Mobilizing Credit for Climate Tech: De-Risking and Public Loan Provision Under Learning Spillovers*

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Abstract

Policymakers often rely on public financial institutions to provide loans for climate technology such as clean energy projects. However, it remains unclear what role they play in a climate policy mix that already internalizes environmental and innovation externalities through first-best instruments. Here, we develop a two-period model of banks providing loans for clean energy projects that use a novel technology. Loans in the first period build up banks' financing experience, which spills over to peers and hence is undersupplied by the market. Unlike de-risking instruments, public loans do not solve this cooperation problem because they crowd out private bank loans. However, bankability requirements can result in an additional coordination problem whereby the banking sector remains stuck in an inferior equilibrium with no loans for the novel technology. Public loans in the first period can resolve this coordination problem by pushing the banking sector to a better equilibrium, ideally combined with additional de-risking policies to internalize learning spillovers. We provide a numerical application to the early stage of offshore wind energy in Germany as a plausible context for our policy implications.

Keywords: Climate finance, credit guarantees, government loans, multiple equilibria, renewable energy, state investment bank, offshore wind, social tipping point.

JEL Codes: G21, H81, Q48, Q55.

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1 Introduction

To mitigate dangerous climate change, the magnitude of the necessary investments in clean energy technologies requires mobilizing substantial private-sector financing, including large amounts of debt (IPCC, 2022; Polzin et al., 2019). To mobilize credit, policymakers regularly opt for financial policy measures like credit guarantees to reduce the risks of clean energy investments (so-called "de-risking"; Schmidt, 2014) and also provide debt directly to projects through public financial institutions. In the United States, the Department of Energy's Loan Programs Office issues loans and guarantees to clean energy projects, while USD 5 billion of Inflation Reduction Act funds were awarded in 2024 to create a new national green bank (Coalition for Green Capital, 2024). In many other OECD countries, state investment banks are remarkably active in renewable energy lending, particularly for higher-risk technologies such as offshore wind (Waidelich & Steffen, 2024).

Despite the widespread use of public loans for the clean energy transition, economic theory provides little guidance on when to favor the direct market activity of public banks over de-risking instruments. Previous sector-agnostic studies discuss the two policies in light of credit rationing that arises from adverse selection, screening costs, or unconsidered social externalities, moral hazard for borrowers, and cyclical credit crunches or adverse incentives due to legacy portfolios. Far less emphasis has been placed on financiers *learning* about novel clean energy technologies through lending. Extending the concept of learning-by-doing from technology use to the financial sector, empirical work has shown that increases in financiers' experience with renewable energy projects have coincided with decreases in their cost of capital (Egli, 2020; Egli et al., 2018; IRENA, 2023; Steffen, 2020). However, the existing literature lacks a theoretical understanding of what this means for the design of optimal policies to mobilize clean energy finance, and for the need for financial policy measures if other policy interventions already address technology-level and consumer-level market failures, such as climate externalities.

To address this gap, this paper investigates the potential and limitations of public loan provision and de-risking measures by developing a two-period partial equilibrium model of loans for clean energy projects using a novel yet immature technology. In the model, learning-by-lending reduces the costs of screening and loan loss provisions, improving the risk-adjusted return to lenders.[1] In each period, a limited number of homogeneous banks decide how much they lend to energy projects using the novel technology where overall credit demand is determined by exogenous government policies, such as renewable energy auctions and feed-in tariffs. In the first "early-stage" period, the screening costs

[1] A risk-adjusted return adjusts the expected return on a loan (or, more generally, any financial asset) for the risks involved, which for loans is based on the probability of default. For instance, banks can subtract the costs of loan loss provisions from the interest income (i.e., the numerator of the return) or adjust the capital deployed (i.e., the denominator) for additional capital buffers required due to the possibility of unexpected losses, which is commonly used in banking regulation (Freixas & Rochet, 2023).

and risk premiums for such loans are excessively high, so loans come at a loss. In the second period, however, these immaturity-related costs decrease convexly in the amount of early-stage loans provided, such that loans can become "bankable"[2] (i.e., profitable for banks given their risk-return characteristics) if banks become sufficiently familiar with the novel technology. This bankability threshold results in a social welfare function that is J-shaped in aggregate first-period lending, as small amounts of early-stage loans are insufficient to push the banking sector past the bankability tipping point and hence result in losses. Depending on whether learning gains can compensate for first-period losses, there are three possible social optima: i) banks do not provide any loans; ii) in both periods, banks finance all available projects; or iii) banks only serve part of the first-period credit demand, due to diminishing returns to financing experience, but provide the maximum amount of loans thereafter.

In a laissez-faire setting, banks do not internalize the lending spillovers of their early-stage loans to competitors. Therefore, they do not provide any financing if the bankability threshold remains out of reach; otherwise, they provide early-stage loans until their own marginal learning gains fall below the negative return on said loans. Since learning spills over, banks reduce their costly early-stage loans if competitors lend more and free-ride the experience generated by their peers. As a result, the possible Nash equilibria in the model are characterized by two different market failures. First, a *cooperation problem*, as early-stage loan provision is inefficiently low given the experience spillovers of early-stage lending. Second, a *coordination problem* where the banking sector remains stuck in a Nash equilibrium with no loans for the immature technology, despite the fact that a better market equilibrium in which the novel technology receives loans is possible.

We introduce two financial policies to address these market failures: a de-risking subsidy (e.g., an interest rate subsidy or a credit guarantee) and the direct provision of renewable energy loans by a public entity (e.g., a state investment bank). Public loans face the same free-riding issues as commercial ones and, therefore, reduce the willingness of commercial banks to incur early-stage risk themselves, shifting the financial burden of early-stage loans to the public sector. However, a sufficiently sized public loan provider can push the banking sector past the bankability threshold to a better Nash equilibrium, particularly if combined with additional de-risking policies to internalize learning spillovers and close the gap to the social optimum. A numerical application of our model to loans for offshore wind projects in Germany between 2007 and 2018 suggests that such a policy mix would have been warranted even without unresolved technology-level externalities and showcases that the intervention's cost-effectiveness strongly depends on how well public loan providers disseminate learnings to the private sectors. When incorporating positive climate externalities of clean energy projects into our model, public

[2]The term "bankability" is commonly used by practitioners and public loan providers to denote a borrowers' ability to secure debt financing due to their perceived ability to repay loans with sufficient interest given the risks of default (IRENA, 2024; PwC, 2023).

loans and de-risking can also serve as second-best policies if first-best carbon pricing is unavailable (Haas & Kempa, 2023).

This paper extends the argument by Rodrik (1996) that "when multiple equilibria exist, the role of government policy is to move the economy out of the bad equilibrium into the good one" to the case of public loans to novel clean energy technologies. Importantly, these insights hold even if technology-level externalities are addressed via first-best policies and hence do not require any market failures on the technology and consumer level. The model thus clarifies the role of public loan provision and de-risking measures in a climate policy strategy that already features instruments such as carbon pricing and research and development subsidies. Our work expands the theoretical understanding of optimal climate policy strategies and indicates under which conditions different financial measures should be considered.

The remainder of this paper is structured as follows. Section 2 summarizes the extant literature and clarifies the research gap we address through our model, the general framework of which is introduced in Section 3. Sections 4 and 5 compare the socially optimal loan financing amount to the market outcome without policy intervention. Section 6 introduces a de-risking instrument and public loan provision as two stylized policy options to address potential market failures. Section 7 provides a numerical application of our model to offshore wind energy in Germany, while Section 8 contains two model extensions with climate externalities and uncertain loan demand growth. Finally, Section 9 concludes with a discussion of policy implications.

2 Background and literature

2.1 Importance of debt finance for clean energy

Clean energy technologies require substantial upfront financing due to their high capital intensity (Borenstein, 2012). Therefore, their cost-competitiveness for large-scale deployment strongly depends on the cost of capital (Hirth & Steckel, 2016; Stocks, 1984), which can be reduced substantially through debt financing (Schmidt et al., 2019)—particularly if higher leverage ratios can be obtained by using project finance (Steffen, 2018). This requires bank loans when technologies and firms have not matured sufficiently to tap bond markets, making accessible credit key for the ramp-up of these technologies (Berger & Udell, 1998; Polzin, 2017). However, credit may be rationed due to financial market frictions (Jaffee & Stiglitz, 1990; Stiglitz, 1993) and remaining externalities at the technology level (Popp, 2019). Indeed, there is empirical evidence that emerging clean energy technologies face financing constraints (cf. Haas and Kempa, 2023, and Campiglio et al., 2024, for an overview), which can also limit firms more generally in their ability to abate and innovate and thus reduce the effectiveness of climate policies (Bartram et al., 2022; de Haas et al., 2024; Ghisetti et al., 2017; Kaldorf & Shi, 2024; Xu & Kim, 2022).

2.2 Common policy interventions

Given the financing constraints for renewable energy technologies and the broader perception of a "financing gap" that hinders the expansion of low-carbon infrastructure, policymakers in many countries have introduced targeted policy interventions to direct financial flows to clean energy assets (Steffen, 2021; Steffen & Michaelowa, 2022). Two common instruments are loan guarantees and public loans, often provided through state investment banks. These instruments typically complement other policy interventions addressing emissions and innovation externalities in clean energy technologies, such as carbon pricing or renewable energy feed-in tariffs (Geddes et al., 2018; Polzin et al., 2019).

An early example of loan guarantees is the U.S. Department of Energy's Loan Guarantee Program, introduced under the Energy Policy Act of 2005 alongside tax incentives for renewables (109th US Congress, 2005). These guarantees aimed to reduce financing risks for lenders investing in innovative clean energy technologies that struggled to secure market-based finance—at the time, including solar photovoltaics and wind turbines (Brown, 2012; IEA, 2017). In addition, export credit agencies, such as the Danish EIFO, are increasingly supporting renewable energy projects through credit guarantees (Censkowsky et al., 2025). Regarding public loan provision, a notable example is Germany's significant expansion of renewable energy loan programs through its state development bank, KfW, in 2009 (D'Orazio & Löwenstein, 2022; Geddes et al., 2018). Since 2012, several countries have established dedicated green state investment banks, such as Australia's Clean Energy Finance Corporation and the United Kingdom's Green Investment Bank. These interventions were designed to mobilize private credit for immature clean energy technologies, particularly renewables (Geddes et al., 2018).

Where public loan programs or green state investment banks were implemented, these policy interventions were integrated into broader policy mixes that also included direct support mechanisms for renewables, such as feed-in tariffs, capacity auctions, and, in some cases, carbon pricing instruments like the European Emissions Trading System. The main stated objectives for establishing green state investment banks and similar programs were to reduce greenhouse gas emissions, to foster growth of the green industry, and to improve capital market efficiency by catalyzing private lending to renewables (Geddes et al., 2020; OECD, 2016b). Especially the "green industry growth" argument seems to be broadly supported by parties and interest groups, and hence contributed to the political feasibility of the policies. (Geddes & Schmidt, 2020; Hughes & Urpelainen, 2015). However, political discourse has rarely addressed why such interventions are necessary within policy mixes that already internalize environmental and innovation externalities through other instruments. Similarly, there has been little discussion on whether and under what conditions public loan provision or de-risking mechanisms, such as guarantees, offer advantages (Geddes et al., 2020). In the following section, we review the existing economic literature on these questions and identify key gaps in our theoretical understanding of

de-risking policies and public loan provision, which this article seeks to address.

2.3 Literature on rationales for policy interventions

A natural starting point concerning policy interventions to address inefficient credit rationing is modern banking theory. This literature has studied the potential of credit guarantees or interest rate subsidies in general, not relating to novel technologies or clean energy specifically (Arping et al., 2010; Hainz & Hakenes, 2012; Janda, 2011; Minelli & Modica, 2009; Philippon & Skreta, 2012). These insights on de-risking measures have been extended to the case of low-carbon technologies (Campiglio et al., 2024; Haas & Kempa, 2023), but there is less theoretical clarity about which role, if any, should be played by the public provision of loans for clean energy projects. The extant literature centers primarily on public (green) banks—which typically engage in both loan provision and de-risking (Eslava & Freixas, 2021; Whitney et al., 2020)—and suggests various reasons why these institutions may limit the extent of credit rationing for low-carbon technologies.

One suggestion is that public loan programs and development banks provide counter-cyclical financing in times of credit crunches (Eslava & Freixas, 2021; Mazzucato & Penna, 2016). However, this notion has not been empirically confirmed for the energy sector specifically (Waidelich & Steffen, 2024), and the question remains why economy-wide credit crunches should be addressed by sector-specific policy interventions instead of general counter-cyclical fiscal and monetary policy. Studies further cite high risk premiums and discount rates at private banks as a rationale for public loan provision (Lehmann & Söderholm, 2018; Mazzucato & Penna, 2016). From an efficiency point of view, the preferences of market players per se cannot represent a market failure. This argument requires either the existence of remaining externalities at the technology level or assuming that the optimal social discount rate is lower than the rate applied by private-sector financiers. Furthermore, the argument abstracts from well-established reasons why banks act in more risk-averse ways than other types of investors, such as regulatory capital requirements or the risk of having to raise external finance due to unexpected deposit withdrawals (Diamond & Dybvig, 1983; Froot & Stein, 1998). Banks, unlike equity investors, cannot participate in any project upsides and hence focus on mitigating default risks.

