by turning deposited funds into loans.

For the intermediaries, the transformation of deposits to loans incurs costs, particularly those from managing the associated risks. The liability of holding deposits exposes the bank to liquidity risk, that is, the risk of insolvency when creditors withdraw their deposits, particularly in a bank run. Lending, on the other hand, exposes the bank to credit risk, that is, the risk of lenders defaulting on their loans. To manage liquidity risk, banks may keep reserves or buy deposit insurance, and by careful screening and monitoring they may reduce credit risk. We use an intermediation cost function to capture these costs within a deterministic modeling setting; the intermediation costs scale in proportion to the managed funds in line with literature that similarly investigates the effect of interest spreads on real resource allocation (e.g., Woodford 2010).[2]

As financial risk is subsumed as one contribution to aggregate intermediation costs, it cannot vary endogenously in this approach. This puts the exploration of emerging risks, such as stranded asset risk, and financial or "carbon" bubbles, out of the scope of this study. Our modeling simply sheds light on the implications of interest spreads in an economy during "normal times" (or "in between crises").[3]

Following the presentation of the industrial organization approach to financial intermediation in Freixas and Rochet (2008), our model incorporates a sector of *N*

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[2] Additional support for this modeling approach comes from Dia and Menna (2016) and VanHoose (2017), who report high shares of real resource costs in total bank expenditure. This lends support to cost functions that scale with the volume of deposits and loans.

[3] Stochastic modeling with explicit representation of financial risks would be essential to capture feedback of the real economy on risk. We discuss this as an outlook in the conclusion.

identical financial intermediaries (banking firms), indexed $i = 1, \dots, N$, such that N is a measure of market concentration in the banking sector (with perfect competition for $N \to \infty$). In the following we will use the terms "financial intermediary" and "bank" interchangeably. The business of the intermediaries is to grant loans L_i at an interest rate r_L (loan rate). Loans are financed either by attracting deposits D_i at an interest rate r_D (deposit rate) or by borrowing M_i on the interbank market at the interbank rate r_M. While the interbank rate is taken as given, the banks anticipate changes in the loan rate $r_L(L)$ and deposit rate $r_D(D)$ with the volumes of loans and deposits, respectively. Management of deposits and associated payment services as well as screening and monitoring of loans are costly (Calice and Zhou 2018). These intermediation costs are captured by a cost function $C(D_i, L_i)$. The regulator may pay a subsidy s_L on loan provision to address a limited supply of loans when the bank exercises market power. The objective of the intermediaries hence reads (suppressing the subscript i of the identical intermediaries)

$$\pi_B = (1 + s_L)r_L(L)L - r_D(D)D - r_M M - C(D, L). \tag{1}$$

Aggregate loans L are either backed by deposits D or the intermediary's net position M on the interbank market.[4] We have

$$L = M + D. \tag{2}$$

Since net positions of all banks need to balance, where they are identical we will always have $M_i = 0$ for all banks. Still, introducing the interbank rate r_M is useful as it will clear capital markets even in the absence of intermediation costs. We will see this when we derive the rules for the equilibrium loan rate and deposit rate.

Using (2) in (1), and writing price elasticities of demand for loans (ε_L) and deposits (ε_D), we can write the first-order conditions of the banks as follows (technical details are found in app. A1):[5]

$$\frac{r_L(L) - (r_M + C_L)/(1 + s_L)}{r_L(L)} = \frac{\Omega_L}{N\varepsilon_L}, \tag{3}$$

$$\frac{r_M - r_D(D) - C_D}{r_D(D)} = \frac{\Omega_D}{N\varepsilon_D}. \tag{4}$$

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[4] In a slight deviation from Freixas and Rochet (2008), who require financial intermediaries to keep a fraction α of the collected deposits as reserves, such that only a fraction $(1 - \alpha)D$ is available for loans. Freixas and Rochet use α to discuss central bank policies. Since central banks are outside our research aim, we omit reserves to keep the model as simple as possible.

[5] Note that we define the demand elasticities ε_L and ε_D to be positive.

Here, we abbreviate the partial derivative $C_L \equiv \partial C(D, L)/\partial L$ and C_D likewise. The factors $\Omega_L = \partial L/\partial L_i$ and $\Omega_D = \partial D/\partial D_i$ represent the response of the aggregate demand for loans L (and supply of deposits D) to changes in the individual demand L_i of one bank and supply D_i to one bank as expected by this bank. The loan rate r_L and deposit rate r_D are thus set above and below the interbank rate r_M according to

$$r_L = \frac{r_M + C_L}{1 + s_L} \cdot \frac{N\varepsilon_L}{N\varepsilon_L - \Omega_L}, \tag{5}$$

$$r_D = (r_M - C_D)\frac{N\varepsilon_D}{N\varepsilon_D + \Omega_D}. \tag{6}$$

The bank spread $(r_L - r_D)$ is thus determined by the marginal costs of intermediation C_L and C_D as well as the degree of market power in the loan and deposit markets. Market power (i.e., strictly positive Ω_L and/or Ω_D for a finite number N of banks with finite elasticities ε_L and ε_D) amplifies and dampens the effect of intermediation costs, respectively. A loan subsidy $s_L > 0$ will counteract monopolistic loan pricing, completely offsetting it for $s_L = \Omega_L(N\varepsilon_L - \Omega_L)^{-1}$.

From this, the effect of the determinants of the interest rate spread on the interest rates is straightforward:

$$\begin{aligned} r_L &= r_L(r_M, C_L, N, \varepsilon_L, \Omega_L, s_L) = r_L(+, +, -, -, +, -), \\ r_D &= r_D(r_M, C_D, N, \varepsilon_D, \Omega_D) = r_D(+, -, +, +, -). \end{aligned}$$

In particular, all else being equal, stronger financial frictions from a higher marginal cost of loans C_L or less competitiveness N raise the loan rate r_L. A loan subsidy will lower it. Similarly, higher marginal costs of deposits C_D and less competitiveness N will reduce r_D.

Figure 2 visualizes the resulting interest rate spread. With perfect competition of intermediaries, the equilibrium loan rate exceeds the interbank rate by the marginal

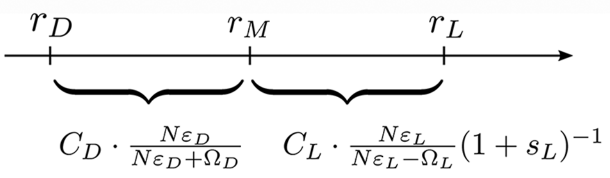

Figure 2. Interest rate spread. The deposit rate r_D and loan rate r_L are set below and above the interbank rate r_M. The wedges between the interest rates are proportional to marginal intermediation costs and a factor reflecting imperfect competition (for $N < \infty$, $\varepsilon_{\{D,L\}} < \infty$, and $\Omega_{\{D,L\}} > 0$).

intermediation costs of making loans. Likewise, the deposit rate is set below the interbank rate, taking marginal costs of deposits into account. The bank spread ($r_L - r_D$) is then determined simply by totaling marginal intermediation costs.

2.2. General Equilibrium Embedding

The capital market equilibrium in the model of Kalkuhl et al. (2012) implies that every dollar saved is invested in the real economy earning the return on capital r_t. Without financial intermediation and interest spreads, r_t is the single interest rate of the economy, balancing the marginal productivity of capital on the demand side and the marginal utility of consumption on the supply side. When we detail the problems of the sectors below, we will introduce the deposit rate r_{Dt} and the loan rate r_{Lt} on the capital supply and demand sides, respectively. In the absence of financial frictions (i.e., no intermediation costs or imperfect competition) all interest rates (including the interbank rate r_{Mt}) collapse to a single, capital market-clearing interest rate $r_{Mt} = r_{Lt} = r_{Dt}$, and the original model is recovered.

Our economy consists of a representative household, a firm producing consumption goods and an energy sector with three representative firms: fossil resource extraction, fossil energy generation, and renewable energy generation. A government oversees all activities in the economy and can use a set of policy instruments to regulate the equilibrium outcome. We briefly describe each economic actor in turn (see Kalkuhl et al. 2012, for an extended presentation including all first-order conditions).

2.2.1. Representative Household

Households maximize intertemporal welfare W, that is their aggregate utility, discounted following a time preference rate ρ and standard convexity assumptions. Households are endowed with labor P_t, which they supply inelastically to earn wage income at w_t. The cumulative savings of the households K_t earn the deposit rate r_{Dt}. Additional income comes from profits π_t from owning the firms in all sectors i of the economy, and through government transfers Γ_t (lump sum recycling of tax income):

$$\begin{aligned} W &= \sum_0^\infty P_t u(C_t/P_t)(1+\rho)^{-t}, \\ C_t + I_t &= w_t P_t + (1-\tau_{Kt}) r_{Dt} K_t + \pi_t + \Gamma_t \quad \text{with } \pi_t = \sum_{i\in\{Y,F,L,N,R,B\}} \pi_{it}, \\ K_{t+1} &= K_t + I_t. \end{aligned} \tag{7}$$

The household's income may be taxed lump sum (when Γ_t is negative), or through a tax on capital income (τ_{Kt}).

