Low-Carbon Investment and Credit Rationing*

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Abstract

This paper offers a novel theoretical approach to analyse the impacts of emission externalities and credit market failures on low-carbon investments. We use a principal-agent model with information asymmetries between borrowing firms and lenders. Firms can choose between a carbon-intensive technology and a low-carbon technology requiring an externally funded initial investment. We find that an emission tax alone is not sufficient to achieve the first-best outcome if the low-carbon technology is immature and risky and thus results in credit rationing. Combining the emission tax with interest subsidies or loan guarantees can eliminate credit rationing. If a carbon price is (politically) not feasible, intervention on the credit market alone can promote low-carbon development. However, such a policy yields a second-best outcome. Our dynamic analysis shows that any intervention on credit markets is finite, as knowledge spillovers reduce the risk of low-carbon technologies. Without such intervention, there are social costs of delay.

Keywords: Low-carbon investment; credit rationing; emission tax; asymmetric information; interest rate subsidy; loan guarantee.

JEL-Classification: G20, H23, H81, Q50.

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1. Introduction

Climate change has been recognised as one of the greatest (economic) challenges in the 21st century. Limiting global warming to well below 2°C, as agreed under the Paris Agreement (UN, 2015), will only be possible with a climate policy that is substantially more ambitious than current policies (Nordhaus, 2018; Stern, 2018). In the absence of (ambitious) policies, the private sector lacks sufficient incentives for required investments to achieve the transition to a low-carbon economy. Emission externalities and spillovers from low-carbon innovation are the frequently discussed market failures impeding low-carbon development (Bennear and Stavins, 2007; Jaffe and Stavins, 1995; Jaffe et al., 2005). Credit market failures are typically not considered, although scholars are increasingly stressing the role of functional financial markets for enabling low-carbon investments (see, e.g., Kempa and Moslener, 2017; Pahle and Schweizerhof, 2016; Polzin, 2017; Steckel and Jakob, 2018). This paper aims to fill this gap by (i) providing a first theoretical analysis of firms' investment decisions between clean and dirty technologies that explicitly models external financing with asymmetric information and (ii) analysing different policies to address the market failures.

Financial market failures are largely caused by information asymmetries between the borrower (agent) and the lender (principal), which may lead to unfavourable loan conditions for the borrower or completely deter socially desirable transactions (Jaffee and Stiglitz, 1993) and thus lead to not optimal allocation of capital in the economy (Akerlof, 1970; Stiglitz, 1993; Stiglitz and Weiss, 1981). Empirical evidence shows that access to external financing, in particular debt, and the development and functioning of the finance sector are core drivers of low-carbon investments such as renewable energy (Ang et al., 2017; Best, 2017; Brunnschweiler, 2010; Haščič et al., 2015; Kim and Park, 2016) or energy efficiency (Apeaning and Thollander, 2013; Fleiter et al., 2012; Kostka et al., 2013). Furthermore, innovative high-tech firms face financing constraints (Carpenter and Petersen, 2002), in particular clean technology firms (Howell, 2017; Nanda et al., 2015; Olmos et al., 2012).

Renewable energy investments highly rely on financial markets, in particular debt provision, due to their capital intensity (Evans et al., 2009; Painuly, 2001; Wiser et al., 1997).[1] Non-recourse project finance structures are frequently used to finance renewable energy investments, where debt typically covers 65%-80% of the investment expenditure (McCrone et al.,

[1] While capital costs only account for around 11% of total life cycle costs of an oil power plant, they can reach 95% in the case of solar PV (Kannan et al., 2007).

2017; Pollio, 1998).[2] Long amortisation periods of 15 years or more (Couture and Gagnon, 2010) foster the susceptibility to credit market failures, as the likelihood of credit rationing, i.e. receiving a loan at unfavourable conditions or no loan at all, increases with the time horizon of the lending contract (Stiglitz, 1993). Similar to renewable energy, energy efficiency investments have high up-front costs and typically long amortisation periods (Gillingham et al., 2009). Information asymmetries can prevent lenders from distinguishing investments with high from those with low potential energy savings (Gillingham and Palmer, 2014). Thus, credit constraints might contribute to the energy efficiency gap (Golove and Eto, 1996).

Finally, clean technology firms require access to external funds to finance the initial clean technology investment, e.g. R&D or initial production capacities. Empirical evidence suggests young firms using new technologies face difficulties to source debt financing, mainly driven by lenders' information asymmetries concerning the new technologies, who may find it too costly or even impossible to assess the firms through screening (see, e.g., Carpenter and Petersen, 2002; Guiso, 1998; Revest and Sapio, 2012). In the absence of a carbon price, new clean technologies have a double disadvantage compared to incumbent dirty technologies: in addition the information asymmetry caused by their immaturity, clean technologies' positive externalities for the climate are unpriced (Howell, 2017). Lenders are likely to be hesitant to finance innovation involving assets that are firm-specific and intangible and thus difficult to collateralise (Berger and Udell, 2002; De Haas and Popov, 2019).[3] These issues are particularly pronounced in the case of clean technology firms (Erzurumlu et al., 2010; Nanda et al., 2015).

Credit constraints might be further reinforced if the borrowing firm does not have a lending relationship with a bank (see, e.g., Bharath et al., 2011; Jiménez and Saurina, 2004; Petersen and Rajan, 1995), as transactions between lender and borrower reduce the information asymmetry. Next to new clean technology firms, renewable energy project developers and independent power producers, which rely highly on external debt (Johnston et al., 2008), are also likely to be negatively affected by limited or non-existent lending relationships.[4] A closely related

[2]In 2016, more than 46% of global renewable energy investments were financed using project finance structures (McCrone et al., 2017). Steffen (2018) finds a similar share for renewable energy investments in Germany, where project finance seems to play a only minor role for conventional investments. One reason is that only large developers and utilities are capable to finance on their balance sheet (Johnston et al., 2008; Kann, 2009).

[3]Collateral can effectively reduce credit rationing by inducing self-selection among borrowers (Bester, 1987).

[4]Kalamova et al. (2011) show that in 2007 and 2008 the majority of new renewable energy plants in North America are owned and operated by renewable energy companies, while before 2007 most were developed by utilities that also own conventional plants. Butler and Neuhoff (2008) interviewed German and UK project developers in the wind sector and found that obtaining financing can be an issue, in particular if the developer does not have a parent company.

issue is lenders' technological conservatism that may deter lending for new (low-carbon) technologies if the information gathered by banks is technology specific (Minetti, 2010). As the technological progress will erode their knowledge on the mature technology, lenders may have an incentive not to finance for new (low-carbon) technologies.

In spite of the increasing evidence of deterring effects of financing constraints on low-carbon investments, there has been, to our best knowledge, no systematic theoretical analysis of this issue.[5] This paper (i) offers a first theoretical mechanism explaining how information asymmetries between lenders and borrowers might induce credit rationing and thus a socially undesirably low level of low-carbon investment and (ii) analyses how different policy interventions might resolve this issue. Our theoretical approach builds on the previous literature on market failures on financial markets (see, e.g., Arping et al., 2010, Gale, 1990, Philippon and Skreta, 2012), in particular the model of Janda (2011). Firms can choose between two technologies: a carbon-intensive (dirty) technology and a low-carbon (clean) technology, which requires external funding for an initial risky investment. Due to asymmetric information, the lender (bank) cannot distinguish between different firm types. Our main findings are as follows. An appropriate (carbon) emissions tax incentivises high emission firms to switch to the clean technology. However, credit rationing may occur, i.e. some firm types do not receive financing for the socially desirable low-carbon technology. Introducing an interest rate subsidy or a loan guarantee can successfully eliminate credit rationing and hence yield the first-best outcome. We further consider the situation where an emission tax, i.e a carbon price, is (politically) not feasible. An interest rate subsidy is also capable of promoting low-carbon investment, but only yields a second-best outcome. Finally, we analyse the dynamic effects of policy interventions. In the presence of low-carbon innovation spillovers, any policy intervention on credit markets is finite. Without any intervention, however, there are social costs of delay.

The paper is structured as follows. Section 2 presents the main analysis starting with the laissez-faire outcome. We then analyse the introduction of an emission tax and interest rate subsidies or loan guarantees addressing credit rationing of firms. We further consider a situation, where an emission tax is (politically) not feasible and finally compare welfare across all scenarios. Section 3 introduces innovation spillovers and analyses dynamic effects of policy interventions. Section 4 discusses the implications of our results before Section 5 concludes.

[5] One exception is Hoffmann et al. (2017), who also introduce a financial market with information asymmetries (moral hazard) in an environmental problem, however with a different focus. The authors analyse the effectiveness of taxes on externalities when firms' abatement activities require external financing.

2. Comparative Analysis of Policy Interventions

2.1. Model Setup

The economy consists of three types of actors: firms that can choose between a low-carbon (clean) and a carbon-intensive (dirty) technology for production, lenders providing loans for firms, and the government. A firm's decision between using the (immature) clean and the (mature) dirty technology depends on the respective expected returns. Choosing the clean technology requires an initial risky investment financed through a loan from the lender. The dirty technology is mature and hence does not require such an initial investment.[6] The firms' decision problem in this model can be applied to any firm (irrespective of the sector) that can choose between dirty and clean production technologies. The risky investment prior to producing with the low-carbon technology can be seen as an initial cost enabling the firm to use this technology, such as R&D expenditures or other costs of introducing it. Alternatively, the model can also be applied to the more specific case of energy producing firms choosing between mature carbon-intensive technologies or immature low-carbon technologies. The latter are substantially more capital-intensive and thus require more external financing, in particular debt.

In the model, the lender faces a perfectly elastic supply of funds at unit cost ρ. Firms have both a carbon-intensive (dirty) and a low-carbon (clean) production technology. There are two types of clean technologies, indexed as type $c \in \left\{\underline{c}, \overline{c}\right\}$, with identical output $y_{\underline{c}} = y_{\overline{c}} = y_C$. The success probabilities of investing into the technologies, however, differs between both types with $0 < \delta_{\underline{c}} < \delta_{\overline{c}} < 1$. $\theta_c \in (0, 1)$ is the proportion of firms with $\underline{c}$-type technologies and $1 - \theta_c$ is the proportion of firms with $\overline{c}$-type technologies in the population. There are two types of dirty technologies, indexed as type $d \in \left\{\underline{d}, \overline{d}\right\}$. Output of both types is identical, $y_{\underline{d}} = y_{\overline{d}} = y_D$, but the carbon emissions associated with output, $e_{\underline{d}}$, $e_{\overline{d}}$, differ between technologies with $e_{\overline{d}} < e_{\underline{d}}$. $\theta_d \in (0, 1)$ is the proportion of firms with $\underline{d}$-type technologies and $1 - \theta_d$ is the proportion of firms with $\overline{d}$-type technologies in the population. Thus, there are overall four types of firms differing in their clean and dirty technologies, i.e. firm types $\underline{cd}$, $\underline{c}\overline{d}$, $\overline{c}\underline{d}$, and $\overline{cd}$, which are illustrated in Table 1.

[6] Alternatively, we could have also introduced an initial investment with external funding for the dirty investment. However, as there are no information asymmetries as the technology is mature and well known and hence no credit rationing could occur on the loan market. This alternative modelling does not offer any additional insights and does not change the results in the model. Hence, we refrain from doing so for the sake of simplicity.

Table 1: Contingency table of firm types in the economy

	$\overline{c}$-type	$\underline{c}$-type	$\sum$
$\overline{d}$-type	$(1-\theta_d)(1-\theta_c)$	$(1-\theta_d)\theta_c$	$1-\theta_d$
$\underline{d}$-type	$\theta_d(1-\theta_c)$	$\theta_d\theta_c$	θ_d
$\sum$	$(1-\theta_c)$	θ_c	1

We assume that the net present value of using the clean technology is below the private returns of dirty production. A social planer also considers emission externalities associated with dirty production, c_e: firms with potentially high emissions $e_{\underline{d}}$ should rather use the clean technology, while low-emission firms, i.e. firms emitting $e_{\overline{d}}$, should choose the dirty technology. This setup is summed up by the following assumption:

Assumption 1. $y_D > y_D - c_e e_{\overline{d}} > \delta_c y_C - \rho > y_D - c_e e_{\underline{d}} > 0 \quad c \in \{\underline{c}, \overline{c}\}$.

The loan required to undertake the clean investment is normalized to 1. Firms (borrowers) are risk-neutral and have full information. The lender and the government cannot distinguish between the types of borrowers due to asymmetric information resulting in a possible adverse selection problem. Other than that, all parameters are known to all actors in the economy.

A contract between a borrowing firm and a lender comprises two parts π_k, R_k, with $k \in \{\underline{cd}, \underline{c}\overline{d}, \overline{c}\underline{d}, \overline{cd}\}$, where π_k is the probability of receiving the loan and R_k denotes the loan repayment (1+interest rate). Like Besanko and Thakor (1987), we assume that both technology choices (clean or dirty) are mutually exclusive, such that the safe returns from dirty production represent the opportunity costs of choosing the clean technology. The expected profit of a borrower of type cd, who applies for a contract designed for a borrower k is:

$$P_{cd,k} = \pi_k \left[\delta_c \left(y_C - R_k\right) - y_D\right]. \tag{1}$$

The lender's expected profit of a loan to a borrower of type k is the difference between the interest repayment, given that the borrower is successful and hence able to repay the loan, and the bank's marginal cost to obtain funds:

$$B_k = \pi_k \left[\delta_c R_k - \rho\right]. \tag{2}$$

Following Janda (2011), we assume that, in the case of indifference between providing and not providing the loan, the bank chooses to provide the loan. When the borrower is indifferent between accepting the loan contract to finance the clean technology investment and choosing the dirty technology, they will decide in favour of the loan contract. In order to conduct welfare analyses, expected social welfare is defined as the sum of agents' profits, bank profits, and government budget, less social costs of emissions.

2.2. Economy without Policy Intervention

We first analyse the laissez-faire equilibrium, i.e. an economy without government intervention. The bank maximises its benefits from lending to the respective borrower of type k. The lender is further subject to the borrowers' individual participation constraints, i.e. their expected profits using the clean technology after repaying the loan are at least as high as their returns from dirty production ($P_{cd,k} \geq 0$). The following Lemma 1 describes the equilibrium in this situation without any government intervention.

Lemma 1. *Without government intervention all firms use the dirty technology. Total welfare is:* $W_l = y_D - (1 - \theta_d)\, c_e e_{\overline{d}} - \theta_d c_e e_{\underline{d}}$.