Another strand of literature argues that novel technologies threaten the value of banks' legacy positions and their information stock in incumbent technologies, calling for new institutions with clean slates (Degryse et al., 2020; Minetti, 2011). This argument primarily motivates sufficient anti-trust policies for the banking sector and underlines the potential benefit of a new entrant bank. However, it provides little reason why the new entrant bank should be public, particularly since dedicated green commercial banks are often important first movers for clean energy technologies (Zhang, 2020). More sector-agnostic

studies have motivated the need for public loan provision based on two issues: first, the existence of projects with a negative net present value that are socially desirable—although, in the case of clean energy, this might be better addressed through first-best policies outside the financial sector; and second, information asymmetries in the form of inefficiently low screening efforts when borrower types are unknown to banks, screening is costly, and project screening outcomes are observable to competitors (Eslava & Freixas, 2021; Hainz & Hakenes, 2012; Williamson, 1994).

Similar to this screening benefit argument, Geddes et al. (2018) highlight that, aside from providing loans and de-risking investments, public green banks often educate markets on novel technologies and provide strong signals on their economic viability. This behavior is motivated by the fact that novel technologies are not only subject to technological learning but also improve their risk–return profile as financing experience accumulates. Such "financial learning" or "learning-by-lending" occurs because an expanding credit track record reduces banks' uncertainty about the default probability of projects (Egli et al., 2018) and leads to repeated interactions with the same borrowers, which eases credit screening and monitoring (Botsch & Vanasco, 2019; Cao et al., 2023). More experienced debt providers accumulate more in-house experience with a given sector or technology (Jiang & Li, 2022) and, therefore, can extract more value from pledged collateral, which reduces losses in the event that a borrower defaults (Minetti, 2011). More experience will also enable lenders to identify relevant loan covenants and to reduce the transaction costs per loan since application reviews can be streamlined and contracts can be standardized (Umbeck & Chatfield, 1982). In the case of syndicated loans in project finance, the predominant financing structure for renewable energy technologies (IRENA, 2023; Steffen, 2018), experience further allows for the standardization of deal structures, the conclusion of frame contracts, and the emergence of proven networks of financiers and financial/technical/legal advisors, all of which can reduce both transaction costs and necessary risk contingencies (Egli et al., 2018; Gatti, 2013; Polzin et al., 2021). These findings from empirical interview studies highlight the need for a rigorous theoretical consideration of market failures and the need for policy if technology- and consumer-level externalities have been sufficiently priced in.

Therefore, we formalize these considerations into a model for bank loans and account for learning spillovers by building on a recent strand of literature incorporating learning effects into models of individual investors' technology investment decisions. In particular, Della Seta et al. (2012) model a novel technology whose marginal costs decrease in cumulative output and find that optimal investment involves significant initial losses that are compensated by later-stage gains, making the technology particularly prone to downside risk. Their model is extended by Sarkar and Zhang (2020), who introduce the option of debt-financing, which leads to more and earlier investment. They conclude that unless there are exogenous borrowing constraints, the optimal gearing ratio is higher if costs

decrease faster in cumulative output. Moreover, Way et al. (2019) explore the optimal portfolio allocation between investments in two technologies under stochastic learning rates and risk aversion. Their model produces a trade-off between specializing in one technology to drive down costs and diversifying to hedge against downsides. It requires numerical optimization to be solved as the learning feedback introduces multiple local optima. Lehmann and Söderholm (2018) review theoretical rationales for renewable energy support schemes in a partial equilibrium framework, including technological learning where second-period costs decrease convexly in first-period output. They suggest that a subsidy scheme can overcome financial market failures caused by inefficiently high risk aversion and discount rates by a private investor. Finally, Campiglio et al. (2024) implement financial intermediaries into a directed technical change model based on Acemoglu et al. (2012). In their model, intermediaries charge research firms in clean technologies higher rates and ignore these technologies' social benefits as well as the improvements in future financing conditions due to a financing experience feedback. Therefore, the optimal policy mix includes a financial subsidy for screening efforts by financial intermediaries, aside from carbon pricing and low-carbon innovation subsidies.

These previous modeling studies either take the perspective of a single equity investor or, in the case of Campiglio et al. (2024), only study a financial subsidy but not public loan provision and do not consider credit rationing. By contrast, we study the interplay between multiple debt providers and include public loan provision as a separate policy measure. In doing so, our paper suggests another important reason for credit rationing: a coordination problem between borrowers to gain sufficient experience with a novel clean energy technology, which public loans can address. Our work is also related to Lessmann and Kalkuhl (2024) who introduce costly financial intermediation into a climate policy model and, among other things, show that the welfare cost of market power-driven interest rate spreads can be mitigated by subsidizing bank loans. In addition, our paper is related to Haas and Kempa (2023), who explain credit rationing for clean energy technology firms with information asymmetries and unobservable project characteristics that can be addressed via de-risking. However, neither their models nor, to the best of our knowledge, any other paper formally assesses public loan provision as a policy instrument and its role relative to de-risking measures in the context of financing experience feedbacks.

3 General framework

We consider a two-period financial sector model populated by a discrete number N of banks. Banks are homogeneous and, in each period, face loan applications by projects using a novel clean energy technology. Here, $l_{i,t}$ represents the overall amount of loan financing granted by bank i in period t, which is financed via deposits. We assume that the desired capacity expansion for the new low-carbon technology is determined exogenously

by policy interventions in the energy sector (e.g., renewable portfolio standards, renewable energy auctions, or carbon prices), combined with global technology evolutions and general macroeconomic conditions. Therefore, the first-period demand for loans to cover the debt-financed part of this capacity expansion, denoted as D, is exogenous. In the second period, the demand for loans increases by an exogenous factor $\psi > 1$, driven by the general advance of the energy transition and the ramp-up in deployment of the novel technology. To abstract from the issue of banking sector concentration, which has been studied extensively elsewhere (cf. Freixas and Rochet, 2023, for an overview), demand is allocated symmetrically across banks, such that

$$l_{i,1} \in [0, \frac{D}{N}], l_{i,2} \in [0, \frac{\psi D}{N}] \ \ \forall \ \ i = 1, ..., N. \tag{1}$$

We introduce two separate periods due to two factors: first, the common bifurcation in financial markets, whereby technologies either are too novel (and hence risky) to attract debt finance or are already mature enough to attract debt finance (i.e., "bankable"); second, the fact that deployment in novel technologies, particularly under continued policy support, can ramp up considerably, which we represent here via ψ. In our model, each period should be considered as representing multiple years such that loans are paid out at the beginning of each period and paid back with interest by its end. In the first, "early-stage" period, the novel clean energy technology is still financially immature and hence risky, while its risk–return structure can improve in the second, "later-stage" period. Therefore, on every unit of early-stage loans $l_{i,1}$ at $t = 1$, bank i earns the following risk-adjusted net return

$$r_1 \coloneqq r - \bar{c} - r_D \tag{2}$$

where r denotes the risk-adjusted return that banks can earn on loans at full financial maturity.[3] The primary source of risk is each project's probability of default, which we do not model explicitly. Instead, we assume that the risk-adjusted return r is monotonically increasing in the expected return and monotonically decreasing in the return variance and the banks' degree of risk aversion. $\bar{c}$ represents a strictly positive, constant penalty on the risk-adjusted return due to financial immaturity, comprised of the risk premium for the novel technology and the higher screening costs due to a lack of experience assessing credit applications.[4] r_D denotes the rate paid out to compensate deposit holders.

[3]Here, we assume that there is no price feedback between the aggregate loan supply and the interest rate paid by projects. Relaxing this assumption for, as one example, a linear demand curve would effectively turn our model into a symmetric two-stage Cournot game, where, if N is finite, interest rate concerns further depress the number of loans that each bank is willing to supply.

[4]For an overview of potential reasons for this immaturity cost and the respective literature, see Section 2.3.

On every unit of later-stage loans $l_{i,2}$, bank i earns the following return

$$r - c\left(\tilde{L}_{i,1}\right) - r_D \tag{3}$$

where

$$\tilde{L}_{i,1} \coloneqq l_{i,1} + \gamma \sum_{j \neq i} l_{j,1} \tag{4}$$

denotes the financing experience gained by bank i through their own first-period loan financing and the financing provided by their peers.[5] Therefore, early-stage loans for the novel technology at $t = 1$ impose a positive experience externality on other banks by improving their later-stage risk-adjusted return at $t = 2$. Without early-stage loan financing by any bank, no learning gains are realized, i.e., $c(0) = \bar{c}$. Because of diminishing returns to experience, we further assume that c decreases convexly in $\tilde{L}_{i,1}$ but remains nonnegative.[6]

Learning spillovers between banks are imperfect, which is represented by $\gamma \in (0, 1)$. Such spillovers can be driven by the visibility of project defaults (or the lack thereof) to financiers not involved, by loan syndicates formed with other banks, by the diffusion of standardized transaction structures within the industry, or by staff switching between banks and exchanging experiences through professional networks (Egli et al., 2018; Geddes et al., 2018). A higher value of γ can denote that banks are more transparent about their financing experience, that their absorptive capacity is higher, or that they regard their peers as more competent and, hence, the financing decisions made by other banks as more instructive.

In this paper, we investigate market failures and policy interventions for novel clean energy technologies that have sufficient potential to become profitable from a lender's perspective at a later stage but are not immediately attractive at an early stage due to lack of experience. Therefore, we assume a negative spread between the risk-adjusted return on loans at full financial immaturity and the deposit rate:

$$r - \bar{c} < r_D. \tag{5}$$

[5] Note that we use capitalized L for aggregates of loan amounts across banks and lowercase l for loan amounts of individual banks.

[6] Our restrictions that $c \geq 0, c' < 0, c'' > 0$ nest the most common functional forms for technological and financial learning curves in the literature (Campiglio et al., 2024; Della Seta et al., 2012; Egli et al., 2018; Samadi, 2018; Thompson, 2012). There are at least two potential microfoundations for this functional form of c: first, decreasing transaction costs of credit screening due to the banking sector's learning-by-doing; second, Bayesian updating about a novel technology's unknown default rate with every loan-financed project, assuming that banks are risk-averse and hence apply a risk premium that scales with the uncertainty about the true default rate. In addition, learning-by-doing in the respective energy technology could also improve risk-return profiles if bank loans enable more projects to be realized, thus enabling more technology-level learning that reduces project costs and hence improves their cash flow profiles.

such that $r_1 < 0$. Notably, this assumption reflects that beyond certain risk levels, banks cannot be compensated for the risk by charging higher interest rates because the required rate, in turn, further increases projects' default risks (Jaffee & Stiglitz, 1990) or because at the required interest rate, projects do not meet the return expectations of their equity investors and, hence, are not pursued further. Such an assumption is informed by interview-based evidence that novel clean energy technologies often struggle to secure debt financing altogether at early stages of market maturity when there is no clear track record of the technology (Egli, 2020; Egli et al., 2018; Geddes et al., 2018). By contrast, if all banks provide the maximum amount of early-stage financing (i.e., each bank provides $\frac{D}{N}$ and all banks jointly provide D), the spread would turn positive such that

$$r > c\left(\tilde{N}\frac{D}{N}\right) + r_D \tag{6}$$

where

$$\tilde{N} := 1 + \gamma(N-1) < N. \tag{7}$$

The term $\tilde{N}$ in Equation 6, which is smaller than N as $\gamma < 1$, accounts for the loss of financing experience due to imperfect spillovers between banks. Therefore, $c\left(\tilde{N}\frac{D}{N}\right)$ is the maximum amount of cost reductions achievable through learning. The risk-adjusted return in the second, later-stage period $r - c(\tilde{L}_{i,1})$ is concavely increasing in $\tilde{L}_{i,1}$ and bounded between $r - \bar{c}$ and r, as displayed in Figure 1.

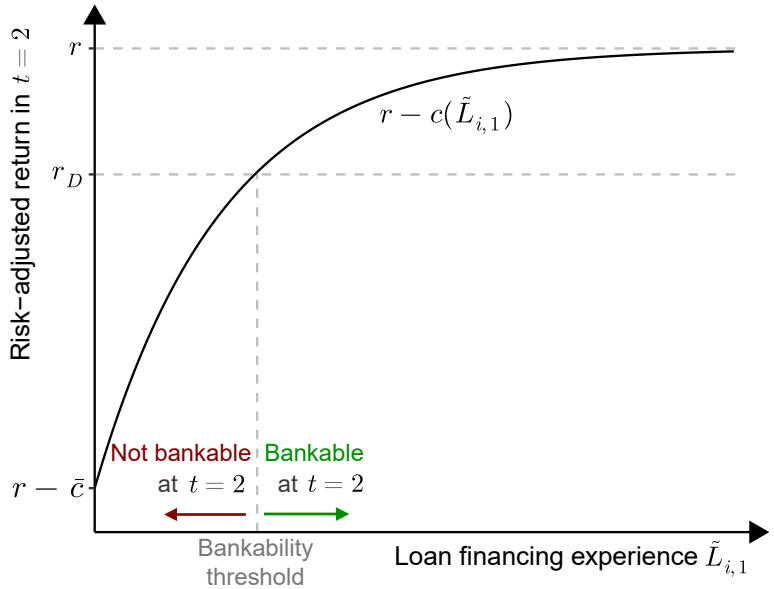


Figure 1: Risk-adjusted return on loans in $t = 2$.