2.2.2. Consumption Goods

Consumption goods are produced with a nested constant elasticity of substitution (CES) technology that combines labor and capital to form a labor-capital composite Z, which in turn is combined with (aggregate) energy E. Energy E aggregates energy from fossil resources E_F with renewable energy E_L. Factor payments go to households and respective firms, and all quantities are chosen to maximize profits π_{Yt}. Capital depreciation at rate δ is borne by the firm:[6]

$$\begin{aligned}\pi_{Yt} = Y(Z(K_{Yt}, P_t), E(E_{Ft}, E_{Lt}))\Xi_t \ -w_t P_t - (r_{Lt} + \delta)K_{Yt} \\ -p_{Ft}E_{Ft} - p_{Lt}E_{Lt}.\end{aligned} \tag{8}$$

Climate change impacts Ξ_t lower economic output. We explore this in section 4.3 but set $\Xi = 1$ otherwise in this study.

2.2.3. *Climate Change*

Climate change impacts are modeled following Dietz and Venmans (2019). The model combines carbon emissions from fossil fuel extraction R with land use change emissions $\mathrm{EM}^{\mathrm{land}}$ to get total emissions $\mathrm{EM}^{\mathrm{tot}}$. Total emission accumulate to yield the cumulative emissions in the atmosphere $\mathrm{EM}^{\mathrm{cum}}$:

$$\mathrm{EM}_t^{\mathrm{land}} = \mathrm{EM}_0^{\mathrm{land}}(1 - d^{\mathrm{land}})^{(t-t_0)}, \tag{9}$$

$$\mathrm{EM}_t^{\mathrm{tot}} = R_t + \mathrm{EM}_t^{\mathrm{land}}, \tag{10}$$

$$\mathrm{EM}_{t+1}^{\mathrm{cum}} = \mathrm{EM}_t^{\mathrm{cum}} + \mathrm{EM}_t^{\mathrm{tot}}. \tag{11}$$

Cumulative emissions translate to an increase in atmospheric temperature T^{atm} relative to preindustrial levels which in turn brings in an exponential damage function. Appendix E (apps. B–H are available online) lists all parameters and their values.

$$T_{t+1}^{\mathrm{atm}} = T_t^{\mathrm{atm}} + \varepsilon(\zeta \mathrm{EM}_t^{\mathrm{cum}}\chi - T_t), \tag{12}$$

$$\Xi_t = \exp\left(-\frac{\gamma}{2}(T_t^{\mathrm{atm}})^2\right). \tag{13}$$

2.2.4. *Energy from Fossil Resources*

The fossil energy sector combines fossil resources R_t, purchased at price p_{Rt} from the resource extraction sector, with capital K_{Ft} using a CES technology to generate energy E_{Ft}. The representative fossil firm seeks to maximize profits π_F given by

$$\pi_{Ft} = p_{Ft}E_F(K_{Ft}, R_t) - (r_{Lt} + \delta)K_{Ft} - (p_{Rt} + \tau_{Rt})R_t.$$

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[6] Capital stock depreciation is often part of the equation of motion similar to (7). This is sensible when households own firms but less so for households who take deposit savings. We have thus included depreciation in the problems of the firms.

Fossil resource combustion is subject to a carbon tax τ_{Rt} levied by the regulator. The fossil energy firm finances its capital at the loan rate r_{Lt} and takes capital depreciation (δK_{Ft}) into account.

2.2.5. Fossil Resource Extraction

The finite stock of fossil resources S_t is owned by the fossil resource sector, which decides on the per-period extraction R_t to sell to the fossil energy sector at price p_{Rt}. Resource extraction employs capital K_{Rt} financed at the loan rate and maintained against depreciation. The per-period profits π_{Rt} are thus

$$\pi_{Rt} = p_{Rt}R(S_t, K_{Rt}) - (r_{Lt} + \delta)K_{Rt}.$$

Resources are harder to extract the more the stock of resources is depleted. This is modeled by decreasing marginal productivity of K_{Rt} as S_t diminishes, that is, $\partial^2 R_t/(\partial K_{Rt}\partial(-S_t)) < 0$. Optimal resource extraction is a dynamic problem; hence the resource sector maximizes the flow of all future discounted profits subject to depletion of the stock of resources:[7]

$$\begin{aligned} &\max_{R_t} \sum_{t=0}^{T} \pi_{Rt}\Pi_{s=0}^{t}(1 + r_{Ds})^{-1} \\ &S_{t+1} = S_t - R_t, \quad S_t \geq 0, S_0 \text{ given.} \end{aligned} \tag{14}$$

2.2.6. Energy from Renewable Energy Sources

Energy generation from renewable energy sources requires capital K_{Lt} and land O_t in a constant elasticity of substitution production function. Land supply is fixed, and capital productivity $A_L(\cdot)$ rises endogenously due to technology learning, that is, it rises with cumulative energy generation H_t in this sector. The regulator can affect the cost of capital with a tax (or subsidy) τ_{Lt}:

$$\begin{aligned} \pi_{Lt} &= p_{Lt}E_L(A_L(H_t)K_{Lt}, O_t) - ((1 + \tau_{Lt})r_{Lt} + \delta)K_{Lt}, \\ H_{t+1} &= H_t + (E_{Lt} - E_{Lt-1}). \end{aligned} \tag{15}$$

Technology learning creates a dynamic problem for the firm; its objective is therefore to maximize the discounted stream of profit:

$$\max_{K_{Lt}} \sum_{t=0}^{T} \pi_{Lt}\Pi_{s=0}^{t}(1 + r_{Ds})^{-1}.$$

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[7] The discount rate r_D is implied by depositing capital as the firm's best outside option. We make the assumption that the firm could not invest its capital elsewhere in a more efficient way than through a bank, which benefits from economies of scale.

2.2.7. Financial Intermediaries

The financial sector is populated by N financial intermediaries as described above in section 2.1. There is no direct equity investment by households. As financial intermediation is subject to economies of scale (e.g., Freixas and Rochet 2008), the households' cost of direct investment would exceed the intermediation costs and hence, in equilibrium, all finance would be intermediated. Intermediated equity, for example, an investment fund, would fall somewhere between the safe deposit and the risky direct investment. Within our simple setting where risk maps to intermediation costs, it would be indistinguishable from the household's perspective. Consequently, we assume that all consumer savings are deposited with the intermediaries, and any demand for capital of the firms is met by loans from the banking sector:

$$\begin{aligned} D_t &= K_t, \\ L_t &= K_{Yt} + K_{Lt} + K_{Ft} + K_{Rt}. \end{aligned} \tag{16}$$

Equation (16) puts no constraints on the allocation (or reallocation) of capital to the sectors. There are also no capital adjustment costs in the four sectors, a simplification that allows us to study the friction that intermediation costs put on capital accumulation in isolation. The capital stock dynamics are therefore very flexible (see sec. 4.5). As in section 2.1, all deposits translate one to one into loans, that is $D_t = L_t$.

The intermediaries set the deposit rate r_{Dt} and loan rate r_{Lt} at each t to maximize profits as in equations (3) and (4). The interbank rate r_{Mt} adjusts to fall in between r_{Dt} and r_{Lt} according to (5) and (6).

The demand for loans $L(r_{Lt})$ arises from the demand for the different capital stocks K_{it}. In this economy, the consumption goods sector demands the lion's share of capital, that is, approximately three-quarters of the total. For the elasticity of demand $\varepsilon_L(L_t) = r_L(L_t)L_t'/L_t$ in equation (3) we thus approximate the demand function for loans by the demand function for K_{Yt} at a fixed level of Z (see app. C).[8]

For simplicity, we assume an additive, linear intermediation cost function $C(D_t, L_t)$ as in Freixas and Rochet (2008) or Diallo and Koch (2018), but see Grechyna (2018) for a model where intermediation costs arise endogenously from loan volume and monitoring activity:

$$C(D_t, L_t) = \gamma_L L_t + \gamma_D D_t.$$

2.2.8. Regulator

We assume a benevolent government; hence the problem of the government is to maximize social welfare assuming preferences identical to those of the representative household:

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[8] The overall elasticity of demand ε_L is a weighted sum of the sectorial elasticities $\varepsilon_L = \Sigma_i s_i \varepsilon_{L_i}$ where the weights s_i reflect the relative size of the sectors in terms of capital $s_i = K_i/K$. Numerically, the elasticity in the consumption goods sector dominates because $s_Y \approx 0.75$ and all ε_i are of a similar magnitude.

$$\max_{\Theta} W \text{ with } \Theta \subseteq \{\tau_{Rt}, \tau_{Lt}, \tau_{Kt}, s_{Lt}\} \tag{17}$$

subject to (a) the equilibrium of the economy

$$\text{(b) budget } \Gamma_t = \tau_{Lt}E_L + \tau_{Rt}R_t + \tau_{Kt}r_{Dt}K_t - s_{Lt}r_{Lt}L_t \tag{18}$$

$$\text{(c) policy targets.} \tag{19}$$

policy target is one of: laissez faire (20)

cost-benefit, i.e., (9)–(13) (21)

fixed cap, i.e., carbon budget $B_0 : S_t \geq S_0 - B_0$ (22)

fixed tax, i.e., $\tau_{Rt} = \tau^*_{Rt}$ (23)

The government chooses its policy subject to all constraints of the economy, including all first-order conditions, acting with perfect knowledge of the response of the economic agents to its policies. Policy instruments available to the regulator are a carbon tax τ_{Rt}, taxes on capital income τ_{Kt} and renewable energy use τ_{Lt}, and a subsidy on loan provision s_{Lt}. Whenever the policy set Θ contains sufficient policy instruments, this allows the government to implement the first-best socially optimal allocation. Second-best solutions are obtained when, for example, the set of instruments Θ is limited—a possible reason being that certain policies are considered politically infeasible. Without market failures in the economy, the optimal choice would be zero for all instruments. This is true for perfect competition in intermediation and no climate change damages; that is, market power in the financial sector and climate change damages are the only distortions in the economy.

