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

## Abstract

Interest rates are central determinants of saving and investment decisions. Costly financial intermediation distort these price signals by creating a spread between the interest rates on deposits and loans with substantial effects on the supply of funds and the demand for credit. This study investigates how interest rate spreads affect climate policy in its ambition to shift capital from polluting to low-carbon sectors of the economy. To this end, we introduce financial intermediation costs in a dynamic general equilibrium climate policy model. We find that costly financial intermediation affects carbon emissions in various ways through a number of different channels. For low to moderate interest rate spreads, carbon emissions increase by up to 7 percent, in particular, because of lower investments into the capital intensive clean energy sector. For very high interest rate spreads, emissions fall because lower economic growth reduces carbon emissions. If a certain temperature target should be met, carbon prices have to be adjusted upwards by up to one third under the presence of capital market frictions.

JEL-Codes: E430, G210, Q540, Q580.

Keywords: financial friction, banking, greenhouse gas mitigation.

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## 1. Introduction

Reducing greenhouse gas emissions to mitigate the adverse effects of global climate change requires shifting investment from emission intensive economic activities towards low-carbon or carbon free alternatives. The International Energy Agency in their sustainable development scenario, for example, estimates annual investment in renewable energy alone until 2025 at 467 billion U.S. dollar annually, and rising thereafter (IEA, 2018, p. 50).

Investment finance frequently includes capital from external sources: recent estimates put the share of external finance for private and public firms in the UK at 20 and 80 percent, respectively (Zetlin-Jones and Shourideh, 2017). For renewable energy investments, Mazzucato and Semieniuk (2018, Table 4) report an investment share close to 30 percent 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 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. Fig. 1 shows investment versus interest spread data: lower investment coincide with higher interest rate spreads with a coefficient of correlation of  $-0.45$ . We take this as evidence that financial frictions reduce investment.<sup>1</sup>

This paper 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, four energy system sectors and a

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<sup>1</sup>Williamson (2018) shows a similar correlation based bond spreads instead of bank spreads, and kindly shared the technical details of his analysis with us.

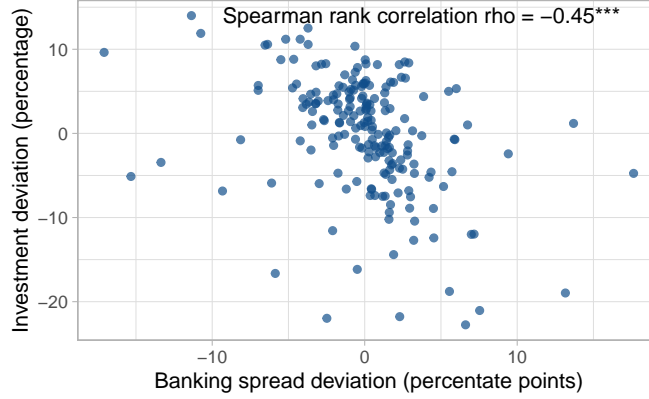


Figure 1: Large bank spreads coincide with periods of low investment. We show private domestic investment for the United States, and the difference of prime loan rate and certificate of deposit as a proxy for the banking spread. The negative correlation is significant at a level of 0.001. All data is taken from FRED.

regulator. For this study we extend the model by financial intermediation of investment flows to capture its effects 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 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 their profits. The supply of deposits and the demand for loans are determined by the preferences of consumers and firms in equilibrium.

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. Furthermore, we consider this a first step towards integrating financial sector actors in the assessment of policies that redirect investment flows towards clean energy on a macroeconomic scale. We find that the interest rate spread due to financial intermediation substantially affects the real economy, and we identify eight channels through which capital market frictions affect the economy and carbon emissions. For all channels, savings and investment 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) or the literature on financial development (Fernández and Tamayo, 2017). For the effect on emissions, 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 the interest spread 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 Section 3. Section 4 presents results and Section 5 concludes.

## 2. 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 to reduce emissions, more consumption becomes possible in the future (either because climate change damages are avoided or because more emissions are still permissible). Investment decisions are taken against this intertemporal backdrop by discounting future income at the interest rate, making the economic dynamics as well as the policy recommendations sensitive to the interest rate (Gollier, 2013). For example, an interest rate that is consistent with observed interest rates (cf. Nordhaus, 2008) may be substantially higher than an interest rate based on normative reasoning (for example Stern et al., 2006). The considerably different policy recommendations from the respective studies 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 supply and demand side. 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 percent shock to the spread between interest rate paid by private businesses and the rate received by consumers, Hall estimates a 4.2 percent decline in output and a 12.6-14.7 percent decline in investment. For investments specifically into renewable energy sources, Hirth and Steckel (2016) model energy system portfolios subject to increasingly high costs of capital. They find that very high costs of capital (of 25 percent) undo the effects of a CO<sub>2</sub> tax of switching the energy system from fossil to renewable energy sources.

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), that impose a limit on the supply of credit. Quadrini's survey is complemented by Brunnermeier et al. (2013), who in their survey emphasize macroeconomic and general equilibrium settings with discussions of instability and persistence issues. Furthermore, Brunnermeier et al. (2013) focus specifically on the role of financial intermediation to eliminate or reduce frictions. Despite measurable success of financial intermediation, the introduction of intermediary agents comes with new problems, for example of agency and system fragility.

The literature on financial intermediation is vast (cf. Gorton and Winton, 2003), with more recent research often inspired by asymmetric information and agency problems (Thakor and Boot, 2008). While 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 the modeling approach and Christiano et al. (2011) for an application – we 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 puts it to use in a consecutive 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. Recent studies using industrial organizations 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, e.g. to characteristics of the financial intermediaries (such as size, liquidity and equity) and regulatory environment (Demirguc-Kunt et al., 2004) and competitiveness (Degryse and Ongena, 2008); see Calice and Zhou (2018) and Dwumfour (2018) for analyzes of recent data. Further empirical support for the link of 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, respectively.



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 bank (rather than financial intermediation), arguing that additional market failures in the banking sector call for a portfolio of policy instruments beyond carbon pricing. 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.”

### 3. The model

In this study, we investigate the effects of interest rate spreads on climate policy. To this end, 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.

#### 3.1. An industrial organizations approach to financial intermediation

Following the presentation of the industrial organization approach to financial intermediation in Freixas and Rochet (2008), we represent financial intermediation by a sector of  $N$  identical financial intermediaries (banking firms), indexed  $i = 1, \dots, N$ . 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 objective of the intermediaries hence reads (suppressing the subscript  $i$  of the identical intermediaries)

$$\pi^B = r_L(L)L - r_D(D)D - r_M M - C(D, L) \quad (1)$$

Regulation requires financial intermediaries (or banks) to keep a fraction  $\alpha$  of the collected deposits as reserves. Thus aggregate loans  $L$  are either backed by  $(1 - \alpha)D$  or the net position on the interbank market  $M$ , that is

$$L = M + (1 - \alpha)D \quad (2)$$

Since net positions of all banks need to balance, for identical banks 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, next.

Using (2) in (1), and writing price elasticities of demand for loans ( $\varepsilon_L$ ) and deposits ( $\varepsilon_D$ ), we can write the first order conditions of the banks as follows (technical details are found in the Appendix A.1).

$$\frac{r_L(L) - r_M - C_L(D, L)}{r_L(L)} = \frac{1}{N\varepsilon_L(L)} \quad (3)$$

$$\frac{r_M(1 - \alpha) - r_D(D) - C_D(D, L)}{r_D(D)} = \frac{1}{N\varepsilon_D(D)} \quad (4)$$

The loan rate  $r_L$  and deposit rate  $r_D$  are thus set above and below the interbank rate  $r_M$  with an interest rate spread according to

$$r_L = [r_M + C_L(D, L)] \frac{N\varepsilon_L}{N\varepsilon_L - 1}$$

$$r_D = [r_M(1 - \alpha) - C_D(D, L)] \frac{N\varepsilon_D}{N\varepsilon_D + 1}$$

From this, the effect of the determinants of the interest rate spread on the interest rates is straight forward.