Proof. See Lemma 4 i. in Appendix A.1. □

All potential borrowers know the bank's per unit cost to obtain funds for lending ρ and hence the minimum interest R_k the bank has to set in order to break even. As the firms' returns from dirty production are so high compared to using the clean technology, all firms know that that the lender cannot offer interest rates that are low enough to raise the profits from clean over those of dirty production without the lender incurring losses. Thus, all four firm types favour the dirty technology. This outcome, however, is not socially optimal, mainly as firms do not consider the true social costs of their actions ($c_e e_d$) in their decisions. According to Assumption 1, it would be welfare maximising if some firms, i.e. the two firm types with high emission dirty technologies (type $c\underline{d}$), chose the clean technology.

2.3. Economy with Environmental Policy

2.3.1. Introduction of Emission Tax

We now introduce policy addressing the externalities of carbon emissions into the model. The government sets an optimal tax τ on emissions that equals their per unit social costs c_e, such that firms internalize the true social costs of their decisions (Knittel and Sandler, 2018). Following from this and Assumption 1, type-$c\overline{d}$ firms will not apply for a loan. Those firms know that the bank cannot offer them a loan contract that makes the clean investment more attractive and, at the same time, allows the bank to break even. This is due to these firms' ability to produce the dirty output at a low emission level $e_{\overline{d}}$. In spite of the introduced emission tax, using the dirty technology is still more profitable than investing in the clean technology, independent of their probability of success δ_c. Hence, only high emission firms, i.e. types $c\underline{d}$, have an incentive to invest in the clean technology.

The group of $c\underline{d}$-type firms applying for a loan to fund the initial investment for the clean technology contains both firms with a low and firms with a high success probability. The bank maximises its benefits from lending to the respective type of borrower. As a baseline, we analyse the model under full information. The lender's maximisation problem can be written as:

$$\begin{aligned} &\max_{\pi_{c\underline{d}}, R_{c\underline{d}}} \; B = \pi_{c\underline{d}} \left(\delta_c R_{c\underline{d}} - \rho \right) \\ \text{subject to} \quad &(PC_{c\underline{d}}) \quad \pi_{c\underline{d}} \left[\delta_c \left(y_C - R_{c\underline{d}} \right) - \left(y_D - \tau e_{\underline{d}} \right) \right] \geq 0, \\ &\qquad 0 \leq \pi_{c\underline{d}} \leq 1, \quad c \in \{\underline{c}, \overline{c}\}. \end{aligned}$$

With full information, the solution to this problem is given by:

$$R^*_{c\underline{d}} = y_C - \frac{y_d - \tau e_{\underline{d}}}{\delta_c} \qquad \pi^*_{c\underline{d}} = 1.$$

With full information the bank can identify each type and offers them different contracts. Lemma 2 sums up the results of the baseline case.

Lemma 2. *With an emission tax* $\tau = c_e$ *and perfect information,* $c\underline{d}$*-type firms use the clean technology.* $c\overline{d}$*-types use the dirty technology. Total welfare is:* $\tilde{W}_\tau = \theta_d y_C \left[(1-\theta_c)\, \delta_{\overline{c}} + \theta_c \delta_{\underline{c}} - \rho \right] + (1-\theta_d) \left(y_D - c_e e_{\underline{d}} \right)$.

Proof. See Lemma 4 i. in Appendix A.1 and Appendix A.2. □

We now introduce information asymmetries between the lender (principal) and the borrower (agent). In this case, the lender cannot distinguish between both borrower types. Hence, the bank maximises its expected benefit from lending subject to the participation constraint (PC) and incentive compatibility constraint (IC) of both borrower types:

$$\max_{\pi_{c\underline{d}}, R_{c\underline{d}}, \pi_{\overline{c}\underline{d}}, R_{\overline{c}\underline{d}}} B = \theta_d \left[\theta_c B_{c\underline{d}} + (1-\theta_c) B_{\overline{c}\underline{d}}\right] = \theta_d \left[\theta_c \pi_{c\underline{d}} \left[\delta_{\underline{c}} R_{c\underline{d}} - \rho\right] + (1-\theta_c)\pi_{\overline{c}\underline{d}} \left[\delta_{\overline{c}} R_{\overline{c}\underline{d}} - \rho\right]\right]$$

$$\begin{aligned}
\text{subject to} \quad (PC_{c\underline{d}}) \quad & \pi_{c\underline{d}} \left[\delta_c \left(y_C - R_{c\underline{d}}\right) - \left(y_d - \tau e_{\underline{d}}\right)\right] \geq 0 \\
(IC_{\overline{c}\underline{d}}) \quad & \pi_{\overline{c}\underline{d}} \left[\delta_{\overline{c}} \left(y_C - R_{\overline{c}\underline{d}}\right) - \left(y_d - \tau e_{\underline{d}}\right)\right] \geq \pi_{c\underline{d}} \left[\delta_{\overline{c}} \left(y_C - R_{c\underline{d}}\right) - \left(y_d - \tau e_{\underline{d}}\right)\right] \\
(IC_{c\underline{d}}) \quad & \pi_{c\underline{d}} \left[\delta_{\underline{c}} \left(y_C - R_{c\underline{d}}\right) - \left(y_d - \tau e_{\underline{d}}\right)\right] \geq \pi_{\overline{c}\underline{d}} \left[\delta_{\underline{c}} \left(y_C - R_{\overline{c}\underline{d}}\right) - \left(y_d - \tau e_{\underline{d}}\right)\right] \\
& 0 \leq \pi_{c\underline{d}} \leq 1.
\end{aligned}$$

The solution to this problem is given by:

$$R^*_{\overline{c}\underline{d}} = \begin{cases} y_C - \frac{y_d - \tau e_{\underline{d}}}{\delta_{\overline{c}}} & if \quad \pi^*_{c\underline{d}} = 0 \\ y_C - \frac{y_d - \tau e_{\underline{d}}}{\delta_{\underline{c}}} & otherwise \end{cases} \qquad \pi^*_{\overline{c}\underline{d}} = 1$$

$$R^*_{c\underline{d}} = \begin{cases} any\ value & if \quad \pi^*_{c\underline{d}} = 0 \\ y_C - \frac{y_d - \tau e_{\underline{d}}}{\delta_{\underline{c}}} & otherwise \end{cases} \qquad \pi^*_{c\underline{d}} = \begin{cases} 0 & if \quad \frac{(\delta_{\underline{c}} y_C - \rho) - (y_D - \tau e_{\underline{d}})}{(y_D - \tau e_{\underline{d}})} < \frac{1-\theta_c}{\theta_c} \frac{\delta_{\overline{c}} - \delta_{\underline{c}}}{\delta_{\underline{c}}} \\ 1 & otherwise. \end{cases}$$

Similar to the case with full information, the high emission firms choose the clean technology investment and hence apply for a loan. When the condition for $\pi^*_{c\underline{d}} = 0$ holds, the high-risk borrower, i.e. the firm with a low success probability $\delta_{\underline{c}}$, does not receive the loan. This outcome is referred to as credit rationing. This credit rationing condition holds if the difference between the success probabilities of both borrowers, $\delta_{\underline{c}}$ and $\delta_{\overline{c}}$, is large enough, which means that credit rationing is more likely for immature and risky clean technologies. When the credit rationing condition holds, the lender sets the uniform interest rate $R^*_{\overline{c}\underline{d}} = y_{\overline{c}} - \left(y_d - \tau e_{\underline{d}}\right)/\delta_{\overline{c}}$, which the type-$c\underline{d}$ borrower cannot afford. It is more profitable for the bank to set a high interest rate and only serve the type-$\overline{c}\underline{d}$ borrower rather than reducing the interest rate and offering loans to both types. Proposition 1 sums up these results.

Proposition 1. *With emission tax* $\tau = c_e$ *and if the credit rationing condition holds, i.e.* $\frac{(\delta_{\underline{c}} y_C - \rho) - (y_D - \tau e_{\underline{d}})}{(y_D - \tau e_{\underline{d}})} < \frac{1-\theta_c}{\theta_c} \frac{\delta_{\overline{c}} - \delta_{\underline{c}}}{\delta_{\underline{c}}}$, *low-emission firm types* $c\overline{d}$ *use the dirty production technology. High-emission firm types* $c\underline{d}$ *prefer the clean technology, but type-*$\underline{cd}$ *firms do not receive a loan and hence use the dirty technology. Only type-*$\overline{c}\underline{d}$ *firms use the clean technology. Total welfare is:* $W_\tau = (1-\theta_d)\left(y_D - c_e e_{\overline{d}}\right) + \theta_d \theta_c \left(y_D - c_e e_{\underline{d}}\right) + \theta_d (1-\theta_c)(\delta_{\overline{c}} y_C - \rho)$.

Proof. See Lemma 4 ii. in Appendix A.1 and Appendix A.3 with $g = s = 0$. □

Although the emission externality is internalised, this outcome is socially inferior to the full information baseline, as some socially desirable investments in low-carbon technology are not realised due to credit rationing. In the next step, we analyse whether an additional policy intervention on the financial market can effectively address the market friction.

2.3.2. Policy intervention on Credit Market

We consider two instruments the government can use to address credit rationing: either interest rate subsidies or credit guarantees. These instruments are frequently used to support low-carbon investment (Buchner et al., 2019; Kempa and Moslener, 2017). Furthermore, such policy instruments are typically analysed in the theoretical literature on financial market failures (Arping et al., 2010; Gale, 1990; Janda, 2011; Minelli and Modica, 2009; Philippon and Skreta, 2012). In order to enable socially optimal clean technology investments of type-$c\underline{d}$ firms, the government offers a limited quantity of these instruments equal to the number (mass) of type $c\underline{d}$ firms, θ_d.[7] The key difference between both instruments is the event, when the associated payment occurs. The interest rate subsidy drives a wedge between the market interest rate and the interest rate the borrower actually pays. As the interest repayment only occurs in the case of a successful investment, the interest rate subsidy is also only paid in this case. Since the interest subsidy lowers the interest repayment of the borrower, we model it as a payment to the borrower. With an interest subsidy s, the expected profit of a borrower (1) changes to

$$P_{cd,k} = \pi_k \left[\delta_c \left(y_C - (R_k - s)\right) - (y_D - \tau e_d)\right]. \tag{3}$$

In contrast, a loan guarantee is only paid if an investment is unsuccessful and the borrower cannot repay the loan. As the loan guarantee g is the share of the loan that is recovered in case of failure of the clean technology investment, the lender's expected profit (2) changes to:

$$B_k = \pi_k \left[\delta_c R_k + (1 - \delta_c)\, g - \rho\right]. \tag{4}$$

With a given interest subsidy s, with

$$s < \frac{\tau e_{\underline{d}} - \tau e_{\overline{d}}}{\delta_{\overline{c}} - \delta_{\underline{c}}} - y_C \equiv \bar{s}, \tag{5}$$

[7]Equivalently, the government can define an overall budget of government intervention on credit markets based on given expenditures on a interest subsidy or a loan guarantee.

the bank maximises its expected benefit from lending subject to the participation and incentive compatibility constraints of both borrowers:

$$\max_{\pi_{c\underline{d}},R_{c\underline{d}},\pi_{\bar{c}\underline{d}},R_{\bar{c}\underline{d}}} B = \theta_d \left[\theta_c B_{\underline{cd}} + (1-\theta_c) B_{\bar{c}\underline{d}}\right] = \theta_d \left[\theta_c \pi_{\underline{cd}} \left[\delta_{\underline{c}} R_{\underline{cd}} - \rho\right] + (1-\theta_c)\pi_{\bar{c}\underline{d}}\left[\delta_{\bar{c}} R_{\bar{c}\underline{d}} - \rho\right]\right]$$

$$\begin{aligned}
\text{subject to} \quad (PC_{c\underline{d}}) \quad & \pi_{c\underline{d}}\left[\delta_c\left(y_C + s - R_{c\underline{d}}\right) - \left(y_d - \tau e_{\underline{d}}\right)\right] \geq 0 \\
(IC_{\bar{c}\underline{d}}) \quad & \pi_{\bar{c}\underline{d}}\left[\delta_{\bar{c}}\left(y_C + s - R_{\bar{c}\underline{d}}\right) - \left(y_d - \tau e_{\underline{d}}\right)\right] \geq \pi_{\underline{cd}}\left[\delta_{\bar{c}}\left(y_C + s - R_{\underline{cd}}\right) - \left(y_d - \tau e_{\underline{d}}\right)\right] \\
(IC_{\underline{cd}}) \quad & \pi_{\underline{cd}}\left[\delta_{\underline{c}}\left(y_C + s - R_{\underline{cd}}\right) - \left(y_d - \tau e_{\underline{d}}\right)\right] \geq \pi_{\bar{c}\underline{d}}\left[\delta_{\underline{c}}\left(y_C + s - R_{\bar{c}\underline{d}}\right) - \left(y_d - \tau e_{\underline{d}}\right)\right] \\
& 0 \leq \pi_{\underline{cd}} \leq 1.
\end{aligned}$$

The solution to this problem is given by:

$$R^*_{\bar{c}\underline{d}} = \begin{cases} y_C + s - \frac{y_d - \tau e_{\underline{d}}}{\delta_{\bar{c}}} & if \quad \pi^*_{\underline{cd}} = 0 \\ y_C + s - \frac{y_d - \tau e_{\underline{d}}}{\delta_{\underline{c}}} & otherwise \end{cases} \qquad \pi^*_{\bar{c}\underline{d}} = 1$$

$$R^*_{\underline{cd}} = \begin{cases} any\ value & if \quad \pi^*_{\underline{cd}} = 0 \\ y_C + s - \frac{y_d - \tau e_{\underline{d}}}{\delta_{\underline{c}}} & otherwise \end{cases} \qquad \pi^*_{\underline{cd}} = \begin{cases} 0 & if \quad \frac{\left(\delta_{\underline{c}}(y_C+s)-\rho\right)-\left(y_D-\tau e_{\underline{d}}\right)}{\left(y_D-\tau e_{\underline{d}}\right)} < \frac{1-\theta_c}{\theta_c}\frac{\delta_{\bar{c}}-\delta_{\underline{c}}}{\delta_{\underline{c}}} \\ 1 & otherwise. \end{cases}$$