We distinguish three climate policy scenarios. First, cost-benefit analysis where the regulator anticipates climate change damages and finds an optimal carbon tax. Second, the regulator can implement a fixed cap on cumulative emissions to any politically given upper limit B_0. This scenario is motivated by politically agreed climate targets (e.g., the Paris Agreement, which aims to limit warming to 1.5 or 2.0 degrees, or emission permit systems with a fixed cap). And third, in the fixed tax scenario we consider an exogenously given tax τ^*_{Rt}.

An additional motivation for intervention arises from imperfect competition in the banking sector. Subsidizing either loan provision ($s_{Lt} > 0$) or capital income ($\tau_{Kt} < 0$) as in section 4.6 can address this distortion.

3. PARTIAL EQUILIBRIUM EFFECTS OF FINANCIAL INTERMEDIATION

The introduction of an interest spread ($r_{Lt} - r_{Dt}$) will tend to lower the interest paid on deposits (r_{Dt}) and put upward pressure on the interest charged for loans (r_{Lt}). To develop an understanding of how this affects economic activity and ultimately the effectiveness of

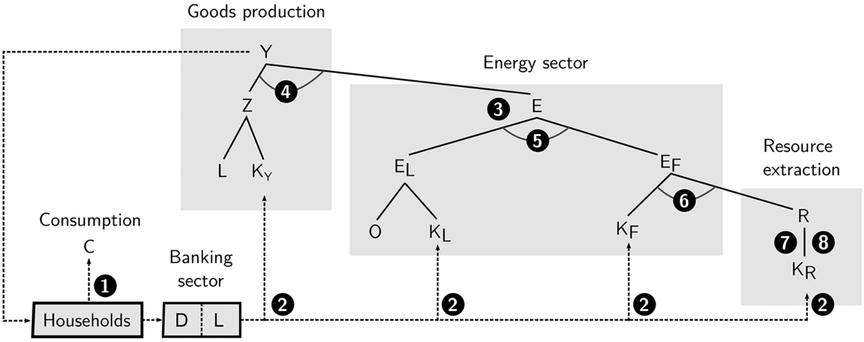

Figure 3. Overview of friction effects. We identify eight partial equilibrium effects that contribute to cumulative emissions in general equilibrium: (1) the consumption-saving decision of the household, (2) capital demand, (3) energy demand, (4) energy intensity in goods production, (5) the portfolio of energy sources, (6) carbon intensity of fossil energy, as well as (7) discounting and (8) extraction cost effect in the resource extraction sector.

climate policy, we discuss the relevant partial equilibrium responses to changes in the interest rate. Figure 3 provides an overview of how households, aggregate goods production, and the energy and resources sectors are affected. For this analysis, we assume that the interest rates for the respective sector change while holding other input prices constant. We then calculate the adjustment to demand for inputs and the supply of outputs (including output prices). We identify eight response channels of the economy that affect emissions and hence effectiveness of climate policy. In the following, we discuss each channel in partial equilibrium and summarize the effects and their implications at the end of the section.

3.1. The Household's Saving Decision

The consumption-saving decision of the representative household is governed by the household's first-order conditions[9]

$$\begin{aligned} P_t \frac{\partial U(C_t/P_t)}{\partial C_t}(1+\rho)^{-t} &= u'(C_t)(1+\rho)^{-t} = \psi_t \\ 0 &= \psi_{t-1} - \psi_t(1+(1-\tau_{Kt})r_{Dt}). \end{aligned} \tag{24}$$

Ignoring the capital income tax τ_{Kt} for now, we eliminate the shadow price of consumption ψ_t to get the Keynes-Ramsey rule $u'(C_{t-1}) = [1/(1+\rho)](1+r_{Dt})u'(C_t)$. For isoelastic utility $u(C_t) = C_t^{1-\eta}/(1-\eta)$ we have

---

[9] The Lagrangian for the household's problem reads: $L = \Sigma_{t=0}^{\infty}[P_t u(C_t/P_t)(1+\rho)^{-t} + \psi_t(K_{t+1} - K_t - w_t P_t - (1-\tau_{kt})r_{Dt}K_t - \pi_t - \Gamma_t)]$. First-order conditions are obtained by maximizing after consumption C_t and capital K_t.

$$\left(\frac{C_t}{C_{t-1}}\right)^{\eta} = \frac{1 + r_{Dt}}{1 + \rho}.$$

With $g_{ct} = C_t/C_{t-1} - 1$ the growth rate of consumption, taking logs and considering that $\log(1 + x) \approx x$ for $x = \{r_{Dt}, \rho, g_{ct}\}$ close to zero the discrete Ramsey rule takes the familiar form $r_{Dt} = \rho + \eta g_{ct}$ where $g_{ct} = \ln(C_{t+1}/C_t)$ is the growth rate of consumption. The bank spread will lower the interest rate r_{Dt} paid on savings. We summarize the effect on the consumption-saving decision in the following proposition.

> **Proposition 1** (Savings effect): A reduction of the deposit rate r_{Dt} affects the savings behavior of the household via the Keynes-Ramsey rule resulting in a reduced consumption growth rate g_{ct}.

With a sustained lower consumption growth rate, savings and, thus, total income have to be lower in the long run as well. Therefore, carbon emissions (that are associated with the production of consumption and investment goods and, thus, income) will also be lower in the long run. In the short run, however, consumption could increase due to a substitution effect: if returns to savings are less attractive, a larger share of the available income could be spent on consumption rather than savings.[10]

If this substitution effect is strong, it implies that (near-term) consumption levels increase and savings decrease when the deposit rate falls. The reduction in savings will subsequently reduce income. Hence, although consumption levels might be greater in the short run, income levels will be lower in the short and in the long run when the deposit rate falls. We therefore expect that in partial equilibrium with an exogenous interest rate, a higher interest spread reduces carbon emissions due to lower short-term and long-term income.

3.2. Capital Demand from Productive Sectors

Capital demand is determined by marginal productivities of production and energy generation technologies as represented in the nested constant elasticity of substitution production functions. Four sectors employ capital: goods production, resource extraction, and energy from fossil and renewable sources. In equilibrium, capital demand follows from first-order conditions for the sectors. In each of the sectors, marginal productivity is balanced with the loan rate $\bar{r}_{Lt} = r_{Lt} + \delta$ (net of depreciation costs and taking prices into account).

---

[10] In the standard two-period life-cycle savings model, income and substitution effects can be analytically derived: while lower income in the first period reduces savings, a lower interest rate reduces savings if and only if $\eta < 1$ (see Barro and Sala-i Martin 2003, chap. 3.8). For $\eta = 1$, the substitution effect is zero. In our context, a lower interest rate would also contribute to lower capital incomes in the first period. Hence, in the case of $\eta > 1$ it is not clear whether the substitution or the income effect dominate for consumption levels in the short run.

$$\begin{aligned}
\bar{r}_{Lt} = r_{Lt} + \delta &= \frac{\partial Y}{\partial K_{Yt}} && \text{(goods production)}\\
&= p_{Ft}\frac{\partial E_F}{\partial \mathrm{K}_{Ft}} && \text{(fossil energy)}\\
&= (p_{Lt} + \mu_t)\frac{\partial E_L}{\partial K_{Lt}} && \text{(renewable energy)}\\
&= (p_{Rt} + \psi_t)\frac{\partial R}{\partial K_{Rt}} && \text{(resource extraction).}
\end{aligned}$$

Lagrange multipliers μ_t and ψ_t are the shadow prices of technological learning in the renewable energy sector, equation (15), and resource scarcity in the extraction sector, equation (14), respectively. An increase in $\bar{r}_{Lt}$ (or likewise r_{Lt}) demands a higher marginal productivity of capital. Technology with decreasing marginal productivity implies that capital demand will fall in response.

> **Proposition 2** (Capital demand): A higher loan rate r_{Lt} will reduce capital demand in all sectors with decreasing marginal productivity.

As capital is essential in goods production, lower levels of K_{Yt} will reduce economic output Y. We therefore expect that higher interest rate spreads reduce carbon emissions because of lower economic activity. Moreover, the lending rates affect energy demand which is a complementary factor input to capital:

> **Proposition 3** (Energy demand): Demand for energy E falls with the cost of capital in goods production r_{Lt}, that is $dE/dr_{Lt} < 0$ when energy is a complement to the labor-capital composite.

> *Proof*: A higher lending rate reduces capital input K_{Yt} in the aggregate production sector. As labor is fixed the demand for energy E also decreases when energy is a complement to the labor-capital composite. QED

Empirical analyses of substitution elasticities support the assumption of complementarity between energy and the labor-capital composite (Van der Werf 2008). Hence, with lower energy demand, assuming everything else is equal in the economy, carbon emissions should therefore decrease when the interest rate spread increases.