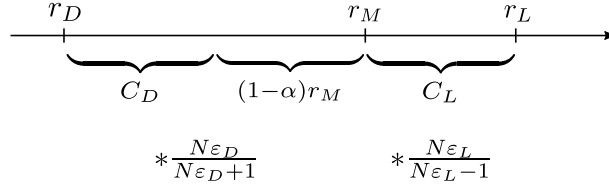


Figure 2: Interest rate spread. The deposit rate  $r_D$  and loan rate  $r_L$  are set below and above the interbank rate  $r_M$  taking into account marginal intermediation costs and the required reserve ratio  $\alpha$ . The spread is amplified by imperfect competition, i.e.  $N < \infty$  and/or price inelasticities  $\varepsilon_{(D,L)} < \infty$ .

$$r_L = r_L(r_M, C_L, N, \varepsilon_L) = r_L(+, +, +, +)$$

$$r_D = r_D(r_M, \alpha, C_D, N, \varepsilon_D) = r_D(+, -, -, +, +)$$

In particular, all else the same, stronger financial frictions from higher marginal cost of loans raise the loan rate  $r_L$  whereas higher marginal costs of deposits  $C_D$  or a higher capital ratio requirement  $\alpha$  will reduce  $r_D$ .

Fig. 2 visualizes the resulting interest rate spread. With perfect competition of intermediaries, the equilibrium loan rate exceeds the interbank rate by the marginal intermediation costs of making loans. Likewise, deposit rate is set below the interbank rate, taking marginal costs of deposits and the reserve requirement into account. Absent of banking regulation (reserve requirements), the banking spread ( $r_L - r_D$ ) is determined simply by the sum of marginal intermediation costs.

### 3.2. 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 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 side, respectively. In absence of financial frictions (i.e. no intermediation costs nor imperfect competition) all interest rates (including the interbank rate  $r_M$ ) 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 representative firm producing consumption goods and an energy sector with four more representative firms, special-

ized in fossil resource extraction, as well as generating energy from fossil resources, and renewable sources. 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 (cf. Kalkuhl et al., 2012, for an extended presentation including all first order conditions).

### 3.2.1. Representative household

Households maximize social welfare  $W$ , i.e. their aggregate utility, discounted following a time preference rate  $\rho$  and standard convexity assumptions. Households are endowed with labor, which they supply inelastically to earn wage income. The cumulative savings of the households  $K_t$  earn the deposit rate  $r_{Dt}$ . Additional income comes via firm profits  $\pi_t$  from owning the firms in all sectors  $i$  of the economy, and through government transfers  $\Gamma_t$  (recycling of tax income).

$$W = \sum_0^{\infty} L_t u(C_t/L_t)(1 + \rho)^{-t} dt$$

$$C_t + I_t = w_t L_t + (1 - \tau_{Kt}) r_{Dt} K_t + \pi_t + \Gamma_t \quad \text{with } \pi_t = \sum_{i \in \{Y, F, L, N, R, B\}} \pi^i$$

$$\dot{K}_t = I_t$$

The household's income may be taxed lump sum (when  $\Gamma_t$  is negative), or through a tax on capital income ( $\tau_K$ ).

### 3.2.2. 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 the households and respective firms, and all quantities are chosen to maximize profits  $\pi_Y$ . Capital depreciation at rate  $\delta$  is borne by the firm.

$$\pi_{Yt} = Y(Z(K_{Yt}, L_t), E(E_{Ft}, E_{Lt})) - w_t L_t - (r_{Lt} + \delta) K_{Yt} - p_{Ft} E_{Ft} - p_{Lt} E_{Lt}$$

### 3.2.3. Energy from fossil resources

The fossil energy sector combines fossil resources  $R$ , purchased at price  $p_R$  from the resource extraction sector, with capital  $K_F$  using a CES technology to generate energy  $E_F$ . The representative fossil firm seeks to maximize profits  $\pi_F$  given by

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

Fossil resource combustion is subject to a carbon tax  $\tau_{Rt}$  levied by the regulator. The fossil energy firm finances its capital at the loan rate  $r_L$  and takes capital depreciation ( $\delta K_F$ ) into account.

### 3.2.4. Fossil resource extraction

The finite stock of fossil resources  $S$  is owned by the fossil resource sector, who decides on the per period extraction  $R_t$  to sell to the fossil energy sector at price  $p_R$ . Resource extraction employs capital  $K_R$  financed at the loan rate and maintained against depreciation. The per period profits  $\pi_{Rt}$  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  $K_R$  as  $S$  diminishes, i.e.  $\frac{\partial^2 R}{(\partial K_R \partial (-S))} < 0$ . 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.

$$\begin{aligned} \max_{R_t} \sum_{t=0}^T \pi_{Rt} \Pi_{s=0}^t (1 + r_{Ds})^{-1} \\ S_{t+1} = S_t - R_t, \quad S_t \geq 0, S_0 \text{ given} \end{aligned} \quad (5)$$

### 3.2.5. Energy from renewable energy sources

Energy generation from renewable energy sources requires capital  $K_L$  in a production function with decreasing marginal returns. Capital productivity  $A_L(\cdot)$  rises endogenously due to technology learning, i.e. it rises with cumulative energy generation  $H_t$  in this sector. The regulator can affect the price of renewable energy with a tax (or subsidy)  $\tau_L$ .

$$\begin{aligned}
\pi_{L_t} &= (p_{L_t} - \tau_{L_t})E_L(A_L(H_t)K_{L_t}) - (r_{L_t} + \delta)K_{L_t} \\
H_{t+1} &= H_t + (E_{L_t} - E_{L_{t-1}})
\end{aligned} \tag{6}$$

Technology learning creates a dynamic problem of the firm, its objective is therefore to maximize the discounted stream of profit.

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

### 3.2.6. Financial intermediaries

The financial sector is populated by  $N$  financial intermediaries as described above in 3.1. There are no direct investments by households, all finance is intermediated. Consequently, all consumer savings are deposited with the intermediaries, and any demand for capital of the firms is met by loans from the financial intermediation sector.

$$\begin{aligned}
D_t &= K_t \\
L_t &= K_Y + K_L + K_N + K_F + K_R
\end{aligned}$$

As in 3.1, we require that financial intermediaries keep a fraction  $\alpha$  of all deposits as cash reserves.

$$(1 - \alpha)D_t = L_t$$

The intermediaries set the deposit rate and loan rate to maximize profits as in equations (3) and (4).

The demand for loans  $L(r_L)$  arises from the demand for the different capital stocks  $K_i$ . In this economy, the consumption good sector demands the lion's share of capital, approximately three quarters of the total. For the elasticity of demand  $\varepsilon_L(L) = r_L(L)L'/L$  in equation (3) we thus approximate the demand function for loans by the demand function for  $K_Y$  at a fixed level of  $Z$  (cf. Appendix B). Following Diallo and Koch (2018), we assume a perfect competition for deposits, i.e.  $\varepsilon_D = \infty$ .

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.