With a loan guarantee g, the bank maximises its expected benefit from lending subject to the participation and incentive compatibility constraints of both borrowers:

$$\begin{aligned}
\max_{\pi_{\underline{cd}},R_{\underline{cd}},\pi_{\bar{c}\underline{d}},R_{\bar{c}\underline{d}}} B &= (1-\theta_d)\left[\theta_c B_{\underline{cd}} + (1-\theta_c) B_{\bar{c}\underline{d}}\right] \\
&= \theta_c \pi_{\underline{cd}}\left[\delta_{\underline{c}}\left(R_{\underline{cd}}\right) - \rho + \left(1-\delta_{\underline{c}}\right) g\right] + (1-\theta_c)\pi_{\bar{c}\underline{d}}\left[\delta_{\bar{c}}\left(R_{\bar{c}\underline{d}}\right) - \rho + (1-\delta_{\bar{c}}) g\right]
\end{aligned}$$

$$\begin{aligned}
\text{subject to} \quad (PC_{c\underline{d}}) \quad & \pi_{c\underline{d}}\left[\delta_c\left(y_C - R_{c\underline{d}}\right) - \left(y_d - \tau e_{\underline{d}}\right)\right] \geq 0 \\
(IC_{\bar{c}\underline{d}}) \quad & \pi_{\bar{c}\underline{d}}\left[\delta_{\bar{c}}\left(y_C - R_{\bar{c}\underline{d}}\right) - \left(y_d - \tau e_{\underline{d}}\right)\right] \geq \pi_{\underline{cd}}\left[\delta_{\bar{c}}\left(y_C - R_{\underline{cd}}\right) - \left(y_d - \tau e_{\underline{d}}\right)\right] \\
(IC_{\underline{cd}}) \quad & \pi_{\underline{cd}}\left[\delta_{\underline{c}}\left(y_C - R_{\underline{cd}}\right) - \left(y_d - \tau e_{\underline{d}}\right)\right] \geq \pi_{\bar{c}\underline{d}}\left[\delta_{\underline{c}}\left(y_C - R_{\bar{c}\underline{d}}\right) - \left(y_d - \tau e_{\underline{d}}\right)\right] \\
& 0 \leq \pi_{c\underline{d}} \leq 1.
\end{aligned}$$

The solution to this problem is given by:

$$R^*_{\bar{c}\underline{d}} = \begin{cases} y_C - \frac{y_d - \tau e_{\underline{d}}}{\delta_{\bar{c}}} & if \quad \pi^*_{\underline{cd}} = 0 \\ y_C - \frac{y_d - \tau e_{\underline{d}}}{\delta_{\underline{c}}} & otherwise \end{cases} \qquad \pi^*_{\bar{c}\underline{d}} = 1$$

$$R^*_{\underline{cd}} = \begin{cases} any\ value & if \quad \pi^*_{\underline{cd}} = 0 \\ y_C - \frac{y_d - \tau e_{\underline{d}}}{\delta_{\underline{c}}} & otherwise \end{cases} \qquad \pi^*_{\underline{cd}} = \begin{cases} 0 & if \quad \frac{\left(\delta_{\underline{c}} y_C - \rho\right)-\left(y_D-\tau e_{\underline{d}}\right)+\left(1-\delta_{\underline{d}}\right)g}{\left(y_D-\tau e_{\underline{d}}\right)} < \frac{1-\theta_c}{\theta_c}\frac{\delta_{\bar{c}}-\delta_{\underline{c}}}{\delta_{\underline{c}}} \\ 1 & otherwise. \end{cases}$$

As in the situation prior loan guarantee or interest rate subsidy, the low-risk borrowers, i.e. the firms with a high success probability $\delta_{\overline{c}}$, always receive a loan. For the borrower with a lower success probability, we obtain conditions for g and s, under which this borrower receives a loan as well. Solving the credit rationing condition, i.e. the solution for $\pi^*_{\underline{cd}}$, for s yields the minimum interest rate subsidy assuring that also type-$\underline{cd}$ borrowers receive a loan and hence no credit rationing occurs. Similarly, there is a minimum share of the loan that has to be covered by the guarantee, g^*, such that no credit rationing occurs. The following proposition sums up the results for both cases.

Proposition 2. *With $\tau = c_e$ and either a guarantee of $g \geq g^* = \min\left\{\frac{\rho+\left(y_D-\tau e_{\underline{d}}\right)\left[1+\frac{1-\theta}{\theta}\frac{\delta_{\overline{c}}-\delta_{\underline{c}}}{\delta_{\underline{c}}}\right]}{1-\delta_{\underline{c}}}; y_C\right\}$, or an interest subsidy of $s \geq s^* = \frac{\rho+\left(y_D-\tau e_{\underline{d}}\right)\left[1+\frac{1-\theta}{\theta}\frac{\delta_{\overline{c}}-\delta_{\underline{c}}}{\delta_{\underline{c}}}\right]}{\delta_{\underline{c}}} - y_C$ and $s^* < \bar{s}$, there is no credit rationing. Total welfare is: $W_{\tau s} = W_{\tau g} = \theta_d y_C\left[(1-\theta_c)\,\delta_{\overline{c}} + \theta_c\delta_{\underline{c}} - \rho\right] + (1-\theta_d)\left(y_D - c_e e_{\underline{d}}\right)$.*

Proof. See Lemma 4 ii. in Appendix A.1 and Appendix A.3 with $g = 0$ in the case of an interest subsidy and $s = 0$ in the case of a loan guarantee. □

However, if an interest subsidy below the threshold level $\bar{s}$ does not resolve credit rationing, i.e. $s^* \geq \bar{s}$, condition (5) does not hold and the effectiveness of this instrument is limited. Interest rate subsidies above the threshold would yield a reversal in private returns for firms of type $\underline{cd}$ and type $\overline{cd}$. As a result, type-$\overline{cd}$ firms would apply for any contract designed for type $\underline{cd}$ and drive (some) firms of type $\underline{cd}$ out of the market.[8] For $s^* < \bar{s}$, total welfare is identical for the interest rate subsidy and the loan guarantee. In order to determine the more preferable option from the government's perspective, we compare the resulting government budget of both instruments. Government budgets with the minimum efficient interest rate subsidy, G_s, or with the minimum efficient loan guarantee, G_g, are given by:

$$G_s = \theta_d\left[\theta_c\delta_{\underline{c}}s^* + (1-\theta_c)\,\delta_{\overline{c}}s^*\right], \tag{6}$$

$$G_g = \theta_d\left[\theta_c\left(1-\delta_{\underline{c}}\right)g^* + (1-\theta_c)\,(1-\delta_{\overline{c}})\,g^*\right]. \tag{7}$$

Lemma 3. *The government budget required to prevent credit rationing is always higher when using interest subsidies compared to loan guarantees, $G_s > G_g$.*

Proof. For $g^* < y_C$ and $s^* < \bar{s}$ it follows that $s^* = \frac{1-\delta_{\underline{c}}}{\delta_{\underline{c}}}g^*$ (see (A.10) and Appendix A.3).

[8] Particularly, type $\overline{cd}$ firms would replace all (some) type-$\underline{cd}$ firms if $\theta_d\theta_c \overset{(>)}{\leq} (1-\theta_d)(1-\theta_c)$.

Combining this with equations (6) and (7) yields:

$$G_s - G_g = \theta_d (1 - \theta_c) g^* \left[\left(1 - \delta_{\underline{c}}\right) \frac{\delta_{\overline{c}}}{\delta_{\underline{c}}} - (1 - \delta_{\overline{c}}) \right] > 0 \quad if \quad \delta_{\underline{c}} < \delta_{\overline{c}}.$$

If $\delta_{\overline{c}}$ increases and $\delta_{\underline{c}}$ or θ_c decreases, G_s increases without bound, while G_g does not exceed $\theta_d \left[y_C \left(\theta_c \left(\delta_{\overline{c}} - \delta_{\underline{c}} \right) + 1 - \delta_{\overline{c}} \right) \right]$. □

2.4. Economy without Environmental Policy

We now analyse an economy without emission tax. In practice, emission taxes often cannot be imposed. If policy makers rely on votes, it is more attractive to financially support low-carbon technologies rather than introduce additional costs for the dirty technologies (Bowen, 2011; Green and Yatchew, 2012; Ito, 2015). Lobbying can also deter taxation (Fredriksson, 1997).

As shown in Section 2.2, there is no incentive for firms to use the clean technology without a price on carbon emissions. Alternatively, the government can use the interest rate subsidy, which is paid to the borrower, to incentivise firms to switch to low-carbon technologies.[9] As argued in Section 2.3, the bank cannot offer an interest rate that is low enough to render the low-carbon investment more attractive for firms without incurring losses. The government can use the interest rate subsidy to fill this gap, such that (at least some) firms choose the clean technology, while the lender is able to break even.

There are two relevant levels of the interest rate subsidy s. If the interest rate subsidy reaches the first threshold $\underline{s}^*$, it becomes profitable for the $\overline{c}d$-type firms to switch from the dirty to the clean technology, while the $\underline{c}d$-type firms still prefer the dirty technology. In this case, only firms with a high success probability of $\delta_{\overline{c}}$ apply for loans. There are no information asymmetries and hence no credit rationing. However, there are new inefficiencies that do not occur with an emission tax. Recall that the emission tax incentivises high-emission firms to switch to the clean technology, while low-emission firms keep using the dirty technology. Now, without tax and with with the interest rate subsidy $\underline{s}^*$, there is no self-selection of emission-intensive firms into choosing the clean technology. Instead, a fraction $(1 - \theta_d)\,\theta_c$ of low-emission firms of type $\underline{c}\overline{d}$ and a fraction $\theta_d\theta_c$ of high-emission firms of type $\underline{c}\underline{d}$ use the dirty technology, resulting in an overall higher more emissions compared to the economy with a carbon price. At the same time,

[9]Theoretically it would also be possible to use a loan guarantee. However, we do not discuss this case, as it is possible that the required level of $g > y_C$ (particularly, if $y_C - \rho < y_D - c_e e_{\overline{d}}$). This would induce a new adverse selection problem, as banks would provide contracts to high risk borrowers only.

the subsidy incentivises a fraction $(1-\theta_d)(1-\theta_c)$ of type $\overline{c}\overline{d}$ firms to choose to invest into the low-carbon technology. But from a social point of view, it would be preferable if these firms chose their low-emission dirty technology. Proposition 3 contains the core results for this case.

Proposition 3. *Without emission tax and with an interest subsidy $s = \underline{s}^* = \frac{y_D}{\delta_{\overline{c}}} - (y_C - \rho)$, firm types $\overline{c}d$ use the clean technology. Firm types $\underline{c}d$ use the dirty technology. Total welfare is: $W_{\underline{s}} = (1-\theta_c)\left[\delta_{\overline{c}} y_c - \rho\right] + \theta_c \left[y_D - \theta_d c_e e_{\underline{d}} - (1-\theta_d) c_e e_{\underline{d}}\right]$.*

Proof. See Lemma 4 iii. in Appendix A.1 and Appendix A.4. □

At the second relevant and higher threshold of the interest subsidy, denoted as $\overline{s}^*$, all firms choose the clean technology. An advantage of this higher subsidy is the abatement of emissions of the $\theta_d\theta_c$ high-emission firms of type $\underline{cd}$, which alternatively use the dirty technology in the case of lower subsidies, such as $\underline{s}^*$. At the same time, however, $\overline{s}^*$ incentivises all of the low-emission type-$\underline{c}\overline{d}$ firms to use the clean technology, although it would have been socially desirable if they kept using the dirty technology. As all firms choose the clean technology for $\overline{s}^*$, firms with both low and high success probabilities now apply for a loan. Hence, with $\overline{s}^*$ credit rationing is a possible issue that does not exist for $\underline{s}^*$. The issue of credit rationing can be addressed by either increasing s above $\overline{s}^*$ or combining it with a loan guarantee, where the latter is the preferable option (see Lemma 3). Proposition 4 sums up the results.

Proposition 4. *Without emission tax and with an interest subsidy $s = \overline{s}^* = \frac{y_D}{\delta_{\underline{c}}} - (y_C - \rho)$ and a loan guarantee $g^*_{n\tau} = \frac{1}{1-\delta_{\underline{c}}} \frac{1-\theta_c}{\theta_c} \frac{\delta_{\overline{c}}-\delta_{\underline{c}}}{\delta_{\underline{c}}} \left(\delta_{\underline{c}} y_c - \rho\right)$, all firms choose the clean technology. Total welfare is: $W_{\overline{s}g} = (1-\theta_c)\,\delta_{\overline{c}} y_c + \theta_c \delta_{\underline{c}} y_c - \rho$.*

Proof. See Lemma 4 iv. in Appendix A.1 and with $g^*_{n\tau} = \frac{1}{1-\delta_{\underline{c}}} \frac{1-\theta_c}{\theta_c} \frac{\delta_{\overline{c}}-\delta_{\underline{c}}}{\delta_{\underline{c}}} \left(\delta_{\underline{c}} y_c - \rho\right)$, $\Lambda_{n\tau} = 0$ and hence there is no credit rationing (see Appendix A.4). □

2.5. Comparative Welfare Analysis

The following proposition sums up the core results of the comparative welfare analysis:[10]

Proposition 5. *The laissez-faire scenario yields the lowest welfare and the reference scenario with emission tax $\tau = c_e$ and perfect information yields the highest welfare, $W_l < \tilde{W}_\tau$. Introducing an emission tax $\tau = c_e$ increases welfare compared to laissez-faire, $W_l < W_\tau < \tilde{W}_\tau$.*

[10] As shown above, the use of interest rate subsidies or loan guarantees to address credit rationing both result in the same welfare. As loan guarantees, however, are associated with lower government expenditure (see Lemma 3), we only consider the latter in the welfare comparison.

The combined use of an emission tax and a loan guarantee can resemble the outcome under perfect information, $W_{\tau g} = \tilde{W}_{\tau}$.

Without emission tax, a low interest rate subsidy $\underline{s}^*$ *and the combination of high interest rate subsidy* $\overline{s}^*$ *and loan guarantee cannot resemble the first-best solution,* $W_{\underline{s}}, W_{\overline{s}g} < \tilde{W}_{\tau}$. *Without emission tax, the welfare superiority of* $\overline{s}^*$ *combined with* g^* *or* $\underline{s}^*$ *depends on:* $W_{\overline{s}g} \gtreqless W_{\underline{s}} \Leftrightarrow y_D - \left[(1-\theta_d)\, c_e e_{\underline{d}} + \theta_d c_e e_{\underline{d}}\right] \gtreqless \delta_{\underline{c}} y_c - \rho$.

Proof. Follows from Propositions 1, 2, 3, 4. □

The welfare levels under laissez-faire and with emission tax and full information represent the lower and the upper bound of total welfare, respectively. If an emission tax is introduced, firms internalise the total social costs of emissions, which increases welfare. However, credit rationing may occur and some firms are deterred from using low-carbon technologies and instead keep using carbon-intensive technologies, which results in a welfare below the welfare-maximum. Credit rationing can be effectively addressed by a loan guarantee or an interest rate subsidy. This combination of a price on emissions and intervention in the credit market is capable to resemble the first-best outcome under full information and thus yields the welfare maximum.