This model can, in principle, represent a wide range of settings but is particularly suited to analyze the clean energy sector, which combines multiple features that motivate our setup. First, as discussed in Section 2, the energy transition implies a directed

technological change toward more capital-intensive technologies. Therefore, the availability of sufficiently cheap bank financing becomes paramount for reducing clean energy projects' costs. Second, these projects meet *technology-agnostic demand* for electricity, leading to direct competition with less capital-intensive incumbent technologies like coal- or gas-fired power plants, whose costs are less sensitive to financing conditions (Hirth & Steckel, 2016; Schmidt et al., 2019). As a result, clean energy projects are less likely to move forward if they fail to secure (sufficiently cheap) debt financing, creating a direct link between bankability and large-scale deployment. Third, renewable energy technologies are predominantly financed via *project finance* (IRENA, 2023; Steffen et al., 2018). Projects are realized through stand-alone special purpose vehicles without recourse to project sponsors. Therefore, creditworthiness is not driven by sponsors' balance sheets but by technology-specific risks, which would otherwise only hold for pure-play firms that rely on a single technology. Fourth, banks' understanding of these technology risks evolves for clean energy technologies because of *sufficiently different working principles across technologies*. Technologically speaking, an offshore wind park has very little in common with a coal-fired power station or a hydropower dam, meaning that banks active in the sector cannot simply transfer financing experience across technologies. Finally, for banks to incur early-stage risks in exchange for learning gains that materialize later on, there must be *substantial and foreseeable policy-driven growth* in technologies' deployment and, hence, loan demand.[7] While project finance is commonly used also in other sectors, such as mining, telecoms, chemical processing plants, and road infrastructure (BCBS, 2006, Art 221–222, p. 53), we argue that the combination of all factors listed above is a distinct feature of clean energy projects, making them by far the best, though not the only conceivable application of our model.

Combining the considerations above, the risk-adjusted profits of bank i discounted to $t = 1$ can be written as

$$\pi_i(l_{i,1}, l_{i,2}, \tilde{L}_{i,1}) = \underbrace{r_1 l_{i,1}}_{\text{Early-stage losses}} + \underbrace{\beta \left(r - c(\tilde{L}_{i,1}) - r_D \right) l_{i,2}}_{\text{Potential later-stage gains}} \tag{8}$$

where $\beta \in (0, 1)$ is the discount factor common to all banks. To strike a profit, early-stage losses must be compensated by later-stage gains. Therefore, a profit-maximizing bank i will only provide loans for the novel technology at $t = 2$ if the financing experience from the first period $\tilde{L}_{i,1}$ is sufficiently high to push the risk-adjusted return above r_D. If this is the case, we will refer to the novel technology as being "bankable" at $t = 2$. The lending decision of bank i at $t = 2$ only depends on whether the financing experience gained at $t = 1$ renders the novel technology bankable and causes no further externalities to other banks. To avoid situations where banks are indifferent between outcomes, we

[7] In our numerical application, we highlight how our policy implication hinges on demand growth between the two periods; see Section 7.

assume that if two outcomes yield the same risk-adjusted return or profits, banks strictly prefer the one with less loan financing. This gives us the following simple rule for the later-stage loan financing at $t = 2$:

Lemma 1. *Let $(l_{i,1}, l_{i,2})$ be the loan financing amounts for any bank i. Then*

$$l_{i,2} = \begin{cases} 0 & \text{if } r - c(\tilde{L}_{i,1}) \leq r_D \\ \psi \frac{D}{N} & \text{otherwise.} \end{cases} \tag{9}$$

Proof. See Appendix B.1. □

Hence, in the later-stage period, banks either finance the technology's entire loan demand if the early-stage financing experience provides a positive return spread or refrain from any loan financing at $t = 2$.

Notably, our model does not specify an explicit "outside option" to lending to the novel technology and assumes that banks do not need to pay interest to deposit holders whose funds they do not use. This is a simplification without loss of generality: In Appendix B.3, we show that it does not change the outcome of the private or social optimization problem if we assume that banks have an outside option and need to pay interest to all their depositors. Intuitively, this is because we can reinterpret zero profits in our setup as the profitability of an outside option with no relevant constraint on its availability, such as the return on a risk-free long-term government bond or a LIBOR-like rate.

4 Social optimum

In our model, the socially optimal solution maximizes the sum of present-value profits over all banks:

$$\max_{\{l_{i,1}, l_{i,2}\}_{i=1}^{N}} \sum_i \pi_i(l_{i,1}, l_{i,2}, \tilde{L}_{i,1}) \qquad \text{s.t. } l_{i,1} \in [0, \frac{D}{N}], l_{i,2} \in [0, \psi \frac{D}{N}]. \tag{10}$$

The full Karush-Kuhn-Tucker conditions are provided in Appendix B and reflect that, in the unconstrained social optimum (SO), $l_{i,1}$ should be chosen to equate the initial return spread at $t = 1$ (r_1) and the marginal learning gain such that

$$\underbrace{-\beta(c'(\tilde{L}^{SO}_{i,1}) l^{SO}_{i,2}}_{\substack{\text{Learning gain} \\ \text{to bank } i}} + \underbrace{\gamma \sum_{j \neq i} c'(\tilde{L}^{SO}_{j,1}) l^{SO}_{j,2})}_{\text{Learning gain to peers}} = \underbrace{- r_1}_{\substack{\text{Initial return spread} \\ (= \text{loss})}}, \tag{11}$$

which might not hold in the constrained optimum if the demand or nonnegativity constraint on $l_{i,1}$ bind. Note that both the left-hand and the right-hand side of Equation 11

are positive since $c' < 0$ and $r_1 < 0$.

An asymmetric solution to the optimization problem in Equation 10 cannot be ruled out entirely but significantly limits the analytic tractability of our model. Therefore, we impose symmetry on the social optimum, as is common in the literature (Eslava & Freixas, 2021). This means that

$$l_{i,t}^{SO} = l_t^{SO} \; \forall \; i = 1, ..., N \tag{12}$$

which by Lemma 1 also implies symmetry in the later-stage loan financing. This is a mild assumption because banks are homogeneous *and* because the profit of each bank $\pi_i(\cdot)$ is strictly concave in $\tilde{L}_{i,1}$. For this reason, allocating early-stage loan financing amounts asymmetrically between firms (which leads to a heterogeneous financing experience $\tilde{L}_{i,1}$ as $\gamma < 1$) is typically dominated by a symmetric allocation. Combining Lemma 1 with the first- and second-order conditions results in the following proposition:

Proposition 1. *Let* $l_1^* \coloneqq \tilde{N}^{-1}(c')^{-1}\left(\frac{r_1}{\beta\frac{\tilde{N}}{N}\psi D}\right)$ *denote the unconstrained symmetric solution to the first-order condition in Equation 11, and let* $(c')^{-1}(\cdot)$ *denote the inverse function of* c'.[8] *Then, the unique symmetric social optimum* (l_1^{SO}, l_2^{SO}) *is either*

- *an immediate financing outcome in which every bank provides the full loan financing amount in the first and second period (*$\frac{D}{N}$ *and* $\psi\frac{D}{N}$*, respectively), or*
- *a gradual financing outcome in which each bank provides* $l_1^* < \frac{D}{N}$ *at* $t = 1$ *before providing full loan financing at* $t = 2$*, or*
- *a no-financing outcome in which banks do not provide any loan financing in either period.*

For gradual or immediate financing to be optimal, second-period profits must outweigh the first-period losses, so each bank strikes strictly positive present-value profits.

Proof. See Appendix B. □

Here, l_1^* denotes the loan financing amount for which the marginal learning gains and the initial return spread balance (prior to any demand or nonnegativity constraints). At the technology level, comparative statics (see Appendix B) reveal that a more favorable risk–return profile (i.e., a higher risk-adjusted return at full maturity r and a lower initial immaturity penalty $\bar{c}$) make a no-financing optimum less likely and increase the socially optimal early-stage financing l_1^{SO}. At the financier level, the same holds if the initial loan demand by projects using the novel technology is higher ($D \uparrow$) and grows more strongly in the second period ($\psi \uparrow$), which increases the scope for learning effects, or if deposits are cheaper ($r_D \downarrow$). The socially optimal l_1^{SO} is also higher if banks are more patient

[8] Note that c' is monotonically increasing, and hence $(c')^{-1}$ exists and is monotonically increasing.

($\beta \uparrow$). However, a less concentrated banking sector ($N \uparrow$) will decrease the loan financing in the optimum because, ceteris paribus, this implies more spillover losses of financing experience as long as $\gamma < 1$.

Since the social optimum is symmetric and, by Lemma 1, $l_{i,2}$ is a binary function of $l_{i,1}$, we can plot total profits $\sum_i \pi_i(\cdot)$ as a function of the first-period financing experience $\tilde{L}_1 = \tilde{N} l_1$. In the left panel of Figure 2, we show this for the gradual-financing optimum (i.e., for a scenario under which total profits peak above zero for some $\tilde{L}_1 < \frac{\tilde{N}}{N} D$). For very low amounts of financing at $t = 1$, the risk-adjusted return on loans at $t = 2$ remains below r_D such that, by Lemma 1, banks do not grant any loans and hence make zero profits from the new technology in the second period. At the same time, profits at $t = 1$ decrease linearly since, for every unit of l_1, each bank loses the negative initial return spread r_1. Therefore, small values of early-stage loan financing that are insufficient to render loans bankable at a later stage reduce overall profits below zero.

If l_1 increases further, the risk-adjusted return at $t = 2$ at some point equals the deposit rate r_D (blue line). Beyond this "tipping point", loans become profitable at $t = 2$, and hence banks will meet the entire loan demand such that $l_2 = \psi \frac{D}{N}$, making the technology bankable at $t = 2$. Note that profits increase concavely because returns on financing experience are diminishing as c is convex. However, the positive profits at $t = 2$ do not immediately offset the incurred losses at $t = 1$. It takes some additional increase in l_1 (i.e., further learning gains) until banks break even in present-value terms across both periods (grey line). As long as the marginal learning gain of l_1 exceeds the negative initial return r_1, a higher l_1 increases profits further until the marginal return and deposit rate equal in the social optimum (green line). Beyond this point, the marginal learning gain no longer compensates for the early-stage losses, and profits again fall.

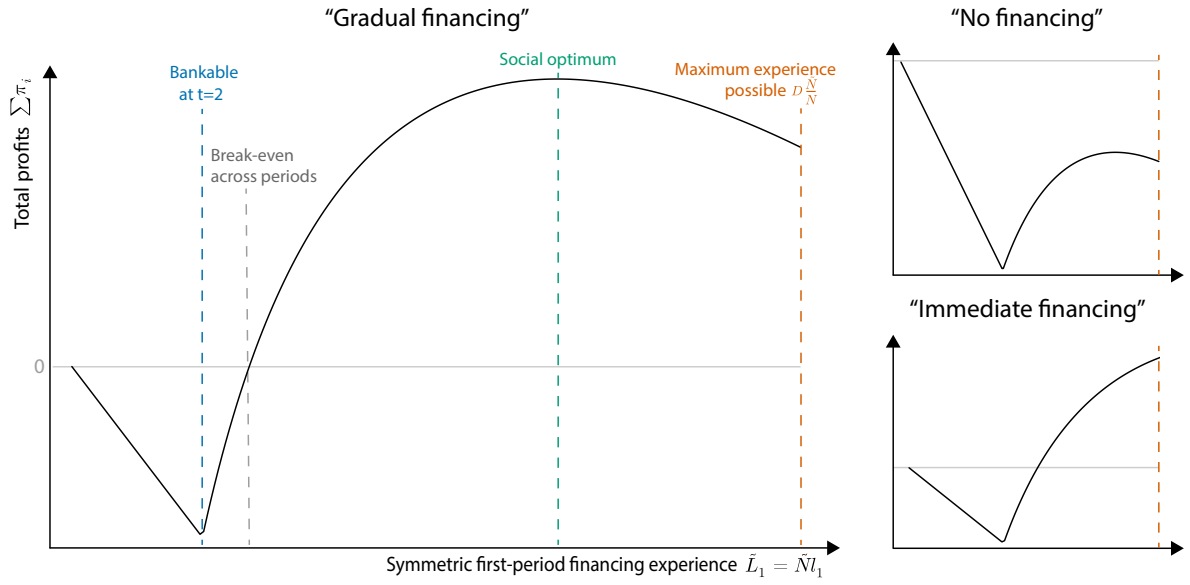


Figure 2: Aggregate bank profits over early-stage loan financing.

Visually speaking, the gradual-financing optimum displayed in Figure 2 exists if the concave section of $\sum_i \pi_i(\cdot)$ peaks within the banking sector's available resources (for some $\tilde{L}_1 < \frac{\tilde{N}}{N}D$) and above zero. The other two potential optima in Proposition 1 have equally straightforward interpretations and are displayed in the right panel of Figure 2. The no-financing scenario is optimal if the concave section does not exceed zero for any $\tilde{L}_1 \in [0, \frac{\tilde{N}}{N}D]$. The immediate-financing optimum requires that the concave section only peaks after $\frac{\tilde{N}}{N}D$, but that total profits at this point already exceed zero.

5 Market outcome

In a market outcome, each individually rational bank carries out the following profit maximization:

$$\max_{l_{i,1}, l_{i,2}} \pi_i(l_{i,1}, l_{i,2}, \tilde{L}_{i,1}) \qquad \text{s.t. } l_{i,1} \in [0, \frac{D}{N}], l_{i,2} \in [0, \psi\frac{D}{N}]. \tag{13}$$

The first-order conditions, given in Appendix C.1, follow the same principles as those given in Equation 11, except that banks ignore the learning spillovers to their peers. Therefore, bank i chooses its early-stage loans such that its marginal learning gains equal the per-unit loss on these loans (r_1) and opts for no loans (the full amount $\frac{D}{N}$) if the marginal learning gains remain below (above) the per-unit loss all the way through the zero lower bound (upper bound $\frac{D}{N}$) for $l_{i,1}$. In the second period, banks' individually rational behavior follows Lemma 1, meaning that they provide the full loan amount $\psi\frac{D}{N}$ only if early-stage learning gains suffice to make second-period loans profitable.

