Clean Energy Investment and Credit Rationing*

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Abstract

This paper offers a novel theoretical approach to jointly analyse emission externalities and credit market failures related to clean energy investments. We use a principal-agent model with information asymmetries between potential borrowers and lenders. Agents can choose between a risk-free dirty investment and a risky clean investment requiring a bank loan. We find that an emission tax alone is insufficient in achieving a desirable outcome due to credit rationing in the clean sector. Combining the emission tax with interest subsidies or loan guarantees eliminates credit rationing and yields a first-best outcome. If an emission tax is (politically) not feasible, intervention on the credit market alone can promote clean investment. However, such a policy yields a second-best outcome. Finally, our analysis of dynamic effects in the presence of knowledge spillovers in the clean sector shows that any intervention on credit markets is finite. Without such intervention, there are costs of delay.

Keywords: Clean energy investment; credit rationing; emission tax; information asymmetry; interest rate subsidy; loan guarantee.

JEL-Classification: G21, G28, Q55, Q58.

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1. Introduction

Climate change has been recognised as one of the greatest (economic) challenges in the 21st century. There is widespread consensus among the scientific community, policy makers, private businesses and wider society that decoupling economic activity from the use of finite sources is imperative in order to reach ambitious climate targets. The required investments to achieve the transition to a low-carbon economy have to be largely done by the private sector. The main economic barriers impeding clean energy investments that are typically discussed are emission externalities and spillovers from clean innovation and technical change (Bennear and Stavins, 2007; Jaffe and Stavins, 1995; Jaffe et al., 2005). Credit market failures are typically not considered in theoretical analyses, 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). This paper aims to fill this gap.

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 investments in (i) renewable energy (Ang et al., 2017; Best, 2017; Brunnschweiler, 2010; Haščič et al., 2015; Kim and Park, 2016), (ii) energy efficiency (Apeaning and Thollander, 2013; Fleiter et al., 2012; Kostka et al., 2013; Nagesha and Balachandra, 2006), and (iii) innovative high-tech firms (Carpenter and Petersen, 2002; Guiso, 1998; Olmos et al., 2012; Revest and Sapio, 2012).

Renewable energy investments require the services of financial markets, in particular debt provision, more than, e.g., conventional investments, 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., 2017; Pollio, 1998).[2] Long amortisation periods of 15 years or more (Couture and Gagnon, 2010) foster the susceptibility to credit market failures, as

[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)

[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).

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). Empirical evidence supports the adverse effect of non-functioning credit markets on renewable energy investments (Best, 2017; Brunnschweiler, 2010; Kim and Park, 2016).

Energy efficiency investments share a key characteristic with renewable energy and thus are similarly dependent on financial markets: they have relatively high up-front costs leading to energy cost savings in the future with typically long amortisation periods (Gillingham et al., 2009). An additional source for financing constraints are the information asymmetries preventing 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). Empirical evidence on the role of functioning financial markets for energy efficiency investments shows that accessing external financing seems less problematic in developed countries (Fleiter et al., 2012; Trianni et al., 2016), while credit rationing is a relevant issue in developing and emerging economies (Apeaning and Thollander, 2013; Kostka et al., 2013; Nagesha and Balachandra, 2006).

Finally, innovative clean-technology firms are likely to be affected by financial market imperfections, as they require access to external funds to finance the initially required investment for entering the clean technology sector, e.g. for 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). The effects of information asymmetries are further enhanced by new clean technology firms' assets, which typically consist of high levels of intangible assets and technology-specific tangible assets that both are difficult to liquidate and hence cannot be used as collateral effectively (Berger and Udell, 2002; Erzurumlu et al., 2010).[3]

For all three types of clean investments, credit constraints might be further increased if the respective firm applying for a loan is comparatively small and young and thus does not have a lending relationship with a bank. Empirical studies show that existing lending relationships between banks and potential borrowers positively affect loan conditions (see, e.g., Bharath et al., 2011; Jiménez and Saurina, 2004; Petersen and Rajan, 1995). One main reason is that past

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

transactions between lender and borrower reduce the information asymmetry. Next to young clean technology firms, young 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]

In spite of the increasing evidence of the importance of financial markets for low-carbon investments, there has been, to our best knowledge, no systematic theoretical analysis of financial market imperfections on these investments. This paper offers (i) a first theoretical mechanism explaining how information asymmetries between lenders and potential clean energy investors might induce credit rationing and thus a socially undesirably low level of investment and (ii) analyses how different policy interventions might resolve this issue.[5] 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 this paper, we extend the credit rationing model of Janda (2011). Agents can choose between two types of projects: a dirty investment without risk, which causes emissions, and a clean investment, which is risky and requires a bank loan. Due to information asymmetry, the lender (bank) cannot distinguish between different types of potential borrowers in the clean sector. Our main findings are as follows. In line with the standard environmental economics literature, an appropriate emissions tax incentivises high emission firms to switch to the clean sector. However, there is credit rationing, i.e. some agents do not receive financing although those clean projects would be socially desirable. An additional government intervention by introducing an interest subsidy or a loan guarantee successfully eliminates credit rationing and hence increases welfare. We further consider the situation where an emission tax is (politically) not feasible. In this case, an interest rate subsidy is also capable of promoting investment in the clean sector. Compared to the situation with an emission tax, however, this policy intervention yields a socially worse outcome. Finally, we analyse the dynamic effects of policy interventions. We show that any government intervention on credit markets is finite, as innovation spillovers reduce technology risk in the clean sector and thus ultimately resolves the issue of credit rationing. However, there are costs of delay if

[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.

[5] An exception is Hoffmann et al. (2017), who also introduce a financial market with information asymetries (moral hazard) into an environmental economics context, however with a different focus. The authors analyse the effectiveness of taxes on externalities, when firms need to raise external financing prior to production.

the government does not address the credit market failure.

The paper is structured as follows. In Section 2, we provide the main analysis of the paper starting with a situation without policy intervention. We then analyse the introduction of an emission tax and interest rate subsidies or loan guarantees in order to address the remaining financial market failure related to clean-energy investments. We also consider a situation, where an emission tax is (politically) not feasible and finally compare welfare across these 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.

2. The Model

2.1. Setup

The economy consists of three types of potential actors: agents that can engage in either clean or dirty production, lenders providing loans for the aforementioned agents, and the government. The agents' decisions to produce in the clean or the dirty sector depends on their individual expected returns in both sectors. Due to the considerations outlined above, we assume that the clean project is risky, while the dirty project is safe, as the former uses new technologies associated with higher uncertainty compared to established technologies used in the dirty sector. Furthermore, the clean investment requires a loan from the lender, who receives funds at unit cost ρ, while engaging in the dirty sector does not require debt financing in this model.[6]

There are two types of risk-neutral borrowers (clean sector), indexed as type $c \in \{\underline{c}, \overline{c}\}$, which differ with respect to their chances of successfully finishing a clean project $0 < \delta_{\underline{c}} < \delta_{\overline{c}} < 1$. Output of both types is identical, $y_{\underline{c}} = y_{\overline{c}} = y_C$. $\theta_c \in (0, 1)$ is the proportion of $\underline{c}$-type borrowers in the population, $1 - \theta_c$ is the proportion of $\overline{c}$-type borrowers in the population. There are two types of producers in the dirty sector, indexed as type $d \in \{\underline{d}, \overline{d}\}$. Output of both types is identical, $y_{\underline{d}} = y_{\overline{d}} = y_D$. The emissions associated with output are $e_{\underline{d}}$, $e_{\overline{d}}$, with $e_{\overline{d}} < e_{\underline{d}}$. $\theta_d \in (0, 1)$ is the proportion of $\overline{d}$-type in the population, $1 - \theta_d$ is the proportion of $\overline{d}$-type in the population. Thus, there are four types of agents or investors differing in their productivities in the dirty and the clean sector, i.e. investors of types $\underline{cd}$, $\underline{c}\overline{d}$, $\overline{c}\underline{d}$, and $\overline{cd}$. Table 1 illustrates the all investor types and their respective shares in the economy.

[6] Alternatively, we could have also introduced lending for the dirty investment. However, as there are no information asymmetries in the case of this safe project, 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 abstract from lending for conventional projects for the sake of simplicity.