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

### 3.2.7. 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.

$$\begin{aligned} \max_{\Theta} W \text{ with } \Theta \subseteq \{\tau_{Rt}, \tau_{Lt}, \tau_{Nt}\} \\ \text{subject to (a) the equilibrium of the economy} \\ \text{(b) policy targets, e.g. } S_t \geq \bar{S} \\ \text{(c) budget } \Gamma = \tau_{Lt} E_L + \tau_{Rt} R_t \end{aligned}$$

As the government adjusts its policy subject to all constraints of the economy including all first order conditions, it acts with perfect knowledge of the response of the economic agents to its policies. Whenever the policy set  $\Theta$  contains sufficient policy instruments, this allows the government to implement the first best socially optimum allocation. Second best solutions are obtained when, for example, the set of instruments  $\Theta$  is limited – a possible reason being that certain policies are considered political infeasible. The government may face additional constraints: in this study we abstract from climate change impacts to motivate climate policy but ask the government to limit carbon dioxide emissions to a fixed “carbon budget”  $B = (S_0 - \bar{S})$ .

## 4. Partial equilibrium effects of financial intermediation

The introduction of an interest spread  $(r_L - r_D)$  from financial intermediation will tend to lower the interest paid on deposits  $(r_D)$  and put upward pressure on the interest charged for loans  $(r_L)$ . To develop an understanding how this effects economic activity and ultimately the effectiveness of climate policy, we discuss the relevant partial equilibrium responses to changes in the interest rate. Fig. 3 provides an overview how households, the aggregate goods production, and the energy and resources sectors are effected. For this analysis, we assume that the interest rates for the respective sector changes while

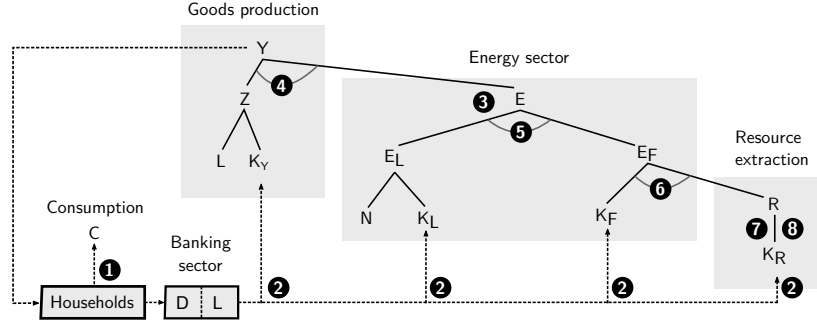


Figure 3: Overview of friction effects. We identify eight partial equilibrium effects that contribute to cumulative emissions in general equilibrium. Financial intermediation affects: (1) the consumption/saving decision of the household, (2) capital demand, (3) energy demand, (4) energy intensity in 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.

holding other input prices constant. We then calculate how demand for inputs and supply of outputs (including output prices) adjust. We identify eight response channels which cover the responses of the economy that are relevant for emissions and hence effectiveness of climate policy. In the following, we discuss each channel in partial equilibrium in turn and summarize the effects and their implication at the end of this section.

#### 4.1. The household's saving decision

The consumption–saving decision of the representative household is governed by the household's first order conditions

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

Ignoring capital income tax  $\tau_K$  for now, we eliminate the shadow price of consumption  $\psi_t$  to get a discrete version of the Keynes-Ramsey rule:

$$u'(C_{t-1}) = \frac{1}{1 + \rho}(1 + r_t^D)u'(C_t)$$

For isoelastic utility  $u(C_t) = C_t^{1-\eta}/(1 - \eta)$  we have



$$\left(\frac{C_t}{C_{t-1}}\right)^\eta = \frac{1 + r_t^D}{1 + \rho}$$

With  $g_C = C_t/C_{t-1} - 1$  the growth rate of consumption, taking logs and considering that  $\log(1 + x) \approx x$  for  $x = \{r^D, \rho, g_C\}$  close to zero the discrete Ramsey rule takes the familiar form

$$r^D = \rho + \eta g_C$$

where  $g_C = \ln(C_{t+1}/C_t)$  is the growth rate of consumption. The banking spread will lower the interest rate  $r_D$  paid on savings. We summarize the effect on the consumption–saving decision in the following Lemma.

**Lemma 1** (Savings effect). *A reduction of the deposit rate  $r_D$  affects the savings behavior of the household via the Keynes-Ramsey Rule resulting in a reduced consumption growth rate  $g_C$ .*

We therefore expect that – all else the same – a higher interest spread reduces carbon emissions due to lower economic growth.

#### 4.2. 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 or 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  $\bar{r}_L = r_L + \delta$  (net of depreciation costs and taking prices into account).

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

Lagrangian multipliers  $\mu_t$  and  $\psi_t$  are the shadow prices of the learning experience in the renewable energy sector, Eq. (6), and the resource scarcity in the extraction sector, Eq. (5), respectively. An increase in  $\bar{r}_L$  (or likewise  $r_L$ ) demands a higher marginal productivity of capital. Technology with decreasing marginal productivity implies that capital demand will fall in response.

**Lemma 2** (Capital demand). *A higher loan rate  $r_L$  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 affects energy demand which is a complementary factor input to capital:

**Lemma 3** (Energy demand). *Demand for energy  $E$  falls with the cost of capital in goods production  $r_L$ , i.e.  $dE/dr_L < 0$ .*

*Proof.* A higher lending rate reduces capital input  $K_Y$  in the aggregate production sector. As labor is fixed and energy is a complement to the labor-capital composite, demand for energy  $E$  decreases as well.  $\square$

With lower energy demand, assuming everything else equal in the economy, carbon emissions should therefore decrease as well.

#### 4.3. 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  $r_L$  puts upward pressure on the price  $p_Z$  of  $Z$  which equals in competitive output markets the unit cost function for the labor-capital composite:<sup>2</sup>

$$p_Z(\bar{r}_L, w) = \left( a_2^{\sigma_2} \bar{r}_L^{1-\sigma_2} + b_2^{\sigma_2} w^{1-\sigma_2} \right)^{\frac{1}{1-\sigma_2}} \quad (7)$$

where  $\sigma_2$  is the elasticity of substitution between capital and labor. This, in turn, affects energy intensity of economic output, given as the ratio of demand for factor inputs  $Z$

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<sup>2</sup>For the derivation of unit cost functions and factor demands for constant elasticity to scale production functions we refer to Rutherford (2002).

and  $E$  as

$$\frac{Z}{E} = \left( \frac{a_1 p_E}{b_1 p_Z} \right)^{\sigma_1}$$

where  $p_E$  is the price of total energy and  $\sigma_1$  the elasticity of substitution between energy and the labor-capital composite. With  $p_Y Y = p_Z Z + p_E E$  we obtain for the energy intensity  $EI(Y, E)$  of final output production

$$EI := \frac{E}{Y} = \frac{p_Y}{p_Z \left( \frac{a_1 p_E}{b_1 p_Z} \right)^{\sigma_1} + p_E}.$$

The energy intensity  $EI$  can be shown to increase in the loan rate when factor prices on labor  $w$  and energy  $p_E$  are held constant:

**Lemma 4** (Energy intensity of goods production). *The energy intensity of goods production increases in the cost of capital in goods production, i.e. the loan rate  $r_L$ . That is,  $dEI/dr_L > 0$ .*

*Proof.* From equation (7) we have  $\frac{\partial p_Z}{\partial r_L} > 0$ . The sign of  $\frac{dEI}{dr_L}$  therefore equals the sign of  $\frac{dEI}{dp_Z}$ . With the price of final output goods equal to unit costs

$$p_Y = \left( a_1^{\sigma_1} p_Z^{1-\sigma_1} + b_1^{\sigma_1} p_E^{1-\sigma_1} \right)^{\frac{1}{1-\sigma_1}}$$

we can substitute  $p_Y$  into  $EI$ . Taking the derivative after  $p_Z$  gives

$$\frac{\partial EI}{\partial p_Z} = \frac{\sigma_1 \left( \frac{a_1 p_E}{p_Z} \right)^{\sigma_1} \left( p_Z \left( \frac{a_1}{p_Z} \right)^{\sigma_1} + b_1^{\sigma_1} p_E^{1-\sigma_1} \right)^{\frac{1}{1-\sigma_1}}}{\left( p_Z \left( \frac{a_1 p_E}{p_Z} \right)^{\sigma_1} + b_1^{\sigma_1} p_E \right) \left( p_Z \left( \frac{a_1 p_E}{b_1 p_Z} \right)^{\sigma_1} + p_E \right)}$$

which is always positive. Hence,  $dEI/dr_L > 0$ . □

If the energy intensity increases due to an interest rate spread, carbon emissions are, – all else the same – expected to increase as well.