Importantly, the solution to the maximization problem of bank i depends on its peers' behavior. For a fully fragmented banking sector (i.e., if $N \to \infty$), it is trivial to show that bank i's contribution to its own financing experience stock $\tilde{L}_{i,1}$ becomes negligible unless $\gamma \to 0$. Note that early-stage loans in the model come at a loss in $t = 1$ and can only be profitable through their impact on $\tilde{L}_{i,1}$ and thus profits in $t = 2$. For $N \to \infty$ where $l_{i,1}$ has no meaningful impact on $\tilde{L}_{i,1}$, the only possible market outcome is $(l_{i,1}, l_{i,2}) = (0, 0)\ \forall\ i = 1, ..., N$. However, banking sectors typically do not exhibit this perfect degree of competition (World Bank, 2022). We instead consider a finite number of N, solve for possible Nash equilibria, and arrive at the following result:

Proposition 2. *The set of Nash equilibria under the market outcome can be characterized as follows:*

- *The possible Nash equilibria are all symmetric and feature a no-financing equilibrium, a gradual-financing equilibrium where each bank provides* $l_1^{*NE} := \tilde{N}^{-1}(c')^{-1}\left(\frac{r_1}{\beta\psi\frac{D}{N}}\right) < \frac{D}{N}$ *at* $t = 1$*, and an immediate-financing equilibrium.*
- *If the gradual-financing equilibrium exists, the immediate-financing equilibrium does not exist, and vice-versa. Both require strictly positive profits for each bank to exist.*

- *Both the gradual-financing and the immediate-financing equilibria can co-exist with the no-financing equilibrium.*

- *The early-stage loan provision in any Nash equilibrium is strictly lower than the social optimum, except for the trivial case, in which both the social optimum and the Nash equilibrium are immediate financing or no financing.*

Proof. See Appendix C. □

To make the equilibrium formation process more intuitive, we illustrate the best-response functions for the simplified case of $N = 2$ for banks i (red line) and j (blue line) in Figure 3. As banks are homogeneous, the two best-response functions are symmetric. For low levels of $l_{j,1}$, bank i's marginal learning gains are high, but it cannot unlock sufficient learning to obtain positive present-value profits and hence its best-response is zero. For a sufficiently high level of $l_{j,1}$, however, positive present-value profits come within reach of bank i and the best-response function of bank i jumps to $l_{i,1} = \frac{D}{N}$, along with maximum loan provision at $t = 2$ (see Figure 3a). From here on, bank i's best response remains at $\frac{D}{N}$ until bank j's loan amount is high enough that for an early-stage loan volume of $l_{i,1} = \frac{D}{N}$, bank i's marginal learning gains fall below the first-period loss r_1. From this point on, $l_{i,1} = \frac{D}{N}$ no longer satisfies bank i's first-order conditions and bank i reduces its early-stage loan provision (though not its loan amounts in $t = 2$), so that marginal learning gains and marginal first-period losses are balanced again, which requires $\tilde{L}_{i,1} = \tilde{N} l_1^{*NE}$. As $\tilde{L}_{i,1} := l_{i,1} + \gamma l_{j,1}$, this means that for every one-unit increase in early-stage loans provided by bank j, bank i reduces their loans by γ, as free-riding the learning gains provided by the other bank is less costly than providing early-stage loans themselves.[9] At some point, bank j's early-stage loans reach $l_{j,1} = \frac{\tilde{N}}{\gamma} l_1^{*NE}$, such that $\tilde{L}_{i,1} = \tilde{N} l_1^{*NE}$ even if bank i provides no loans at all. Therefore, the best response drops to zero and remains there if bank j increases their loan provision further.

Importantly, the "plateau" of the best-response function at $l_{i,1} = \frac{D}{N}$ need not exist. Specifically, the plateau does not exist if marginal learning gains decrease so fast that, by the level of bank j's investment at which it becomes profitable for bank i to invest at all (i.e., when the best-response function jumps), bank i would already overshoot the optimal learning level of $\tilde{N} l_1^{*NE}$ if it invested the full amount $\frac{D}{N}$.[10] In this case, bank i never invests the full amount $\frac{D}{N}$ but jumps from zero investment to a first-period investment of $\tilde{N} l_1^{*NE} - \gamma l_{j,1} < \frac{D}{N}$ and the best-response function decreases linearly until reaching zero for $l_{j,1} = \frac{\tilde{N}}{\gamma} l_1^{*NE}$ (see Figure 3b–c). More detailed mathematical expressions

[9] The best-response function's linear slope of $-\frac{\gamma}{1}$ results from $l_{i,1}$ and $l_{j,1}$ entering bank i's experience $\tilde{L}_{i,1}$ linearly with coefficients of one and γ. Assuming a lower degree of substitutability between banks' own experience and learning gains provided by peers would result in non-linear slopes and the possibility of the best response not dropping entirely to zero; however, doing so would reduce the analytical tractability of the model considerably.

[10] Mathematically, this happens if $\tilde{N} l_1^{*NE} < \eta$ where η is defined implicitly such that $\frac{1}{\gamma}(\eta - \frac{D}{N})$ is the lowest level of bank j's investment at which bank i breaks even when investing the maximum $l_{i,1} = \frac{D}{N}$.

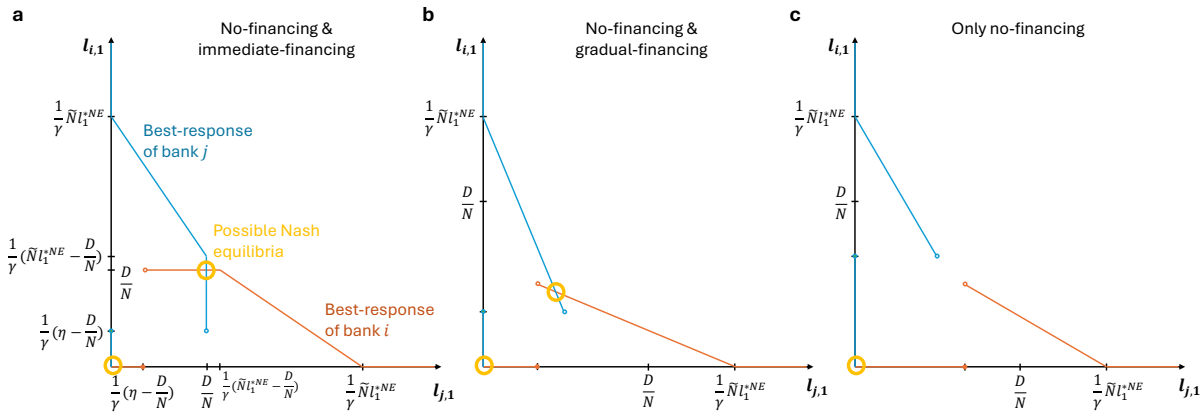


Figure 3: Best-response functions and Nash equilibria for $N = 2$ banks

on the best-response functions' shape under different cases can be found in Appendix C.2.

Figure 3 shows that only symmetric Nash equilibria are possible in the two-bank case. The reason for this is imperfect knowledge spillovers ($\gamma < 1$). Visually speaking, the linearly decreasing part of the best response function has a slope of $-\gamma$ for each bank. As long as $\gamma < 1$, that leaves at most one possible intersection of the best response functions' linearly decreasing parts in the graphs above. Under perfect knowledge spillovers ($\gamma = 1$) the best response functions would overlap on their linearly decreasing intervals and give rise to an arbitrary number of equilibria. This is because, in that case, it would not matter to each bank *who* generates the learning gains, just how much learning takes place in total. However, this case is very unlikely to hold in practice as banks' financial models, terms, and practices are confidential and partly tacit, meaning that at least some in-house experience cannot spill over to peers.

Therefore, we have two potential intersections of the best-response functions. One at $(l_{i,1}, l_{j,1}) = (0, 0)$ (no financing) and one where the non-zero sections of the best-response functions intersect either throughout the plateau section at $(\frac{D}{N}, \frac{D}{N})$ for an immediate-financing equilibrium (see Figure 3a) or at (l_1^{*NE}, l_1^{*NE}) for a gradual-financing equilibrium (see Figure 3b). If the best-response functions jump too late to produce an intersection or never jump at all due to unattractive financing conditions, no financing is the only possible equilibrium (see Figure 3c). Conversely, if the best response function of bank i jumps already at $l_{j,1} = 0$ (i.e., bank i can obtain positive present-value profits unilaterally), the no-financing equilibrium does not exist. Importantly, all these fundamental intuitions for $N = 2$ carry over to the case of several banks.[11]

Notably, the closed-form expressions for the potential gradual-financing social optimum l_1^* and the gradual-financing Nash equilibrium l_1^{*NE} are almost identical. However, the latter features only the individual loan amount at $t = 2$ (i.e., $\psi\frac{D}{N}$) and not the overall loan amount net of spillover losses (i.e., $\psi\frac{\tilde{N}}{N}D$) because banks ignore spillovers to peers.

[11] See Appendix C for the formal proofs.

As a result, l_1^{NE} is strictly lower than l_1^{SO} except in three boundary cases where social optimum and market outcome coincide. First, if $\gamma = 0$, then there are no externalities from one bank to another, and hence, the social planner cannot improve the market outcome. Second, if no financing for the novel technology is socially optimal, then the market also provides zero loans, and hence, there is no market failure. Finally, if the social optimum is an immediate-financing outcome, then the market can settle on a no-financing equilibrium, a gradual-financing equilibrium or, if financing conditions are very beneficial, an immediate-financing equilibrium. In the latter case, trivially, the socially optimal level of learning cannot be strictly greater than the equilibrium level of learning. However, the policy implications of this last case extrapolate well from the more relevant setting in which only a gradual-financing equilibrium exists. The only notable difference is that if the only Nash equilibrium with positive investment is the immediate financing equilibrium, the market outcome and the social optimum coincide without further policy intervention once a zero-financing equilibrium is avoided. For this reason, we place less emphasis on the case where immediate financing is both the social optimum and a market equilibrium in the following discussion of market failures and policy instruments.

Since the market outcome must be symmetric, the conditions in Proposition 2 under which the different Nash equilibria exist have straightforward visual interpretations displayed in Figure 4. The no-financing equilibrium (left yellow ring) exists unless a single bank i can push beyond the "no-financing valley" and obtain positive profits by unilaterally providing loans for the novel technology at $t = 1$.[12] The gradual-financing equilibrium $\tilde{L}_{i,1} = \tilde{N} l_1^{*NE}$ (right yellow ring) exists if and only if this point falls beyond the no-financing valley and provides above-zero profits because otherwise every bank would be better off by switching to the no-financing equilibrium instead.

[12]Note that Figure 4 rests on the assumption that all banks behave symmetrically, so the valley for such a unilateral financing provision is somewhat shorter as, in this case, there would be no spillover losses of financing experience. In addition, the valley displayed here refers to bank financing for (large-scale) deployment and hence does not represent the conventional "valley of death" for the transition between laboratory and commercialization (Popp, 2019).

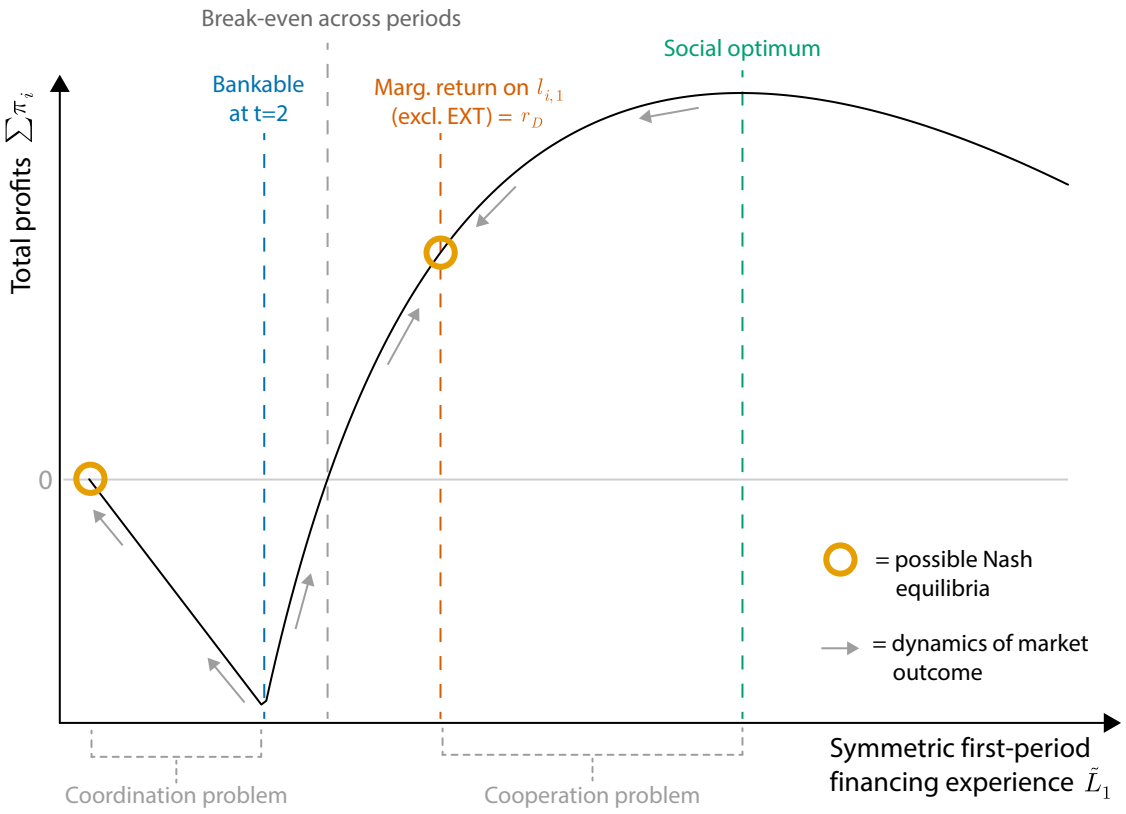


Figure 4: Possible Nash equilibria for a gradual-financing social optimum

If gradual or immediate financing is optimal, then Proposition 2 implies two separate elements of market failures: first, a *cooperation problem* because banks ignore positive learning spillovers to their peers and hence choose a sub-optimally low amount of early-stage loan financing (as visualized in Figure 4 above); and second, a *coordination problem* because even if a gradual-financing market outcome exists (which by definition must be profitable for every bank), the banking sector might remain stuck in the inferior no-financing equilibrium with zero profits.[13]

From an equilibrium selection perspective, there are at least two arguments for why the no-financing equilibrium might be more likely. First, providing no financing to a novel technology is a natural Schelling focal point (Mehta et al., 1994; Schelling, 1997) because it continues banks' past behavior (before the technology reached the deployment stage), is more straightforward, and resonates with the banking sector's general risk aversion. Second, providing no loans guarantees each bank nonnegative profits in the spirit of the risk dominance criterion used by Harsanyi (1995).[14] For these reasons, this equilibrium and the associated coordination problem warrant particular attention, although another

[13]Note that in the less interesting case that immediate financing is the social optimum *and* a possible Nash equilibrium, then there is only a potential coordination problem but no cooperation problem.