Table 1: Contingency table of agent 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 the clean investment is below the private return of the dirty project, as the agent does not consider the social cost of the emission externalities associated with dirty production, c_e. From the social planers perspective, the emissions have to be considered and inefficient producers in the dirty sector, i.e. producers emitting $e_{\underline{d}}$, should engage in clean investment, while efficient producers, i.e. producers emitting $e_{\overline{d}}$, should remain in the dirty sector. This setup is summed up by the 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 a borrower needs to undertake the clean investment is normalized to 1. Supply of funds facing lenders is perfectly elastic at unit cost ρ. Borrowers have full information. The lender and the government cannot distinguish between the types of borrowers (information asymmetry). Other than that, all parameters are known to all actors in the economy.

A contract between a borrower in the clean sector 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). As Besanko and Thakor (1987) we assume that both projects are mutually exclusive, such that the returns from the safe dirty project represent the opportunity costs of the clean project. The expected profit of a borrower of type c in the clean sector and type d in the dirty sector, who applies for a contract designed for a borrower k is:

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

The lender's expected profit for 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:

$$B_k = \pi_k \left[\delta_c R_k - \rho\right]. \quad (2)$$

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 and engaging in the dirty project, he 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, government budget and social costs of emissions.

2.2. Economy without Government Intervention

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

Lemma 1. *Without government intervention all types produce in the dirty sector. 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 3 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 not to make a loss with their lending business. As the private returns of the safe dirty project is so high compared to the risky clean project, all borrowers know that that the lender cannot offer the potential borrowers an interest rate that is low enough such that the potential borrower chooses the clean over the dirty project without the lender incurring losses. Thus, all four types of agents decide in favour of the dirty sector. This situation, however, cannot be socially optimal. According to Assumption 1, it would be socially desirable if some of the agents, i.e. the agents with high emission levels in the dirty sector (type $c\underline{d}$), decided to switch the clean-energy sector. The main reason for this outcome is that the producers in the dirty sector do not consider the negative effects of emissions ($c_e e_d$) in their decisions and hence decide to produce in the dirty sector.

2.3. Economy with Environmental Policy

2.3.1. Introduction of Emission Tax

We now introduce government intervention into the model. As the government can observe the social costs of emission, it introduces an environmental policy to address the externalities of emissions. It sets a tax τ on emissions equal to the per unit social costs of emissions c_e, such that the agents internalize the externality and appropriately consider it in their decision process. Following from this and Assumption 1, type-$c\overline{d}$ agents will not apply for a loan. The reasoning behind this behaviour is similar to the situation for all agents in the case without government intervention analysed above. The bank cannot offer type $c\overline{d}$-agents a loan contract without incurring losses. This is due to these agents' ability to produce the dirty output efficiently, i.e. at a low emission level. In spite of the introduced emission tax, their return in the dirty sector in still higher than their expected return from attempting the uncertain clean investment, independent of their probability of success. Hence, only $c\underline{d}$-type agents decide to switch to the clean sector due to the introduction of an emission tax.

As the group of $c\underline{d}$-type agents applying for a loan contains both potential borrowers with a high and a low probability of successfully implementing the clean project, 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:

$$\max_{\pi_{c\underline{d}}, R_{c\underline{d}}} \; B = \pi_{c\underline{d}} \left(\delta_c R_{c\underline{d}} - \rho \right)$$

$$\text{subject to} \quad (PC_{c\underline{d}}) \quad \pi_{c\underline{d}} \left[\delta_c \left(y_C - R_{c\underline{d}} \right) - \left(y_D - \tau e_{\underline{d}} \right) \right] \geq 0$$

$$0 \leq \pi_{c\underline{d}} \leq 1,$$

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

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

With perfect information the bank can identify each type and offers them different contracts. As the lender extracts both agents' additional profits from engaging in the clean sector, the borrower with a higher probability of success pays a higher interest on the loan. Lemma 2 sums up the results of the baseline case.

Lemma 2. *With an emission tax $\tau = c_e$ and perfect information, $c\underline{d}$-types apply for loans* *and produce in the clean sector. $c\bar{d}$-types produce in the dirty sector. Total welfare is* $\tilde{W}_\tau = \theta_d y_D + (1-\theta_d)\, y_C \left[(1-\theta_c)\,\delta_{\bar{c}} + \theta_c \delta_{\underline{c}}\right] - (1-\theta_d)\,\rho - \theta_d c_e e_{\bar{d}}$.

Proof. See Lemma 3 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 types of borrowers. Hence, the bank maximises its expected benefit from lending subject to the participation constraint (PC) and incentive compatibility constraint (IC) of both borrowers:

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

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

The solution to this problem is given by:

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

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

Similar to the case with full information, the agents that are inefficient in producing the dirty output choose to engage in a clean energy project and hence apply for a loan. When the condition for $\pi^*_{\underline{c}\underline{d}} = 0$ holds, the high-risk borrower, who receives a loan under full information, does not receive the loan. This outcome is referred to as credit rationing. The credit rationing condition holds if the difference between the success probabilities of both borrowers, $\delta_{\underline{c}}$ and $\delta_{\bar{c}}$, is large enough, i.e. there is credit rationing if the clean technologies are new and rather risky. When the credit rationing condition holds, the lender sets the uniform interest rate $R^*_{\bar{c}\underline{d}} = y_{\bar{c}} - \left(y_d - \tau e_{\underline{d}}\right)/\delta_{\bar{c}}$, which the type-$\underline{c}\underline{d}$ borrower cannot afford. It is more profitable for the bank to set a high interest rate and only serve the type-$\bar{c}\underline{d}$ borrower rather than reducing the interest rate and offering loans to both types. Proposition 1 contains these results.

Proposition 1. *With emission tax* $\tau = c_e$ *and* $\frac{(\delta_{\underline{c}} y_C - \rho) - (y_D - \tau e_{\underline{d}})}{(y_D - \tau e_{\underline{d}})} < \frac{1-\theta_c}{\theta_c} \frac{\delta_{\overline{c}} - \delta_{\underline{c}}}{\delta_{\underline{c}}}$, *types* $c\underline{d}$ *apply for a credit, type* $\underline{cd}$ *is credit rationed, type* $\overline{c}\underline{d}$ *produces in the clean sector. Types* $c\overline{d}$ *produce in the dirty sector. Total welfare is* $W_\tau = (1 - \theta_d)\, y_D + \theta_d\, (1 - \theta_c)\, (\delta_{\overline{c}} y_C - \rho) - (1 - \theta_d)\, c_e e_{\overline{d}}$.

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

Although the emission externality is addressed by the introduction of environmental policy, this outcome still cannot be socially optimal. Compared to the full information baseline, there is inefficient credit rationing. Some socially desirable projects are not realised as some agents are credit rationed by the lender due to asymmetric information. Thus, in the next step, we analyse whether an additional policy intervention on the financial market can effectively address credit rationing induced by information asymmetries.

2.3.2. Government intervention on Credit Market

We consider two instruments the government can use to address the socially undesirable credit rationing of borrowers in the clean sector: interest rate subsidies and credit guarantees. These instruments are frequently used to support climate mitigation, particularly clean energy investments (Buchner et al., 2017; 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 foster clean investments of type $c\underline{d}$ investors, the government offers a limited quantity of these instruments equal to the number (mass) of type $c\underline{d}$ agents, i.e. θ_d, which should be allocated to the clean sector from the social planer's perspective.[7] The key difference between both instruments is the event, when the associated payment occurs. The interest subsidy drives a wedge between the market interest rate an the interest rate the borrower actually pays. As the interest repayment only occurs in case of a successful project, 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

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

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

In contrast, a loan guarantee is only paid if a project is unsuccessful and hence the borrower cannot repay the loan. As the loan guarantee g is the share of the loan that is recovered in case of the failure of the project, the the credit provision condition with loan guarantee (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

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

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

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

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

The solution to this problem is given by:

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

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

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

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

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

$$\text{subject to} \quad (PC_{c\underline{d}}) \quad \pi_{c\underline{d}}\left[\delta_c\left(y_C - R_{c\underline{d}}\right) - \left(y_d - \tau e_{\underline{d}}\right)\right] \geq 0$$

$$(IC_{\bar{c}\underline{d}}) \quad \pi_{\bar{c}\underline{d}}\left[\delta_{\bar{c}}\left(y_C - R_{\bar{c}\underline{d}}\right) - \left(y_d - \tau e_{\underline{d}}\right)\right] \geq \pi_{\underline{cd}}\left[\delta_{\bar{c}}\left(y_C - R_{\underline{cd}}\right) - \left(y_d - \tau e_{\underline{d}}\right)\right]$$

$$(IC_{\underline{cd}}) \quad \pi_{\underline{cd}}\left[\delta_{\underline{c}}\left(y_C - R_{\underline{cd}}\right) - \left(y_d - \tau e_{\underline{d}}\right)\right] \geq \pi_{\bar{c}\underline{d}}\left[\delta_{\underline{c}}\left(y_C - R_{\bar{c}\underline{d}}\right) - \left(y_d - \tau e_{\underline{d}}\right)\right]$$

$$0 \leq \pi_{c\underline{d}} \leq 1.$$

The solution to this problem is given by:

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

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

For both cases, the low-risk borrower always receives a loan, as in the case without any government intervention. For the borrower with a lower success probability, we obtain conditions, under which this borrower receives a loan, i.e. there is no credit rationing. The minimum subsidy, s^*, necessary to eliminate credit rationing can be derived from the solution for $\pi^*_{\underline{c}}$. Solving for s yields the minimum size of the interest rate subsidy to assure that also the type-$\underline{cd}$ borrower receives a loan and hence no credit rationing occurs. There is a similar condition in the solution of the maximisation problem in the case of the loan guarantee that yields the 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. *Given the combined use of an emission tax $\tau = c_e$ and the (minimum required) credit guarantee $g^* = \min\left\{\frac{\rho + (y_D - \tau e_{\underline{d}})\left[1 + \frac{1-\theta}{\theta}\frac{\delta_{\bar{c}} - \delta_{\underline{c}}}{\delta_{\underline{c}}}\right] - \delta_{\underline{c}}(y_C + s)}{1 - \delta_{\underline{c}}}; y_C\right\}$ there is no credit rationing. With the combined use of an emission tax $\tau = c_e$ and the (minimum required) interest subsidy $s^* = \frac{\rho + (y_D - \tau e_{\underline{d}})\left[1 + \frac{1-\theta}{\theta}\frac{\delta_{\bar{c}} - \delta_{\underline{c}}}{\delta_{\underline{c}}}\right] - (1-\delta_{\underline{c}})g}{\delta_{\underline{c}}} - y_C$ there is no credit rationing if and only if $s^* < \bar{s}$. Total welfare with g^* or s^* and if $s^* < \bar{s}$ is $W_{\tau s} = W_{\tau g} = \theta_d y_D + (1-\theta_d)\, y_C\left[(1-\theta_c)\,\delta_{\bar{c}} + \theta_c \delta_{\underline{c}}\right] - (1-\theta_d)\,\rho - \theta_d c_e e_{\bar{d}}$.*

Proof. See Lemma 3 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. □

Both interventions in the credit market can be used to address the credit rationing in the clean sector and hence yield a socially more desirable situation compared to the situation, where only an emission tax exists, but the government does not intervene on the credit market. 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 to investors of type $\underline{cd}$ and type $\overline{cd}$. As a result, type $\overline{cd}$ agents will apply for any contract designed for type $\underline{cd}$ and furthermore will drive (some) agents of type $\underline{cd}$ out of the market.[8] For $s^* < \bar{s}$, 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 also compare the resulting government budget of both instruments. Government budgets with the minimum efficient interest subsidy, G_s, or with the minimum efficient loan guarantee, G_g, are given by:

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

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

Proposition 3. *Government expenditure to assure no credit rationing is always higher when using interest subsidies compared to loan guarantees, $G_g < G_s$.*

Proof. For $g^* < y_C$ and $s^* < \bar{s}$ it follows that $s^* = \frac{1-\delta_{\underline{c}}}{\delta_{\underline{c}}} g^*$ (see equation (18) and Appendix A.3). Combining this with equations (6) and (7) yields:

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

Furthermore, note that s^* is only bound by the limited effectiveness, by contrast, g has a upper limit of y_C. Hence, with increasing $\delta_{\overline{c}}$ and decreasing $\delta_{\underline{c}}$, θ_C, G_s increases without bound (as long as the use of this instrument is indicated), 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

As shown above, a mix of emission tax and a government intervention on the credit market is able to achieve a first best solution. In practice, however, it is often the case that an emis-

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

sion tax can not be imposed, which could be explained from a political economy perspective.(Fredriksson, 1997) In particular in economies, where policy makers rely on votes of the population, it is more attractive to financially support the clean sector rather than introduce additional costs for the established conventional / dirty sector (Bowen, 2011; Green and Yatchew, 2012). This high importance of financial support for clean investments can also be observed in the international climate policy, where the debate seems to have shifted from emission targets to mainly debating financial commitments. The industrialised countries promised to to mobilise climate financing of USD 100 billion per year from 2020 onwards (UNFCCC, 2012). Thus, we now analyse the model for an economy, where an emission tax is (politically) not feasible.

Without an emission tax (as shown in Section 2), there is no incentive for agents to give up dirty production and switch to the clean sector. The government can use the interest rate subsidy, which is paid to the borrower, in order to incentivise agents to switch from the dirty to the clean sector.[9] As argued in Section 2, the bank cannot offer an interest rate that is low enough such that the potential borrower chooses the clean over the dirty project without incurring losses. The government can use the interest rate subsidy to fill this gap, such that (at least some) agents choose the clean investment and the banks is able to receive an interest that covers its costs to acquire funds for lending.

There are two relevant levels of the interest rate subsidy s. If the interest rate subsidy reaches a certain threshold, $\underline{s}^*$, it becomes profitable for the $\overline{c}d$-type agents to switch to the clean sector, while the $\underline{c}d$-type agents remain in the dirty sector. As there is only one type of borrowers applying for loans, i.e. the low-risk borrowers, there is no credit rationing in this case. However, there are inefficiencies that do not occur with emission taxes. Recall that the emission tax incentivise the producers with high emission levels to switch to the clean sector, while the efficient producers remain in the dirty sector. In the case of the interest rate subsidy $\underline{s}^*$, there is no self-selection of emission-intensive dirty producers into the clean sector. Instead, a fraction $(1 - \theta_d)\,\theta_c$ of efficient producers of type $\underline{c}\overline{d}$ and a fraction $\theta_d \theta_c$ of inefficient producers of type $\underline{c}\underline{d}$ remain active in the dirty sector, which yields a higher emission level compared to the economy with emission tax. At the same time, there is a fraction $\theta_d(1 - \theta_c)$ of type $\overline{c}\underline{d}$ agents that are pulled into the clean sector by the subsidy. But from a social point of view, it would have been preferable if these agents chose the dirty sector, where they can produce at a low

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

emission level. The following proposition contains the core results in this scenario:

Proposition 4. *Without emission tax, but with an interest subsidy* $s = \underline{s}^* = \frac{y_D}{\delta_{\bar{c}}} - (y_C - \rho)$*, types* $\bar{c}d$ *apply for loans and produce in the clean sector. Types* $\underline{c}d$ *produce in the dirty sector. Total welfare is* $W_{\underline{s}} = (1 - \theta_c)\left[\delta_{\bar{c}} y_c - \rho\right] + \theta_c \left[y_D - \theta_d c_e e_{\underline{d}} - (1 - \theta_d)\, c_e e_{\underline{d}}\right]$.

Proof. See Lemma 3 iii. in Appendix A.1 and Appendix A.4. □

Alternatively to $\underline{s}^*$, the government has also the option to set a higher interest rate subsidy, denoted as $\bar{s}^*$, such that all agents choose to switch to the clean sector. An argument for the higher interest rate subsidy would be that it avoids the high emissions of the $(1-\theta_d)\theta_c$ inefficient dirty producers of type $\underline{c}\underline{d}$ that remain in the dirty sector in the case of $\underline{s}^*$. Thus, $\bar{s}^*$ avoids the negative impact of high emission producers in the dirty sector. At the same time, however, a high interest rate subsidy incentivises more of the efficient type-$\underline{c}\bar{d}$ producers in the dirty sector to switch into the clean sector, although it would have been socially desirable if they continued producing in the dirty sector. As all agents engage in the clean sector for $\bar{s}^*$, both types of borrowers, the low-risk and the high-risk type, now apply for a loan. Hence, with $\bar{s}^*$ the possibility of credit rationing is introduced, which does not exist for $\underline{s}^*$. As shown in the previous section, it is possible to address the information asymmetry in the credit market with an interest subsidy or a loan guarantee. Hence, a high subsidy can be either further increased to avoid credit rationing or combined with a loan guarantee. Similar to the scenario with emission tax analysed above, the preferable option to address credit rationing is a loan guarantee (see Proposition 3). The following proposition sums up the core results for this scenario:

Proposition 5. *Without emission tax, but with the combined use of an interest subsidy* $s = \bar{s}^* = \frac{y_D}{\delta_{\underline{c}}} - (y_C - \rho)$ *and a loan guarantee* $g^*_{n\tau} = \frac{1}{1-\delta_{\underline{c}}} \frac{1-\theta_c}{\theta_c} \frac{\delta_{\bar{c}}-\delta_{\underline{c}}}{\delta_{\underline{c}}} \left(\delta_{\underline{c}} y_c - \rho\right)$*, types cd apply for a credit and produce in the clean sector. Total welfare is* $W_{\bar{s}g} = (1 - \theta_c)\,\delta_{\bar{c}} y_c + \theta_c \delta_{\underline{c}} y_c - \rho$.