#### 4.4. Portfolio of energy sources

For analyzing 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  $E_F(K_F, R)$  that is produced with capital and fossil resources, and renewable energy  $E_L(K_L, N)$  that is produced with capital and land, both using CES technology. As fossil and renewable energy are substitutes in the production

sector, we can show that an increase in the loan rate  $r_L$  biases the energy mix to the less capital intensive technology:

**Lemma 5** (Portfolio effect). *An increase in the loan rate  $r_L$  that raises the cost of capital in the fossil and renewable energy sectors biases the energy mix towards the less capital intensive sector, i.e.  $\frac{d(E_F/E_R)}{dr_L} > 0 \Leftrightarrow \frac{K_L}{p_L E_L} > \frac{K_F}{p_F E_F}$ .*

*Proof.* Let  $c_i$  be the unit cost of producing energy  $E_i$ . For competitive markets and for  $E_F$  and  $E_L$  being substitutes in the aggregate production function follows:  $\frac{d(E_F/E_R)}{dr_L} > 0 \Leftrightarrow \frac{d(c_F/c_R)}{dr_L} \frac{c_R}{c_F} < 0$ . The unit cost function for CES technology  $\phi_i(a_i K_i^{\rho_i} + b_i X_i^{\rho_i})^{1/\rho_i}$  with  $\rho_i = \frac{\sigma_i - 1}{\sigma_i}$  and  $\bar{r}_L$  the net loan rate of capital and  $p_{X_i}$  the price for fossil resource or land input, respectively,  $X_i \in \{R, N\}$  is

$$c(\bar{r}_L, p_{X_i}) = \frac{1}{\phi_i} \left( a_i^{\sigma_i} \bar{r}_L^{1-\sigma_i} + b_i^{\sigma_i} p_{X_i}^{1-\sigma_i} \right)^{\frac{1}{1-\sigma_i}}$$

Thus, we get

$$\begin{aligned} \frac{d(c_F/c_R)}{d\bar{r}_L} \frac{c_R}{c_F} r_L &= \frac{1}{b_L^{-\sigma_L} a_L^{\sigma_L} p_L^{\sigma_L-1} \bar{r}_L^{1-\sigma_L} + 1} \\ &\quad - \frac{1}{b_F^{-\sigma_F} a_F^{\sigma_F} \bar{r}_L^{1-\sigma_F} p_R^{\sigma_F-1} + 1} \end{aligned}$$

And, hence,

$$\begin{aligned} \frac{d(c_F/c_R)}{d\bar{r}_L} \frac{c_R}{c_F} &< 0 \\ \Leftrightarrow \quad b_L^{-\sigma_L} a_L^{\sigma_L} p_L^{\sigma_L-1} \bar{r}_L^{1-\sigma_L} &> b_F^{-\sigma_F} a_F^{\sigma_F} \bar{r}_L^{1-\sigma_F} p_R^{\sigma_F-1} \end{aligned}$$

We further have from the CES technology  $\frac{K_i}{X_i} = \left( \frac{a_i p_{X_i}}{b_i \bar{r}_L} \right)^{\sigma_i}$  so that we can rearrange the previous equation to:  $\frac{d(c_F/c_R)}{d\bar{r}_L} \frac{c_R}{c_F} < 0 \Leftrightarrow \frac{\bar{r}_L K_L}{p_N N} > \frac{r_L K_F}{p_R R}$ . With  $p_i E_i = \bar{r}_L K_i + p_{X_i} X_i$ , we can rearrange further to  $\frac{d(c_F/c_R)}{d\bar{r}_L} \frac{c_R}{c_F} < 0 \Leftrightarrow \frac{\bar{r}_L K_L}{p_L E_L} > \frac{r_L K_F}{p_F E_F} \Leftrightarrow \frac{K_L}{p_L E_L} > \frac{K_F}{p_F E_F}$ .  $\square$

Empirical as well as modeling studies have shown renewable energy to be more capital-intensive than fossil energy generation (Schmidt, 2014; Hirth and Steckel, 2016; Best, 2017). We therefore expect that the portfolio effect contributes to higher carbon emissions.

#### 4.5. 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  $\frac{K_F}{R} =$

$\left(\frac{a_F p_R}{b_F \bar{r}_L}\right)^{\sigma_F}$ . With  $p_F E_F = \bar{r}_L K_F + p_R R$ , we obtain for the carbon intensity of fossil energy production

$$CI := \frac{R}{E_F} = \frac{p_F}{\bar{r}_L \left(\frac{a_F p_R}{\bar{r}_L b_F}\right)^{\sigma_F} + p_R} \quad (8)$$

The following holds for carbon intensity CI when the loan rate  $r_L$  is increases with the interest spread.

**Lemma 6** (Carbon intensity of fossil energy). *The carbon intensity of fossil energy generation increases in the cost of capital in the fossil energy sector  $r_L$ , i.e.  $dCI/dr_L > 0$ .*

*Proof.* The proof is analogous to the proof of Lemma 4. We substitute the unit cost-function for  $p_F$  in equation (8) and obtain

$$\frac{dCI}{dr_L} = \frac{\sigma_F \left( \bar{r}_L \left( \frac{a_F}{\bar{r}_L} \right)^{\sigma_F} + b_F^{\sigma_F} p_R^{1-\sigma_F} \right)^{\frac{1}{1-\sigma_F}} \left( \bar{r}_L \left( \frac{a_F^2 p_R^2}{\bar{r}_L^2 b_F} \right)^{\sigma_F} + p_R \left( \frac{a_F p_R}{\bar{r}_L} \right)^{\sigma_F} \right)}{\left( \bar{r}_L \left( \frac{a_F p_R}{\bar{r}_L} \right)^{\sigma_F} + p_R b_F^{\sigma_F} \right) \left( \bar{r}_L \left( \frac{a_F p_R}{\bar{r}_L b_F} \right)^{\sigma_F} + p_R \right)^2}$$

which is always positive.  $\square$

#### 4.6. 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  $c(S, r_L) := c(S) := \frac{\bar{r}_L + \delta}{\kappa(S)}$  and  $S_{t+1} = S_t - R_t$  (see Kalkuhl et al., 2012).<sup>3</sup> The discrete Hotelling rule for this problem is then:

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

with  $\psi_t := p_{Rt} - c(S_t)$  the user cost of the fossil resource. For illustrative purposes, we assume that all resources will be extracted over an infinite time horizon (see also Sinn,

<sup>3</sup>Note that  $c'(S) \leq 0$  and  $c''(S) \geq 0$  as  $\kappa'(S) \geq 0$  and  $\kappa''(S) \leq 0$ .