[14]To see this, consider the simplified case of only two banks that choose between the two potential equilibrium strategies. The no-financing option minimizes the downside if one bank picks one equilibrium and the other banks opt for the other, compared to the gradual-financing option. By contrast, opting for the gradual-financing equilibrium strategy leaves a bank vulnerable to potential losses.

market outcome is, of course, also possible.

Since the closed-form expression for l_1^{*NE} is very similar to that of the socially optimal l_1^*, the comparative statics for the gradual-financing social optimum similarly apply to the early-stage financing under the market outcome. More favorable conditions at the technology ($r \uparrow$, $\bar{c} \downarrow$) and financier level ($D \uparrow$, $\psi \uparrow$, $N \downarrow$, $r_D \downarrow$, $\beta \uparrow$) make it more likely that a gradual-financing Nash equilibrium exists and increase the financing amount in such a market outcome. Regarding the potential early-stage financing gap between the social optimum and the market outcome, we conclude as follows:

Lemma 2. *Let the social optimum be $0 < l_1^{SO} < \frac{D}{N}$ (gradual financing). Then, the minimum early financing gap between the market outcome and the social optimum is as follows:*

$$\frac{l_1^{SO}}{l_1^{*NE}} = \frac{(c')^{-1}\left(\frac{r_1}{\beta\psi\frac{D}{N}\tilde{N}}\right)}{(c')^{-1}\left(\frac{r_1}{\beta\psi\frac{D}{N}}\right)}. \tag{14}$$

Ceteris paribus, the minimum early financing gap increases monotonically in γ.

Proof. Combine the expressions from Propositions 1–2 and take the partial derivatives, keeping in mind that $(c')^{-1}$ is monotonically increasing and $\tilde{N} := 1 + \gamma(N-1)$. □

Therefore, the gap between the market outcome and the gradual-financing optimum is higher if more of a bank's learning gains spill over to competitors or if competitors are more capable of absorbing these spillovers ($\gamma \uparrow$). In addition, if the marginal learning gain c' decreases more steeply in the cumulative financing experience, this reduces the financing gap. This is because rapidly diminishing returns to experience mean that taking learning spillovers into account (or not) makes less of a difference.[15] However, these comparative statics only hold locally for limited changes in the given parameters since larger changes could also render the gradual-financing outcome sub-optimal from a social point of view.

6 Policy interventions

6.1 Framework for modeling policies

The previous section has established that if the social optimum is a gradual-financing (immediate-financing) outcome, the market outcome will (can) feature an inefficiently low provision of loan financing at $t = 1$ and might even fail to provide any loan financing. We consider two different policy interventions within the framework of our model to address this market failure. First, the government can improve the risk-adjusted return for banks, either by increasing the expected return on loans or by reducing the volatility

[15] The financing gap also decreases for a more concentrated market ($N \downarrow$) because the positive externality is lower when fewer peers benefit from spillovers. However, this obviously increases the scope for competition-related market failures, from which our model setup abstracts.

of returns (Polzin et al., 2019). Two of the most commonly discussed instruments to do so in the literature are interest rate subsidies and credit guarantees (Haas & Kempa, 2023)[16]. Due to our framework of risk-adjusted returns, we can represent both of these options as stylized state-financed additive premiums on the risk-adjusted return of all private banks in both periods denoted by $s_1, s_2 \geq 0$.[17]

Second, the government can provide loans directly to projects that use the novel technology in both periods, with loan amounts denoted by $g_1, g_2 \geq 0$.[18] Importantly, public loan provision generates financial experience at $t = 1$ that partially spills over to the private banks at a rate $\gamma^g > 0$. Public green banks can be mandated to actively share their expertise with the private sector, for instance, by taking lead roles in loan syndicates and showcasing their risk assessment and due diligence processes, by providing technical assistance to commercial lenders, and by creating and diffusing new deal structures (Geddes et al., 2018), which would imply $\gamma^g > \gamma$. However, γ^g might be lower than γ if the public loan provider is perceived as less competent than a commercial bank or prone to political distortions, thus making banks hesitant to learn from the public sector's lending track record. In addition, public loan provision can reduce the demand for loans faced by each bank since the overall demand for loans by projects using the novel technology is policy-induced and hence fixed.[19]

Subject to the policy interventions, each bank i then carries out the following maximization problem:

$$\begin{aligned} \max_{l_{i,1}, l_{i,2}} \pi_i = (r_1 + s_1) l_{i,1} + & \\ \beta \left(r - c(\gamma \sum_{j \neq i} l_{j,1} + \gamma^g g_1 + l_{i,1}) - r_D + s_2 \right) l_{i,2} & \\ \text{s.t. } l_{i,1} \in [0, \frac{D - g_1}{N}], l_{i,2} \in [0, \psi \frac{D - g_2}{N}]. & \end{aligned} \tag{15}$$

A direct takeaway from Equation 15 is that public loan provision at $t = 2$ (i.e., once no further learning gains are possible) factors into banks' decisions only by reducing the loan demand in $t = 2$ that they can serve if they do not opt for a no-financing strategy. Furthermore, we note that neither the de-risking instrument nor public loan provision moderate our previous findings with respect to either the deterministic rule of behavior for banks at $t = 2$ or the symmetric behavior of private banks in any possible Nash equilibrium. Therefore, Lemma 1 and the symmetry of the market outcome by

[16] An example is the U.S. Department of Energy's Loan Guarantee Program, cf. section 2.2.

[17] In addition, the government could also adjust capital requirements for banks through a green-supporting factor (Campiglio et al., 2018), which in our framework would have the same effect ($r \uparrow$).

[18] An example is the German KfW renewable energy loan program, cf. section 2.2 .

[19] Such a "crowding-out" effect rests on the model's assumption that financing terms of public loan provision are usually concessional and hence out-compete the market rates charged by the banks.

Proposition 2 continue to hold (see Appendix D).

6.2 De-risking measures

Economic theory suggests that a subsidy should be calibrated to the magnitude of the unaccounted positive externality at the social optimum (Pigou, 1932), which in our model only exists in $t = 1$. By incorporating such a well-calibrated de-risking subsidy into the first- and second-order conditions of individually rational banks, we arrive at the following proposition:

Proposition 3. *Let the social optimum be $0 < l_1^{SO} < \frac{D}{N}$ (gradual financing) and let $s_1^* := -\beta\gamma(N-1)\psi\frac{D}{N}c'(\tilde{N}l_1^{SO}) > 0$ be the optimally calibrated de-risking subsidy. Then, under $s_1 = s_1^*$ and for any $s_2 \geq 0$, the set of Nash equilibria can be characterized as follows:*

- *A symmetric Nash equilibrium exists in which banks behave as in the social optimum.*
- *Another Nash equilibrium with no financing by any bank exists if and only if no single bank can unilaterally break even by providing loans. If such an equilibrium exists for $s_1 = s_2 = 0$ (i.e., without policy intervention) because no bank can unilaterally ensure bankability at $t = 2$, it also exists for $s_1 = s_1^*, s_2 = 0$.*
- *A sufficient condition for the no-financing equilibrium not to exist is $s_2 > -r_1$.*[20]

Proof. See Appendix D. □

Notably, under the optimal de-risking subsidy s_1^* (which is positive since $c' < 0$), there exists a gradual-financing or immediate-financing Nash equilibrium that coincides with the social optimum—even if without the policy intervention the only possible Nash equilibrium featured no financing. However, such a well-calibrated subsidy does not necessarily rule out the coordination problem. Even for $s_1 = s_1^*$, the return in the first period $r_1 + s_1^*$ remains strictly negative.[21] Hence, early-stage loans still come at a loss, albeit a smaller one. If bank i cannot ensure bankability at $t = 2$ unilaterally, it cannot make a profit at $t = 2$ and no financing remains the best response. Visually speaking, a reduced initial return spread makes the no-financing valley in Figure 4 less deep without removing it. Hence, if no bank can reach the tipping point unilaterally without any policy intervention, then introducing $s_1 = s_1^*$ will not remove the no-financing equilibrium. Furthermore, if the government were to set $s_1 > s_1^*$ to resolve the coordination problem, this subsidy would lead to an *oversupply* of early-stage loans unless the social optimum is an immediate-financing outcome.

[20] Note that this sufficient condition for s_2 is not a *necessary* one to rule out the no-financing equilibrium. However, as it is more tractable mathematically, it better facilitates policy comparisons.

[21] To show this, recall that in the social optimum, this expression equates the marginal learning gain of bank i, excluding spillovers, which is strictly positive.

However, the existence of the no-financing Nash equilibrium can always be ruled out via a sufficiently high de-risking subsidy at $t = 2$. The logic behind this is simple: If there is a profitable gradual-financing equilibrium (which is ensured by $s_1 = s_1^*$), the coordination problem only arises because, for low amounts of early-stage loan financing, banks are not fully committed to providing loans at a later stage and, therefore, withdraw to the no-financing Nash equilibrium to avoid losses. This no-financing equilibrium collapses once the de-risking measures at $t = 2$ improve the risk–return structure of loans such that unilateral financing of $l_{i,2} = \frac{\psi D}{N}$ suffices for bank i to make a profit in $t = 2$—even if all other banks do not grant any loans. A sufficient condition to ensure this is to set s_2 marginally above the initial negative return r_1. Then, loans will always be profitable at $t = 2$, banks commit to loan financing at $t = 2$ and always prefer the gradual-financing Nash equilibrium, which, due to the internalization of spillovers via $s_1 = s_1^*$, coincides with the social optimum.

6.3 Direct loan provision

Turning to a policy intervention in which the government provides loans directly instead of using the de-risking subsidy, the respective first- and second-order conditions lead us to the following proposition:

Proposition 4. *Let the social optimum be* $0 < l_1^{SO} < \frac{D}{N}$ *(gradual financing), let* $l_1^{*NE}|g \coloneqq (c')^{-1}\left(\frac{r_1}{\beta\psi\frac{D-g_2}{N}}\right) - \frac{\gamma^g}{N}g_1$*, and let* $g_1^* \coloneqq \frac{1}{\gamma^g}c^{-1}(r - r_D)$*. Under public loan provision in the absence of any de-risking subsidy (i.e.,* $s_1 = s_2 = 0$*), the set of Nash equilibria can be characterized as follows:*

- *Both a zero-financing Nash equilibrium and a symmetric equilibrium where each bank provides* $\max\left\{0, \min\{\frac{D-g_1}{N}, l_1^{*NE}|g\}\right\}$ *in* $t = 1$ *and* $\psi\frac{D-g_2}{N}$ *in* $t = 2$ *can exist.*
- *The zero-financing Nash equilibrium cannot exist if* g_1 *exceeds* g_1^* *(marginally) as long as* $g_2 \in [0, \psi D)$*.*
- *The higher* g_2*, the lower* $l_1^{*NE}|g$*, and the less likely it becomes that the Nash equilibrium with nonzero financing by each bank exists.*

Proof. See Appendix D.3. □

Hence, under public loan provision in $t = 1$, each bank provides either $\max\{0, l_1^{*NE}|g\}$ or $\frac{D-g_1}{N}$ (if this is lower) in $t = 1$ in the gradual-financing equilibrium, which is less than in the market outcome without the policy intervention. This is because public loan provision does not alter the best response function of each bank. If the government provides early-stage loans on top of the gradual-financing Nash equilibrium, then for every unit of g_1, each bank reduces their own costly early-stage financing by $\frac{\gamma^g}{N}$ and instead benefits from

the credit track record created by the public sector. By doing so, banks reduce their losses in $t = 1$ at the expense of the public sector while earning the same profits in $t = 2$. The higher the spillover rate γ^g, the better that public loan provision substitutes banks' own financing experience, exacerbating this crowding-out dynamic.