Proof. See Lemma 3 iv. in Appendix A.1 and with $g^*_{n\tau} = \frac{1}{1-\delta_{\underline{c}}} \frac{1-\theta_c}{\theta_c} \frac{\delta_{\bar{c}}-\delta_{\underline{c}}}{\delta_{\underline{c}}} \left(\delta_{\underline{c}} y_c - \rho\right)$, $\Lambda_{n\tau} = 0$ and hence there is no credit rationing (see Appendix A.4). □

2.5. Comparative Welfare Analysis

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 Proposition 3), we only consider the latter in the welfare comparison. The following proposition sums up the core results of the comparative welfare analysis:

Proposition 6. *The laissez-faire scenario yields the lowest welfare and the scenario with emission tax $\tau = c_e$ and perfect information yields the highest welfare, $W_l < \tilde{W}_\tau$.*
The isolated use of environmental instruments (emission tax) is welfare increasing compared to the laissez-faire scenario, $W_l < W_\tau < \tilde{W}_\tau$. 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, the sole use of a low interest rate subsidy ($\underline{s}^*$) and the combination of high interest rate subsidy ($\overline{s}^*$) and loan guarantee can not 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, 4, 5. □

The welfare levels under laissez-faire without any government intervention and the outcome under full information and the availability of an emission tax represent the lower and the upper bound of total welfare, respectively. Under laissez-faire, no market failure is addressed and the low welfare is due to high emissions and the absence of socially desirable activity in the clean sector. The introduction of an emission tax addresses the emission externalities and this leads to higher welfare as under laissez-faire. Due to credit rationing, some socially desirable clean projects are not realised, such that the resulting welfare is below the full information outcome, which is caused by the credit market failure. This market failure can be effectively addressed by a loan guarantee or an interest rate subsidy. Such a combination of emission tax and intervention in the credit market is capable to resemble the first best outcome under full information and thus the highest possible welfare level.

When an emission tax is (politically) not feasible, the emission externalities cannot be internalised by environmental policy, but are rather addressed by financial instruments. Welfare superiority of government intervention is only given if the weighted average of emissions in the dirty sector exceeds a threshold. Above this threshold, there are two relevant scenarios with government intervention to be differentiated, as outlined in Propositions 4 and 5. The ordering with respect to the welfare properties of the two scenarios for government intervention on credit markets only is not as clear cut. The relative welfare of the scenario with low interest rate subsidy $\underline{s}^*$ and the scenario with high interest rate subsidy $\overline{s}^*$ combined with a loan guarantee largely depends on two factors. Firstly, it is driven by the share of the high-emission producers in the economy and their emission level. The larger the share of high-emission producers and the higher their emissions, the larger is the negative effect of the emission externality due to those producers remaining in the dirty sector. Hence, the higher is the welfare under $\overline{s}^*$ that draws all dirty producers into the clean sector. Secondly, the relative welfare between high and low interest rate subsidy is affected by the success probability of the high-risk agents in the clean sector, $\delta_{\underline{c}}$. The higher the success probability of the $\underline{c}d$-type agents that are drawn into the clean sector by $\overline{s}^*$, the higher is the resulting welfare in this case compared to $\underline{s}^*$, where those high-risk borrowers remain in the dirty sector.[10] A main result of the welfare comparison is that, for any of these possible outcomes for the government intervention on the credit market only, the resulting total welfare is always below the first-best level that can be achieved by combining environmental policy and government intervention on the credit market.

3. Innovation Spillovers and Dynamic Effects of Policy Instruments

In this section, we investigate the dynamic effects of different policies as well as to shed some light on the costs of delay, i.e. forgone welfare if the government chooses a non-optimal policy. For this dynamic analysis, we introduce innovation spillovers in the clean energy sector. The main idea is that there is learning-by-doing and learning through observing successfully implemented clean energy projects. Hence, successful clean energy investments positively affect the success probability of all firms' future projects in the clean sector, i.e. they provide private benefits for the borrower as well as all other firms whose probability of success increases. 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 also relevant in the clean energy sector.[11]

In our model, we assume that the success probability $\delta_{\underline{c}}$ increases over time based on the number of successfully implemented clean energy projects, while $\delta_{\overline{c}}$ stays constant. Thus, firms with low success probabilities can increase their chances to successfully implement a project in the clean energy sector.[12] We define the absolute change in the $\underline{c}d$-types' probability of successfully finishing a clean project as an increasing function of the number of investors active

[10] For $y_D - \left[(1-\theta_d)\, c_e e_{\underline{d}} + \theta_d c_e e_{\underline{d}}\right] < \delta_{\overline{c}} y_c - \rho$, i.e. social costs associated with production in the dirty sector are relatively low, while clean technologies are relatively risky, and if an emission tax is (politically) not feasible, it is socially optimal if the government does not intervene.

[11] Braun et al. (2010) provide evidence for knowledge spillovers in the wind and the solar sector. Dechezleprêtre et al. (2017) show that spillovers of clean innovations are comparable to the IT sector and substantially higher than those of dirty innovations.

[12] Alternatively, it is possible to assume that both $\delta_{\underline{c}}$ and $\delta_{\overline{c}}$ grow due to innovation 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 makes the analysis more concise without qualitatively affecting the results.

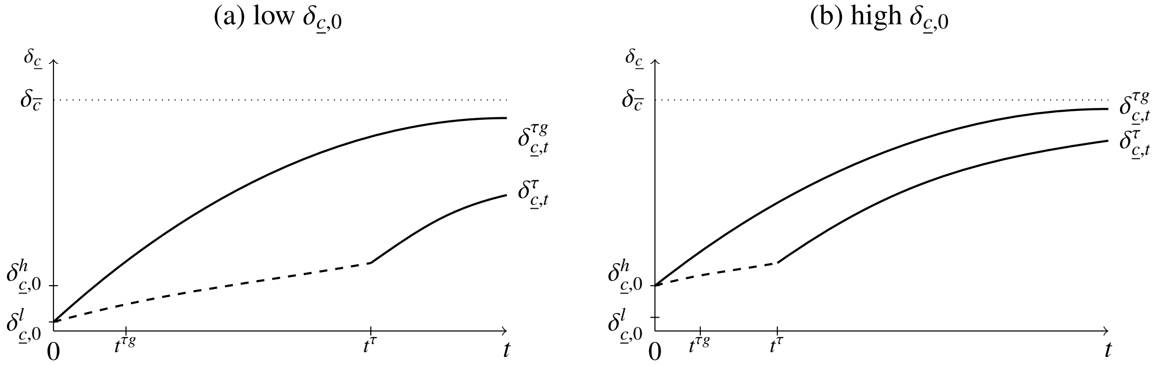

Figure 1: Evolution of the probability of success of $\underline{c}d$-type borrowers in the clean energy sector with government intervention on credit markets ($\delta^{\tau g}_{\underline{c},t}$) and without ($\delta^{\tau}_{\underline{c},t}$).

in the clean sector and the relative gap between the two types of clean investors:

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

Thus, $\underline{c}d$-type borrowers gradually catch up to the more efficient $\overline{c}d$-type borrowers, but cannot reach or even overtake them in finite time.

As shown above, a combination of an emission tax and an interest rate subsidy or a loan guarantee yields a static first-best result with a welfare level of $W_{\tau g}$. 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 a welfare level of W_{τ}.[13] As in the static analysis, we consider that there initially is credit rationing without government intervention on the financial market (see Proposition 1).

The development of the success probability or productivity of $\underline{c}d$-type borrowers is illustrated in Figure 1. The sole difference between sub-figures (a) and (b) is a different initial value of $\underline{c}d$-type borrowers' productivities, namely a low value, $\delta^{l}_{\underline{c},0}$, in sub-figure (a) and a high value, $\delta^{h}_{\underline{c},0}$, in sub-figure (b). Other than that, both sub-figures are qualitatively identical and we will address the specific differences between both scenarios below. For both initial starting values, the success probability / productivity of a low-risk borrower in the clean energy sector, $\delta_{\overline{c}}$, remains constant over time.