3.3. Energy Intensity in Goods Production

Goods production combines the labor-capital composite Z with energy E in a nested constant elasticity production function. A higher lending rate r_{Lt} puts upward pressure on the price p_{Zt} of Z which equals in competitive output markets the unit cost function for the labor-capital composite:[11]

$$p_{Zt}(\bar{r}_{Lt}, w_t) = \left(a_2^{\sigma_2} \bar{r}_{Lt}^{1-\sigma_2} + b_2^{\sigma_2} w_t^{1-\sigma_2}\right)^{\frac{1}{1-\sigma_2}}, \tag{25}$$

where σ_2 is the elasticity of substitution between capital and labor. This, in turn, affects the energy intensity of economic output, given as the ratio of demand for factor inputs Z and E as

$$\frac{Z}{E} = \left(\frac{a_1 p_{Et}}{b_1 p_{Zt}}\right)^{\sigma_1},$$

where p_{Et} is the price of total energy and σ_1 the elasticity of substitution between energy and the labor-capital composite. Intuitively, when capital becomes relatively more expensive, some of it is substituted with energy. With $p_{Yt}Y = p_{Zt}Z + p_{Et}E$ we obtain EI(Y, E) for the energy intensity of final output production

$$\mathrm{EI} := \frac{E}{Y} = \frac{p_{Yt}}{p_{Zt}\left(\frac{a_1 p_{Et}}{b_1 p_{Zt}}\right)^{\sigma_1} + p_{Et}}.$$

The energy intensity EI can be shown to increase in the loan rate when factor prices on labor w_t and energy p_{Et} are held constant:

Proposition 4 (Energy intensity of goods production): The energy intensity of goods production increases with the cost of capital in goods production, that is, the loan rate r_{Lt}. That is, $dEI/dr_{Lt} > 0$.

Proof: See appendix B.1. QED

If the energy intensity increases due to an interest rate spread, carbon emissions are—all else being equal—also expected to increase.

3.4. Portfolio of Energy Sources

In order to analyze the energy portfolio effect, we evaluate how the ratio of fossil to renewable energy E_F/E_L changes when the loan rate increases. We consider in the following the general case of fossil energy $E_F(K_{Ft}, R_t)$ that is produced with capital K_{Ft} and fossil resources R_t, and renewable energy $E_L(K_{Lt}, O_t)$ that is produced with capital K_{Lt} and land O_t, both using CES technology. We again assume for the partial equilibrium analysis that factor prices of other inputs (here: fossil resource R_t and land O_t)

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[11] For the derivation of unit cost functions and factor demands for constant elasticity to scale production functions we refer to Rutherford (1995).

are exogenous and do not change with the interest rate.[12] As fossil and renewable energy are substitutes in the production sector, we can show that an increase in the loan rate r_{Lt} biases the energy mix to the less capital-intensive technology:

> **Proposition 5** (Portfolio effect): An increase in the loan rate r_{Lt} that raises the cost of capital in the fossil and renewable energy sectors biases the energy mix toward the less capital intensive sector, that is, $d(E_F/E_R)/d\bar{r}_{Lt} > 0 \Leftrightarrow K_{Lt}/p_{Lt}E_L > K_{Lt}/p_{Lt}E_L$.
>
> *Proof*: See appendix B.2. QED

Empirical as well as modeling studies indicate that various renewable energy technologies are more capital intensive than fossil energy technologies (Schmidt 2014; Hirth and Steckel 2016; Best 2017), in particular natural gas–based technologies (Lazard 2021). In this case, proposition 5 suggests that the portfolio effect contributes to higher carbon emissions.

3.5. Carbon Intensity of Fossil Energy

Besides changing the allocation of capital across energy sectors, changes in the loan rate affect capital versus carbon input in the fossil energy production sector as $K_{Ft}/R_t = (a_F p_{Rt}/b_F \bar{r}_{Lt})^{\sigma_F}$. With $p_{Ft}E_F = \bar{r}_{Lt}K_{Ft} + p_{Rt}R_t$, we obtain for the carbon intensity of fossil energy production

$$\mathrm{CI} := \frac{R_t}{E_F} = \frac{p_{Ft}}{\bar{r}_{Lt}\left(\frac{a_F p_{Rt}}{\bar{r}_{Lt} b_F}\right)^{\sigma_F} + p_{Rt}}. \tag{26}$$

The following holds for carbon intensity CI when the loan rate r_{Lt} increases with the interest spread.

> **Proposition 6** (Carbon intensity of fossil energy): The carbon intensity of fossil energy generation increases in the cost of capital in the fossil energy sector r_{Lt}, that is, $dCI/dr_{Lt} > 0$.
>
> *Proof*: See appendix B.3. QED

---

[12] While we address the impact of the interest rate spread on the price of fossil resource, p_{Rt} in sec. 3.6, the impact on land prices p_{Ot} is straightforward: as land is only used in the renewable energy sector and as it is a fixed factor, the land price decreases in the cost of capital for the renewable energy sector. This is because the first-order conditions in the renewable sector are $p_{Lt}\partial F(\cdot)/\partial K_L = r_{Lt}$ and $p_{Lt}\partial F(\cdot)/\partial O = p_{Ot}$. Taking the total derivative after r_{Lt} with fixed land use O gives: $dp_{Ot}/dr_{Lt} = (\partial^2 F(\cdot)/\partial O \partial K)/(\partial^2 F(\cdot)/\partial K^2) < 0$.

3.6. Resource Extraction Dynamics

In the extraction sector, interest rates affect extraction dynamics twofold: first, the deposit rate r_D determines the discount rate of the resource owner for deciding how much to extract today and how much to leave underground for future extraction; second, the loan rate r_L affects the costs of capital that is used for extracting resources. The optimization problem of the resource owner reads $\sum_{t=0}^{T}[p_{Rt}R_t - c(S_t, \bar{r}_{Lt})R_t]\prod_{s=0}^{t}(1 + r_{Ds})^{-1}$ with $R_t = \kappa(S_t)K_{Rt}$ and $c(S, r_L) \coloneqq c(S) \coloneqq (\bar{r}_L + \delta)/\kappa(S)$ and $S_{t+1} = S_t - R_t$ (see Kalkuhl et al. 2012).[13] The discrete Hotelling rule for this problem is then:

$$\frac{\psi_t + c'(S_t)R_t}{\psi_{t-1}} = 1 + r_{Dt},$$

with $\psi_t \coloneqq p_{Rt} - c(S_t)$ the user cost of the fossil resource. For illustrative purposes, we assume that all resources will eventually be extracted (see also Sinn 2008). Changes in the interest rate only affect the time profile of extraction rather than the cumulative amount.[14]

Proposition 7 (Discounting effect): A decrease in the deposit rate r_D implies a flatter resource extraction path. Resource extraction will therefore initially be lower.

Proof: See appendix B.4. QED

We now turn to the lending rate r_L that affects extraction costs through $c(S, r_L) = (r_L + \delta)/\kappa(S)$. An increase in the lending rate leads to an upward shift of the extraction costs $c(S)$ as well as $-c'(S)$:

Proposition 8 (Extraction costs): An increase in the lending rate r_L implies a flatter resource extraction path (i) if the extraction cost curve is constant or (ii) if it is sufficiently flat. Resource extraction will then initially be lower.

Proof: See appendix B.5. QED

Summing up, as costs of intermediation decrease the deposit rate r_D and increase the lending rate r_L fossil resource extraction is affected in two ways: a lower deposit rate unambiguously flattens the resource extraction path, implying lower extraction rates, and thus initially lower carbon emissions (proposition 7); a higher lending rate increases extraction costs due to higher capital costs. This also flattens the resource

---

[13] Note that $c'(S) \leq 0$ and $c''(S) \geq 0$ as $\kappa'(S) \geq 0$ and $\kappa'(S) \leq 0$.

[14] Allowing for cumulative volume effects requires a more sophisticated modeling of the timing when the backstop price is reached. This requires further functional assumptions and simplifications.

extraction path and reduces carbon emissions if the extraction cost curve is sufficiently flat (proposition 8).

3.7. Synthesis of Impact Channels

Table 1 summarizes the partial equilibrium effects. Column 2 collects the ceteris paribus first-order effects as shown in the propositions. In column 3, we list the expected effect on carbon emissions. For example, lower consumption growth and hence lower consumption levels imply less economic activity and hence lower emissions (row 1), and a similar argument applies in the case of lower capital accumulation (row 2). The effect on emissions for rows 3–6 follows directly. The effect on resource extraction (rows 7 and 8) is less clear; a flatter resource extraction path suggests initial lower emissions but cumulative emissions in the very long run are unaffected if all underground resources are extracted.

We have thus identified a range of effects with opposite effects on emissions. To assess their relative strength and interactions in general equilibrium is a task for the numerical simulations in the next sections.

4. NUMERICAL SIMULATION: GENERAL EQUILIBRIUM

4.1. Calibration

We calibrate our model to match observed interest rates, bank spreads, energy prices, and growth dynamics similar to Nordhaus (2017). Table 2 compares model and data.

We also calibrate the model to match the bank spread and Lerner index from the Global Financial Development Database (World Bank 2022). Following Diallo and Koch (2018), we assume perfect competition for deposits, that is $\Omega_D = 0$ but adopt the Cournot conjecture for the oligopolistic market for loans. In this the behavior of other banks is taken as given, such that $\Omega_L \equiv 1$ (see Francois and Roland-Holst

Table 1. Overview of Partial Equilibrium Effects

Proposition (1)	Effect of a Wider Interest Spread (first-order effect) (2)	Effect on Emissions (ceteris paribus effect) (3)
1. Savings effect	Lower consumption growth	Lower emissions
2. Capital demand	Lower capital accumulation/GDP	Lower emissions
3. Energy demand	Lower demand for energy	Lower emissions
4. Energy intensity	Higher energy intensity	Higher emissions
5. Portfolio effect	Bias toward fossil energy	Higher emissions
6. Carbon intensity	Higher carbon intensity	Higher emissions
7. Discounting	Flatter resource extraction path	Lower emissions
8. Extraction cost	Flatter or steeper extraction path	Lower or higher emissions

Table 2. Model Calibration

Variable		Model	Data	Source
Deposit rate	r_D	3.2	3.0	IFS
Bank spread		5.1	5.1	GFDD
Loan rate	r_L	8.4	8.9	IFS
Lerner index		.27	.27	GFDD
Fossil energy prices	p_{EF}	6	5–10	IEA (2020)
Renewable energy prices	p_{EL}	14	4–16	IEA (2020)
Output per capita growth rate		2.1	2.1	Nordhaus (2017)

Note. The model was calibrated to match interest rates and energy prices. All rates are in percent, prices are in cents/kWh (2018 USD). Energy prices are given for 2020, other values are averages; see text for details. GFDD = Global Financial Development Database (World Bank 2022); IFS = International Financial Statistics data set (IMF 2022).