When an emission tax is (politically) not feasible, emission externalities are not internalised, but can be indirectly addressed by financial instruments. However, only if the weighted average of all firms' emissions when using the dirty technology exceeds a threshold, such government interventions on credit markets only are welfare superior relative to laissez-faire. Below this threshold, i.e. with, on average, very low emissions of dirty technologies, laissez-faire would result in a higher welfare. Above this threshold, there are two relevant subsidy levels as outlined in Propositions 3 and 4: a low and a high interest rate subsidy. Their ordering with respect to welfare depends on two factors. Firstly, the order is driven by the share of the high-emission firms in the economy and their actual emission levels: the larger the share of high-emission firms and the higher their emissions, the larger are the social costs of emissions when those firms use the dirty technology. Hence, the higher is the welfare with the high subsidy $\overline{s}^*$ that incentivises all firms to use the clean technology. Secondly, relative welfare is affected by the success probability of firms with a low success probability, $\delta_{\underline{c}}$. The higher the success probability of the $\underline{c}d$-type firms that are incentivised to use the clean technology by $\overline{s}^*$, the higher is the resulting welfare compared to $\underline{s}^*$, where those firms use the dirty technology. However, if emission levels of dirty technologies and thus their social costs are relatively low, while low-carbon alternatives are relatively risky, it is socially optimal if the government does not intervene at all (if emission pricing is not feasible).[11]

3. Innovation Spillovers and Dynamic Effects of Policy Interventions

In this section, we investigate the dynamic effects of different policies and shed some light on the costs of delay, i.e. forgone welfare if the government chooses a non-optimal policy (mix). For this dynamic analysis, we introduce spillovers of clean technology innovation. The main idea is that learning-by-doing and learning through observing firms using low-carbon technologies positively affects the success probability of all firms' future clean technology investments. Such spillovers do not only occur at the invention or innovation stage, but also during the deployment and diffusion of new technologies on the relevant market (Popp, 2010). These spillovers are particularly pronounced in the case of low-carbon technologies.[12]

In our model, we assume that $\delta_{\underline{c}}$, the likelihood of a successful clean technology investment by low probability firms of type $\underline{c}d$, increases over time, whereas $\delta_{\overline{c}}$ remains constant.[13] We define the absolute change in $\delta_{\underline{c}}$ as an increasing function of the number of firms producing with low-carbon technologies and the gap between the two success probabilities of low-carbon technology investments, such that $\underline{c}d$-type firms gradually catch up with $\overline{c}d$-type firms, but cannot reach or even overtake them in finite time:

$$\dot{\delta}_{\underline{c},t} \equiv \delta_{\underline{c},t} - \delta_{\underline{c},t-1} = \theta_d \left(\pi_{\underline{c},t-1}\theta_c + \pi_{\overline{c},t-1}\left(1-\theta_c\right)\right)\left(\delta_{\overline{c},t-1} - \delta_{\underline{c},t-1}\right) \quad \forall\, t > 0. \tag{8}$$

In the static model, a combination of a tax on carbon emission with an interest rate subsidy or a loan guarantee yields the first-best welfare level $W_{\tau g}$ (see Proposition 2). In order to show the dynamic effects of the intervention on the credit market, we compare this optimal static policy mix to the situation, where the government only imposes an emission tax resulting in credit rationing and a lower welfare level W_{τ} (see Proposition 1).[14]

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[11] This holds if $y_D - \left[(1-\theta_d)\, c_e e_{\underline{d}} + \theta_d c_e e_{\underline{d}}\right] < \delta_{\overline{c}} y_c - \rho$.

[12] Ang et al. (2017) and Braun et al. (2010) provide evidence for knowledge spillovers in the renewable energy sector. Dechezleprêtre et al. (2017) find that spillovers of clean innovations are comparable to the IT sector and substantially higher than those of dirty innovations.

[13] Alternatively, it is possible to assume that both $\delta_{\underline{c}}$ and $\delta_{\overline{c}}$ grow due to spillovers. In our analysis, however, the reduction of the difference between $\delta_{\underline{c}}$ and $\delta_{\overline{c}}$ is the main driver of the results and not their respective absolute values. Thus, our assumption simplifies the analysis without qualitatively affecting the results.

[14] We do not explicitly analyse all the cases we analysed in the static model above. The main reason is that the ordering of all policy mixes from a social planers perspective does basically not change, when going from a static to a dynamic context. To avoid redundancies, we concentrate on the core issue of this paper, namely

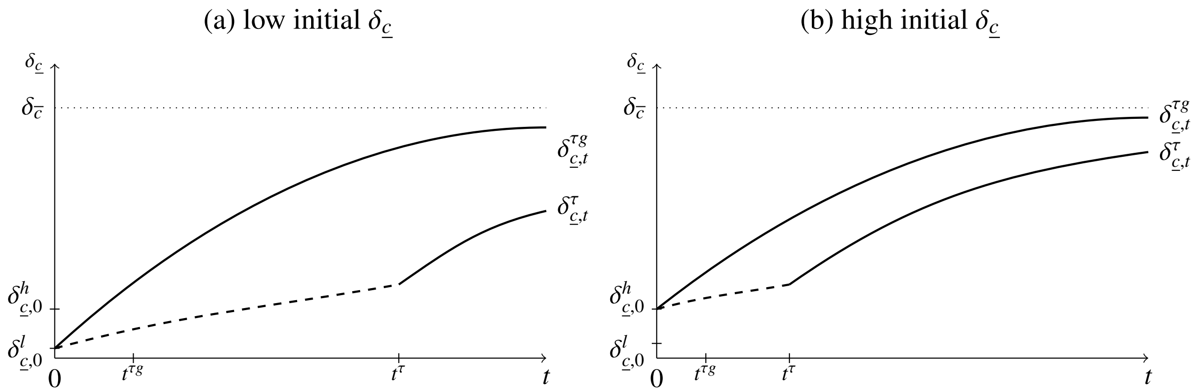

Figure 1: Evolution of $\underline{c}d$-type firms' success probability of investing in the clean technology with government intervention on credit markets ($\delta^{\tau g}_{\underline{c},t}$) and without ($\delta^{\tau}_{\underline{c},t}$).

Figure 1 depicts the development of the success probability of $\underline{c}d$-type firms. The sole difference between Figures 1a and 1b is a different initial value of $\underline{c}d$-type borrowers' success probabilities, namely a low value, $\delta^{l}_{\underline{c},0}$, in Figure 1a and a high value, $\delta^{h}_{\underline{c},0}$, in Figure 1b. Otherwise, both cases are qualitatively identical and the specific differences will addressed below. When the government combines an emission tax with a loan guarantee, there is no credit rationing and also high-risk firms invest in the clean technology. As can be seen in the figure, their productivity $\delta^{\tau g}_{\underline{c},t}$ gradually increases over time and gets closer to the success probability of low-risk firms, $\delta^{h}_{\underline{c},0}$, due to innovation spillovers. At time $t = t^{\tau g}$, the decreasing difference between $\delta_{\underline{c},0}$ and $\delta_{\bar{c}}$ has reached a threshold, where the credit rationing condition does not hold anymore and credit rationing disappears. From this point onwards, government intervention on credit markets is not necessary, as the emission tax is sufficient to achieve the first-best outcome.

In the alternative case of an emission tax only, there is credit rationing and $\underline{cd}$-type firms are not able to use the clean technology. Although they use the dirty technology, however, their success probability $\delta^{\tau}_{\underline{c},t}$ increases over time, as depicted by the dashed line, due to the knowledge spillovers from observing successful clean technology investments by $\bar{c}\underline{d}$-type firms. This increase is slower than under the first-best policy mix without credit rationing, where more firms use the low-carbon technology, which results in more spillovers. At time $t = t^{\tau}$, $\delta^{\tau}_{\underline{c},t}$ has reached the threshold, where credit rationing of $\underline{cd}$-type borrowers vanishes. Due to lower spillovers caused by credit rationing, this threshold is reached later than under the first-best policy mix with government intervention in the credit market. As now high-risk firms start investing in the clean technology, the growth rate of $\delta_{\underline{c}}$ increases as total number of firms using

the market failure on credit markets and its dynamic impacts if it addressed properly compared to a situation, where it is not addressed by the government.

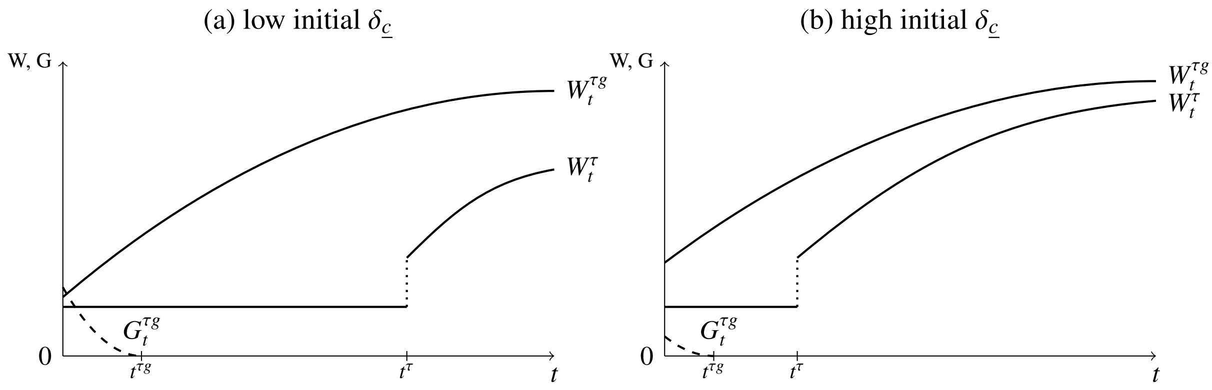

Figure 2: Evolution of total welfare with emission tax and with government intervention on credit market ($W_t^{\tau g}$), without government intervention on credit market (W_t^{τ}), and government expenditures ($G_t^{\tau g}$).

the clean technology increases, i.e. the curve becomes steeper at $t = t^{\tau}$. However, due to head start induced by the government intervention on the financial market, $\delta_{\underline{c},t}^{\tau g}$ remains above $\delta_{\underline{c},t}^{\tau}$.

The main difference between a low initial probability $\delta_{\underline{c},0}^{l}$ and a high initial probability $\delta_{\underline{c},0}^{h}$ is the timing of the developments outlined above. For $\delta_{\underline{c},0}^{h}$, the difference between the success probabilities of high-risk and low-risk firms is smaller. Thus, the threshold, where credit rationing dissipates is reached earlier. In Figure 1a, which depicts the case of $\delta_{\underline{c},0}^{l}$, $t^{\tau g}$ and t^{τ} are reached later compared to the case of $\delta_{\underline{c},0}^{h}$ illustrated in Figure 1b.

We now turn to the development of welfare for both policy mixes, which are depicted in Figure 2. Again, Figure 2a illustrates the case for a low initial $\delta_{\underline{c},0}$, Figure 2b for a high initial $\delta_{\underline{c},0}$. In both cases the welfare at time t for the first-best policy mix, $W_t^{\tau g}$, is initially above W_t^{τ}, the welfare at time t with an emission tax only (see Proposition 5). $G_t^{\tau g}$ denotes government expenditures for loan guarantees. The development of $W_t^{\tau g}$ is qualitatively similar to the evolution of $\delta_{\underline{c},t}^{\tau g}$. As the government intervenes on credit markets, there is no credit rationing and high-risk $\underline{c}d$-type firms use the clean technology as well. The increase in welfare $W_t^{\tau g}$ over time is driven by the growing $\delta_{\underline{c},t}^{\tau g}$. Furthermore, government expenditures $G_t^{\tau g}$ decreases over time: the higher the success probability of $\underline{cd}$-type borrowers, the lower the probability of failure and thus the required government expenditures for loan guarantees. At time $t^{\tau g}$, the threshold $\delta_{\underline{c},t}^{\tau g}$ is reached, where credit rationing disappears and government intervention on financial markets is not required anymore, i.e. $G_t^{\tau g} = 0$.

In the case of an emission tax only, welfare W_t^{τ} remains constant until $t = t^{\tau}$. Although the success probability of high-risk firms $\delta_{\underline{c},t}^{\tau}$ is growing, as depicted by the dashed line in Figure 1, there is no effect on welfare. Due to credit rationing, these firms use the dirty technology.

At $t = t^{\tau}$, all $\underline{c}d$-type firms switch from the dirty to the clean technology and thus benefit from the increased success probability, which results in an immediate increase in welfare. From this point onwards, W_t^{τ} increases over time driven by the growth of $\delta^{\tau}_{\underline{c},t}$. However, W_t^{τ} will not reach or even supersede $W_t^{\tau g}$ in finite time due to the head start induced by the government intervention. The net present value of welfare is always higher for the case with government intervention on credit markets.[15]

Similar to the evolution of success probabilities, a main difference between the development of welfare of low $\delta_{\underline{c},0}$ and high $\delta_{\underline{c},0}$ is the timing, when credit rationing vanishes, i.e. $t^{\tau g}$ and t^{τ}. Furthermore, the difference between initial welfare levels $W_0^{\tau g}$ and W_0^{τ} is smaller for a low $\delta_{\underline{c},0}$. Due to the relatively low success probability of $\underline{c}d$-type firms in this case, the additional welfare without credit rationing compared to the case with credit rationing is relatively low. The opposite can be observed for government expenditures. When $\delta_{\underline{c},0}$ is low, the required government funding for loan guarantees (or interest rate subsidies), $G_t^{\tau g}$, is relatively high, as can be seen in Figure 2a. For higher $\delta_{\underline{c},0}$, i.e. less risky $\underline{c}d$-type borrowers, the required government expenditures to successfully address credit rationing are lower (see Figure 2b). This might lead to possible adverse incentives for government behaviour. The overall welfare gain of government intervention in credit markets is depicted as the area between $W_t^{\tau g}$ and W_t^{τ} in Figure 2. This area represents the costs of delay if the government does not intervene. Comparing Figures 2a and 2b shows that the welfare gains of government intervention, or alternatively the costs of delay, are larger for immature and risky clean technologies (low $\delta_{\underline{c},0}$) than for less risky clean technologies (high $\delta_{\underline{c},0}$) in finite time.[16] Thus, government intervention is particularly beneficial if the clean technology is very immature and risky. However, the initial welfare gain is larger for higher values of $\delta_{\underline{c},0}$: the initial difference between $W_t^{\tau g}$ and W_t^{τ} is higher for a high $\delta_{\underline{c},0}$. Furthermore, the required government expenditures are smaller in this case. Consider a government that wants to maximize welfare and minimise expenditures. The more myopic the government, i.e. the larger its discount rate, the more likely the government is to intervene when $\delta_{\underline{c}0}$ is high, as initial welfare gains are relatively high, while government expenditures are relatively low. Supporting more immature and risky technologies that would lead to overall higher welfare gains to society in the long-run, are relatively less likely to be supported by the government. The severity of this issue depends on the policy makers discount rate as well as the risk-profiles of low-carbon technologies.