When the government combines the emission tax with an intervention on the credit market,

[13]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 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.

there is no credit rationing and thus also high-risk borrowers produce in the clean sector. As can be seen in the figure, their productivity $\delta_{\underline{c},t}^{\tau g}$ gradually increases over time and gets closer to the success probability of low-risk borrowers due to the innovation spillovers. At time $t = t^{\tau g}$, the decreasing difference between $\delta_{\underline{c},0}$ and $\delta_{\overline{c}}$ has reached a threshold, where credit rationing disappears. Thus, from this point onwards the government does not have to intervene on credit markets any more and just an emission tax is sufficient to achieve the first-best outcome.

When the government does not intervene on the financial markets at all, $\underline{cd}$-type borrowers are initially credit rationed and do not produce clean output. Their productivity, $\delta_{\underline{c},t}^{\tau}$, increases over time due to the knowledge spillovers from observing successfully implemented projects by $\overline{c}\underline{d}$-type borrowers, as depicted by the dashed line. The resulting productivity increase, however, is slower than under the first-best policy mix. As there is no credit rationing in the first-best case, also $\underline{cd}$-type agents are active and produce clean output. Thus, there are overall more implemented clean energy projects and thus more spillovers that induce a higher growth rate of productivity. At time $t = t^{\tau}$, credit rationing disappears in the scenario with emission tax only, as $\delta_{\underline{c},t}^{\tau}$ has reached the threshold, where credit rationing of $\underline{cd}$-type borrowers vanishes. Due to lower spillovers, this threshold is reached later than in the case with government intervention. As high-risk borrowers now enter the clean sector, the growth rate of productivity increases as more projects are being realized, i.e. the curve becomes steeper. 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 lower initial productivity $\delta_{\underline{c},0}^{l}$ and a higher initial productivity $\delta_{\underline{c},0}^{h}$ is the timing of the developments outlined above. In the case of $\delta_{\underline{c},0}^{h}$, the difference between the productivities of high-risk and low-risk borrowers is smaller. Thus, the threshold, where credit rationing dissipates due to an increasing productivity of high-risk borrowers is reached earlier. In Figure 1(a), 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 1(b). Hence, government intervention on the financial market also has dynamic effects. The success probability of high-risk borrowers increases faster, when the government offers interest rate subsidies or loan guarantees.

We now turn to the resulting development of welfare based on both policy mixes, which are depicted in Figure 2. As in Figure 1, sub-figure (a) illustrates the case for a low initial $\delta_{\underline{c},0}$ and panel (b) for a high initial $\delta_{\underline{c},0}$. Otherwise, both cases are qualitatively identical and the specific differences will addressed below. In both cases, $W_t^{\tau g}$, the welfare at time t for the first-best policy mix, is initially above W_t^{τ}, the welfare at time t with an emission tax only, as shown in

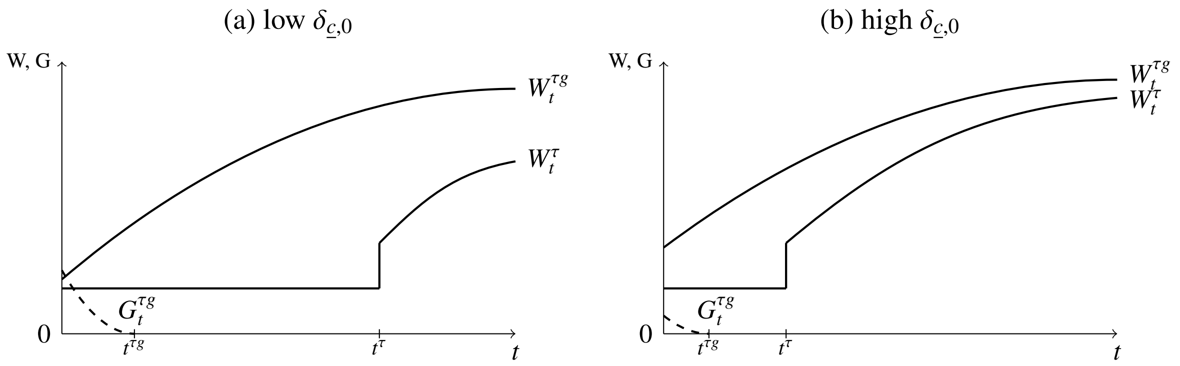

Figure 2: Evolution of total welfare with emission tax and with government intervention on credit market ($W_t^{\tau g}$), without government intervention on credit market (W_t^{τ}), and government expenditures ($G_t^{\tau g}$).

Proposition 6. $G_t^{\tau g}$ denotes government expenditures for their activities on financial markets, i.e. their expenditures for loan guarantees. The development of $W_t^{\tau g}$ is qualitatively similar to the the evolution of the productivity of $\underline{cd}$-type borrowers, $\delta_{\underline{c},t}^{\tau g}$. As the government intervenes on credit markets, there is no credit rationing and high-risk borrowers are active in the clean sector. Their productivity increases over time, as shown in Figure 1, which results in an increasing welfare $W_t^{\tau g}$. This welfare increase is driven by the growing $\delta_{\underline{c},t}^{\tau g}$. Furthermore, the government expenditure $G_t^{\tau g}$ decreases over time, as the higher the productivity of $\underline{cd}$-type borrowers, the lower is the required expenditure for financial instruments to avoid credit rationing. At time $t^{\tau g}$, the threshold of $\delta_{\underline{c},t}^{\tau g}$ is reached, where credit rationing does not occur, such that government intervention on financial markets is not required any more, i.e. $G_t^{\tau g} = 0$.

In the case of environmental policy only, however, the welfare level W_t^{τ} remains constant until the threshold is reached at $t = t^{\tau}$. Although the productivity of high-risk borrowers $\delta_{\underline{c},t}^{\tau}$ is growing, as depicted by the dashed line in Figure 1, there is no effect of this productivity increase on welfare, as these borrowers are credit rationed. These high-risk borrowers cannot profit from the increasing success probability until it reaches the threshold at $t = t^{\tau}$. At this point, all $\underline{cd}$-type borrowers switch from the dirty to the clean sector, which results in an immediate increase in welfare. From this point onwards W_t^{τ}, similar to $W_t^{\tau g}$, increases over time due to the growing productivity $\delta_{\underline{c},t}^{\tau}$. However, W_t^{τ} won't 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.[14]

Similar to the evolution of success probabilities, a main difference between the development

[14] See Appendix A.5.

of welfare between low $\delta_{\underline{c},0}$ and a high $\delta_{\underline{c},0}$ are the timings, when credit rationing vanishes, i.e. $t^{\tau g}$ and t^{τ}. Furthermore, the difference between both 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 borrowers in this case, the additional welfare compared to the case of 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 2 (a). For higher $\delta_{\underline{c},0}$, i.e. more productive or less risky $\underline{c}d$-type borrowers, the required government expenditures to successfully address credit rationing are lower.

The dynamic analysis sheds some light on possible adverse effects on government behaviour. When the clean technology is still very new and thus risky, i.e. the difference $\delta_{\underline{c},0}$ and $\delta_{\bar{c},0}$ is very large, the overall welfare gain seems to be larger, as can be seen in Figure 2 (a). The costs of delay, which can be defined as the area between $W_t^{\tau g}$ and W_t^{τ}, are in finite time larger the smaller $\delta_{\underline{c},0}$ is.[15] However, initially the welfare gain is larger for higher values of $\delta_{\underline{c},0}$, as illustrated in Figure 2 (b). Furthermore, the required government expenditures are smaller in this case. Consider a government that wants to maximize welfare and minimise expenditures. The larger the discount rate of the government, i.e. the more important the present is for its decisions, the more likely the government is to intervene when $\delta_{\underline{c}0}$ is high. For high $\delta_{\underline{c}0}$, initial welfare gains are high, while government expenditures are rather low. Newer and more risky technologies that require such support more urgently and would overall lead to higher welfare gains to society, are relatively less likely to be supported by the government. Whether this problem is relevant depends, of course, on the policy makers discount rate as well as on clean technology specific aspects, as the success probabilities of high-risk and low-risk borrowers.

Overall, the dynamic analysis shows that any intervention on capital markets is finite. At some point the productivity of high-risk borrowers will increase enough, such that they are not credit rationed by private banks any more. Thus, compared to the environmental policy, the intervention on financial markets is only temporary. Furthermore, even when the government does not intervene to address the credit rationing, it will disappear at some point. There are, however, costs of delay in the absence of any government intervention on financial markets.