2008). Changes in the interest rate affect only the time-profile of extraction but not the cumulative amount.<sup>4</sup>

**Lemma 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.* Re-arranging the Hotelling rule gives  $\psi_t = (1 + r_{Dt})\psi_{t-1} - c'(S_t)R_t$ . If  $r_D$  decreases, the growth of the user cost  $\psi_t$ , and thus of the resource price  $p_{Rt}$ , decreases due to the Hotelling rule (holding  $c'(S_t)R_t$  constant for the moment). This, in turn, implies a lower decline of resource use  $R_t$  through the demand function and therefore also a lower increase in  $-c'(S_t)$  as  $c''(S) \geq 0$ . Both effects reinforce the lower growth of  $\psi_t$  in the Hotelling rule through the  $c'(S_t)R_t$  term. As  $\lim_{t \rightarrow \infty} S_t = 0$ , total cumulative extraction remains unchanged and a flatter resource extraction path implies a lower initial resource extraction.  $\square$

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

**Lemma 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) it is sufficiently flat. Resource extraction will then initially be lower.*

*Proof.* (i) When we ignore the  $c'(S_t)R_t$  term in the Hotelling rule for the moment and assume constant unit extraction costs  $c \equiv c(S)$  then an increase in  $r_L$  (and thus  $c$ ) would lead to a lower initial  $\psi_0$  if the initial resource price  $p_{R0}$  remained unchanged (as  $\psi_t = p_{Rt} - c(S_t)$ ). As  $\psi_t$  grows always at rate  $r_D$ , a lower  $\psi_0$  implies a lower resource price  $\tilde{p}_{rt}$  for  $t > 0$  compared to the original price path before the increase in  $r_L$ . Because  $p_{Rt}$  led to full extraction and  $\tilde{p}_{rt} < p_{rt}$  for  $t > 0$ , the new price path is inconsistent with the transversality condition. Hence, the initial price level after an increase in  $r_L$  must be higher. The resource extraction path therefore becomes flatter.

(ii) If  $c'(S_t)R_t < 0$ , an increase in  $r_L$  leads to a steeper extraction cost curve which implies a stronger growth in  $\psi_t$  and, thus,  $p_{Rt}$ . Hence, the effect of the shift in extraction cost from (i) is weakened. It might be reversed if  $|c'(S_t)|$  is sufficiently large.  $\square$

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<sup>4</sup>Allowing for cumulative volume effects requires a more sophisticated modeling of the timing when the backstop price is reached which requires further functional assumptions and simplifications.

Table 1: Overview of partial equilibrium effects

Lemma	Effect of a <i>wider</i> interest spread (first order effect)	Effect on emissions ( <i>ceteris paribus</i> effect)
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 towards 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

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 carbon emissions, in the beginning (Lemma 7); a higher lending rate increases extraction costs due higher capital costs. This also flattens the resource extraction path and reduces carbon emissions if the extraction cost curve is sufficiently flat (Lemma 8).

#### 4.7. Synthesis of impact channels

Table 1 summarizes the partial equilibrium effects. Column 2 collects the *ceteris paribus* first order effects as shown in the lemmas. In the last column, 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 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 lower emissions initially but cumulative emissions in the very long-run are unaffected if all resources under ground will be 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, where we will return to the eight response channels with an effort to characterize their relative contributions numerically in Section (5.3).

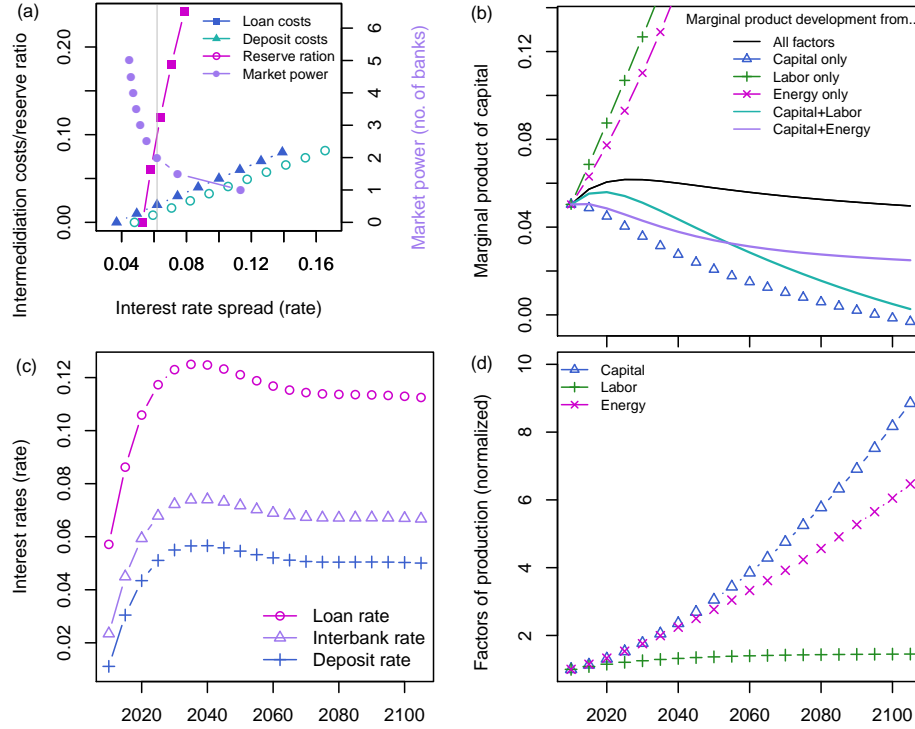


Figure 4: Interest rates and interest rate spreads. Panel (a) shows how the interest rate spread changes with different assumption about parameter values (based on a default case of  $\gamma_L = 0.02$ ,  $\gamma_D = 0.01$ ,  $\alpha = 0.10$  and  $N = 3$ ). The term structure of interest rates in Panel (c) can be traced back to marginal productivity of capital (Panel b) and factor utilization (Panel d).

## 5. Numerical simulation: general equilibrium

### 5.1. Calibration

We calibrate our model to a global economy baseline following Edenhofer et al. (2010) for the basic growth dynamics. Energy generation costs are calibrated from IEA (2000) and Edenhofer et al. (2011). The model is implemented in GAMS (Zenios, 1996) and solved using CONOPT (Drud, 2007). Further details are found in Kalkuhl et al. (2012).

### 5.2. 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, keeping cash reserves, and imperfect competition (Section 3.1). Due to the linearity of the cost function  $C(D, L)$ , the cost parameters  $\gamma_L$  and  $\gamma_D$  contribute one-to-one to the spread. In



contrast, the contributions from the reserve requirement  $\alpha$  depends on the level of the interbank rate  $r_M$ . Similarly the effect of the degree of market imperfection, given by the number of intermediaries  $N$ , depends on the price elasticity of demand  $\varepsilon_L(r_L, w)$ , which itself is a function of loan rate and wage rate. Fig. 4a summarizes the different contributions to the interest spread, relating the spread to the corresponding parameter values. The figure confirms the linear relationship of spread and marginal cost. We see that the interest spread is less sensitive to variations of the reserve ratio. Imperfect competition has, of course, the strongest impact for  $N = 1$ . With rising  $N$ , the contribution of imperfect competition declines to zero.

The joint effect of intermediation costs, reserve ratio and imperfect competition is an interest spread that peaks before the mid of the century and stabilizes in the long term (Fig. 4c). The dynamics in the level of the interest rate are driven by marginal productivity of capital: firms will employ capital up to the point where marginal productivity is balanced with the loan rate (net of depreciation). Thus net marginal productivity in Fig. 4b along the equilibrium paths of factor inputs perfectly coincides with  $r_L$ . Fig. 4b also shows counterfactual marginal productivities of capital which keep one or more input factors at their initial levels. With capital accumulation alone, marginal productivity (and hence the loan rate) would decline throughout the century. Conversely the increasing use of labor (population growth) and energy boost capital productivity (Fig. 4d).