[15]See Appendix A.5.

[16]For $t \to \infty$ the costs of delay converge to the same value.

4. Discussion

In this section, we discuss our results and present conditions when credit rationing is likely to occur based on the characteristics of low-carbon investments and market conditions, as the development of the financial sector. We then discuss main policy recommendations.

A main result of our analysis is that a carbon price alone is not enough to achieve a first-best outcome if information asymmetries lead to credit rationing. Whether a carbon price is sufficient depends on the risks of low-carbon technologies, i.e. the difference between project success probabilities $\delta_{\underline{c}}$ and $\delta_{\overline{c}}$. The riskier the initial investment in the technology, the more likely is credit rationing. Empirical evidence on investments in renewable energy supports this prediction. Mazzucato and Semieniuk (2018) find that private banks largely finance low-risk renewable energy technologies, while high-risk investments are rather externally financed by state banks or internally by state-owned utilities or corporations. Geddes et al. (2018) find project developers, IPPs, and utilities in Australia, Germany, and the UK firms faced issues or were even unable to source debt for their renewable energy projects when using new technologies.[17] Empirical studies further find that renewable energy project developers seem to have less or no issues to source debt financing when technology mature and are perceived as less risky (Egli et al., 2018; Geddes et al., 2018; Mazzucato and Semieniuk, 2018). In our dynamic analysis, we show that knowledge spillovers from the use of clean technologies reduce the risks of future investment and ultimately resolve the issue of credit rationing: the lender is willing to serve all potential borrowers choosing the low-carbon technology.

In addition to the characteristics of the low-carbon technology, the development of the financial sector is of key importance. Main drivers of credit rationing are information asymmetries between lenders and borrowers. The more developed a country's financial sector, the better is the ability of lenders to initially screen firms and assess risks of low-carbon investments. This reduces information asymmetries and thus the likelihood of credit rationing. Empirical evidence shows that renewable energy investments benefit from financial sector development, mainly due to better access to external debt financing (Ang et al., 2017; Best, 2017; Brunnschweiler, 2010; Haščič et al., 2015; Kim and Park, 2016). Access to external financing for energy efficiency investments seems less problematic in developed countries (Fleiter et al., 2012; Trianni et al., 2016), while credit rationing might deter energy-efficient investment in developing and emerg-

[17] Examples are utility-scale PV investments in Germany, in particular before 2005, and offshore wind investments prior 2012. The interviewees reported issues to receive debt from private banks that were largely unfamiliar with the risks of the respective technologies (Geddes et al., 2018).

ing economies (Apeaning and Thollander, 2013; Kostka et al., 2013). Consequently, the more mature a low-carbon technology and the more developed an economy's financial sector, the lower is likelihood of credit rationing impeding low-carbon investments.

We show that government intervention on credit markets can dissolve credit rationing and thus induce higher low-carbon investments. This finding is in line with empirical evidence. With respect to high-tech firms, Cowling et al. (2018) find that public guarantees can reduce credit rationing. Haščič et al. (2015) find that public finance provided by multilateral, bilateral, or domestic state-owned banks positively affects private investment in renewable energy. Geddes et al. (2018) show that intervention of state-owned banks with instruments as loan guarantees or interest subsidised loans has a de-risking effect on renewable energy investments. As shown in the dynamic analysis, any intervention on financial markets is finite, as credit rationing ultimately disappears due to declining technology risks. This process is further enhanced by learnings in the financial sector (Egli et al., 2019): lenders observe investments and thus are better able to assess the risks of a potential borrower. Hence, financial instruments as loan guarantees and interest rate subsidies should be used in the case of immature and risky low-carbon technologies and / or in countries where financial institutions are less developed or less experienced in screening and assessing low-carbon investments. Even without policy intervention on the credit market, credit rationing vanishes due to decreasing risk of low-carbon investments. There are, however, costs of delay if the government does not deal with credit rationing.

Irrespective of the potential issue of credit rationing, a carbon price is the best option to incentivise high-emission firms to substitute their dirty production technology by low-carbon alternatives. Although the coverage of carbon prices has been increasing over time, they only cover around 20% of global emissions (Hepburn et al., 2020; Ramstein et al., 2019). At the same time, an increasing public involvement in financing for low-carbon investment could be observed. Currently, there are 135 loan / debt financing or guarantee programmes mainly for renewable energy and energy efficiency in force worldwide.[18] According to Buchner et al. (2019), annual average public climate finance flows increased from USD 216 billion in 2015 and 2016 to USD 253 billion in 2017 and 2018. [19]

[18]The data is based on the IEA Policies database: https://www.iea.org/policies (last accessed 18 December 2019).

[19]The International Development Finance Club (2017) reports that finance commitments to green energy and mitigation of greenhouse gases by 20 national development banks in 2016 totalled USD 153 billion: USD 47 billion by institutions based in the OECD and the remaining USD 106 billion by non-OECD based national development banks. In their joint report for 2017, six multilateral development banks' climate finance commitments totalled USD 35.2 billion (European Bank for Reconstruction and Development, 2018).

Our findings stress the importance of a carbon price. Using public finance as a substitute for a carbon price, however, can yield a second best outcome if a carbon price is (politically) not feasible. As emission externalities are largely not internalised by firms due to the low coverage of carbon pricing, public interventions through finance instruments we currently observe are likely to be inefficiently high. For this current scenario without a global coverage of carbon price, we also offer valuable guidelines on the choice of finance instruments, i.e. interest rate subsidies and loan guarantees, to optimize the second best outcome. The socially optimal choice of financial market interventions largely depends on the risk profiles of new low-carbon technologies and the emission intensities of dirty technologies. The riskier new technologies are, the more careful government expenditure should be used to promote these technologies through financial instruments. If dirty alternatives are particularly emission intensive, however, higher levels of support for clean investments are socially more beneficial.

5. Conclusion

This paper offers a novel theoretical analysis of firms' decisions between low-carbon (clean) and carbon-intensive (dirty) technologies that explicitly models external financing. We analyse how information asymmetries between lenders and firms might induce credit rationing and thus socially undesirably low level of investments and how different policy interventions might resolve this issue. We find that an emission tax (carbon price) alone is not sufficient to achieve a first-best outcome if the low-carbon technology is immature and risky and thus results in credit rationing. Introducing interest rate subsidies or loan guarantees can solve the issue of credit rationing and achieve a first-best outcome.

Given the low coverage of carbon pricing worldwide, we also consider an economy, where an emission tax is (politically) not feasible. In this scenario, an interest rate subsidy can be used as an alternative to the emission tax to induce a switch to low-carbon technologies. We find that, independent of the size of the interest subsidy or its combination with a loan guarantee, the economy with emission tax yields always superior results with respect to welfare. This means that both market failures – the emission externality and information asymmetry on the credit market – can be best eliminated by addressing both with respective instruments. Hence, our findings stress the importance of a carbon price. Using only finance instruments bears the danger of substantially increasing the social costs of the transition to a low-carbon economy and should be only considered if an emission price is (politically) not feasible.

We further offer some insights on dynamic effects. We show that any intervention on capital markets is finite, as credit rationing vanishes due to decreasing risks of low-carbon technologies, even without policy intervention on the credit market. There are, however, costs of delay if the government does not intervene. Finally, there might be adverse incentives for government behaviour. The more immature and riskier a low-carbon technology, the more beneficial is policy intervention from a welfare perspective. The smaller social benefit for rather mature and less risky technologies, however, materialises relatively quickly. Myopic policy makers might have a preference for the latter.

This paper provides only a first theoretical investigation of the impact of financial market imperfections on low-carbon investments. Extensions of this approach or alternative model setups seem to be valuable directions of future research. In our dynamic analysis, we consider learning effects on the part of the firms. A possible extension could be a dynamic analysis of information asymmetries with learning effects for lenders.

A. Appendix

A.1. Applicants

A necessary condition of a lender's profit maximisation problem is that the expected benefit of providing a contract with a positive probability is non-negative (expressions (2) $\geq$ 0 and (4) $\geq$ 0), i.e. the minimum loan repayments of types $\overline{c}d$, $R^{\overline{c}}_{min}$, and types $\underline{c}d$, $R^{\underline{c}}_{min}$, are given by

$$R^{\underline{c}}_{min} = \frac{\rho - \left(1 - \delta_{\underline{c}}\right) g}{\delta_{\underline{c}}}, \tag{A.1}$$

$$R^{\overline{c}}_{min} = \frac{\rho - (1 - \delta_{\overline{c}}) g}{\delta_{\overline{c}}}. \tag{A.2}$$

With (A.1) and (A.2), the PCs, and the ICs of all types, the following Lemma 4 can be derived.

Lemma 4.

i. *Without an emission tax (and with $g = s = 0$), conditions (A.1) and (A.2) are incompatible with PCs of all types.*

ii. *With an emission tax $\tau = c_e$ and an interest subsidy $s \in \left[0, \frac{y_D - \tau e_{\overline{d}} + \rho - (1-\delta_{\overline{c}})g}{\delta_{\overline{c}}} - y_C\right)$ or a loan guarantee $g \in \left[0, \frac{y_D - \tau e_{\overline{d}} + \rho - \delta_{\overline{c}}(y_C + s)}{1 - \delta_{\overline{c}}}\right)$, conditions (A.1) and (A.2) are compatible with PCs of types $c\underline{d}$ and incompatible with PCs of types $c\overline{d}$.*

   With an emission tax $\tau = c_e$ and an interest subsidy $s \in \left[\frac{y_D - \tau e_{\overline{d}} + \rho - (1-\delta_{\overline{c}})g}{\delta_{\overline{c}}} - y_C, \infty\right)$ or a loan guarantee $g \in \left[\frac{y_D - \tau e_{\overline{d}} + \rho - \delta_{\overline{c}}(y_C + s)}{1 - \delta_{\overline{c}}}, \infty\right)$, conditions (A.1) and (A.2) are compatible with PCs of all types.

iii. *Without an emission tax and with an interest subsidy $s \in \left[\frac{y_D + \rho - (1-\delta_{\overline{c}})g}{\delta_{\overline{c}}} - y_C, \frac{y_D + \rho - \left(1-\delta_{\underline{c}}\right)g}{\delta_{\underline{c}}} - y_C\right)$ or a loan guarantee $g \in \left[\frac{y_D + \rho - \delta_{\overline{c}}(y_C + s)}{1 - \delta_{\overline{c}}}, \frac{y_D + \rho - \delta_{\underline{c}}(y_C + s)}{1 - \delta_{\underline{c}}}\right)$, conditions (A.1) and (A.2) are compatible with PCs of types $\overline{c}d$ and incompatible with PCs of types $\underline{c}d$.*

iv. *Without an emission tax and with an interest subsidy $s \in \left[\frac{y_D + \rho - \left(1-\delta_{\underline{c}}\right)g}{\delta_{\underline{c}}} - y_C, \infty\right)$ or a loan guarantee $g \in \left[\frac{y_D + \rho - \delta_{\underline{c}}(y_C + s)}{1 - \delta_{\underline{c}}}, \infty\right)$, conditions (A.1) and (A.2) are compatible with PCs of all types.*

Proof. i. PCs of types cd are incompatible with R^{c}_{min}, as with $\pi_{k=cd} > 0$, it follows:

$$P_{cd(k=cd)} = \pi_{cd}\left[\delta_c\left(y_C - R^c_{min}\right) - y_D\right] = \pi_{cd}\left[\delta_c y_C - \rho - y_D\right] < 0$$

$$iff \quad \delta_c y_C - \rho - y_D < 0 \Leftrightarrow \delta_c y_C - \rho < y_D, \text{ which is true if Assumption 1 holds.}$$

ii. PCs of types $c\underline{d}$ are compatible with R^{c}_{min}, as with $\pi_{k=cd} > 0$, it follows:

$$P_{c\underline{d}(k=c\underline{d})} = \pi_{c\underline{d}}\left[\delta_c\left(y_C - R^{c}_{min}\right) - \left(y_D - \tau e_{\underline{d}}\right)\right] = \pi_{c\underline{d}}\left[\delta_c\left(y_C + s\right) - \rho + \left(1-\delta_c\right)g - \left(y_D - c_e e_{\underline{d}}\right)\right] \geq 0$$

$$iff \quad \delta_c\left(y_C + s\right) - \rho + \left(1-\delta_c\right)g - \left(y_D - c_e e_{\underline{d}}\right) \geq 0 \Leftrightarrow s \geq \frac{y_D - \tau e_{\underline{d}} + \rho - \left(1-\delta_c\right)g}{\delta_c} - y_C \;\; (<0)$$

$$\text{with} \quad \frac{y_D - \tau e_{\underline{d}} + \rho - \left(1-\delta_c\right)g}{\delta_c} - y_C < \frac{y_D - \tau e_{\overline{d}} + \rho - \left(1-\delta_{\overline{c}}\right)g}{\delta_{\overline{c}}} - y_C,$$

which follows from $\delta_{\overline{c}} > \delta_{\underline{c}}$, $g \geq 0$ and Assumption 1 with $\tau = c_e$.