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

4. Discussion

Our theoretical analysis provides insights of the impact of information asymmetries on financial markets on clean energy investments. We show that the information asymmetries might lead to welfare-reducing credit rationing, which are particularly likely, when technologies are risky. However, learning effects might reduce these risks and thus may ultimately dissolve the issue of credit rationing. In this section, we discuss these results and, in particular, their applicability and relevance for (i) investments in renewable energy capacity and (ii) investments in clean production processes, i.e. energy efficient technologies to produce a certain output with lower emissions, and (iii) financing for innovative clean-tech companies.

One of the core predictions of the model is that the associated risk of a clean energy investment, i.e. the difference between project success probabilities $\delta_{\underline{c}}$ and $\delta_{\overline{c}}$, is a core driver of the results. The riskier a clean energy investment, the more likely credit rationing occurs. Empirical evidence on investments in renewable energy supports this prediction. Mazzucato and Semieniuk (2018) analyse the involvement of different types of actors in financing renewable energy investments from 2004 - 2014. They find that private banks largely finance low-risk technologies, while high-risk investments are rather financed by state banks or state-owned utilities or corporations. Geddes et al. (2018) collected data through in-depth semi-structured interviews with project developers, IPPs, and utilities in Australia, Germany, and the UK. The authors find that firms faced issues or were even unable to source debt for their renewable energy projects when using new technologies.[16] Thus, as predicted by our model, credit rationing is more likely if potential borrowers use rather new technologies.

We show that government intervention on credit markets can dissolve credit rationing and thus induce higher clean energy investments. This result is in line with empirical evidence. With respect to high-tech firms, Cowling et al. (2018) find that public guarantees can reduce credit rationing. For renewable energy, 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 projects. A track record of successfully financed projects is a positive signal for private banks. On the one hand, the actual risk of a technology declines through investments due to

[16]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).

learning by doing and spillover effects. On the other hand, information asymmetries decline as lenders observe investments and thus are better able to assess the risks of a potential borrower.

In our dynamic analysis, we argue that knowledge spillovers from successfully implemented clean energy investments reduce the risks of future investment. Empirical studies provide evidence for innovation spillover in clean energy sectors (see, e.g., Ang et al., 2017, Braun et al., 2010, Dechezleprêtre et al., 2017). The risk reduction over time, i.e. a decreasing difference between success probabilities $\delta_{\underline{c}}$ and $\delta_{\overline{c}}$, ultimately resolves the issue of credit rationing as the lender is willing to serve all potential borrowers, who seek a clean energy investment. This result is supported by empirical evidence on renewable energy. Project developers seem to have less or no issues to source debt financing as soon as a technology matures and is perceived less risky (Geddes et al., 2018; Mazzucato and Semieniuk, 2018). Thus, any interventions on financial markets addressing information asymmetries should only be temporary. Public involvement should be terminated as soon as there is no credit rationing by private lenders any more. Main drivers of credit rationing are the information asymmetries on the part of the lenders and the technology risk. Both issues decline the clean energy investments are successfully implemented. Furthermore, the information asymmetries decline with financial sector development. Consequently, the more mature a clean energy technology and the more developed an economy's financial sector, the lower is the requirement for government intervention on financial markets. Financial instruments as loan guarantees and interest rate subsidies should be used for new and (still) risky clean technologies in countries with less developed financial markets.

Finally, our results provide important insights concerning the recently increasing public involvement in financing for clean energy. Currently, there are 227 (43) grant or loan programmes for renewable energy (energy efficiency) in force worldwide.[17] According to Buchner et al. (2017), annual public flows were constantly high between 2012 and 2016 ranging from USD 136 billion to USD 141 billion. 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.[18] 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). Overall, information asymmetries on finan-

[17] The data is based on the IEA/IRENA Global Renewable Energy Policies and Measures Database and IEA's Energy Efficiency Database, both available at https://www.iea.org/policiesandmeasures/ (last accessed 03 September, 2018).

[18] USD 47 billion are commitments by institutions based in the the OECD, while the remaining USD 106 billion are commitments of non-OECD based national development banks.

cial markets provide some justification for this public involvement. In our model, however, we explicitly analyse a scenario, where a carbon price is not feasible in order to investigate the outcome with intervention on financial markets only. We show that the absence of a carbon price can, to a certain degree, be offset by increasing government intervention on financial markets. However, this policy leads to socially less desirable results from a welfare perspective and is likely to require substantially higher government expenditures. Hence, as there currently is no global carbon price, these public interventions through finance instruments are likely to be inefficiently high. As long as the emission externalities is not internalised by investors deciding between clean and dirty investments, the amount of public funds needed to make a clean investment more attractive from the investor's perspective is likely to be inefficiently high.

5. Conclusion

We offer a novel theoretical approach to jointly analyse emission externalities and capital market failures related to clean energy investments. We first analyse an economy with environmental policy, where an emission tax is available to internalise the emission externalities in the dirty sector. Due to information asymmetries on the credit market, however, such a tax alone is not enough to achieve a first-best solution due to credit rationing. We find that both interest rate subsidies and loan guarantees can solve the issue of credit rationing and lead to the same level of welfare, while loan guarantees are more desirable from a government's perspective, as they lead to a smaller government expenses.

We then 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 clean energy. 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, i.e. a tax on emissions and interest rate subsidies or loan guarantees. 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 investment risk in the clean energy sector. Even when the government does not intervene to address the credit rationing, it will disappear at some point. There are, however, costs of delay if the government only addresses the emission externality, but does not deal with credit market failure. The risk of insufficient government intervention seems to increase with the governments discount rate.

These results have high policy relevance as climate policy is increasingly using investment support / financial instruments, such as grants, concessional loans, and guarantees, while market based instruments that yield a price for CO_2 emissions seems to loose relevance. This is particularly the case for developing and emerging, as can be seen by the industrialised countries' promise to to mobilise climate financing of USD 100 billion per year by 2020 (UNFCCC, 2012). Our findings stress the importance of a CO_2 price and indicate that a shift towards relying too much on investment support instruments bear the danger of substantially increasing the social costs of the transition to a clean economy.

Thus, using finance instruments only should be only considered if an emission price is (politically) not feasible. We show that government intervention on financial markets alone can yield a second best outcome. Without the self-selection induced by an emission price, there is an increased risk of inefficient government spending. For such a case, our model also offers valuable insights on the choice of these finance instruments, i.e. interest rate subsidies and loan guarantees. We show that the socially optimal choice of financial market interventions largely depends on the characteristics of risk profile of new clean technologies and the emission intensity of conventional dirty technologies. The riskier new technologies are, the more careful government expenditure should be used to promote these technologies through financial instruments. If conventional alternatives are particularly emission intensive, however, higher levels of support for clean investments are socially more beneficial.

This paper provides only a first theoretical investigation of the impact of financial market imperfections on clean energy investments. A natural next step would be to empirically test the predictions of this theoretical analysis. Alternatively, 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 possibility would be to introduce a probability to successfully identify the borrower by the lender, which increases over time through learning-by-doing.

A. Appendix

A.1. Applicants

To examine candidates for a loan in the clean sector, we derive the lower bound of the loan repayment in any contract. A necessary condition of the profit maximisation problem of a lender is that the expected benefit of providing a contract with a positive probability is non-negative (expressions (2) > 0 and (4) > 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

$$R^{\underline{c}}_{min} = \frac{\rho - \left(1 - \delta_{\underline{c}}\right) g}{\delta_{\underline{c}}}, \tag{9}$$

$$R^{\overline{c}}_{min} = \frac{\rho - (1 - \delta_{\overline{c}})\, g}{\delta_{\overline{c}}}. \tag{10}$$

With (9) and (10), the PCs, and the ICs of all types, the following Lemma 3 can be derived.