In equilibrium, the interest spread has a substantial effect on prices throughout the economy. Fig. 5 shows a variation of the interest spread. For now, we focus on the first column with 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. Prices for all factors that use capital as an input rise with the loan rate  $r_L$ , reflecting the increasing cost of capital. While capital becomes relatively more scarce, this makes the (fixed) supply of labor relatively more abundant, and consequently we see a decline in the wage rate. Capital accumulation in the different sectors (bottom row of Fig. 5) mirrors these effects, with the strongest effect on capital in renewable energy generation just as its price also increased the most (cf. Lemma 2).

### 5.3. Effectiveness of climate policy

The previous section considers *laissez faire* equilibria of the economy, i.e. business as usual without climate policy intervention. To study the effect of intermediation on climate policy, we now impose a carbon tax  $\tau_{Rt}$  on the combustion of fossil resources for fossil energy generation. We compute the tax  $\tau_{Rt}$  by setting a policy target to limit

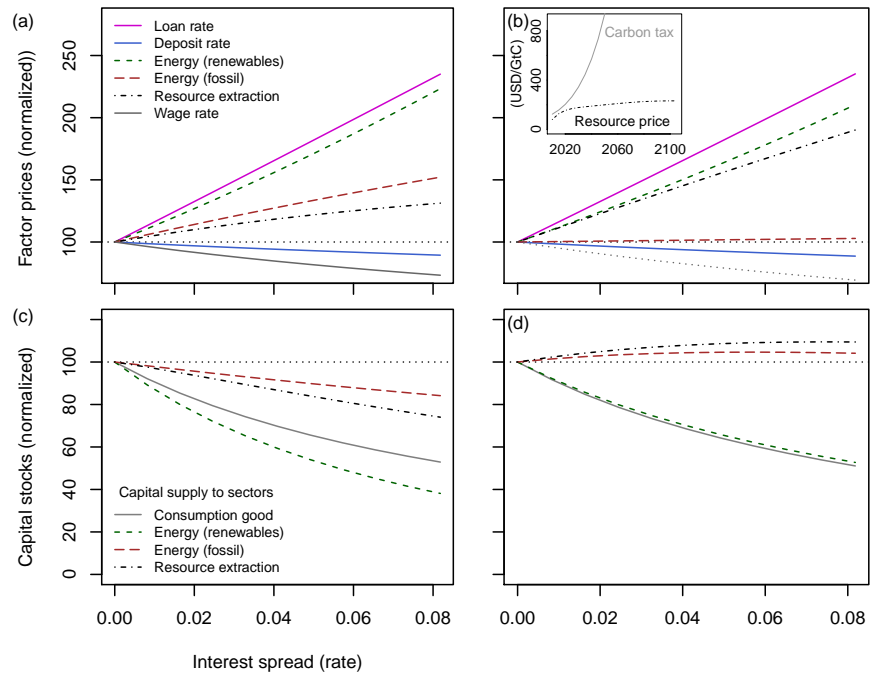


Figure 5: Interest spread effect on prices (top) and capital accumulation (bottom) in (a) business as usual and (b) in climate policy scenarios. Prices and (cumulative) capital are normalized such that the equilibrium of the frictionless economy is at 100.

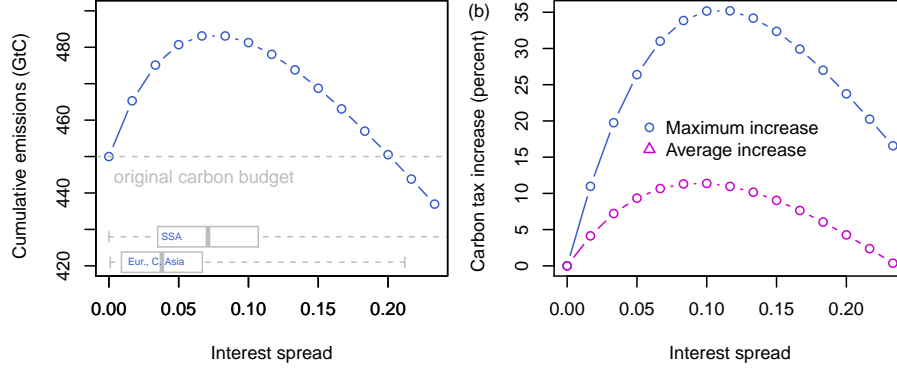


Figure 6: Overshooting policy targets. With interest spreads, the original carbon budget of 450 GtC is exceeded (Panel a). The data ranges at the bottom are net interest margins taken from Dwumfour (2018, Table 1) for “Europe & Central Asia” and “Sub-saharan Africa”. Panel (b) shows how the overshooting is corrected by raising the carbon tax, giving the difference between the overshooting carbon price and the carbon price in a carbon budget calculation (maximum and mean over the time period 2015-2100).

cumulative emissions to a carbon budget of  $B = 450$  GtC in the frictionless economy, i.e. without intermediation costs. In the policy case, factor prices and interest rates are affected in a way similar to the *laissez faire* equilibria with an important exception: the price for fossil energy  $p_F$  that rose in the no policy scenario now remains almost flat. Climate policy is the reason why  $p_F$  has become less sensitive to the cost of capital  $r_L$ . To see this, consider how unit cost  $c_F$  of fossil energy are determined by the factor prices of capital  $r_L$  and resource,  $p_R + \tau_R$ .

$$c_F(r_L, p_R + \tau_R) = \left( a^\sigma r_L^{1-\sigma} + b^\sigma (p_R + \tau_R)^{1-\sigma} \right)^{(1-\sigma)^{-1}}$$

Whereas previously the resource price and the cost of capital 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 carbon tax and resource price dwarf the cost of capital (cf. inset in Fig. 5b). When interest spreads thus put renewable energy generation at a disadvantage, the allocation of capital is biased towards fossil energy (cf. Lemma 5). Fig. (5b, bottom) shows the effect on capital accumulation.

Fig. 6a shows how this distortion of the capital allocation translates to cumulative emissions. At a zero interest rate spread, the tax reproduces the result of the carbon budget. As the interest spread rises, the original carbon budget of 450 GtC is overshoot by actual emissions, peaking at 483 GtC. Thus, cumulative emissions exceed the carbon budget by up to 7 percent. As a point of comparison, Fig. 6 includes exemplary net interest

margins from Dwumfour (2018). Based on these numbers, the entire interval of this parameter study is relevant.

We know from the partial equilibrium analysis in Section 4 that eight response channels contribute to the overshooting effect in Fig. 6. To disentangle the contributions of the effects captured in Lemma 1–8, we run additional scenarios that remove the financial friction from one sector at a time but fixing the interest rates  $r_D$  or  $r_L$  to their levels in the frictionless economy  $r^0$ . For example, we eliminate the effect of the interest spread for the consumer problem by setting the return on deposits to  $r_t^0 L_t$  instead of  $r_{Dt} L_t$  in Section 3.2.1. We can then compute the reduction of the consumption growth rate according to Lemma 1 as well as the effect on emissions by taking the differences between this scenario and the economy with frictions in all sectors. Table 2 collects the results from these experiments.