If $\frac{\gamma^g}{\tilde{N}} g_1 \geq l_1^{*NE}$, then the best response function of private banks flatlines at zero (see Figure 3) and private loan financing only occurs in $t = 2$. Only in this case, the financing experience available to each bank (and, hence, profits at $t = 2$) increases beyond the market outcome without policy intervention but at the expense of shifting early-stage loans entirely to the public sector. In all other cases, the best-response functions of banks ensure that the *financing experience* available to them remains identical to the market outcome (unless this is impossible given their demand constraint $\frac{D-g_1}{N}$). However, how the overall *amount of loans* issued in $t = 1$ evolves depends on the relative magnitude of the public loans' spillovers (γ^g), the market size (N) and the spillovers of commercial loans (γ). Banks learn less from public loans than from their own. Therefore, shifting early-stage loans from the private to the public sector requires a greater amount of public early-stage loans for the same level of experience if spillovers of public and commercial loans to other banks are the same ($\gamma^g = \gamma$) and even more so if $\gamma^g < \gamma$. However, if public loans' spillovers exceed those of commercial loans by a certain extent ($\gamma^g > \frac{\tilde{N}}{N}$), then fewer early-stage loans are required because banks learn so much more from the public loans compared to loans by their peers that it compensates them for having less experience from their own loans. Ceteris paribus, this condition is more likely to hold for markets with many banks ($N \uparrow$), which increases the share of experience banks obtain from observing peers (including the government loans) vis-a-vis the experience from their own loans.

As a result, public loan provision is an inept policy instrument to close the gap between a market outcome with nonzero loan financing and the social optimum unless favorable characteristics of the public loan provider, such as higher experience spillovers, make it attractive to concentrate early-stage loans on their balance sheet. Furthermore, public loan provision in $t = 2$ can only exacerbate the existing market failure. Reducing how much banks can lend at a later stage lowers the value of early-stage learning and hence the amount that banks are willing to lend—and might even undermine the existence of a gradual-financing Nash equilibrium altogether.

However, a certain minimum amount of public loan provision at $t = 1$ can overcome the coordination problem by ensuring that the no-financing equilibrium no longer exists. Note that for $g_1 = g_1^*$, the financing experience that spills over to banks is exactly the threshold for later-stage bankability since $r - c(\gamma^g g_1^*) = r_D$. Therefore, any $g_1 > g_1^*$ ensures that each bank provides $\psi \frac{D-g_2}{N}$ of loan financing at $t = 2$. Importantly, the required g_1^* decreases the more the public loan provider can diffuse its own financing experience to market players and the more willing private banks are to learn from the public sector

($\gamma^g \uparrow$). However, under $g_1 > g_1^*$ the cooperation problem not only continues to exist, such that the gradual-financing Nash equilibrium still falls short of the social optimum, but also the market outcome then features a strictly *lower* early-stage contribution by private banks due to free-riding.

6.4 Policy comparisons and policy mix

By Proposition 3, sufficient de-risking subsidy at $t = 2$ could also address the coordination problem, similar to early-stage public loans—which poses the question of which of the two policy measures is more cost-effective in our model. A key difference between the two policies is that, unlike for the de-risking subsidy, the money spent on public loan provision is (at least partially) recovered once loans are paid back. The accumulated financing experience might be turned into further profits at $t = 2$, albeit at the cost of crowding out commercial loans. To assess this, we define the costs of public loan provision as follows:

$$PC(g_1, g_2, l_1) \coloneqq (r_D^g + \bar{c} - r^g)g_1 - \beta^g \left(r^g - c(g_1 + \gamma N l_1) - r_D^g\right) g_2 \tag{16}$$

where the parameters $r^g, r_D^g > 0, \beta^g \in (0, 1)$ have the same meaning as for private banks. Policy costs can be understood as the negative of the public loan provider's profits. Note that here we allow for model parameters to vary between private banks and the public sector. For instance, the public loan provider might have a lower discount rate (such that $\beta^g > \beta$), a higher risk appetite (such that $r^g > r$), or access to capital at better rates than the private sector ($r_D^g < r_D$). By contrast, the opportunity cost of public money could also be higher ($r_D^g > r_D$) since funds for public loan provision could otherwise be invested in core public responsibilities, such as military defense or education, with high, albeit nonfinancial returns.

Furthermore, the cost of the de-risking subsidy paid at $t = 2$ in the absence of public loan provision is defined as follows:

$$PC(s_2) \coloneqq s_2 \, \beta^g \psi D \, r_D^g. \tag{17}$$

This reflects that resolving the coordination problem will lead to a policy-induced Nash equilibrium where $l_2^{NE} = \psi \frac{D}{N}$, and where the subsidy must be paid on all loans (ψD). Similarly to the funds for public loans, the money for de-risking subsidies must be raised from somewhere and comes at a cost r_D^g. Since policy costs only occur at $t = 2$, they are discounted at β^g.

We first compare the costs of the minimum public loan provision or second-period de-risking that necessarily rule out the coordination problem if the government parameters mirror the private sector's characteristics. Then we consider how deviations from this starting point change results, which results in the following finding:

Lemma 3. *Let $\epsilon > 0$, $g_1 = g_1^* + \epsilon$, and $s_2 = -r_1 + \epsilon$. Then, it holds that:*

- *If $g_1^* < \beta^g r_D^g \psi D$, the costs of the policy intervention g_1 are lower than the costs of the policy intervention s_2 if the costs of raising funds (r_D^g) and risk-adjusted loan return (r^g) for the public loan provision are identical to the rates faced by the banking sector.*

- *A higher r_D^g increases the policy costs of both measures, while the costs of providing g_1 also decrease in r^g and γ^g.*

- *If the return spread for public loan provision in $t = 2$, i.e., $r^g - c(g_1 + \gamma N l_1) - r_D^g$, is positive (negative), the costs of this policy intervention decrease (increase) in g_2.*

Proof. See Appendix E.1. Comparative statics can be derived directly from the definitions above. □

Even if the public loan provider does not differ systematically from commercial banks, public loan provision will be the cheaper policy instrument unless the public loan financing required to resolve the coordination problem exceeds $\beta^g r_D^g \psi D$ (i.e., the entirety of available loan demand at $t = 2$ plus financing costs discounted by one period). However, suppose the Nash equilibrium induced via public loan provision suffices to make loans at $t = 2$ profitable for the public sector. In that case, continued public loan provision in the second period can reduce policy costs, particularly if the public loan provider has lower risk aversion than private banks ($r^g \uparrow$). However, such later-stage loan provision would come at the cost of exacerbating the market failure. The more the public sector's learning gains spill over to private banks ($\gamma^g \uparrow$), the lower the amount of public loan provision required to resolve the coordination problem and, hence, the policy costs.

In conclusion, unlike de-risking subsidies, public loan provision cannot address the cooperation problem in our model, and later-stage loan provision even exacerbates market failures. However, early-stage loan provision can be used to overcome the coordination problem (i.e., to rule out the existence of an inferior no-financing Nash equilibrium) and is a more cost-effective measure to do so unless the required loan financing amounts are excessively large. Importantly, the effectiveness of public loans increases in the knowledge spillovers to private banks, while costs depend on the public sector's financing cost and risk aversion. Therefore, the case for this policy tool strongly depends on i) whether public loan providers are better at disseminating their learning to the market and tolerating risk, and on ii) which Nash equilibrium policymakers consider as more likely to be realized without any intervention, particularly since public loan provision will induce free-riding behavior by private banks to some degree. This free-riding effect in our model would be exacerbated by including price feedback if the additional supply of loans reduces market rates but would be less pronounced if financing experience from banks' own loans could not be fully substituted with experience spillovers from peers and the public sector.

These potential limitations of public loan provision as a stand-alone measure stem from banks' unaffected response function as they continue disregarding learning spillovers to peers. This can be addressed by combining public loan provision to rule out the zero-financing Nash equilibrium with the optimally calibrated de-risking subsidy at $t = 1$ in a policy mix:

Lemma 4. *Let $\epsilon > 0$ and the social optimum be $0 < l_1^{SO} < \frac{D}{N}$, and consider the following policy mix: $g_1 = g_1^* + \epsilon, s_1 = s_1^*, g_2 = s_2 = 0$. Then, it holds that:*

- *In the unique Nash equilibrium, each bank provides $\max\left\{0, \min\{\frac{D-g_1}{N}, l_1^{SO} - \frac{\gamma^g}{\tilde{N}} g_1\}\right\}$ in $t = 1$ (i.e., less than in the social optimum) and $\psi \frac{D}{N}$ in $t = 2$.*
- *The loan financing amount provided by each bank in the policy-mix equilibrium is higher than in the Nash equilibrium resulting from the same public loan provision $g_1 = g_1^* + \epsilon$ without the de-risking subsidy ($s_1 = 0$).*
- *If the characteristics of the public loan provider (r^g, r_D^g, γ^g) are identical to commercial banks, total bank profits net of policy costs in this equilibrium are lower than in the social optimum. This also holds for $\gamma^g \neq \gamma$ unless $\gamma^g \geq \frac{\tilde{N}}{N}$.*

Proof. See Appendix E.2. □

Such a policy mix, therefore, removes the risk of any no-financing Nash equilibrium and ensures a gradual-financing Nash equilibrium. From a private bank's perspective, this policy mix provides the same financing experience as in the social optimum unless γ^g is so low that ruling out the no-financing market outcome requires substantial amounts of public loans, leaving each bank with only $\frac{D-g_1}{N}$ that is insufficient to reach the socially optimal financing experience. In all cases, however, some of the financing burden shifts from commercial banks to the public sector to avoid the coordination problem.

How this affects overall profits and efficiency strongly depends on how the public loan provider and private banks differ in terms of their characteristics. If the only difference between banks and the public loan provider is a very high γ^g, then early-stage loans by the public loan provider come with the same negative return spread but, unlike commercial loans, spill over near-perfectly to other market participants. In this case, it is clearly beneficial to concentrate early-stage loans at the public sector and hence, the policy mix described above increases overall profits. By contrast, if $\gamma^g = \gamma$, then the public loan provider can be seen as just another bank (although with policy-stipulated behavior) and the policy mix reduces efficiency vis-a-vis a gradual-financing Nash equilibrium with optimal de-risking for two reasons. First, the number of banks increases by one, leading to more spillover losses. Second, the additional bank (i.e., the public loan provider) behaves asymmetrically, whereas a symmetric allocation of early-stage loans among banks would ensure more learning gains for everyone. Such dynamics are exacerbated for $\gamma^g < \gamma$. If γ^g equals exactly $\frac{\tilde{N}}{N} \in (\gamma, 1)$, then the efficiency losses and the gains of concentrating loans

at public sector entities with higher spillovers cancel each other out and total profits net of policy costs equal exactly the same as in the social optimum.

Similar considerations can be applied if the public loan provider has lower financing costs ($r_D^g < r_D$) or is less risk-averse and hence obtains a higher risk-adjusted return ($r^g > r$), which can either reduce the price tag of addressing the coordination problem or, for very beneficial characteristics, make it efficient to shift early-stage loans entirely to the public sector. In any case, however, the loan financing amount provided by private banks under the policy mix of public loan provision and the optimally calibrated first-period de-risking subsidy is higher compared to public loan provision as a stand-alone measure and is, therefore, more effective.

In our model framework, the relative merits of later-stage de-risking subsidies to address the coordination problem are primarily that more financing experience is generated directly within the private sector. This is because no crowding-out occurs and the policy instrument induces no free-riding behavior. Therefore, the social optimum can be obtained, albeit at a relatively high policy cost, if the policy is successful.

Beyond policy costs, direct loan provision has at least two distinctive advantages. First, an institutionalized public loan provider can easily be re-directed to other novel technologies as they emerge and pose new coordination problems for the financial sector. By doing so, institutions can leverage their previous financing experience even if high opportunity costs and crowding-out risks should force them to withdraw from matured technologies. If new technologies emerge and the institution's mandate is sufficiently flexible, then private debt markets for these technologies can be kickstarted without the need for introducing additional policies, which can accelerate the ramp-up of deployment. If no such technologies emerge, then selling the public loan provider to the private sector, as the UK did with its UK Green Investment Bank in 2017 (Whitney et al., 2020), can further provide an exit strategy to (partially) recover policy costs by monetizing the accumulated in-house experience.

Second, addressing the coordination problem through early-stage loan provision avoids the issue of time inconsistency on the government's side. By Proposition 3, a sufficiently high de-risking subsidy at $t = 2$ suffices to avoid an inferior no-financing equilibrium. However, once the second period begins, banks have already provided the required early-stage loan financing. Therefore, merely the *anticipation* of the support policy at $t = 2$ rules out the no-financing equilibrium. The actual payment of s_2 does not affect total profits and instead simply redistributes money from the public to the private sector. As a result, policymakers could be tempted to go back on their promises, which in turn will reduce policy effectiveness if banks assign a nonzero probability to such an outcome ex ante. Similar concerns exist with respect to public loan provision at $t = 2$. A government that initially promised to phase out loan provision once the novel technology becomes bankable might be tempted to keep providing loans in $t = 2$ when they become

profitable. These considerations seem particularly relevant for countries with lower institutional quality and low trust in the public sector or with highly bipartisan politics on climate change, such that elections pose severe risks of policy reversal. It also matters for countries with lower creditworthiness that might be forced by adverse macroeconomic shocks to revoke expensive support policies —as happened to renewable energy subsidies in Spain and Italy following the Euro crisis (Karneyeva & Wüstenhagen, 2017)—and for technologies with a lower later-stage demand potential ψ where public loan volumes can account for high market shares.