Lemma 3.

i. *Without an emission tax (and with $g = s = 0$), the lower bound of R (i.e. equation (9) and (10)) is 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 $g \in \left[0, \frac{y_D - \tau e_{\overline{d}} + \rho - \delta_{\overline{c}}(y_C + s)}{1-\delta_{\overline{c}}}\right)$, the lower bound of R (i.e. equation (9) and (10)) is 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 $g \in \left[\frac{y_D - \tau e_{\overline{d}} + \rho - \delta_{\overline{c}}(y_C + s)}{1-\delta_{\overline{c}}}, \infty\right)$, the lower bound of R (i.e. equation (9) and (10)) is 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 $g \in \left[\frac{y_D + \rho - \delta_{\overline{c}}(y_C + s)}{1-\delta_{\overline{c}}}, \frac{y_D + \rho - \delta_{\underline{c}}(y_C + s)}{1-\delta_{\underline{c}}}\right)$, the lower bound of R (i.e. equation (9) and (10)) is 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 $g \in \left[\frac{y_D + \rho - \delta_{\underline{c}}(y_C + s)}{1-\delta_{\underline{c}}}, \infty\right)$, the lower bound of R (i.e. equation (9) and (10)) is 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:

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

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

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

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:

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

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

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

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

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:

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

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

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

In contrast, PCs of types $\underline{c}d$ are incompatible with $R^{\underline{c}}_{min}$, as with $\pi_{k=\underline{c}d} > 0$, 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 $g \in \left[\frac{y_D+\rho-\delta_{\bar{c}}(y_C+s)}{1-\delta_{\bar{c}}}, \frac{y_D+\rho-\delta_{\underline{c}}(y_C+s)}{1-\delta_{\underline{c}}}\right)$ 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 $c\bar{d}$ (see Lemma 3 ii.). Hence the reduced[19] Lagrangian to the profit maximisation problem of the bank is

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

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

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

With $R_{c\underline{d}} > 0$ and $\pi_{c\underline{d}} > 0$ it follows, that $\partial L/\partial R_{c\underline{d}} = 0$, $\lambda_1 > 1$, $\partial L/\partial \pi_{c\underline{d}} = \partial L/\partial \lambda_1 = 0$ 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. As it is clear from Lemma 3 ii., with $s = g = 0$ only investors of type $c\underline{d}$ are potential candidates for credits

[19] 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.

if the bank offers profit maximising contracts. With $s, g > 0$, investors of type $c\overline{d}$ may become potential candidates for credits (see Lemma 3 ii.). However, we will show that for the case of a loan guarantee, with optimal behaviour of the government only investors of type $c\underline{d}$ apply for a credit in the profit-maximising scenario - and hence investors of type $c\overline{d}$ can be omitted in the profit-maximisation problem of the lender. Furthermore, we show that in the case of an interest subsidy and if the optimal behaviour of the government is to introduce a interest subsidy smaller than a threshold level $\bar{s}$, particularly, $s < \bar{s} \equiv \frac{\tau e_{\underline{d}} - \tau e_{\overline{d}}}{\delta_{\overline{c}} - \delta_{\underline{c}}} - y_C$ (> 0), only investors of type $c\underline{d}$ apply for a credit in the profit-maximising scenario - and hence investors of type $c\overline{d}$ 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 credit (and drive (some) investors of type $\underline{cd}$ out of the clean market).

We derive optimal behaviour of all agents, the lender, and optimal government intervention assuming only investors of types $c\underline{d}$ are potential candidates for a credit 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 investors of types $c\underline{d}$ as potential candidates for a credit 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 investor 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, since there exists no contract with $\pi_k > 0$ that is compatible with the lower bound of R (equations (9) and (10)) and the participation constraints of any 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

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

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 a $R^*_{\bar{c}\underline{d}} = R_{\underline{cd}}$ and $\pi^*_{\bar{c}\underline{d}} = \pi_{\underline{cd}}$ such that PC of type $\bar{c}\underline{d}$ holds with strict inequality (follows from $\delta_{\underline{c}} < \delta_{\bar{c}}$). From that it follows that Regime(s) 2 is only profit maximizing if the profit maximizing contract is identical for both 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. We then show that these solutions satisfy IC of types $\underline{cd}$. The Lagrangian is given by:

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

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

$$\frac{\partial L}{\partial R_{c\underline{d}}} = \theta_c \pi_{c\underline{d}} \delta_{\underline{c}} - \lambda_1 \pi_{c\underline{d}} \delta_{\underline{c}} + \lambda_2 \pi_{c\underline{d}} \delta_{\overline{c}} \leq 0, \quad R_{c\underline{d}} \geq 0$$

$$\frac{\partial L}{\partial R_{\overline{c}\underline{d}}} = (1-\theta_c)\,\pi_{\overline{c}\underline{d}} \delta_{\overline{c}} - \lambda_2 \pi_{\overline{c}\underline{d}} \delta_{\overline{c}} \leq 0, \quad R_{\overline{c}\underline{d}} \geq 0$$

$$\frac{\partial L}{\partial \pi_{c\underline{d}}} = \theta_c \left(\delta_{\underline{c}} R_{c\underline{d}} + \left(1-\delta_{\underline{c}}\right) g - \rho\right) + \lambda_1 \left[\delta_{\underline{c}} \left(y_C + s - R_{c\underline{d}}\right) - \left(y_D - \tau e_{\underline{d}}\right)\right]$$

$$- \lambda_2 \left[\delta_{\overline{c}} \left(y_C + s - R_{c\underline{d}}\right) - \left(y_D - \tau e_{\underline{d}}\right)\right] + \lambda_3 - \lambda_4 \leq 0, \quad \pi_{c\underline{d}} \geq 0$$

$$\frac{\partial L}{\partial \pi_{\overline{c}\underline{d}}} = (1-\theta_c)\left(\delta_{\overline{c}} R_{\overline{c}\underline{d}} + (1-\theta_{\overline{c}})\, g - \rho\right) + \lambda_2 \left[\delta_{\overline{c}} \left(y_C + s - R_{\overline{c}\underline{d}}\right) - \left(y_D - \tau e_{\underline{d}}\right)\right] + \lambda_5 - \lambda_6 \leq 0, \quad \pi_{\overline{c}\underline{d}} \geq 0$$

$$\frac{\partial L}{\partial \lambda_1} = \pi_{c\underline{d}} \left[\delta_{\underline{c}} \left(y_C + s - R_{c\underline{d}}\right) - \left(y_D - \tau e_{\underline{d}}\right)\right] \geq 0, \quad \lambda_1 \geq 0$$

$$\frac{\partial L}{\partial \lambda_2} = \pi_{\overline{c}\underline{d}} \left[\delta_{\overline{c}} \left(y_C + s - R_{\overline{c}\underline{d}}\right) - \left(y_D - \tau e_{\underline{d}}\right)\right] - \pi_{c\underline{d}} \left[\delta_{\overline{c}} \left(y_C + s - R_{c\underline{d}}\right) - \left(y_D - \tau e_{\underline{d}}\right)\right] \geq 0, \quad \lambda_2 \geq 0$$

$$\frac{\partial L}{\partial \lambda_3} = \pi_{c\underline{d}} \geq 0, \quad \lambda_3 \geq 0$$

$$\frac{\partial L}{\partial \lambda_4} = 1 - \pi_{c\underline{d}} \geq 0, \quad \lambda_4 \geq 0$$

$$\frac{\partial L}{\partial \lambda_5} = \pi_{\overline{c}\underline{d}} \geq 0, \quad \lambda_5 \geq 0$$

$$\frac{\partial L}{\partial \lambda_6} = 1 - \pi_{\overline{c}\underline{d}} \geq 0, \quad \lambda_6 \geq 0$$

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

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

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

With $\pi_{c\underline{d}} > 0 \Rightarrow \lambda_3 = 0$ and $\pi_{\overline{c}\underline{d}} > 0 \Rightarrow \lambda_5 = 0$ (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 $R_{c\underline{d}} > 0 \Rightarrow \partial L/\partial R_{c\underline{d}} = 0$ and $R_{\overline{c}\underline{d}} > 0 \Rightarrow \partial L/\partial R_{\overline{c}\underline{d}} = 0$ (both follow from c.s.). With $\partial L/\partial R_{\overline{c}\underline{d}} = 0,\ \pi_{\overline{c}\underline{d}} > 0 \Rightarrow \lambda = (1-\theta_c) > 0$ and together with $\lambda_5 = 0,\ \partial L/\partial \pi_{\overline{c}\underline{d}} = 0 \Rightarrow \lambda_6 > 0 \Rightarrow \pi_{\overline{c}\underline{d}} = 1$ (follows from c.s.). With $\partial L/\partial R_{c\underline{d}} = 0,\ \lambda_2 = (1-\theta_c) \Rightarrow \lambda_1 = \theta_c + (1-\theta_c)\,\delta_{\overline{c}}/\delta_{\underline{c}}$. Together with $\partial L/\partial \pi_{c\underline{d}} = 0$ it follows that $\lambda_4 > 0$ if $\delta_{\underline{c}}\,(y_C + s) - y_D + \tau e_{\underline{d}} - \rho > \frac{1-\theta_c}{\theta_c} \delta_{\overline{c}} \left(y_D - \tau e_{\underline{d}}\right)\left(\frac{1}{\delta_{\underline{c}}} - \frac{1}{\delta_{\overline{c}}}\right) - \left(1 - \delta_{\underline{c}}\right) g$ and hence $\pi_{c\underline{d}} = 1$ (follows from c.s.). If $\delta_{\underline{c}}\,(y_C + s) - y_D + \tau e_{\underline{d}} - \rho > \frac{1-\theta_c}{\theta_c} \delta_{\overline{c}} \left(y_D - \tau e_{\underline{d}}\right)\left(\frac{1}{\delta_{\underline{c}}} - \frac{1}{\delta_{\overline{c}}}\right) - \left(1 - \delta_{\underline{c}}\right) g \Rightarrow \lambda_4 = 0$ and hence