The general equilibrium results from the numerical simulations are in all cases in line with our partial equilibrium analysis, as the indicated signs by  $\ominus$  and  $\oplus$  in Table 2 suggest (the numbers in the row refer to the particular lemma). For example, if only the interest rate on savings  $r_D$  is reduced, consumption growth is predicted to decrease (Lemma 1), which is confirmed in our simulation (growth decreases by 12 percent). If only the lending rate for capital in the production sector,  $r_L K_Y$ , were increased by financial frictions, capital accumulation would be reduced by 26 percent see column (1) in Table 2. This again corresponds to Lemma 2. However, the table also reveals that no clean separation of the partial equilibrium effects is possible with regards to the overall impact on carbon emissions. Consider again the impact of the interest spread on consumption behavior (column 1), which reduced consumption growth by 12 percent and economic output by 11 percent. If the rest of the economy were unchanged (i.e. the same amount of carbon emissions are required to produce one unit of output), carbon emissions should also decrease by that magnitude as well. Contrary, total emissions increase by 10 percent (see last row in Table 2). The change in the deposit rate has strong general equilibrium effects. Importantly, it substantially changes the energy portfolio (row 6) which is heavily biased towards fossil energy, which could be a consequence from the different time-path for energy demand that affects the learning-by-doing innovation dynamics in the renewable energy sector. Apart from the case reported in column (1), however, total emissions change as suggested by the partial equilibrium analysis.

Finally, Table 2 sheds some light on the quantitative contribution of the capital market frictions in different sectors to overall emissions (row 9). Frictions for savings and investments in the energy sector in columns (1) and (5) contribute strongly to emissions

Table 2: Isolating sectoral frictions. Each row shows how the indicators investigated in the partial equilibrium analysis are affected by the frictions (i.e. changes in interest rates) of the different sectors. We report percentage changes to the indicator when the friction in the column header is enabled. For example, enabling the distortion of the savings decision through  $r_D K$  (column 1) reduces the respective indicator (consumption growth  $g_C$ ) by 12 percent (row 1). The em dash (—) indicates values less than 0.01. Where we expect a positive or negative impact on the indicator from the partial equilibrium considerations in Lemma 1–8, we use the  $\ominus$  and  $\oplus$  symbols indicates negative and positive effects, respectively.

	Sector:	(1)	(2)	(3)	energy sectors			(5)	(6)	(7)
		Friction:	consumer	goods	fossil	renewable	portfolio	extraction	discounting	
Effects (Lemma)		$r_D K$	$-r_L K_Y$	$-r_L K_F$	$-r_L K_L$	$-r_L K_{(L,F)}$	$-r_L K_R$	$(1 + r_D)^{-1}$		
consumption growth rate (1)	$g_C$	$\ominus$	-0.12	-0.06	-0.01	-0.01	-0.01	—	—	
capital formation (2)	$K$	-0.40	$\ominus$	-0.26	$\ominus$	-0.13	$\ominus$	-0.13	—	
energy demand (3)	$E_{TOT}$	-0.32	$\ominus$	-0.06	-0.01	-0.21	-0.22	—	—	
energy intensity of output (4)	$E_{TOT}/Y$	-0.18	$\oplus$	0.01	-0.02	-0.13	-0.15	—	—	
carbon intensity of energy (5)	$R/E_F$	0.01	—	$\oplus$	0.01	—	0.01	—	—	
energy portfolio (6)	$E_F/E_L$	0.45	-0.05	-0.05	-0.59	0.46	$\oplus$	0.23	-0.13	
growth rate: resource price (7, 8)	$g_{PR}$	0.97	-0.08	-0.08	-0.06	0.10	0.04	$\ominus/\oplus$	0.50	
economic output	$Y$	-0.11	-0.08	—	—	-0.04	-0.04	—	—	
cumulative emissions	$S_t - S_0$	0.10	-0.06	-0.12	-0.12	0.23	0.11	-0.04	—	
cumulative emissions (high spread)	$S_t - S_0$	0.73	-0.34	-0.35	-0.35	0.67	0.30	-0.12	—	

growth. In particular, the portfolio effect in the energy sector has strong implications for emissions (11 percent) as investments are biased towards less capital intensive fossil energy production. Contrary, reduced macroeconomic output (column 2) and a flatter resource extraction path can only compensate emission increases partially. Importantly, the energy intensity and carbon intensity channels (Lemma 4 and 5) are quantitatively less relevant as energy and carbon intensity hardly change in our partial equilibrium simulations (cf. columns (2) and (3)). The shape of the emissions overshooting in Fig. 6 can thus be understood as a result of the portfolio effect (Lemma 6) dominating for low to moderate interest spreads. For large interest spreads, emissions are driven down by slower growth from lower capital demand (Lemma 2) and postponed resource extraction (Lemma 7 and 8). The last row in Table 2 illustrates this with numbers from a very high interest rate spread scenario (24 percent). Emissions reduction from reduced capital demand increases five-fold (from 6 percent to 34 percent) and triples from the effect on resource extraction (12 percent from 4 percent before), while the emission increase due to the portfolio effect rises from 11 percent to 30 percent. As before, the effect on consumption growth is strongly affected by general equilibrium effects.

#### 5.4. *Second-best carbon tax*

An interest rate spread hence reduces the effectiveness of a carbon tax. Next, we look at the implications for a regulator to implement a given climate policy target in the presence of intermediation costs. Again, we consider a carbon budget ( $B = 450$  GtC), this time computing the optimal carbon tax at each level of the interest rate spread. We find that the carbon tax required to limit emissions to the carbon budget exceeds the default carbon tax of the frictionless economy by up to 35 percent. In Fig. 6b we show the required carbon tax markup. The necessary price markup mirrors the overshooting: interest rate spreads where the original carbon budget is far exceeded coincide with spreads that necessitate a much increased carbon price.

## 6. Conclusions

We study the implications of financial intermediation costs on the implementation of climate policy in a deterministic, dynamic, general equilibrium model. Taking a deterministic approach implies clear limitations: 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 for capital accumulation and allocation in the economy: intermediation costs can explain interest spreads, which have substantial impact on the interest rates in capital markets, specifically the deposit rate and the loan rate. Both the supply of finance and the demand for finance will be affected by financial intermediation.

We find a significant effect of financial intermediation costs on climate policy: The resulting interest rate spread reduces capital allocation 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 determines the overall impact on emissions. For small to moderate intermediation costs, we find that the portfolio effect exceeds the growth effect and emissions increase. When climate policy does not take this financial friction into account, climate policy targets are overshoot. At high intermediation costs, reduced economic activity due to the growth effect leads to lower overall carbon emissions. While interest rate spreads also affect the energy intensity of GDP, the carbon intensity of fossil energy production and the intertemporal resource extraction dynamics, the portfolio effect and the macroeconomic growth effect are quantitatively the most important channels.

The distortions from interest rate spread can be taken into account by adjusting carbon prices upwards. In fact, whereas intermediation costs need to be considered explicitly for the implementation of a carbon tax, an emission permit system that sets the quantity is robust with respect to this friction. A higher price of emission permits by up to 35 percent on top of the no-friction permit price will reflect the additional friction.

Our analysis sheds light on the sensitivity of climate policy towards financial frictions. Many questions remain: Is there a mandate for regulatory intervention that directly addresses financial intermediaries? Should governments aim to address sectoral misallocation of capital with specific policies like targeted investment subsidies or rather aim to reduce overall interest rate spreads? If private intermediation costs are excessively high, should governments provide alternative sources of finance? Financial crisis frequently causes unanticipated spikes in the interest spread. Does this put the success of climate policy at risk?