In contrast, PCs of types $c\overline{d}$ are incompatible with R^{c}_{min}, as with $\pi_{k=cd} > 0$, it follows:

$$P_{c\overline{d}(k=c\overline{d})} = \pi_{c\overline{d}}\left[\delta_c\left(y_C - R^{c}_{min}\right) - \left(y_D - \tau e_{\overline{d}}\right)\right] = \pi_{c\overline{d}}\left[\delta_c\left(y_C + s\right) - \rho + \left(1-\delta_c\right) - \left(y_D - c_e e_{\overline{d}}\right)\right] \geq 0$$

$$iff \quad \delta_c\left(y_C + s\right) - \rho + \left(1-\delta_c\right)g - \left(y_D - c_e e_{\overline{d}}\right) \geq 0 \Leftrightarrow s \geq \frac{y_D - \tau e_{\overline{d}} + \rho - \left(1-\delta_c\right)g}{\delta_c} - y_C$$

$$\text{with} \quad \frac{y_D - \tau e_{\overline{d}} + \rho - \left(1-\delta_c\right)g}{\delta_c} - y_C \geq \frac{y_D - \tau e_{\overline{d}} + \rho - \left(1-\delta_{\overline{c}}\right)g}{\delta_{\overline{c}}} - y_C, \text{which follows from}$$

$$\delta_{\overline{c}}\left[y_D - \tau e_{\overline{d}} + \rho - \left(1-\delta_c\right)g\right] \geq \delta_c\left[y_D - \tau e_{\overline{d}} + \rho - \left(1-\delta_{\overline{c}}\right)g\right] \Leftrightarrow y_D - \tau e_{\overline{d}} \geq g - \rho,$$

where strict inequality holds for $g \leq \delta_c y_C$ (follows from Assumption 1 with $\tau = c_e$). Proofs for $g \in \left[0, \frac{y_D - \tau e_{\underline{d}} + \rho - \delta_{\overline{c}}(y_C + s)}{1-\delta_{\overline{c}}}\right)$ can be derived analogously.

iii. PCs of types $\overline{c}d$ are compatible with $R^{\overline{c}}_{min}$, as with $\pi_{k=cd} > 0$, it follows:

$$P_{\overline{c}d(k=\overline{c}d)} = \pi_{\overline{c}d}\left[\delta_{\overline{c}}\left(y_C - R^{\overline{c}}_{min}\right) - y_D\right] = \pi_{\overline{c}d}\left[\delta_{\overline{c}}\left(y_C + s\right) - \rho + \left(1-\delta_{\overline{c}}\right) - y_D\right] \geq 0$$

$$iff \quad \delta_{\overline{c}}\left(y_C + s\right) - \rho + \left(1-\delta_{\overline{c}}\right)g - y_D \geq 0 \Leftrightarrow s \geq \frac{y_D + \rho - \left(1-\delta_{\overline{c}}\right)g}{\delta_{\overline{c}}} - y_C$$

$$\text{with} \quad \frac{y_D + \rho - \left(1-\delta_{\overline{c}}\right)g}{\delta_{\overline{c}}} - y_C < \frac{y_D + \rho - \left(1-\delta_{\underline{c}}\right)g}{\delta_{\underline{c}}} - y_C, \text{ which follows from Assumption 1.}$$

In contrast, PCs of types $\underline{c}d$ are incompatible with $R^{\underline{c}}_{min}$, as with $\pi_{k=cd} > 0$, it follows:

$$P_{\underline{c}d(k=\underline{c}d)} = \pi_{\underline{c}d}\left[\delta_{\underline{c}}\left(y_C - R^{\underline{c}}_{min}\right) - y_D\right] = \pi_{\underline{c}d}\left[\delta_{\underline{c}}\left(y_C + s\right) - \rho + \left(1-\delta_{\underline{c}}\right) - y_D\right] < 0$$

$$iff \quad \delta_{\underline{c}}\left(y_C + s\right) - \rho + \left(1-\delta_{\underline{c}}\right)g - y_D < 0 \Leftrightarrow s < \frac{y_D + \rho - \left(1-\delta_{\underline{c}}\right)g}{\delta_{\underline{c}}} - y_C.$$

Proofs for $g \in \left[\frac{y_D + \rho - \delta_{\overline{c}}(y_C + s)}{1-\delta_{\overline{c}}}, \frac{y_D + \rho - \delta_{\underline{c}}(y_C + s)}{1-\delta_{\underline{c}}}\right)$ can be derived analogously.

iv. Proof can be derived analogously to iii. □

A.2. Perfect Information with Emission Tax

With an emission tax $\tau = c_e$ (and $s = g = 0$), there exists no contract provided with a positive probability that fulfills the PCs of types $c\overline{d}$ (see Lemma 4 ii.). Hence the reduced[20] Lagrangian to the profit maximisation problem of the bank is

$$L(\pi_{c\underline{d}}, R_{c\underline{d}}, \lambda_1, \lambda_2, \lambda_3) =$$
$$\pi_{c\underline{d}}\left(\delta_c R_{c\underline{d}} - \rho\right) - \lambda_1 \pi_{c\underline{d}}\left[\delta_c\left(y_C - R_{c\underline{d}}\right) - \left(y_D - \tau e_{\underline{d}}\right)\right] - \lambda_2\left(-\pi_{c\underline{d}}\right) - \lambda_3\left(\pi_{c\underline{d}} - 1\right).$$

The Kuhn-Tucker conditions for this problem are given by first-order conditions:

$$\frac{\partial L(\cdot)}{\partial R_{c\underline{d}}} = \pi_{c\underline{d}}\delta_c + \lambda_1 \pi_{c\underline{d}}\delta_c \leq 0, \quad R_{c\underline{d}} \geq 0$$
$$\frac{\partial L(\cdot)}{\partial \pi_{c\underline{d}}} = \delta_c R_{c\underline{d}} - \rho - \lambda_1\left[\delta_c\left(y_C - R_{c\underline{d}}\right) - \left(y_D - \tau e_{\underline{d}}\right)\right] + \lambda_2 - \lambda_3 \leq 0, \quad \pi_{c\underline{d}} \geq 0$$
$$\frac{\partial L(\cdot)}{\partial \lambda_1} = \delta_c R_{c\underline{d}} - \rho - \pi_{c\underline{d}}\left[\delta_c\left(y_C - R_{c\underline{d}}\right) - \left(y_D - \tau e_{\underline{d}}\right)\right] \geq 0, \quad \lambda_1 \geq 0$$
$$\frac{\partial L(\cdot)}{\partial \lambda_2} = \pi_{c\underline{d}} \geq 0, \quad \lambda_2 \geq 0$$
$$\frac{\partial L(\cdot)}{\partial \lambda_3} = 1 - \pi_{c\underline{d}} \geq 0, \quad \lambda_3 \geq 0$$

With $R_{c\underline{d}} > 0$ and $\pi_{c\underline{d}} > 0$ it follows, that $\partial L(\cdot)/\partial R_{c\underline{d}} = 0$, $\lambda_1 > 1$, $\partial L(\cdot)/\partial \pi_{c\underline{d}} = \partial L(\cdot)/\partial \lambda_1 = 0$ and with this $\lambda_3 = 0$. From that it follows that $\pi_{c\underline{d}} = 1$ and $R_{c\underline{d}} = y_C - \frac{y_D - \tau e_{\underline{d}}}{\delta_c}$.

A.3. Imperfect Information with Emission Tax

In the case of an emission tax $\tau = c_e$, we derive optimal behaviour of the lender. Following from Lemma 4 ii., with $s = g = 0$ only type-$c\underline{d}$ firms are potential loan candidates if the bank offers profit maximising contracts. With $s, g > 0$, type-$c\overline{d}$ firms may become potential candidates for loans (see Lemma 4 ii.). However, we will show that for the case of a loan guarantee (an interest subsidy smaller than a threshold level $\bar{s}$, $s < \bar{s} \equiv \frac{\tau e_{\underline{d}} - \tau e_{\overline{d}}}{\delta_{\overline{c}} - \delta_{\underline{c}}} - y_C$ (> 0)), only type-$c\underline{d}$ firms apply for a loan and hence type-$c\overline{d}$ firms can be omitted in the profit-maximisation problem of the lender. However, if $s < \bar{s} \equiv \frac{\tau e_{\underline{d}} - \tau e_{\overline{d}}}{\delta_{\overline{c}} - \delta_{\underline{c}}} - y_C$ does not resolve credit rationing, government intervention with $s \geq \bar{s}$ incentivise investors of type $\overline{cd}$ to apply for a loan (and drive (some) investors of type $\underline{cd}$ out of the clean technology market).

[20]As a result of the incompatibility of $PC_{c\underline{d}}$, we do not explicitly consider types $c\underline{d}$ in the profit maximisation problem.

We derive optimal behaviour of all firms, the lender, and the government assuming only firms of types $c\underline{d}$ are potential candidates for a loan and show that the claims stated above are true. The analysis of contract regimes (π_k, R_k) in a situation with imperfect information and only firm types $c\underline{d}$ as potential candidates for a loan is structured along the following groups of regimes: Regime(s) 1: $\pi_{\underline{cd}} = 0,\ \pi_{\overline{c}\underline{d}} = 0$, Regime(s) 2: $\pi_{\underline{cd}} > 0,\ \pi_{\overline{c}\underline{d}} = 0$, Regime(s) 3: $\pi_{\underline{cd}} = 0,\ \pi_{\overline{c}\underline{d}} > 0$, Regime(s) 4: $\pi_{\underline{cd}} > 0,\ \pi_{\overline{c}\underline{d}} > 0$.

Regime(s) 1:

Regime(s) 1 is not profit maximizing as long as there exist some firm i with $i \in \{\overline{c}, \underline{c}\}$ and $\delta_i (y_C + s) + (1 - \delta_i) g - \rho \geq \left(y_D - \tau e_{\underline{d}}\right)$ holds, which is true for $s, g \geq 0$ and if Assumption 1 holds. If $\delta_i (y_C + s) + (1 - \delta_i) g - \rho < \left(y_D - \tau e_{\underline{d}}\right)$ holds, Regime(s) 1 is profit maximizing, as there exists no contract with $\pi_k > 0$ that is compatible with the lower bound of R (equations (A.1) and (A.2)) and the participation constraints of any firm type.

Regime(s) 2:

From IC of type $\overline{c}$ and with $\delta_{\overline{c}} > \delta_{\underline{c}}$ it follows for the case of an emission tax $\tau = c_e$ that

$$
\begin{aligned}
(IC_{\overline{c}\underline{d}}) \quad \pi_{\overline{c}\underline{d}}\left[\delta_{\overline{c}}\left(y_C - R_{\overline{c}\underline{d}}\right) - \left(y_d - \tau e_{\underline{d}}\right)\right] &\geq \pi_{\underline{cd}}\left[\delta_{\overline{c}}\left(y_C - R_{\underline{cd}}\right) - \left(y_d - \tau e_{\underline{d}}\right)\right] \\
(PC_{\underline{cd}}) \quad &> \pi_{\underline{cd}}\left[\delta_{\underline{c}}\left(y_C - R_{\underline{cd}}\right) - \left(y_d - \tau e_{\underline{d}}\right)\right]
\end{aligned}
$$

and without an emission tax that

$$
\begin{aligned}
(IC_{\overline{c}\underline{d}}) \quad \pi_{\overline{c}\underline{d}}\left[\delta_{\overline{c}}\left(y_C + s - R_{\overline{c}\underline{d}}\right) - y_d\right] &\geq \pi_{\underline{cd}}\left[\delta_{\overline{c}}\left(y_C + s - R_{\underline{cd}}\right) - y_d\right] \\
(PC_{\underline{cd}}) \quad &> \pi_{\underline{cd}}\left[\delta_{\underline{c}}\left(y_C + s - R_{\underline{cd}}\right) - y_d\right]
\end{aligned}
$$

where the last inequality holds for $\pi_{\underline{cd}} > 0$ (with $\pi_{\underline{cd}} = 0$ the last inequality changes to equality). If PC of type $\underline{cd}$ holds there exists an $R^*_{\overline{c}\underline{d}} = R_{\underline{cd}}$ and $\pi^*_{\overline{c}\underline{d}} = \pi_{\underline{cd}}$ such that PC of type $\overline{c}\underline{d}$ holds with strict inequality (follows from $\delta_{\underline{c}} < \delta_{\overline{c}}$). From that it follows that Regime(s) 2 is only profit maximizing if the profit maximizing contract is identical for both firm types (hence there is no distinction between providing two identical contracts or one contract). However, this case is included in Regime(s) 4 (with identical contracts for all applicants) and hence we can omit considering Regime(s) 2 for profit maximisation.

Regime(s) 3 and 4:

In the following, we analyse Regime(s) 3 and 4. We assume IC of types $\underline{cd}$ is satisfied and solve for the maximising solutions to the Lagrangian $L(\cdot)$. We then show that these solutions satisfy

IC of types $\underline{cd}$. The Lagrangian is given by:

$$
\begin{aligned}
& L(\pi_{\underline{cd}}, R_{\underline{cd}}, \pi_{\bar{c}\underline{d}}, R_{\bar{c}\underline{d}}, \lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5, \lambda_6) = \\
& \theta_c \pi_{\underline{cd}} \left[\delta_{\underline{c}} R_{\underline{cd}} + \left(1 - \delta_{\underline{c}}\right) g - \rho\right] + (1 - \theta_c)\, \pi_{\bar{c}\underline{d}} \left[\delta_{\bar{c}} R_{\bar{c}\underline{d}} + (1 - \delta_{\bar{c}})\, g - \rho\right] \\
& + \lambda_1 \pi_{\underline{cd}} \left[\delta_{\underline{c}} \left(y_C + s - R_{\underline{cd}}\right) - \left(y_d - \tau e_{\underline{d}}\right)\right] \\
& + \lambda_2 \left(\pi_{\bar{c}\underline{d}} \left[\delta_{\bar{c}} \left(y_C + s - R_{\bar{c}\underline{d}}\right) - \left(y_d - \tau e_{\underline{d}}\right)\right] - \pi_{\underline{cd}} \left[\delta_{\bar{c}} \left(y_C + s - R_{\underline{cd}}\right) - \left(y_d - \tau e_{\underline{d}}\right)\right]\right) \\
& + \lambda_3 \pi_{\underline{cd}} + \lambda_4 \left(1 - \pi_{\underline{cd}}\right) + \lambda_5 \pi_{\bar{c}\underline{d}} + \lambda_6 \left(1 - \pi_{\bar{c}\underline{d}}\right)
\end{aligned}
$$