$\pi_{\underline{cd}} \leq 1$ is compatible with c.s.. With $\partial L/\partial\lambda_2 = 0,\ \pi_{\overline{c}\underline{d}} = 1,\ R_{\underline{cd}} = y_C + s - \frac{y_D - \tau e_{\underline{d}}}{\delta_{\underline{c}}} \Rightarrow R_{\overline{c}\underline{d}} = y_C + s - \left(\pi_{\underline{cd}}\left((\delta_{\overline{c}} - \delta_{\underline{c}})/\delta_{\underline{c}}\right) + 1\right)\left(y_D - \tau e_{\underline{d}}\right)/\delta_{\overline{c}}$. For $\pi_{\underline{cd}} = 1 \Rightarrow R_{\overline{c}\underline{d}} = y_{\overline{c}} + s - \frac{y_D + -\tau e_{\underline{d}}}{\delta_{\underline{c}}}$. In a next step, we show that although in the case of $\delta_{\underline{c}}(y_C + s) - y_D + \tau e_{\underline{d}} - \rho = \frac{1-\theta_c}{\theta_c}\delta_{\overline{c}}\left(y_D - \tau e_{\underline{d}}\right)\left(\frac{1}{\delta_{\underline{c}}} - \frac{1}{\delta_{\overline{c}}}\right) - \left(1 - \delta_{\underline{c}}\right)g$ all $\pi_{\underline{cd}} \in (0, 1]$ fulfil the necessary conditions, only $\pi_{\underline{cd}} = 1$ also fulfils the sufficient conditions (proof by contradiction: We try to show that there $\exists\ \tilde{\pi}_{\underline{c}} \in (0, 1)$ such that $\sum_k B_k\left(\pi_{\underline{cd}} = \tilde{\pi}_{\underline{c}}\right) \geq \sum_k B_k\left(\pi_{\underline{cd}} = 1\right)$):

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

With $0 < \pi_{\underline{cd}} < 1$

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

With $\delta_{\underline{c}}(y_C + s) - y_D + \tau e_{\underline{d}} - \rho = \frac{1-\theta_c}{\theta_c}\delta_{\overline{c}}\left(y_D - \tau e_{\underline{d}}\right)\left(\frac{1}{\delta_{\underline{c}}} - \frac{1}{\delta_{\overline{c}}}\right) - \left(1 - \delta_{\underline{c}}\right)g$, we can substitute $\frac{1-\theta_c}{\theta_c}\left(y_D - \tau e_{\underline{d}}\right)\left(\frac{\delta_{\overline{c}} - \delta_{\underline{c}}}{\delta_{\underline{c}}}\right) - (1-\delta_{\overline{c}})\,g$ 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: $\pi^*_{\overline{c}\underline{d}} = 1,\ R^*_{\overline{c}\underline{d}} = y_C + s - \frac{\left(\pi_{\underline{cd}}\left(\delta_{\overline{c}} - \delta_{\underline{c}}\right) + \delta_{\underline{c}}\right)\left(y_D - \tau e_{\underline{d}}\right)}{\delta_{\overline{c}}\delta_{\underline{c}}}$. Furthermore

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

and

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

We define

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

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

Interest rate subsidy and loan guarantee might be used to resolve 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 credit:

$$s^* \equiv \frac{\rho + \left(y_D - \tau e_{\underline{d}}\right)\left[1 + \frac{1-\theta}{\theta}\frac{\delta_{\overline{c}} - \delta_{\underline{c}}}{\delta_{\underline{c}}}\right] - \left(1 - \delta_{\underline{c}}\right) g}{\delta_{\underline{c}}} - y_C. \tag{11}$$

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 investors of type $c\underline{d}$ and note that the lender is able to skim the interest subsidy paid to the borrowers of type $c\underline{d}$ (see solutions for $R^*_{c\underline{d}}$ and $R^*_{\underline{cd}}$). If $s < \bar{s}$, than it follows from Assumption 1 that no investor of types $\overline{cd}$ will apply for a credit designed for types $c\underline{d}$. Furthermore, since the lender is able skim the maximum interest subsidy ($\theta_d s$) by providing credits to investors of type $c\underline{d}$, there is no incentive to provide credits (by lowering the repayment) to investors of type $\overline{cd}$ (follows from Lemma 3 ii.).

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

Solving $\Lambda = 0$ for g yields:

$$g = \frac{\rho + \left(y_D - \tau e_{\underline{d}}\right)\left[1 + \frac{1-\theta}{\theta}\frac{\delta_{\overline{c}} - \delta_{\underline{c}}}{\delta_{\underline{c}}}\right] - \delta_{\underline{c}}\left(y_C + s\right)}{1 - \delta_{\underline{c}}}. \tag{12}$$

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

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

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 equation (12), i.e.,

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

Furthermore, we can use equations (11) and (12) 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.):

$$s^* = \frac{1 - \delta_{\underline{c}}}{\delta_{\underline{c}}} g^* \tag{13}$$

A.4. Imperfect Information without Emission Tax

Without an emission tax $\tau = c_e$, banks will not provide borrowers with credits (see Lemma 3 i). Government intervention in the form of a loan subsidy s can increase profitability of credits. Solving (3) = 0 for s and substituting (10) for R_k yields the minimum loan subsidy such that type-$\overline{c}d$ borrowers apply for a credit:

$$\underline{s}^* = \frac{y_D}{\delta_{\overline{c}}} - \left(y_C - \rho\right). \tag{14}$$

Solving (3) = 0 for s and substituting (9) yields the minimum loan subsidy such that all types cd are potential candidates for credits:

$$\overline{s}^* = \frac{y_D}{\delta_{\underline{c}}} - \left(y_C - \rho\right). \tag{15}$$

For $s < \overline{s}^*$, only types $\overline{c}d$ are potential candidates for a credit (see Lemma 3 iii.). Since in the absence of an emission tax the return to an investment in the dirty sector is identical for all types cd, the lender is unable to discriminate investors with identical technology in the clean sector. 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:

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

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 without an emission tax and $s \geq \overline{s}^*$,(i.e. all types apply for a credit, see Lemma 3 iv.). As mentioned above, in the absence of an emission tax the return to an investment in the dirty sector is identical for all types cd, the lender is unable to discriminate investors with identical technology in the clean sector. Hence it is sufficient to derive (uniform) profit maximising contracts for types $\overline{c}d$.

The analysis of contract regimes (π_k, R_k) in a situation with imperfect information 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 the 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).

Loan subsidy and loan guarantee can be used to avoid credit rationing. Solving $\Lambda_{n\tau} = 0$ for

s yields the minimum interest subsidy that eliminates credit rationing:

$$s^*_{n\tau} = \frac{\rho + y_D \left[1 + \frac{1-\theta}{\theta}\frac{\delta_{\overline{c}} - \delta_{\underline{c}}}{\delta_{\underline{c}}}\right] - \left(1 - \delta_{\underline{c}}\right) g}{\delta_{\underline{c}}} - y_C \tag{16}$$

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

$$g^*_{n\tau} = \frac{\rho + y_D \left[1 + \frac{1-\theta}{\theta}\frac{\delta_{\overline{c}} - \delta_{\underline{c}}}{\delta_{\underline{c}}}\right] - \delta_{\underline{c}} \left(y_C + s\right)}{1 - \delta_{\underline{c}}} \tag{17}$$

Furthermore, we can use equations (16) and (17) to determine the relation of s^* and g^* (if both instruments are used isolated):

$$s^*_{n\tau} = \frac{1 - \delta_{\underline{c}}}{\delta_{\underline{c}}} g^*_{n\tau}. \tag{18}$$

A.5. Dynamic analysis

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

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

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

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

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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