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## Appendix

### A. First order conditions

#### A.1. Financial intermediaries

For the solution of the financial intermediaries problem, we follow Freixas and Rochet (2008). What the financial intermediary (banking firm) does not collect in terms of deposits (minus reserves), it needs to borrow on the interbank market at interbank rate  $r_M$ , hence the net position  $M$  on the interbank market is

$$M = (1 - \alpha)D - L$$

Bank profits are thus

$$\begin{aligned}\pi^B &= r_L(L)L + r_M M - r_D(D)D - C(D, L) \\ &= r_L(L)L + r_M((1 - \alpha)D - L) - r_D(D)D - C(D, L) \\ &= (r_L(L) - r_M)L + (r_M(1 - \alpha) - r_D(D))D - C(D, L)\end{aligned}$$

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

$$\frac{\partial \pi^B}{\partial L} = r'_L(L)L + L' r_L(L) - r_M - C_L(D, L) = 0 \quad (\text{A.1})$$

$$\frac{\partial \pi^B}{\partial D} = r_M(1 - \alpha) - r'_D(D)D - D' r_D(D) - C_D(D, L) = 0 \quad (\text{A.2})$$

The derivatives  $D' = \partial D / \partial D = 1$  and  $L' = 1$ . We have

$$\begin{aligned}
r'_L(L)L + r_L(L) - r_M - C_L(D, L) &= 0 \\
r_L(L) - r_M - C_L(D, L) &= r'_L(L)L \\
r_L(L) - r_M - C_L(D, L) &= r'_L(L)L
\end{aligned}$$

Now introduce the price elasticity of demand (for loans)

$$\begin{aligned}
\varepsilon_L &= \frac{dQ/Q}{dP/P} = \frac{L'/L}{r'_L/r_L} \\
&= \frac{1}{L} \frac{r_L}{r'_L} \\
&= \frac{r_L(L)L'}{L}
\end{aligned}$$

The latter by applying the inverse function theorem whereby  $r'_L(L) = 1/L'(r_L)$

We introduce  $\varepsilon_L(L)$  into the first order condition

$$\begin{aligned}
\frac{r_L(L) - r_M - C_L(D, L)}{r_L(L)} &= \frac{r'_L(L)L}{r_L(L)} \\
\frac{r_L(L) - r_M - C_L(D, L)}{r_L(L)} &= \frac{L}{r_L(L)L'} \\
\frac{r_L(L) - r_M - C_L(D, L)}{r_L(L)} &= \frac{1}{\varepsilon_L(L)}
\end{aligned} \tag{A.3}$$

Similarly, for (A.2) we have

$$\begin{aligned}
r_M(1 - \alpha) - D'r_D(D) - C_D(D, L) &= r'_D(D)D \\
\frac{r_M(1 - \alpha) - r_D(D) - C_D(D, L)}{r_D(D)} &= \frac{r'_D(D)D}{r_D(D)} \\
\frac{r_M(1 - \alpha) - r_D(D) - C_D(D, L)}{r_D(D)} &= \frac{D}{r_D(D)D'} \\
\frac{r_M(1 - \alpha) - r_D(D) - C_D(D, L)}{r_D(D)} &= \frac{1}{\varepsilon_D(D)}
\end{aligned} \tag{A.4}$$

Equations (A.3) and (A.4) define the behavior of one monopolistic bank.

For  $N$  identical banks, each bank faces a profit of

$$\pi_i^B = r_L(L_i + \sum_{j \neq i} L_j)L_i + r_M M_i - r_D(D_i + \sum_{j \neq i} D_j)D - C(D_i, L_i)$$

In equilibrium, all banks behave the same, i.e.  $L_i = L/N$  and hence first order conditions become

$$\frac{r_L(L) - r_M - C_L(D, L)}{r_L(L)} = \frac{1}{N\varepsilon_L(L)} \quad (\text{A.5})$$

$$\frac{r_M(1 - \alpha) - r_D(D) - C_D(D, L)}{r_D(D)} = \frac{1}{N\varepsilon_D(D)} \quad (\text{A.6})$$

#### A.2. Real economy

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

### B. Price elasticity of demand for loans

Under imperfect competition, financial intermediaries take the demand and supply response of firms and households into account when they set the deposit and loan rates. This is reflected by the price elasticity of demand. For the demand of loans, it is defined as follows.

$$\varepsilon_L = - \frac{r_L \frac{\partial}{\partial r_L} L(r_L)}{L(r_L)}$$

Aggregate demand for loans is given by the demand from all economic sectors. As the demand from production of consumption goods is three quarters of total demand, we focus on this sector. Within the production of consumption goods, capital  $K_Y$  is part of the capital-labor composite of the nested CES technology  $Y(Z(K_Y, L), E)$  with

$$Z(K_Y, L) := (aK_Y^\rho + b(AL)^\rho)^{\frac{1}{\rho}}$$

For CES technology, the factor demand for capital  $K_Y$  for a fixed level of  $Z$  is given by

$$K(r_L, w, Z) := \frac{Z \left( \frac{r_L}{a} \right)^{\frac{1}{\rho-1}}}{\left( b \left( \frac{w}{b} \right)^{\frac{1}{\rho-1}} + a \left( \frac{r_L}{a} \right)^{\frac{1}{\rho-1}} \right)^{\frac{1}{\rho}}}$$

Factor demand responds to the interest rate according to

$$\frac{\partial K(r_L, w, Z)}{\partial r_L} = \frac{\left(\frac{r_L}{a}\right)^{\frac{1}{\rho-1}} \left(a\left(\frac{r_L}{a}\right)^{\frac{1}{\rho-1}} + b\left(\frac{w}{b}\right)^{\frac{1}{\rho-1}}\right)^{-\frac{\rho+1}{\rho}} \left(a(\rho-1)\left(\frac{r_L}{a}\right)^{\frac{1}{\rho-1}} + b\rho\left(\frac{w}{b}\right)^{\frac{1}{\rho-1}}\right) Z}{r(\rho-1)\rho}$$

The price elasticity of demand is therefore

$$\varepsilon_L = -\frac{a(\rho-1)\left(\frac{r_L}{a}\right)^{\frac{1}{\rho-1}} + b\rho\left(\frac{w}{b}\right)^{\frac{1}{\rho-1}}}{(\rho-1)\rho\left(b\left(\frac{w}{b}\right)^{\frac{1}{\rho-1}} + a\left(\frac{r_L}{a}\right)^{\frac{1}{\rho-1}}\right)}$$

Rearranging and using  $\rho = (\sigma - 1)/\sigma$  we have

$$\varepsilon_L(r_L, w) = -\frac{\sigma\left(b\left(\frac{r_L}{a}\right)^\sigma - b\left(\frac{r_L}{a}\right)^\sigma \sigma + a\left(\frac{w}{b}\right)^\sigma\right)}{(\sigma-1)\left(a\left(\frac{w}{b}\right)^\sigma + b\left(\frac{r_L}{a}\right)^\sigma\right)} \quad (\text{B.1})$$

### C. Changes with respect to Kalkuhl et al. (2012)

This section summarizes the changes with respect to the base model Kalkuhl et al. (2012) for readers who are familiar with the earlier publications.

- The base model knows no financial sector, instead of the deposit and loan rates  $r_D$  and  $r_L$ , there is only the rental rate of capital  $r$ . The rental rate clear the capital market, i.e.  $\sum_i K_i = K$ . It is interpreted as the economy wide interest rate and therefore used to the discount cash flows when firms' problems are dynamic (in the resource extraction sector and the renewable energy sector, in the latter due to technology learning).
- Depreciation has been moved to sectors, it was previously part of the household's problem.
- We removed the non-learning clean carbon-free energy sector (nuclear power). While distinguishing incumbent versus innovating carbon-free energy sectors was essential for the research in Kalkuhl et al. (2012), it is not essential for the analysis of financial frictions, and dropping the sector from the model greatly simplified the proofs in Section 4.