The Kuhn-Tucker conditions for this problem are given by first-order conditions:

$$
\begin{aligned}
& \frac{\partial L(\cdot)}{\partial R_{\underline{cd}}} = \theta_c \pi_{\underline{cd}} \delta_{\underline{c}} - \lambda_1 \pi_{\underline{cd}} \delta_{\underline{c}} + \lambda_2 \pi_{\underline{cd}} \delta_{\bar{c}} \leq 0, \quad R_{\underline{cd}} \geq 0 \\
& \frac{\partial L(\cdot)}{\partial R_{\bar{c}\underline{d}}} = (1 - \theta_c)\, \pi_{\bar{c}\underline{d}} \delta_{\bar{c}} - \lambda_2 \pi_{\bar{c}\underline{d}} \delta_{\bar{c}} \leq 0, \quad R_{\bar{c}\underline{d}} \geq 0 \\
& \frac{\partial L(\cdot)}{\partial \pi_{\underline{cd}}} = \theta_c \left(\delta_{\underline{c}} R_{\underline{cd}} + \left(1 - \delta_{\underline{c}}\right) g - \rho\right) + \lambda_1 \left[\delta_{\underline{c}} \left(y_C + s - R_{\underline{cd}}\right) - \left(y_D - \tau e_{\underline{d}}\right)\right] \\
& \qquad - \lambda_2 \left[\delta_{\bar{c}} \left(y_C + s - R_{\underline{cd}}\right) - \left(y_D - \tau e_{\underline{d}}\right)\right] + \lambda_3 - \lambda_4 \leq 0, \quad \pi_{\underline{cd}} \geq 0 \\
& \frac{\partial L(\cdot)}{\partial \pi_{\bar{c}\underline{d}}} = (1 - \theta_c) \left(\delta_{\bar{c}} R_{\bar{c}\underline{d}} + (1 - \theta_{\bar{c}})\, g - \rho\right) + \lambda_2 \left[\delta_{\bar{c}} \left(y_C + s - R_{\bar{c}\underline{d}}\right) - \left(y_D - \tau e_{\underline{d}}\right)\right] + \lambda_5 - \lambda_6 \leq 0, \\
& \qquad \pi_{\bar{c}\underline{d}} \geq 0 \\
& \frac{\partial L(\cdot)}{\partial \lambda_1} = \pi_{\underline{cd}} \left[\delta_{\underline{c}} \left(y_C + s - R_{\underline{cd}}\right) - \left(y_D - \tau e_{\underline{d}}\right)\right] \geq 0, \quad \lambda_1 \geq 0 \\
& \frac{\partial L(\cdot)}{\partial \lambda_2} = \pi_{\bar{c}\underline{d}} \left[\delta_{\bar{c}} \left(y_C + s - R_{\bar{c}\underline{d}}\right) - \left(y_D - \tau e_{\underline{d}}\right)\right] - \pi_{\underline{cd}} \left[\delta_{\bar{c}} \left(y_C + s - R_{\underline{cd}}\right) - \left(y_D - \tau e_{\underline{d}}\right)\right] \geq 0, \quad \lambda_2 \geq 0 \\
& \frac{\partial L(\cdot)}{\partial \lambda_3} = \pi_{\underline{cd}} \geq 0, \quad \lambda_3 \geq 0 \\
& \frac{\partial L(\cdot)}{\partial \lambda_4} = 1 - \pi_{\underline{cd}} \geq 0, \quad \lambda_4 \geq 0 \\
& \frac{\partial L(\cdot)}{\partial \lambda_5} = \pi_{\bar{c}\underline{d}} \geq 0, \quad \lambda_5 \geq 0 \\
& \frac{\partial L(\cdot)}{\partial \lambda_6} = 1 - \pi_{\bar{c}\underline{d}} \geq 0, \quad \lambda_6 \geq 0
\end{aligned}
$$

Regime(s) 3: $\pi_{\underline{cd}} = 0,\ \pi_{\bar{c}\underline{d}} > 0$

Profit maximising $R_{c\underline{d}}$ requires $R_c^* \geq \rho > 0$ if $\pi_{c\underline{d}} > 0$. With $\pi_{\bar{c}\underline{d}} > 0 \Rightarrow \lambda_5 = 0$ and $\partial L(\cdot)/\partial \pi_{\bar{c}\underline{d}} = 0$ (both follow from c.s.) and $R_{\bar{c}\underline{d}} > 0 \Rightarrow \partial L(\cdot)/\partial R_{\underline{cd}} = 0$ (follows from c.s.). From that $\lambda_2 = (1 - \theta_c)$. With $\lambda_2 > 0 \Rightarrow \partial L(\cdot)/\partial \lambda_2 = 0$. Together with $\pi_{\underline{cd}} = 0$ and $\pi_{\bar{c}\underline{d}} > 0$ it follows that $R_{\bar{c}\underline{d}} = y_{\bar{c}} + s - \frac{y_D - \tau e_d}{\delta_{\bar{c}}}$. Furthermore, with $\lambda_2 > 0,\ \lambda_5 = 0,\ \pi_{\bar{c}\underline{d}} > 0,\ \partial L(\cdot)/\partial \pi_{\bar{c}\underline{d}} = 0 \Rightarrow \lambda_6 > 0$

and hence $\partial L(\cdot)/\partial\lambda_6 = 0 \Rightarrow \pi_{\bar{c}\underline{d}} = 1$ (follows from c.s.).

Regime(s) 4: $\pi_{c\underline{d}} > 0,\ \pi_{\bar{c}\underline{d}} > 1$.

With $\pi_{c\underline{d}} > 0 \Rightarrow \lambda_3 = 0$ and $\pi_{\bar{c}\underline{d}} > 0 \Rightarrow \lambda_5 = 0$ (both follow from c.s.). Profit maximizing $R_{c\underline{d}}$ requires $R_c^* \geq \rho > 0$ if $\pi_{c\underline{d}} > 0$ and hence with $R_{c\underline{d}} > 0 \Rightarrow \partial L(\cdot)/\partial R_{c\underline{d}} = 0$ and $R_{\bar{c}\underline{d}} > 0 \Rightarrow \partial L(\cdot)/\partial R_{\bar{c}\underline{d}} = 0$ (both follow from c.s.). With $\partial L(\cdot)/\partial R_{\bar{c}\underline{d}} = 0,\ \pi_{\bar{c}\underline{d}} > 0 \Rightarrow \lambda = (1-\theta_c) > 0$ and together with $\lambda_5 = 0,\ \partial L(\cdot)/\partial\pi_{\bar{c}\underline{d}} = 0 \Rightarrow \lambda_6 > 0 \Rightarrow \pi_{\bar{c}\underline{d}} = 1$ (follows from c.s.). With $\partial L(\cdot)/\partial R_{c\underline{d}} = 0,\ \lambda_2 = (1-\theta_c) \Rightarrow \lambda_1 = \theta_c + (1-\theta_c)\,\delta_{\bar{c}}/\delta_{\underline{c}}$. Together with $\partial L(\cdot)/\partial\pi_{c\underline{d}} = 0$ it follows that $\lambda_4 > 0$ if $\delta_{\underline{c}}\,(y_C + s) - y_D + \tau e_{\underline{d}} - \rho > \frac{1-\theta_c}{\theta_c}\delta_{\bar{c}}\left(y_D - \tau e_{\underline{d}}\right)\left(\frac{1}{\delta_{\underline{c}}} - \frac{1}{\delta_{\bar{c}}}\right) - \left(1-\delta_{\underline{c}}\right)g$ and hence $\pi_{c\underline{d}} = 1$ (follows from c.s.). If $\delta_{\underline{c}}\,(y_C + s) - y_D + \tau e_{\underline{d}} - \rho > \frac{1-\theta_c}{\theta_c}\delta_{\bar{c}}\left(y_D - \tau e_{\underline{d}}\right)\left(\frac{1}{\delta_{\underline{c}}} - \frac{1}{\delta_{\bar{c}}}\right) - \left(1-\delta_{\underline{c}}\right)g \Rightarrow \lambda_4 = 0$ and hence $\pi_{c\underline{d}} \leq 1$ is compatible with c.s.. With $\partial L(\cdot)/\partial\lambda_2 = 0,\ \pi_{\bar{c}\underline{d}} = 1,\ R_{c\underline{d}} = y_C + s - \frac{y_D - \tau e_{\underline{d}}}{\delta_{\underline{c}}} \Rightarrow R_{\bar{c}\underline{d}} = y_C + s - \left(\pi_{c\underline{d}}\left((\delta_{\bar{c}} - \delta_{\underline{c}})/\delta_{\underline{c}}\right) + 1\right)\left(y_D - \tau e_{\underline{d}}\right)/\delta_{\bar{c}}$. For $\pi_{c\underline{d}} = 1 \Rightarrow R_{\bar{c}\underline{d}} = y_{\bar{c}} + s - \frac{y_D + -\tau e_d}{\delta_{\underline{c}}}$. In a next step, we show that although in the case of $\delta_{\underline{c}}\,(y_C + s) - y_D + \tau e_{\underline{d}} - \rho = \frac{1-\theta_c}{\theta_c}\delta_{\bar{c}}\left(y_D - \tau e_{\underline{d}}\right)\left(\frac{1}{\delta_{\underline{c}}} - \frac{1}{\delta_{\bar{c}}}\right) - \left(1-\delta_{\underline{c}}\right)g$ all $\pi_{c\underline{d}} \in (0,1]$ fulfil the necessary conditions, only $\pi_{c\underline{d}} = 1$ also fulfils the sufficient conditions. Proof by contradiction: We try to show that there $\exists\, \tilde{\pi}_{\underline{c}} \in (0,1)$ such that $\sum_k B_k\left(\pi_{c\underline{d}} = \tilde{\pi}_{\underline{c}}\right) \geq \sum_k B_k\left(\pi_{c\underline{d}} = 1\right)$:

$$
\begin{aligned}
&(1-\theta_c)\left[\delta_{\bar{c}}\left[y_C + s - \left(y_D - \tau e_{\underline{d}}\right)\left(\frac{\pi_{c\underline{d}}}{\delta_{\underline{c}}} - \frac{\pi_{c\underline{d}}}{\delta_{\bar{c}}} + \frac{1}{\delta_{\bar{c}}}\right)\right] + (1-\delta_{\bar{c}})\,g - \rho\right] \\
&+ \theta_c\pi_{c\underline{d}}\left[\delta_{\underline{c}}\left(y_C + s - \frac{y_D - \tau e_{\underline{d}}}{\delta_{\underline{c}}}\right) + \left(1-\delta_{\underline{c}}\right) - \rho\right] \geq \\
&(1-\theta_c)\left[\delta_{\bar{c}}\left(y_C + s - \frac{y_D - \tau e_{\underline{d}}}{\delta_{\underline{c}}}\right) - \rho\right] + \theta_c\left[\delta_{\underline{c}}\left(y_C + s - \frac{y_D - \tau e_{\underline{d}}}{\delta_{\underline{c}}}\right) + \left(1-\delta_{\underline{c}}\right) - \rho\right] \\
&\Rightarrow \theta_c\delta_{\underline{c}}\,(y_C + s)\left(\pi_{c\underline{d}} - 1\right) - \theta_c\left(\rho - (1-\delta_{\bar{c}})\,g\right)\left(\pi_{c\underline{d}} - 1\right) \\
&\geq \left(y_D - \tau e_{\underline{d}}\right)\left(\pi_{c\underline{d}} - 1\right)\left[\frac{\delta_{\bar{c}} - \delta_{\underline{c}}}{\delta_{\underline{c}}} + \theta_c\frac{2\delta_{\underline{c}} - \delta_{\bar{c}}}{\delta_{\underline{c}}}\right]
\end{aligned}
$$

With $0 < \pi_{c\underline{d}} < 1$

$$
\begin{aligned}
\Rightarrow \theta_c\left(\delta_{\underline{c}}\,(y_c + s) - \rho + (1-\delta_{\bar{c}})\,g\right) &\leq \left(y_D - \tau e_{\underline{d}}\right)\left[\frac{\delta_{\underline{c}}\,(2\theta_c - 1) + \delta_{\bar{c}}\,(1-\theta_c)}{\delta_{\underline{c}}}\right] \\
\Leftrightarrow \delta_{\underline{c}}\,(y_c + s) - \rho &\leq y_D - \tau e_{\underline{d}} + \frac{1-\theta_c}{\theta_c}\left(y_D - \tau e_{\underline{d}}\right)\left(\frac{\delta_{\bar{c}} - \delta_{\underline{c}}}{\delta_{\underline{c}}}\right) - (1-\delta_{\bar{c}})\,g
\end{aligned}
$$

With $\delta_{\underline{c}}\,(y_C + s) - y_D + \tau e_{\underline{d}} - \rho = \frac{1-\theta_c}{\theta_c}\delta_{\bar{c}}\left(y_D - \tau e_{\underline{d}}\right)\left(\frac{1}{\delta_{\underline{c}}} - \frac{1}{\delta_{\bar{c}}}\right) - \left(1-\delta_{\underline{c}}\right)g$, we can substitute $\frac{1-\theta_c}{\theta_c}\left(y_D - \tau e_{\underline{d}}\right)\left(\frac{\delta_{\bar{c}} - \delta_{\underline{c}}}{\delta_{\underline{c}}}\right) - (1-\delta_{\bar{c}})\,g$ with $\delta_{\underline{c}}\,(y_C + s) - y_D + \tau e_{\underline{d}} - \rho$. From that it follows: $\delta_{\underline{c}}\,(y_c + s) - \rho \leq y_D - \tau e_{\underline{d}} + \delta_{\underline{c}}\,(y_C + s) - y_D + \tau e_{\underline{d}} - \rho \Leftrightarrow 1 \leq \theta_c$ which contradicts assumption: $\theta_c \in (0,1)$.

Summary Regimes 1-4:

For the case of an emission tax $\tau = c_e$ and given Assumption 1: $\delta_c(y_C + s - \rho) + \left(1 - \delta_{\underline{c}}\right) g > (y_D - \tau e_d)$ for types $c\underline{d}$ and hence Regime 1 is not profit maximising. Regime 2 is not profit maximizing (except maximising behaviour requires identical contracts for all types). It follows from Regimes 3 and 4: $\pi^*_{\bar{c}\underline{d}} = 1,\ R^*_{\bar{c}\underline{d}} = y_C + s - \frac{\left(\pi_{\underline{c}\underline{d}}\left(\delta_{\bar{c}} - \delta_{\underline{c}}\right) + \delta_{\underline{c}}\right)\left(y_D - \tau e_{\underline{d}}\right)}{\delta_{\bar{c}}\delta_{\underline{c}}}$. Furthermore

$$\pi^*_{\underline{cd}} = \begin{cases} 1 & \text{if} \quad \delta_{\underline{c}}(y_C + s) - y_D + \tau e_{\underline{d}} - \rho \geq \frac{1-\theta_c}{\theta_c}\delta_{\bar{c}}\left(y_D - \tau e_{\underline{d}}\right)\left(\frac{1}{\delta_{\underline{c}}} - \frac{1}{\delta_{\bar{c}}}\right) - \left(1 - \delta_{\underline{c}}\right) g \\ 0 & \text{if} \quad \delta_{\underline{c}}(y_C + s) - y_D + \tau e_{\underline{d}} - \rho < \frac{1-\theta_c}{\theta_c}\delta_{\bar{c}}\left(y_D - \tau e_{\underline{d}}\right)\left(\frac{1}{\delta_{\underline{c}}} - \frac{1}{\delta_{\bar{c}}}\right) - \left(1 - \delta_{\underline{c}}\right) g \end{cases}$$

and

$$R^*_{\underline{cd}} = \begin{cases} y_C + s - \frac{y_D - \tau e_{\underline{d}}}{\delta_{\underline{c}}} & \text{if} \quad \delta_{\underline{c}}(y_C + s) - y_D + \tau e_{\underline{d}} - \rho \geq \frac{1-\theta_c}{\theta_c}\delta_{\bar{c}}\left(y_D - \tau e_{\underline{d}}\right)\left(\frac{1}{\delta_{\underline{c}}} - \frac{1}{\delta_{\bar{c}}}\right) - \left(1 - \delta_{\underline{c}}\right) g \\ \textit{any value} & \text{if} \quad \delta_{\underline{c}}(y_C + s) - y_D + \tau e_{\underline{d}} - \rho < \frac{1-\theta_c}{\theta_c}\delta_{\bar{c}}\left(y_D - \tau e_{\underline{d}}\right)\left(\frac{1}{\delta_{\underline{c}}} - \frac{1}{\delta_{\bar{c}}}\right) - \left(1 - \delta_{\underline{c}}\right) g \end{cases}$$

We define

$$\Lambda \equiv \delta_{\underline{c}}(y_C + s) - \rho - \left(y_D - \tau e_{\underline{d}}\right)\left[1 + \frac{1 - \theta_c}{\theta_c}\frac{\delta_{\bar{c}} - \delta_{\underline{c}}}{\delta_{\underline{c}}}\right] + \left(1 - \delta_{\underline{c}}\right) g,$$

such that with $\Lambda < 0$ there is credit rationing (and with $\Lambda \geq 0$ there is no credit rationing).