1997), which is frequently used as a benchmark (see Takeda [2010] for a discussion of different ways to model imperfect competition). The Lerner index measures the competitiveness of a country's banking sector, and we use it to calibrate the share of the bank spread attributable to intermediation costs ($\gamma_L = 0.029$) and the share that arises from market power ($N = 1.6$). We take GDP-weighted means of all available countries for the most recent 15 years up to 2014, beyond which the Lerner index has not been reported. We match the level of interest rates by setting the pure rate of time preference to ρ to 0.5% and use an isoelastic utility function with an elasticity of marginal consumption set to $\eta = 1.45$ (as in Nordhaus 2017). Table 2 shows the deposit rate and loan rate from the International Financial Statistics data set (IMF 2022), averaged over the most recent decade (2012–21).

We calibrate fossil energy generation such that the fossil energy price is 6¢/kWh (kilowatt-hour) in 2020 (all prices are in 2018 USD). This is at the lower end of the interquartile ranges for lignite, coal, and gas of [5, 10]¢/kWh (IEA 2020, fig. ES1). The resulting fossil energy price rises due to resource scarcity (increasing marginal extraction costs) to 10¢/kWh in 2100 (11¢ in 2125). In the carbon-pricing scenarios, the carbon price pushes the fossil energy price to 28¢ in 2100 (and 47¢ in 2125). Renewable energy technology is calibrated such that the renewable energy price is 14¢/kWh in 2020. This is the upper end of the interquartile range of [4, 16]¢/kWh for wind (onshore and offshore) and solar (IEA 2020). Renewable energy technologies are subject to technological learning such that productivity increases at the learning rate for every doubling of installed capacity. The review paper of Samadi (2018) suggests future learning rates for renewable energy ranging from 3% to 20% (means per technology). We select a rate within this range of 17%, corresponding to a learning parameter $\varphi = 0.27$ in equation (D.9) in appendix D. We calibrate to the lower end of cost estimates for fossil fuels and the higher end for renewable energy costs for two reasons: first, the cost estimates ignore the fact that variable renewables have lower value when used at large scale; second, we want to take a conservative approach regarding the difficulty of the low-carbon transition. We further disregard an explicit differentiation between electric and nonelectric energy sources. Due to increasing electrification in the heating and transport sector and due to the use of electricity to generate synthetic (carbon-free) fuels, electricity is becoming the dominant energy type in most decarbonization scenarios (Luderer et al. 2022). Hence, the costs of energy will increasingly be dominated by electricity costs.

Economic growth is driven by exogenous increases in population and labor productivity (following Nordhaus 2017). Initial population P_0 is 7.4 billion and increases toward a maximum of 11.5 billion. Labor productivity follows $A_{Y,t+1} = A_{Y,t}(1 + 1 - (g_0 e^{-\xi t})^{-1})$, its growth rate is initially g_0 but declines at rate ξ. The resulting average growth rate over the next century is 2.1% (as in Nordhaus 2017).

Our choice of elasticities of substitution reflects that energies from different sources are good substitutes (adoption $\sigma_3 = 3$ from Acemoglu et al. 2012), that the elasticity of capital and labor is well below unity ($\sigma_2 = 0.7$, which is consistent with the empirical range reported in Knoblach and Stöckl [2020] and estimates between 0.64 and 0.72 in the recent meta-regression of Knoblach et al. [2020]), and good substitutability with energy $\sigma_1 = 0.5$, which is a common choice in energy-economy models (see Zha and Zhou 2014, table 4).

We assume that fossil resource use is limited by its finite availability ($S_0 = 4{,}000$ GtC [gigatons of carbon]) and increasing marginal cost of extraction following Rogner (1997) and taking into account resource extraction since then. For fossil energy generation, we allow only for limited substitutability of capital and fossil energy resources (elasticity of substitution $\sigma_F = 0.15$).

For the climate system equations, values for ε, ζ, and γ are taken from Dietz and Venmans (2019, table 1), where we select the central values for ζ and for γ. Land use parameters are from Nordhaus (2017).

We summarize the parameter values in appendix E and list functional forms that were not specified in section 2.2 in appendix D. The model is implemented in GAMS (Zenios 1996) and solved using CONOPT (Drud 1994). Further details are found in Kalkuhl et al. (2012); we summarize structural model adjustments in appendix F.

4.2. Interest Rates and Interest Spread in the Economy

Financial intermediation creates an interest rate spread between the deposit rate and the loan rate, with contributions from the costs of managing deposits and loans and imperfect competition (sec. 2.1). Due to the linearity of the cost function $C(D_t, L_t)$, the cost parameters γ_L and γ_D contribute one to one to the spread. The effect of the degree of market imperfection, given by the number of intermediaries N, depends on the price elasticity of demand $\varepsilon_L(r_{Lt}, w_t)$, which itself is a function of loan rate and wage rate. Figure 4 illustrates the contributions of intermediation costs and market

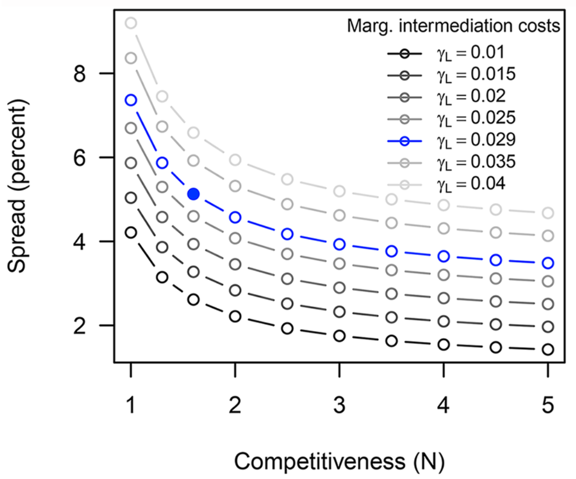

Figure 4. Interest rate spreads. Average interest rate spreads (over the first 100 years) are shown for a variation of competitiveness (where $N \to \infty$ is perfect competition) and intermediation costs (marginal intermediation costs of loans γ_L). Our default is indicated as a solid bullet.

imperfection to the interest spread. The curves are almost equidistant for large N, confirming the linear relationship of spread and marginal cost γ_L. Imperfect competition has the strongest impact for high concentration in the banking sector. With rising N, the contribution of imperfect competition eventually declines to zero. Imperfect competition presents a market failure that may need additional policies to correct, and we investigate such policies in section 4.6. When we explore the effects of the interest spread in the following section, we can abstract from its underlying causes (whether intermediation costs or imperfect competition) and focus on a perfectly competitive banking sector ($N \to \infty$).

In equilibrium, the interest spread has a substantial effect on prices throughout the economy. Figure 5 shows a variation of the interest spread by varying marginal intermediation costs γ_L. Panels A and C show the laissez faire (no policy) case. The interest spread raises the loan rate more than it lowers the deposit rate, reflecting a higher elasticity of supply compared to demand for loans. Energy and resource prices, which use capital as an input, rise with the loan rate r_{Lt}, reflecting their increasing cost of capital. While capital becomes more scarce, the (fixed) supply of labor becomes more abundant, and consequently we see a decline in the wage rate. The capital accumulation in all sectors (fig. 5C) mirrors these effects, with the strongest effect on capital in renewable energy generation, which also shows the strongest increase in its price (see proposition 2).

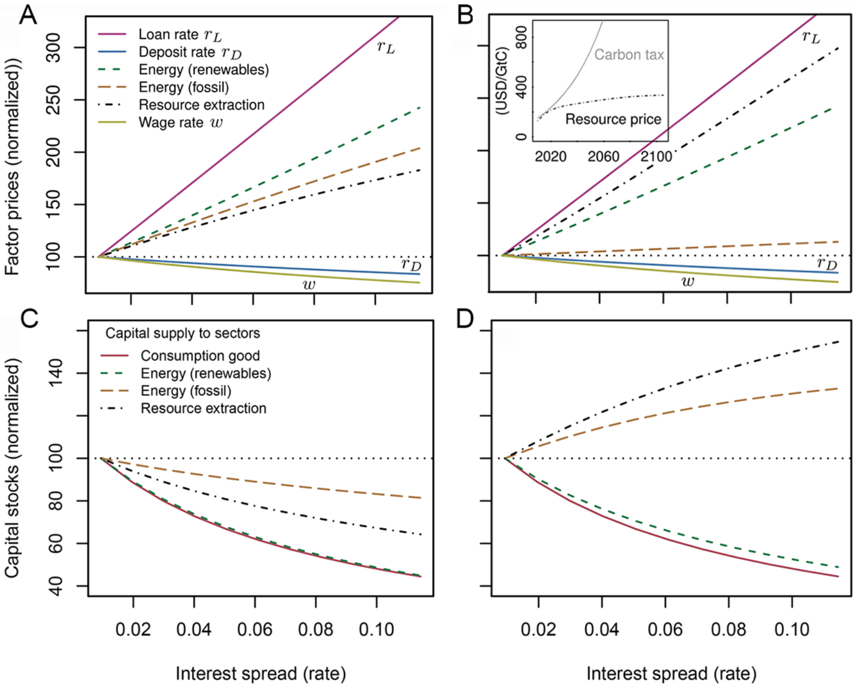

Figure 5. Interest spread effect on prices (*A*, *B*) and capital accumulation (*C*, *D*) in business as usual (*A*, *C*) and in the fixed tax policy scenario (*B*, *D*) for a perfectly competitive banking sector. Prices and capital supply are averaged over the modeled time horizon and normalized such that the equilibrium of the frictionless economy is at 100.