7 Numerical application

To illustrate the applicability of the theoretical considerations above to realistic policy contexts, we calibrate our model to the bank loan market for offshore wind projects in Germany. We select offshore wind for several reasons. Compared to onshore wind and solar photovoltaics, it is a more recent technology with relatively low deployment in most markets. It is generally viewed as riskier due to long and logistically challenging construction periods and large project sizes (Dukan et al., 2023). These characteristics translate into higher financing costs charged by banks and investors (Calcaterra et al., 2024; Steffen, 2020). As a result, offshore wind has been subject to substantial financial policy interventions, with state investment banks like the European Investment Bank involved in over two-thirds of new-build projects in OECD countries (Waidelich & Steffen, 2024) and several public financial institutions having loan programs and funds specifically for offshore (Geddes et al., 2018). Lastly, offshore wind remains a financially immature technology in many key markets, including the United States, which makes our numerical application relevant for policymaking.

We focus on offshore wind financing in Germany for several reasons. First, it is relatively straightforward to identify the early-stage phase of the deployment ramp-up (see Figure 9 in Appendix F). Investment began in 2007 and by 2010, the first commercial offshore wind farm, Alpha Ventus, began operations. Subsequently, several other projects reached financial close, sparking a sudden ramp-up of deployment with annual capacity additions jumping from 80 MW in 2012 to 2.3 GW in 2015 when several projects reached commissioning (Umweltbundesamt, 2024). From there on, roughly one gigawatt of capacity was installed every year until the COVID-19 pandemic, during which deployment declined again. Second, there is detailed evidence from interviews with developers, financiers, and consultants on the sector's early-stage struggles to secure financing, including banks' lack of technical expertise, and how these struggles had mostly faded by the mid-2010s (Geddes et al., 2018). Third, financing costs for German renewable energy projects have been studied extensively (Egli, 2020; Egli et al., 2018; IRENA, 2023; Kitzing & Weber, 2015), leading to relatively high data availability (Steffen, 2020). Fi-

nally, the German state investment bank Kreditanstalt fuer Wiederaufbau (KfW) and the European Investment Bank, two key providers of public loans and de-risking measures (through guarantees and concessional financing terms), were very active during the early stage of the market ramp-up (more details below). For these reasons, German offshore wind represents a well-suited application for our model.

Offshore wind projects typically take around five years from obtaining permits to commissioning in OECD countries (Gumber et al., 2024). As financiers continue to gain experience after commissioning, learning about the accuracy of wind resource estimations and generation interruptions (Egli, 2020), we assume that it takes six years until most learning gains to lenders have materialized. As investments commence in 2007, we, therefore, define the early-stage period $t = 1$ as 2007–2012 and the later-stage period $t = 2$ as 2013–2018, which avoids any pandemic-related distortions. These period definitions align well with Geddes et al. (2018) distinguishing two phases of offshore wind financing in Germany prior to 2012 and afterward.

The parameters used to apply our model to the case of German offshore, along with the underlying sources, are listed in Table 1. Since credit-rationed demand cannot be directly observed (Jaffee & Stiglitz, 1990), we estimate period-specific loan demands based on observed investments and average debt shares of German offshore wind projects. We use an average weighted cost of capital for European banks as a discount rate and estimate the number of banks based on how many banks lent repeatedly to German offshore wind projects through 2018. The extent of experience spillovers between banks is not readily observable. Given that banks typically form large loan syndicates for offshore wind transactions and interact frequently, we assume that 20% of experience spills over and use average deposit rates for Germany as banks' financing cost.

The most challenging part of the calibration is how much banks earn beyond this rate, how high immaturity-related costs and risk premiums are, and how much risk-adjusted returns improved through experience. Since financing terms are highly confidential and even banks themselves may struggle to quantify how financing experience has shaped their willingness to lend and their transaction costs, any such calibration will be inevitably imperfect. We address this issue as follows. First, we take debt margins for three early-stage offshore wind deals in Germany (3.25%) from Kitzing and Weber (2015) and for 2020 offshore deals (1.81%) as well as for deals in a fully mature market like Denmark (1.50%) from IRENA (2023), implying that market maturity can decrease debt margins by up to 1.75 percentage points.[22] Using these data points, we fit a learning curve for offshore wind debt margin premiums over the 1.5% value at full maturity and relate them to banks' cumulative financing experience in a given year, based on the empirically observed investments in Germany (ZSW, 2024). As a functional form for this learning

[22]Following Egli et al. (2018), we consider debt margins vis-a-vis a risk-free rate, such as the yield of ten-year government bonds, to avoid fluctuations in the general interest rate level distorting our learning curve.

Table 1: Calibrated parameters

#	Parameter	Value	Source
1	Years per period	6	Accounting for up to five years of commissioning time for offshore (Gumber et al., 2024) and first year(s) of operations until learning gains are fully realized. Periods represent 2007–2012 ($t = 1$) and 2013–2018 ($t = 2$)
2	D	EUR 2.92 bn	Based on 2007–2012 investments (ZSW, 2024) and a debt share of 62% for early-stage DE offshore wind projects (Kitzing & Weber, 2015). All monetary values are converted to 2021 EUR using the producer price index for industrial products by Destatis (2024)
3	ψ	$6.38 = \frac{18.65}{2.92}$	Based on 2013–2018 investments (ZSW, 2024) and a later-stage debt share of 73% for DE offshore wind projects (IRENA, 2023)
4	β	$0.79 = \frac{1}{1.04}^6$	Based on a 4% weighted average cost of capital for European commercial banks taken from Damodaran (2024)
5	N	15	No. of lenders (excl. KfW & EIB) involved in ≥ 3 DE offshore wind deals through 2018 in BNEF (2022), which are listed in Table 3 in Appendix F
6	γ	0.2	Author assumption based on the prevalence of loan syndicates for DE offshore wind
7	r_D	2.07%	DE rate for deposits with a maturity of over two years, taken from Bundesbank (2025) and averaged across 2007—2018
8	r	2.27%	Assuming a typical 0.2% profit margin for bank loans without financial immaturity based on World Bank (2022) data on German banks' average pre-tax return on assets throughout 2007–2018 (see Appendix F)
9	$\bar{c}$	0.44%	Based on a 1.75% debt margin premium of DE offshore wind in 2010 (Kitzing & Weber, 2015) relative to fully matured markets (IRENA, 2023) and an 80% pass-through rate for German banks (Heckmann-Draisbach & Moertel, 2020) to infer cost reductions not passed through to projects. For more details, see Appendix F
11	b (Wright's Law)	0.344	Calibrated to reproduce observed debt margin reductions for DE offshore wind between 2010 and 2020 (IRENA, 2023; Kitzing & Weber, 2015) based on annual debt provisions. For more details, see Appendix F
10	$\tilde{L}_0$ (Wright's Law)	EUR 28 m	Cumulative debt provision until 2010, adjusted for experience spillovers and gradual experience gaining. For more details, see Appendix F
12	$c\left(\frac{\tilde{N}}{N}D\right)$	0.14%	Direct implication of the parameters above

curve of debt margins DS_a in year a, we use a Wright's Law curve, meaning that for every doubling of cumulative experience from loans to German offshore projects, $c(\cdot)$ decreases by a constant rate with the 2010 value as a baseline:

$$DS(\tilde{L}_a) = DS_{2010}\left(\frac{\tilde{L}_a}{\tilde{L}_{2010}}\right)^{-b}, \tag{18}$$

which results in a b estimate of 0.344 (i.e., costs decrease by $1-2^{-b} = 21\%$ if experience doubles). Wright's Law is the predominant learning curve for technological learning and also among the few studies that model financing experience feedback for novel low-carbon technologies (Campiglio et al., 2024; Egli et al., 2018; Way et al., 2019).

The learning curve above gives us an estimate for the pace of cost reductions but relates to debt pricing, that is, cost reductions passed through to offshore wind projects. By contrast, the learning curve $c(\cdot)$ in our model indicates how banks' margins change based on cost reductions that are not passed through (as the model assumes for simplicity that banks appropriate rents). Using a pass-through rate estimate of 80% for German bank loans (Heckmann-Draisbach & Moertel, 2020), we convert the maximum debt margin shift of $3.25 - 1.5 = 1.75\%$ since 2010 and estimate the cost reduction that banks

pocketed as $1.75\%\frac{20\%}{80\%} = 0.44\% = \bar{c}$. Then, we use the same learning rate parameter b estimated for the observed debt margins for the immaturity-related cost reductions that are not passed through. Lastly, we assume that at full maturity ($\tilde{L}_t \to \infty$ such that $c(\cdot) \to 0$), banks can obtain a typical profit margin of 0.2% based on average profitability margins for German banks throughout our modeling period (World Bank, 2022). Given that $c(\cdot)$ is non-negligible for 2013–2018 loans in our calibration even if all early-stage loan demand is served (0.14%), this is a rather conservative calibration, particularly given that we do not consider potential consumer rents to offshore wind projects (and their electricity off-takers) due to debt spread reductions that are passed through.

Figure 5 illustrates the model dynamics for our numerical application without policy intervention. IRENA (2023) did not consider the German offshore wind market fully matured by 2020, which is reflected by the fact that our 2007–2012 demand of $D = 2.92$ billion can drive down $c(\cdot)$ only to 0.14% (Figure 5a), implying a profit margin of 0.06% for 2013–2018 loans instead of the 0.2% at full maturity (Figure 5b). If banks behave symmetrically, roughly one billion of early-stage loans is required to ensure bankability in the 2013–2018 period. Accounting for spillover losses, this amount is equivalent to approximately EUR 250 million of each bank's own loans in terms of experience—almost a tenth of the entire loan demand in the 2007–2012 period. Therefore, if all other banks provide no loans, then the sheer amount of financing required to unlock bankability makes it a best-response for bank i to not provide loans either (Figure 5c), meaning that a zero-financing Nash equilibrium exists.[23]

[23]Note that the bankability threshold in Figure 5c is higher than in Figure 5b because loan provision by all other banks, excluding bank i, are displayed, whereas Figure 5b and Figure 5d assume symmetric behavior. For all other banks to push bank i beyond the bankability threshold, this requires more loans than if bank i also provides loans.

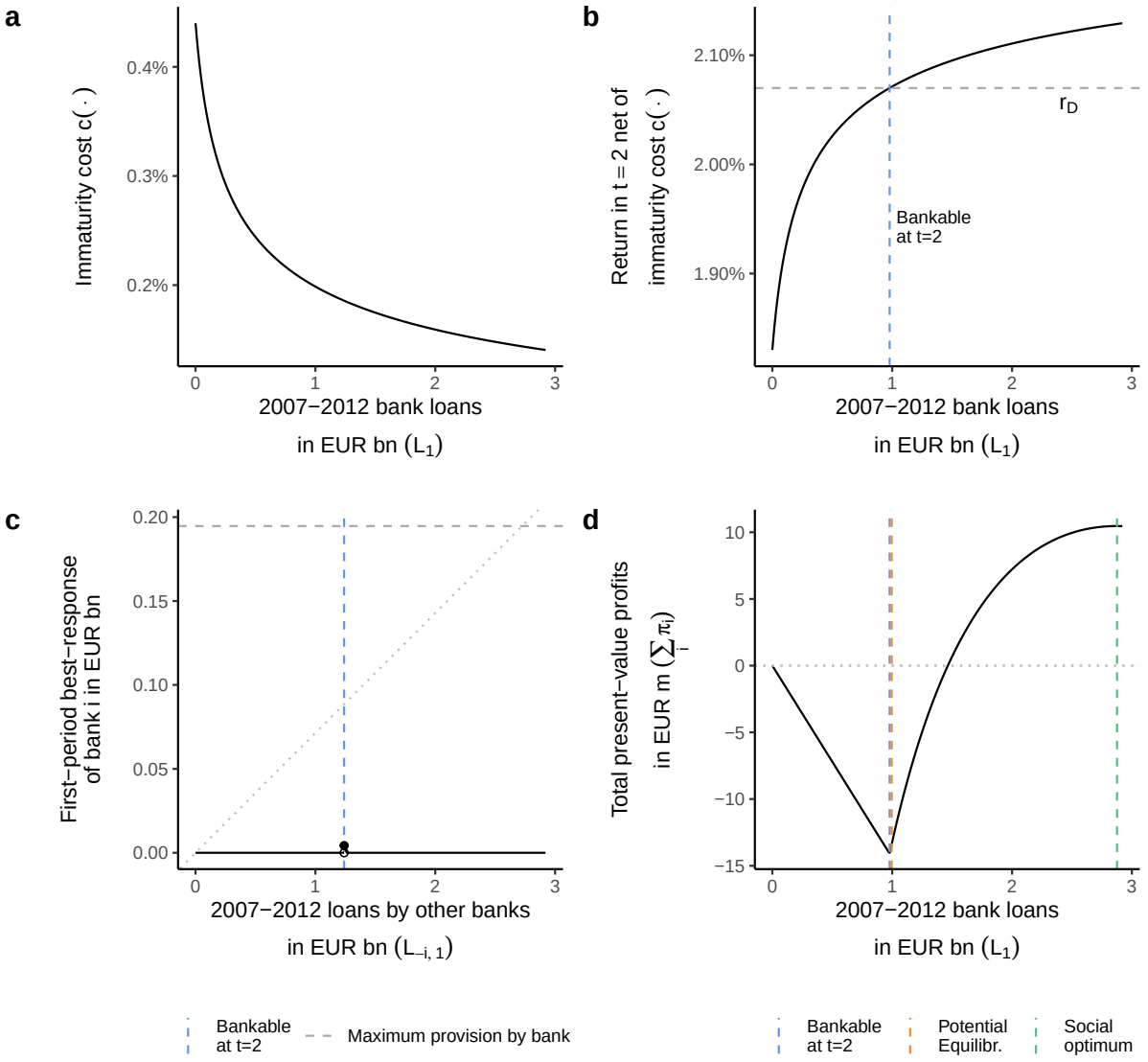


Figure 5: Model application to offshore wind in Germany over 2007–2018 without policy interventions

If other banks provide a financing experience almost equivalent to the EUR 250 million of own loans, the best-response function jumps up but only marginally, meaning that there is no gradual-financing equilibrium as a possible market outcome. Total present-value bank profits have the typical J-shape and peak slightly below D at $L_1^{SO} = 2.88$ billion (Figure 5d, green line), which leads to present-value profits of around EUR 10 million. By contrast, the potential Nash equilibrium with non-zero loan financing (orange line) implies losses of EUR 13 million and hence does not exist.