Solving $\Lambda = 0$ for s yields the minimum interest subsidy that eliminates credit rationing if only types $c\underline{d}$ are potential candidates for a loan:

$$s^* \equiv \frac{\rho + \left(y_D - \tau e_{\underline{d}}\right)\left[1 + \frac{1-\theta}{\theta}\frac{\delta_{\bar{c}} - \delta_{\underline{c}}}{\delta_{\underline{c}}}\right] - \left(1 - \delta_{\underline{c}}\right) g}{\delta_{\underline{c}}} - y_C. \tag{A.3}$$

To show that the effectiveness of an interest subsidy is limited, recall that supply of credit market instruments is limited to a mass of θ_d. Suppose all instruments are allocated among type-$c\underline{d}$ firms and note that the lender is able to skim the interest subsidy paid to the borrowers of type $c\underline{d}$ (see solutions for $R^*_{\underline{cd}}$ and $R^*_{\bar{c}\underline{d}}$). If $s < \bar{s}$, it follows from Assumption 1 that no type-$c\bar{d}$ firms will apply for a loan designed for types $c\underline{d}$. Furthermore, since the lender is able to skim the maximum interest subsidy ($\theta_d s$) by providing loans to firms of type $c\underline{d}$, there is no incentive to provide loans (by lowering the repayment) type-$c\bar{d}$ firms (follows from Lemma 4 ii.).

However, if $s = \bar{s}$, type-$\overline{cd}$ firms would apply for a loan designed for type $\underline{cd}$ (follows from Assumption 1). If interest subsidies are randomly assigned to loan applicants, there is the risk of misallocation of some firms: some type-$\overline{cd}$ firms might receive a loan and crowd out some type-$\underline{cd}$ firms. Note with $s > \bar{s}$ all (some) type-$\underline{cd}$ firms will be driven out of the market if $\theta_d\theta_c \overset{(>)}{\leq} (1-\theta_d)(1-\theta_c)$ and hence misallocation of firms is inevitable. Hence, the effectiveness of an interest subsidy is limited.

Solving $\Lambda = 0$ for g yields:

$$g = \frac{\rho + \left(y_D - \tau e_{\underline{d}}\right)\left[1 + \frac{1-\theta}{\theta}\frac{\delta_{\bar{c}}-\delta_{\underline{c}}}{\delta_{\underline{c}}}\right] - \delta_{\underline{c}}\left(y_C + s\right)}{1-\delta_{\underline{c}}}. \tag{A.4}$$

Note that the expected profit from lending to firm of type $\underline{cd}$ is equal to the expected profit from lending to a firm of type $\bar{c}\underline{d}$ if $g = y_C$:

$$\begin{aligned}\delta_{\underline{c}}R^*_{\underline{cd}} = \delta_{\bar{c}}R^*_{\bar{c}\underline{d}} \Leftrightarrow \delta_{\underline{c}}\left(y_C + s - \frac{y_D - \tau e_{\underline{d}}}{\delta_{\underline{c}}}\right) + \left(1-\delta_{\underline{c}}\right)g - \rho \\ = \delta_{\bar{c}}\left(y_C + s - \frac{y_D - \tau e_{\underline{d}}}{\delta_{\bar{c}}}\right) + \left(1-\delta_{\bar{c}}\right)g - \rho \Leftrightarrow g = y_C.\end{aligned}$$

From this it follows that credit rationing does not occur if $g = y_C$. Hence the minimum effective loan guarantee is the minimum of y_C and the level determined by (A.4), i.e.,

$$g^* \equiv \min\left\{\frac{\rho + \left(y_D - \tau e_{\underline{d}}\right)\left[1 + \frac{1-\theta}{\theta}\frac{\delta_{\bar{c}}-\delta_{\underline{c}}}{\delta_{\underline{c}}}\right] - \delta_{\underline{c}}\left(y_C + s\right)}{1-\delta_{\underline{c}}}; y_C\right\}.$$

Furthermore, we can use equations (A.3) and (A.4) to determine the relation of s^* and g^* (if both instruments are used isolated and not bound by their upper limit (y_C and $\bar{s}$, resp.):

$$s^* = \frac{1-\delta_{\underline{c}}}{\delta_{\underline{c}}}g^* \tag{A.5}$$

A.4. Imperfect Information without Emission Tax

Without an emission tax, banks will not provide loans (see Lemma 4 i). A loan subsidy s can increase profitability of choosing the clean technology. Solving (3) = 0 for s and substituting (A.2) for R_k yields the minimum loan subsidy such that type-$\bar{c}d$ firms apply for a credit:

$$\underline{s}^* = \frac{y_D}{\delta_{\bar{c}}} - \left(y_C - \rho\right). \tag{A.6}$$

Solving (3) = 0 for s and substituting (A.1) yields the minimum loan subsidy such that all firm types cd are potential candidates for loans:

$$\overline{s}^* = \frac{y_D}{\delta_{\underline{c}}} - (y_C - \rho). \tag{A.7}$$

For $s < \overline{s}^*$, only types $\overline{c}d$ are potential candidates for a loan (see Lemma 4 iii.). Without an emission tax, their returns of using the dirty technology are identical for all firms and the lender cannot discriminate potential borrowers with identical success probabilities and returns to dirty production. Hence, it is sufficient to derive profit maximising (uniform) contracts for types $\overline{c}d$. The Lagrangian to the (reduced) lender's profit maximisation problem is given by:

$$L(\cdot) = (1-\theta_c)\,\pi_{\overline{c}d}\left[\delta_{\overline{c}}R_{\overline{c}d} + (1-\delta_{\overline{c}})\,g - \rho\right] + \lambda\pi_{\overline{c}d}\left[\delta_{\overline{c}}\,(y_C + s - R_{\overline{c}d}) - y_d\right]$$

The profit maximising solutions are given by $\pi_{\overline{c}d} = 1, R_{\overline{c}d} = y_C - \frac{y_D}{\delta_{\overline{c}}}$.

We now turn to the scenario with $s \geq \overline{s}^*$, i.e. all types apply for a credit (see Lemma 4 iv.). Similar to $s < \overline{s}^*$, it is sufficient to derive (uniform) profit maximising contracts for types $\overline{c}d$ and $\underline{c}d$. The analysis of contract regimes (π_k, R_k) is structured along the following groups of regimes: Regime(s) 1: $\pi_{\underline{c}d} = 0$, $\pi_{\overline{c}d} = 0$, Regime(s) 2: $\pi_{\underline{c}d} > 0$, $\pi_{\overline{c}d} = 0$, Regime(s) 3: $\pi_{\underline{c}d} = 0$, $\pi_{\overline{c}d} > 0$, Regime(s) 4: $\pi_{\underline{c}d} > 0$, $\pi_{\overline{c}d} > 0$. The analysis of regimes can be derived analogously to the analysis in Appendix A.3 and is summarized as follows:

Summary Regimes 1-4:

For the case without an emission tax and with $s \geq \frac{y_D+\rho-\left(1-\delta_{\underline{c}}\right)g}{\delta_{\underline{c}}} - y_C$ and $g \geq \frac{y_D+\rho-(\delta_{\overline{c}}y_C+s)}{1-\delta_{\overline{c}}}$: $\delta_c\,(y_C + s - \rho) + \left(1-\delta_{\underline{c}}\right)g > y_D$ for all types and hence regime 1 is not profit maximising. Regime 2 is not profit maximizing (except maximising behaviour requires identical contracts for all types). It follows from regimes 3 and 4 that $\pi^*_{\overline{c}d} = 1$ and $R^*_{\overline{c}d} = y_C + s - \frac{\left(\pi_{\underline{c}d}\left(\delta_{\overline{c}}-\delta_{\underline{c}}\right)+\delta_{\underline{c}}\right)y_D}{\delta_{\overline{c}}\delta_{\underline{c}}}$,

$$\pi^*_{\underline{c}d} = \begin{cases} 1 & \text{if} \quad \delta_{\underline{c}}\,(y_C+s) - y_D - \rho \geq \frac{1-\theta_c}{\theta_c}\delta_{\overline{c}}y_D\left(\frac{1}{\delta_{\underline{c}}} - \frac{1}{\delta_{\overline{c}}}\right) - \left(1-\delta_{\underline{c}}\right)g \\ 0 & \text{if} \quad \delta_{\underline{c}}\,(y_C+s) - y_D - \rho < \frac{1-\theta_c}{\theta_c}\delta_{\overline{c}}y_D\left(\frac{1}{\delta_{\underline{c}}} - \frac{1}{\delta_{\overline{c}}}\right) - \left(1-\delta_{\underline{c}}\right)g, \end{cases}$$

$$R^*_{\underline{c}d} = \begin{cases} y_C + s - \frac{y_D}{\delta_{\underline{c}}} & \text{if} \quad \delta_{\underline{c}}\,(y_C+s) - y_D - \rho \geq \frac{1-\theta_c}{\theta_c}\delta_{\overline{c}}y_D\left(\frac{1}{\delta_{\underline{c}}} - \frac{1}{\delta_{\overline{c}}}\right) - \left(1-\delta_{\underline{c}}\right)g \\ \textit{any value} & \text{if} \quad \delta_{\underline{c}}\,(y_C+s) - y_D - \rho < \frac{1-\theta_c}{\theta_c}\delta_{\overline{c}}y_D\left(\frac{1}{\delta_{\underline{c}}} - \frac{1}{\delta_{\overline{c}}}\right) - \left(1-\delta_{\underline{c}}\right)g. \end{cases}$$

We define $\Lambda_{n\tau} \equiv \delta_{\underline{c}}\,(y_C + s) - \rho - y_D\left[1 + \frac{1-\theta_c}{\theta_c}\frac{\delta_{\overline{c}}-\delta_{\underline{c}}}{\delta_{\underline{c}}}\right] + \left(1-\delta_{\underline{c}}\right)g$ such that with $\Lambda_{n\tau} < 0$ there is credit rationing (and with $\Lambda_{n\tau} \geq 0$ there is no credit rationing).

Solving $\Lambda_{n\tau} = 0$ for s yields the minimum interest subsidy that eliminates credit rationing:

$$s^*_{n\tau} = \frac{\rho + y_D\left[1 + \frac{1-\theta}{\theta}\frac{\delta_{\bar{c}} - \delta_{\underline{c}}}{\delta_{\underline{c}}}\right] - \left(1 - \delta_{\underline{c}}\right) g}{\delta_{\underline{c}}} - y_C \tag{A.8}$$

Solving $\Lambda_{n\tau} = 0$ for g yields the minimum loan guarantee that eliminates credit rationing:

$$g^*_{n\tau} = \frac{\rho + y_D\left[1 + \frac{1-\theta}{\theta}\frac{\delta_{\bar{c}} - \delta_{\underline{c}}}{\delta_{\underline{c}}}\right] - \delta_{\underline{c}}\left(y_C + s\right)}{1 - \delta_{\underline{c}}} \tag{A.9}$$

Furthermore, we can use equations (A.8) and (A.9) to determine the relation of s^* and g^* (if both instruments are used isolated):

$$s^*_{n\tau} = \frac{1 - \delta_{\underline{c}}}{\delta_{\underline{c}}} g^*_{n\tau}. \tag{A.10}$$

A.5. Dynamic analysis

Consider $t = z$ as the time period when credit rationing disappears, i.e. $\Lambda \geq 0$. The net present value of total welfare with $\tau = c_e$ and without political intervention on credit market is:

$$NPVW^{\tau} = \sum_{t=0}^{\infty} \sigma^{-t}\left[\theta_d\left(1-\theta_c\right)\left(\delta_{\bar{c}} y_C - \rho\right) + \left(1-\theta_d\right)\left(1-\theta_c\right)\left(y_D - c_e e_{\underline{d}}\right) + \left(1-\theta_d\right)\theta_c\left(y_D - c_e e_{\bar{d}}\right)\right]$$
$$+\theta_d\theta_c\left[\sum_{t=0}^{z-1}\sigma^{-t}\left(y_D - c_{\underline{d}}\right) + \sum_{t=z}^{\infty}\sigma^{-t}\left(\delta_{\underline{c}t} y_C - \rho\right)\right].$$

The net present value of total welfare with $\tau = c_e$ and loan guarantee / interest subsidy that avoids credit rationing of type $\underline{cd}$ is given by

$$NPVW^{\tau g} = \sum_{t=0}^{\infty} \sigma^{-t}\left[\theta_d\left(1-\theta_c\right)\left(\delta_{\bar{c}} y_C - \rho\right) + \theta_d\theta_c\left(\delta_{\underline{c}t} y_C - \rho\right)\right.$$
$$\left. + \left(1-\theta_d\right)\left(1-\theta_c\right)\left(y_D - c_e e_{\underline{d}}\right) + \left(1-\theta_d\right)\theta_c\left(y_D - c_e e_{\bar{d}}\right)\right].$$

The difference in net present value of welfare between scenario with and without government intervention on credit markets, $\Delta NPVW^{\tau g-\tau} \equiv NPVW^{\tau g} - NPVW^{\tau}$, is given by

$$\Delta NPVW^{\tau g-\tau} = \theta_d \theta_c \left[\sum_{t=0}^{z-1} \sigma^{-t} \left[\left(\delta^{g}_{\underline{c}t} y_C - \rho \right) - \left(y_D - c_{\underline{d}} \right) \right] + \sum_{t=z}^{\infty} \sigma^{-t} \left[\left(\delta^{g}_{\underline{c}t} y_C - \rho \right) - \left(\delta^{l}_{\underline{c}t} y_C - \rho \right) \right] \right] > 0,$$

where in each period t both parts of the sums are positive (follows from Assumption 1).

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