The reduced capital accumulation in figure 5C implies that interest spreads are accompanied by lower investment. We show how aggregate investment I_t varies in response to changes in the interest spread in the model compared to historical data in figure 1. The model shows good agreement with the trend in the data.

4.3. Effectiveness of Climate Policy

The previous section considered laissez faire equilibria of the economy, that is, business as usual without climate policy intervention. To study the effect of intermediation on climate policy, we compute three carbon-pricing scenarios. First, for the cost-benefit scenario we compute the optimal carbon tax that internalizes climate change damages from the welfare maximization of the regulator (21). For the case without financial frictions, this cost-benefit scenario keeps the temperature increase below 1.85 degrees and cumulative emissions to 393 GtC. Second, in the fixed cap scenario, the regulator sets the optimal tax that limits cumulative emissions to an upper limit B_0. To make the scenarios easily comparable, we limit cumulative emissions to a carbon budget of $B_0 = 393$ GtC. We denote the carbon price that implements this carbon budget τ^*_{Rt}. Third, for the fixed tax scenario, we impose a carbon tax $\tau_{Rt} = \tau^*_{Rt}$ on the combustion of fossil resources for fossil energy generation.[15]

This set of scenarios is comparable in the sense that without financial frictions, cumulative emissions are the same in all three cases. For figure 5*B* and 5*D*, we again vary the bank spread by increasing the marginal costs of loans γ_L. Figure 5*B* shows that for the fixed tax scenario, factor prices and interest rates are affected in a way similar to the laissez faire equilibria but with an important exception: the price for fossil energy p_{Ft} that rose in the no policy scenario now remains almost flat. The reason why p_{Ft} has become less sensitive to the cost of capital r_{Lt} is climate policy. To see this, consider how unit costs c_F of fossil energy are determined by the factor prices of capital r_{Lt} and resource, $p_{Rt} + \tau_{Rt}$:

$$c_F(r_{Lt}, p_{Rt} + \tau_{Rt}) = \left(a_F^{\sigma_F} r_{Lt}^{1-\sigma_F} + b_F^{\sigma_F}(p_{Rt} + \tau_{Rt})^{1-\sigma_F}\right)^{(1-\sigma_F)^{-1}}.$$

Where the resource price and the cost of capital previously jointly determined the unit cost of fossil energy, with climate policy these unit costs are predominantly determined by the carbon tax charged on top of the resource price. Jointly the carbon tax and resource price dwarf the cost of capital (see inset in fig. 5*B*). When interest spreads thus put renewable energy generation at a disadvantage, the allocation of capital is biased toward fossil energy (cf. proposition 5). Figure 5*D* shows the effect on capital accumulation.

Figure 6*A* shows how this distortion of the capital allocation affects temperature increase and carbon taxes in the three policy scenarios. At a zero interest rate spread, where the three scenarios coincide by design, the temperature increase from a cost benefit analysis in this model is 1.85 degrees, and 2.05 degrees for the 5.1 percentage points (pp) baseline value for the spread. These low temperature increases are consistent with the model assumptions of the temperature and impact module and the low costs of renewable energy in recent years (see sec. 4.1), and coincide with the peak warming of the median expert path scenario of Hänsel et al. (2020).

For the fixed cap scenario, the mean temperature increase is minimally affected by the interest spread, as cumulative emissions remain at 393 GtC by definition of this scenario.[16] For the other two policy scenarios, temperature increase is highly sensitive to the interest spread, peaking at 2.3 degrees and 2.5 degrees warming for the fixed tax

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15. Note that only cost-benefit scenarios include equations for climate change damages. In the other scenarios we assume $\Xi_t = 1$ in (8).

16. The slight decline with increasing interest spread is due to the fact that temperature increases at a reduced rate.

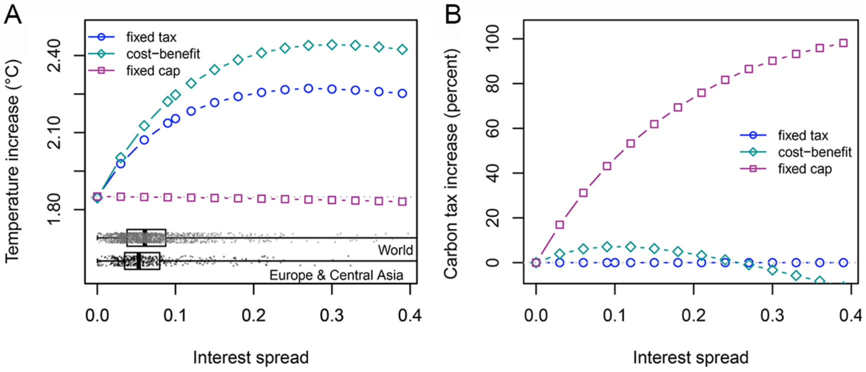

Figure 6. Overshooting policy targets. With interest spreads, the optimum temperature of the frictionless economy is exceeded in the fixed tax and cost-benefit scenarios (panel *A*). We show the temperature increase by 2150. The empirical bank spreads at the bottom are taken from World Bank (2022). Boxes indicate quartiles and median of the observations. Panel *B* shows the corresponding carbon prices, given as the carbon price increase relative to the case without interest spread (averaged over the time period 2020–2150). We assume a perfectly competitive banking sector in these calculations.

and cost-benefit scenarios, respectively. The temperature increase is driven by a corresponding increase of cumulative emissions that overshoot the original carbon budget of 393 GtC by 39% and 51%, respectively. We show a very broad range of interest spreads in figure 6 to reveal how the temperature increase levels off for large spreads and to identify when its maximum is reached. Up to the maximum, the effects that section 3 showed to increase emissions dominate; after this point the balance shifts toward the emission-reducing effects (see table 1). But not all interest spreads in this range are plausible at a global scale. As a point of comparison, figure 6*A* includes observed bank spreads from World Bank (2022), where we show worldwide numbers that include outliers from less developed financial systems, and numbers for Europe and Central Asia to represent modern financial systems. The second quartile, median, and third quartile for worldwide numbers are 3.8, 6.1, and 8.8 pp. At these spreads, the temperature increase in the fixed tax case is 0.16, 0.22, and 0.28 degrees higher than in the frictionless economy and 0.19, 0.28, and 0.37 degrees higher in the cost-benefit case. For the default calibration with a 5.1 pp spread, the additional temperature increase is about 0.20 degrees.

4.4. Second-Best Carbon Tax

Figure 6*B* shows the corresponding carbon prices. Here, the carbon price of the fixed tax scenario is constant by definition. To keep cumulative emissions below the B = 393 GtC budget despite an increasing interest spread requires a substantially higher price on carbon. The fixed cap scenario shows the necessary relative increase: at the default calibration of a 5.1 pp bank spread, the carbon price needs to rise by 27%; at a 0.40 interest rate spread, the carbon price needs to be doubled (i.e., increased by 100%) to achieve the same as in an economy without financial friction.

In the cost-benefit scenario, the carbon price increase is less than in the fixed cap scenario, and then peaks and eventually declines below the original level.[17] Here, emissions and carbon tax levels are determined by the balance of marginal costs of avoiding emissions and the marginal damages caused by the emissions. With higher interest spreads, emissions increase as the energy portfolio is biased toward less capital-intensive energy technologies (proposition 5), and with higher emissions, marginal abatement costs increase. Additionally, marginal damages are discounted at r_D (the household's interest rate), which is (slightly) decreasing in the interest spread (see fig. 5). Hence at higher interest spreads, marginal damages are discounted at a lower rate, implying a higher social cost of carbon. The abatement cost and the discounting effect both tend to increase the optimal carbon price in a cost-benefit approach. There is, however, a counteracting effect that dominates for high spreads: interest spreads substantially reduce capital accumulation (proposition 2) and ultimately economic output. As marginal climate damages scale with economic output, higher interest spreads imply lower absolute climate damages, driving down the social cost of carbon and, thus, optimal carbon prices. The latter effect explains why the optimal carbon price in the cost-benefit approach remains below the carbon price under a fixed-cap scenario. The ambiguous impact of interest rate spreads on the optimal carbon price is also in line with Barrage (2020), who finds that optimal carbon prices with distortionary capital taxes can be below or above the Pigouvian level due to various counteracting effects.

4.5. Energy Transition

The impact of financial frictions on aggregate emissions is mirrored at the sector level by a slowdown of the expansion of the renewable energy sector. Figure 7*A* shows declining growth rates of capital accumulation and energy generation with increasing bank spreads. Likewise, the phase-out of fossil energy is less rapid with financial frictions. For renewable energy, the growth rate of energy generation is greater than the growth rate of the corresponding capital stock because of the endogenous technological change in this sector. The growth rates are of comparable magnitude to historically observed growth rates; for example, Hansen et al. (2017) report 95% confidence intervals of

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[17] Carattini et al. (2021, table 2) report a lower second-best carbon price in the steady state when frictions are included—in agreement with our modeling only for large bank spreads. This is a major difference between our study's ambition of climate policy (internalizing the climate change externality globally vs. the United States, as in their model). Indeed we find that for less ambitious climate policy, second-best carbon prices fall below the frictionless case for small bank spreads (for the role of the carbon pricing ambition, see sec. 4.2).

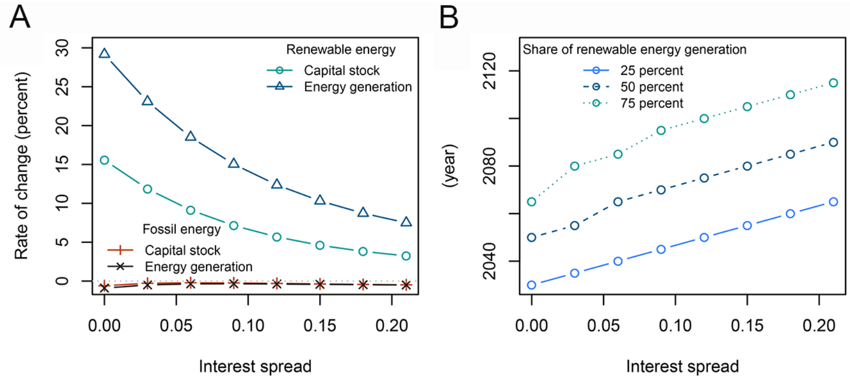

Figure 7. Energy transition. The rapid expansion of the renewable energy sector, triggered here by the carbon tax τ^*_{Rt} of the fixed tax scenarios, slows down with increasing bank spreads (shown here using the average rate of change up until 2040).

17%–20% and 30%–35% growth rates of energy generation 1996–2015 for global wind and global solar power, respectively. For a zero bank spread, the growth rates are at the higher end of the historic observations. Since we focus on financial frictions and do not model other constraints to capital reallocation such as capital adjustment costs, the model is highly flexible, and the speed of the capacity expansion optimistic. Note that most analyses in this study focus on long-term averages that depend less on the flexibility of the model. With increasing interest spreads, growth rates diminish to about half this speed. Figure 7*B* shows the implication for the date by which the share of renewable energy in total energy generation exceeds 50% (and 25% and 75% for comparison). We find that the delay of the transition to a low-carbon economy is close to linear in this metric, such that an increase of the interest rate spread by 10 pp delays the transition by about 15 years.

4.6. Investment Policies and Market Failures

In the previous section, interest rate spreads originated exclusively from financial intermediation costs. Intermediation costs constitute a real economic opportunity cost of resources dedicated to the selection, evaluation, and monitoring of investment projects. As such, intermediation costs do not constitute a market failure, and while an investment subsidy might succeed in reducing the interest rate spread, it could not improve overall welfare. Worse, the policy would likely raise welfare costs by distorting investment decisions from their optimal values.

There are, however, at least two cases where policy intervention in the presence of intermediation costs might be welfare increasing: (1) if intermediation costs are lower for a public financial institution compared to the banking sector or (2) when monopolistic competition in the banking sector raises the interest rate spread above the marginal cost level. In the remainder of the section we will focus on the second case as it receives considerable empirical support (e.g., Saunders and Schumacher 2000; Dwumfour 2019). Conceptually, the first case could be analyzed in an analogous way.

In the following, we assess how an investment policy interacts with carbon prices and to what extent it can increase overall welfare. The results of various policy runs are summarized in table 3. We measure welfare impact in balanced growth equivalent consumption loss (BGE) which denotes the welfare-equivalent first-year consumption loss of an exponentially growing consumption path (Stern et al. 2006; Anthoff and Tol 2009). We further include the impacts on lending and deposit rates, spreads, carbon prices, and government expenditures (relative to GDP) as they are important outcome variables. Policies are calculated to maximize intertemporal welfare for the mitigation target of $B_0 = 393$ GtC.

The first line in table 3 shows the baseline mitigation scenario where the interest spread of 2.9 pp is determined exclusively by the intermediation costs (γ_L parameter). As already discussed for figure 6*B*, intermediation costs imply an increase in carbon prices to optimally achieve a given carbon budget. For $\gamma_L = 0.029$ this increase is 18.6%. Line 1 is our reference case, thus there are no BGE welfare losses.

The second line in table 3 indicates that monopolistic competition (Monop.) increases the spread to 5.16 pp in total. This implies an additional welfare loss of 0.46% (BGE) compared to the case with intermediation costs only (line 1). Consistent with figure 6*B*, carbon prices have to increase further (to 30.9%) to achieve the mitigation target. If the government implements an optimal capital subsidy, the welfare losses due to monopolistic competition can be alleviated and the first-best outcome equal to the perfect competition case is obtained. The capital subsidy is, averaged over time, 1.6% of capital income; it is financed by a lump-sum tax on households that amounts to 3.87% of GDP. A subsidy on bank loans (line 5) achieves the same effect but requires higher lump-sum taxes on households. Finally, considering a second-best approach in which the only investments to be subsidized are those in renewable energy (line 4) reduces welfare losses of monopolistic competition to 0.33%. Contrary to the first-best policy with economy-wide investment policies, carbon prices fall even below the frictionless case (by −3.5%).

Zero welfare costs in lines 3 and 5 show that—in line with the Tinbergen rule—two instruments, that is, the carbon tax τ_R and either τ_K or s_L, are sufficient to address the climate change externality and imperfect competition to achieve the first-best.[18] Indeed, even with additional instruments the regulator cannot improve welfare, that is when $\Theta = \{\tau_R, \tau_K, \tau_L\}$ or $\Theta = \{\tau_R, s_L, \tau_L\}$, then the tax on capital in the renewable energy sector is not used, $\tau_L = 0$. The two instruments τ_K or s_L can be used interchangeably by the regulator, that is, when either instrument is used less than in lines 3 and 5, the other instrument can make up for it—welfare costs are zero for any such scenario.

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[18] The climate externality is represented by the carbon budget, not climate change damages, in this section but this is of no consequence for this argument.

Table 3. Policy Analysis

Line No.	γ_L (1)	Monop. (2)	τ_K (3)	τ_L (4)	s_L (5)	r_D (6)	r_L (7)	$r_L - r_D$ (8)	Net Spread (9)	$\Delta\tau_R$ (10)	Expenditure (11)	BGE (12)
Reference Case (intermediation costs, perfect competition)												
1	2.90					3.38	6.28	2.90	2.90	18.61		.00
Intermediation Costs and Imperfect Competition												
2	2.90	Yes				3.19	8.31	5.16	5.16	30.94		.46
. . . With Optimized Investment Policies												
3	2.90	Yes	−1.60			1.70	6.28	4.58	2.90	18.61	3.87	.00
4	2.90	Yes		−2.38		3.21	8.34	5.16	2.65	−3.53	1.81	.33
5	2.90	Yes			2.18	3.30	6.28	2.90	2.90	18.61	5.29	.00
High Intermediation Costs, Perfect Competition												
6	5.17					3.15	8.32	5.17	5.17	31.31		6.09
. . . With “Wrong” Investment Policies at Levels from Lines 3–5												
7	5.17		−1.58			1.65	6.82	5.17	3.51	22.84	3.66	6.35
8	5.17			−2.38		3.16	8.33	5.17	2.66	−2.35	1.81	6.24
9	5.17				2.17	3.26	6.26	2.88	2.88	19.47	5.30	6.62

Note. All values are percentages, unless stated otherwise; γ_L denotes marginal intermediation costs, Monop. denotes whether competition among banks is monopolistic (or perfect), τ_K and τ_L are tax rates on capital income of households and cost of capital for renewable firms, respectively, s_L is the subsidy rate on bank loans, the net spread is $(1 + \tau_L)r_L - (1 - \tau_K)r_D$, $\Delta\tau_R$ is the carbon price markup on top of the frictionless carbon price (in percentage points as in fig. 6*B*), expenditure is average annual expenditure of the government for (τ_K, τ_L, s_L) in percentage of GDP, BGE (balanced growth equivalent) is the welfare difference to the first row scenario in balanced growth equivalents. All variables numbers are averages of the first 100 years.

The remaining four scenarios consider an increased spread of 5.17 pp that is purely related to intermediation costs. Hence, although the spread equals the one of line 2 with imperfect competition, there is no monopolistic distortion present. This has considerable implications on the welfare costs: spreads related to intermediation costs now cause significant welfare losses (6.09%, line 6) compared to spreads of same magnitude that are caused by intermediation costs and imperfect competition (0.46%, line 2).[19] As discussed, the welfare costs of spreads caused exclusively by intermediation costs cannot be reduced by policy instruments. Optimal investment or loan subsidies are therefore zero (not shown in table 3). We model, however, the impacts of investment policies that were optimal if the spread had been caused by imperfect competition. This case can be understood as a "policy error" scenario where the government assumes the wrong causality for an observed interest rate spread.[20] The "regret" of having implemented a "wrong" policy is measured by the additional welfare losses due to the erroneous problem analysis range from 0.15% (renewable energy investments subsidy) to 0.53% (loan subsidy). As a side effect, carbon prices decline slightly—in the case of renewable energy investment subsidies the decline is considerable compared to the no-policy case (line 6).

The necessary policies in rows 3–5 as well as the regret in rows 7–9 depend on the strength of market power in the banking sector. This section takes a global perspective by using an average of market power across countries worldwide. We complement this view with a calibration to the bank spread and market power in the region of Europe and Central Asia in appendix G, which has the lowest Lerner index in the data set. The results remain qualitatively the same. The necessary policies (rows 3–5) and the regrets (rows 7–9) are approximately 40% lower compared to table 3; for details, see table G.3.

These analyses emphasize that investment subsidies for clean technologies can be a reasonable second-best instrument if the banking sector suffers from monopolistic competition. A first-best approach would, however, be to target all investments with an economy-wide investment or loan subsidy. Finally, a profound understanding of the underlying reasons for interest spreads is necessary, as investment policies reduce rather than increase welfare if spreads relate only to intermediation costs.

5. CONCLUSIONS

We study the implications of financial intermediation costs and imperfect competition in the banking sector on the implementation of climate policy in a deterministic, dynamic, general equilibrium model. Taking a deterministic approach has clear limitations;

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[19] The reason is that the spread due to monopolistic competition acts like a capital tax where its revenues are recycled to households (via banks' profits). The spread due to intermediation costs is, however, comparable to a capital tax that is not recycled because intermediation costs represent losses to the economy because of the opportunity costs of financial intermediation.

[20] The analysis of considering a "wrong" policy is in a similar spirit to Barrage (2020), who models a government implementing a naive Pigouvian tax, disregarding the fiscal distortions.

economic (and other) uncertainties that give rise to risks cannot be endogenously modeled, and important functions of financial intermediation, such as risk transformation, are subsumed in an aggregate function of intermediation costs. We capture, however, an important implication of financial intermediation costs and market power for capital accumulation and allocation in the economy: jointly, they can explain interest spreads, which have substantial impact on the interest rates in capital markets, specifically the deposit rate and the loan rate.[21] Both the supply of finance and the demand for finance will be affected by financial intermediation. Our approach sheds new light on the discounting debate since with interest spreads, a low pure time preference rate is consistent with rather high interest rates observed in capital markets.[22]

We find a significant effect of financial intermediation costs on climate policy: the resulting interest rate spread reduces capital accumulation and distorts the allocation of capital between fossil fuel–based and carbon-free energy sources (portfolio effect), as the latter are more capital intensive. The relative strength of the macroeconomic growth effect from reduced accumulation and the portfolio effect determine the overall impact on emissions. For small to moderate intermediation costs, we find that the portfolio effect exceeds the growth effect and emissions increase for a fixed carbon tax. When climate policy does not take this financial friction into account and adjusts the carbon tax accordingly, an exogenously given temperature target is overshot. Hence, to achieve a specific temperature target, cost-effective carbon taxes have to be increased considerably to offset the impact of interest rate spreads.

When the temperature target is determined endogenously by a cost-benefit analysis, interest rate spreads raise the optimal temperature level considerably. Optimal carbon prices in such a cost-benefit framework respond, however, only weakly due to counteracting forces; while marginal abatement costs increase in interest rate spreads, absolute climate damages, and thus the social cost of carbon, are lower due to lower economic growth. Therefore, optimal carbon prices are slightly higher for small to medium interest rate spreads and lower for high interest rate spreads.

If interest spreads arise due to imperfect competition in the banking sector, complementary investment policies can increase welfare further; an economy-wide capital subsidy constitutes a first-best policy that ensures an efficient level of overall investments. Targeted investment subsidies for clean technologies are only a second-best instrument which reduces capital market distortions only in the renewable energy sector. While such a policy reduces carbon prices below their first-best level, welfare impacts are only very moderate compared to the economy-wide first-best capital subsidy. Importantly,

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[21] Empirically, the observations of the Lerner index (World Bank 2022) suggest that market power and residual intermediation costs contribute approximately equally to the interest spread (43% and 57%, respectively; cf. sec. 4.1).

[22] For different perspectives on how to approach discounting in climate policy assessment, see. e.g., Nordhaus (2007) or Bauer and Rudebusch (2021).

investment policies require a profound understanding of the underlying reasons for interest spreads: if the banking sector is highly competitive and thus interest spreads relate only to intermediation costs, investment subsidies distort capital markets and reduce overall welfare.

This analysis has investigated how interest rate spreads, driven by costly financial intermediation, affect capital allocation, economic activity, and the associated greenhouse gas emissions to impede and counteract climate policy. Conversely, uncertainty about the timing and ambition of climate policy creates transition risk for financial intermediaries (see Battiston et al. [2017], though focusing on equity rather than loan portfolios). When interest rate spreads reflect the changing risk exposure of intermediaries, a feedback loop of climate policy and interest rates could emerge. How far the resulting dynamics pose a challenge for climate policy is a question that we leave for future research.

APPENDIX A
FIRST-ORDER CONDITIONS

A1. Financial Intermediaries

For the solution of the financial intermediaries problem, we follow Freixas and Rochet (2008). We consider the oligopolistic case with N financial intermediaries. What an individual financial intermediary (banking firm) i does not collect in terms of deposits D_i, it needs to borrow on the interbank market at interbank rate r_M; hence the net position M_i on the interbank market is

$$M_i = D_i - L_i.$$

Each bank i takes the effects of its choices of L_i and D_i on the supply of loans $L = \Sigma_{j=1}^N L_j$ and demand for deposits $D = \Sigma_{j=1}^N D_j$ into account. We assume that banks therefore perceive the loan and deposit rates $r_L(L)$ and $r_D(D)$ as functions of aggregate demand for loans L and deposits D (but no other variables beyond the banking sector (see, e.g., Francois and Roland-Holst 1997). Profits are thus

$$\pi_i^B = r_L(L)(1 + s_L)L_i + r_M(D_i - L_i) - r_D(D)D_i - C(D_i, L_i).$$

Taking first-order conditions (chain rule for $r_D(D)D$ and $r_L(L)L$) we have

$$\frac{\partial \pi_i^B}{\partial L_i} = (1 + s_L)\left(\frac{\partial r_L(L)}{\partial L}\frac{\partial L}{\partial L_i}L_i + r_L(L)\frac{\partial L_i}{\partial L_i}\right) - r_M - \frac{\partial C(D_i, L_i)}{\partial L_i} = 0, \tag{A1}$$

$$\frac{\partial \pi_i^B}{\partial D_i} = r_M - \frac{\partial r_D(D)}{\partial D_i}D_i - \frac{\partial D}{\partial D_i}r_D(D) - \frac{\partial C(D_i, L_i)}{\partial D_i} = 0. \tag{A2}$$

Now expand and rearrange to introduce the elasticity of demand $\varepsilon_L \equiv -(\partial L/\partial r_L)(r_L/L)$, defined such that $\varepsilon_L \geq 0$. We abbreviate marginal intermediation costs $(\partial C_{L_i}(L_i, D_i)/\partial L_i \equiv C_{L_i}$ and likewise C_{D_i}:

$$0 = (1 + s_L)\left(\frac{\partial r_L(L)}{\partial L}\frac{\partial L}{\partial L_i}L_i + r_L(L)\frac{\partial L_i}{\partial L_i}\right) - r_M - C_{L_i} \tag{A3}$$

$$= (1 + s_L)\left(\frac{\partial r_L(L)}{\partial L}\frac{L}{r_L}\frac{r_L}{L}L_i\Omega_L + r_L(L)\right) - r_M - C_{L_i} \text{ with } \Omega_L \equiv \frac{\partial L}{\partial L_i} \tag{A4}$$

$$= (1 + s_L)\left(-\frac{1}{\varepsilon_L}\frac{L_i}{L}r_L\Omega_L + r_L(L)\right) - r_M - C_{L_i}. \tag{A5}$$

We can rearrange to get

$$\frac{(1 + s_L)r_L(L) - r_M - C_{L_i}}{r_L} = (1 + s_L)\frac{\Omega_L}{\varepsilon_L}\frac{L_i}{L}. \tag{A6}$$

Now consider N financial intermediaries with equal market share such that $NL_i = L$:

$$\begin{aligned} \frac{(1 + s_L)r_L(NL_i) - r_M - C_{L_i}}{r_L(NL_i)} &= (1 + s_L)\frac{\Omega_L}{\varepsilon_L}\frac{1}{N} \\ \frac{r_L(L) - (r_M + C_{L_i})/(1 + s_L)}{r_L(L)} &= \frac{\Omega_L}{N\varepsilon_L}. \end{aligned} \tag{A7}$$

The factor $\Omega_L = \partial L/\partial L_i$ is the response of the aggregate demand L to changes in the individual demand L_i of one bank as expected by this bank. Equation (A7) is a standard result (equivalent, for example, to [3.18] in Freixas and Rochet [2008] and [11.12] in Francois and Roland-Holst [1997]) where the oligopolistic agent chooses L_i (as part of $L = \Sigma_j L_j$) to put the price r_L at a markup above the marginal costs, here $(r_M + C_{L_i})$ including opportunity costs r_M. The subsidy s_L on loans has the effect of offsetting marginal costs.

Similarly, from (A2) with $\varepsilon_D = (\partial D/\partial r_D)(r_D/D)$ we have

$$\frac{r_M - r_D(D) - C_{D_i}}{r_D(D)} = \frac{\Omega_D}{N\varepsilon_D}. \tag{A8}$$

The factor $\Omega_D \equiv \partial D/\partial D_i$ determines the market power on the deposit market.

A2. Real Economy

Please see Kalkuhl et al. (2012, app. B).

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