Our theoretical considerations show that in such a case, public loan provision can rule out the no-financing equilibrium and create another Nash equilibrium with bank loans. To calibrate the amount of early-stage public loan provision (g_1), we review the European Investment Bank's project database and KfW's financial reporting and find a

total of $g_1 = 1.63$ billion provided to German offshore wind projects through 2011 (for more details, see Appendix F).

Under the assumption that spillovers of public loans are identical to those of commercial ones, these public loans put the banking sector comfortably past the bankability threshold. However, since they also push banks beyond the point where their own learning gains are high enough to warrant costly early-stage loans, banks in our model would respond to this loan provision by simply free-riding the public loans, no matter what their peers do (Figure 6a). As bankability at $t = 2$ is ensured by the public loans, bank profits are no longer J-shaped and, instead, monotonically increasing. The free-riding Nash equilibrium arising from public loans as a stand-alone intervention (orange line) yields profits of EUR 14 million for banks, but this is below the costs of these substantial public loans (EUR 23 million). However, if loans are paired with a de-risking measure that internalizes experience spillovers ($s_1^* = 0.18\%$), banks meet the remaining loan demand of EUR 1.3 billion, leading to a policy-induced immediate-financing equilibrium (green line).

Importantly, several policy measures were in place to de-risk German offshore wind projects. First, the loan conditions by KfW and EIB are concessional, reducing the debt service burden for projects and hence their default risks, which benefits commercial co-lenders (Geddes et al., 2018). Second, aside from guarantees by KfW, offshore wind projects regularly receive credit guarantees by public export credit agencies, such as the Danish EIFO (Censkowsky et al., 2025). Third, the German feed-in tariff scheme for renewables protects electricity producers against market price and off-taker risks. While it is not straightforward to quantify the effect of such de-risking policies, risk premiums charged for credit guarantees by the World Bank's Multilateral Investment Guarantee Agency range between 0.5% and 1.5% (Steffen & Schmidt, 2020). Assuming for simplicity that these premiums charged simply equal the return-equivalent benefit to banks and accounting for our pass-through rate assumption of 80%, this would put the de-risking benefits of such guarantees to banks at around 0.1-0.3%. Therefore, it is plausible that existing policy interventions beyond sheer loan provision provided a de-risking effect similar to our estimated s_1^*.

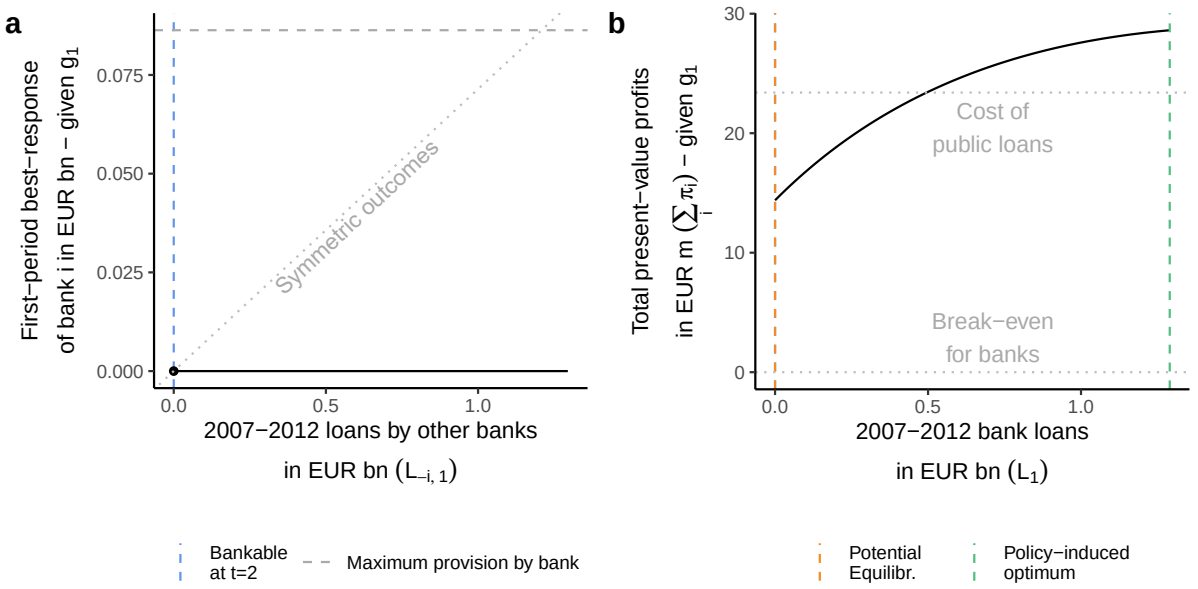


Figure 6: Bank profits given the empirically observed activity of KfW and EIB

For the policy mix of $s_1^* = 0.18\%$ and $g_1 = 1.63$ billion, banks obtain EUR 29 million of profits. Net of the public loan costs of EUR 23 million, this is lower than profits in the social optimum without policy intervention (EUR 10 million) because pushing the banking sector beyond the bankability threshold comes at the cost of banks learning less from their own loans. This result, however, rests on the conservative assumption that knowledge spillovers from KfW and EIB are the same as for commercial loans. In contrast, there is interview-based evidence that KfW's subsidiary KfW IPEX began providing technical and risk assessment services to the industry in the early 2000s, was involved in nearly every offshore wind project since the first Alpha Ventus wind farm and often took a lead role in bank syndicates where they shared their expertise with commercial co-lenders (Geddes et al., 2018). In our calibration, assuming that $\gamma^g = \frac{\tilde{N}}{N} = 25.33\%$ of public loans' experience spills over (compared to the 20% of commercial loans) suffices to ensure that profits net of public loan costs reach the same amount as a social optimum where the public loan provider does not exist. Importantly, such a calculation assumes that a higher $\gamma^g > \gamma$ comes at no cost to the public sector. In reality, however, policymakers likely face a trade-off between spending resources on loans, knowledge dissemination (e.g., through technical assistance to financiers), and other policy objectives. However, our results are in line with the theoretical reasoning that increasing γ^g is a key lever to ensure policy effectiveness and that rather small differences in experience spillovers between public and commercial loans can reduce or overcome profit losses related to crowding out commercial loans.

As our model's policy implications depend on parameters beyond γ^g, we explore sensitivities with respect to key assumed parameters in Figure 7. Red lines denote the socially optimal amount of early-stage loans, with values of EUR 2.92 billion indicating immediate-financing outcomes. Blue lines show the market outcome without policy in-

tervention, with a dashed line used if the gradual-financing outcome displayed is not the only possible Nash equilibrium. Mirroring our theoretical considerations, low demand growth (Figure 7a) and high discount rates of banks (Figure 7b) can lead to the decrease and collapse of the gradual-financing optimum. At the same time, changes in the shape of the learning curve $c(\cdot)$ have more drastic implications, with no-financing becoming optimal for low learning rates and high initial immaturity costs. For b and $\bar{c}$, however, it is important to keep in mind that the unilateral changes displayed here mean that the resulting learning curves are no longer consistent with the empirical debt margin reductions used for calibration. A gradual-financing Nash equilibrium exists under more generous calibrations but is typically not unique except if initial immaturity costs are much lower such that even small amounts of experience ensure bankability.

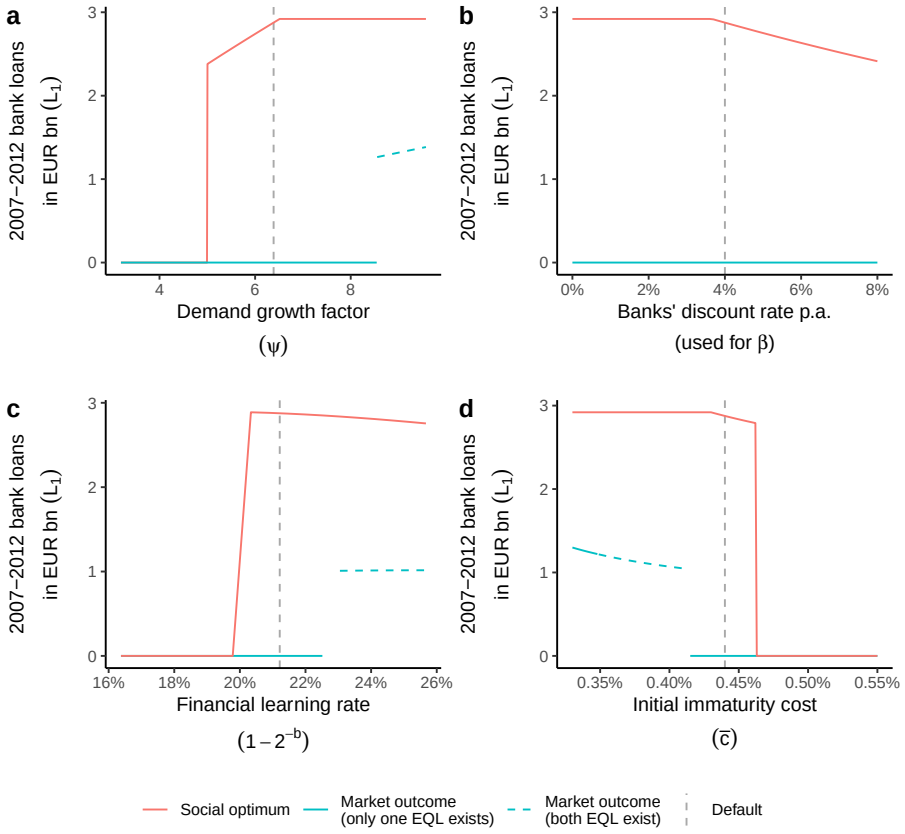


Figure 7: Sensitivity of model outcomes to key parameters

Overall, our numerical application is by no means the only possible calibration of the model and, due to the non-observable nature of many parameters, should be interpreted with caution. Nevertheless, it illustrates several key findings. First, plausible calibrations produce outcomes consistent with empirically observed policy patterns for German offshore wind, namely that early-stage commercial lending was initially unattractive for banks, but bankability and market ramp-up could be obtained through public loans for a few early-stage projects combined with additional de-risking measures. Second, the sensitivity checks highlight that for most calibrations, there is no unique Nash equilibrium with

non-zero financing. Hence, the rationale for public loan provision to push the banking sector away from a non-financing outcome exists. Third, even minor differences between public loan providers and commercial banks can motivate public loan interventions as a coordination device if they disseminate experience more effectively, while the extent of possible financial learning, initial risk-return characteristics, and foreseeable demand growth are key determinants of whether or not policy interventions are desirable.

8 Model extensions

8.1 Positive climate externality of clean energy projects

In our main setup, we assume that technology-level externalities of clean energy projects (e.g., reduced greenhouse gas emissions, learning-by-doing spillovers on technology costs) are addressed through first-best policies, such as carbon pricing. This setup serves to clarify our model's case for financial policy interventions if such first-best policies are already adopted. However, policymakers often justify green financial policy interventions through the social benefits of green investment projects. In addition, first-best carbon pricing may face considerable political constraints and opposition, which hinders implementation and stringency.

To reflect such non-financial considerations, we extend our model and assume that bank financing enables clean energy projects, meaning that at least some of the projects that make up the total loan demand D will not be realized if they do not obtain loans. In this case, each loan contributes to a lower carbon intensity of the electricity grid. If the positive climate externalities of clean energy projects (or the negative externalities of their fossil fuel-based competition) are not fully addressed through the first-best carbon price, then each loan comes with a positive climate externality which we assume to manifest as a fixed proportion $\tau \geq 0$ of provided loan volumes.[24] As a result, the external climate benefits of loans to the novel clean energy technology given out by bank i can be written as

$$\tau \left(l_{i,1} + l_{i,2} \right). \tag{19}$$

In our model, the socially optimal amount of loans then maximizes the sum of banks' present-value profits and the positive climate externality caused by their loans:

$$\max_{\{l_{i,1}, l_{i,2}\}_{i=1}^{N}} \sum_i \pi_i(l_{i,1}, l_{i,2}, \tilde{L}_{i,1}) + \tau(l_{i,1} + \beta l_{i,2}) \qquad \text{s.t. } l_{i,1} \in [0, \frac{D}{N}], l_{i,2} \in [0, \psi \frac{D}{N}]. \tag{20}$$

[24] Assuming a constant τ seems reasonable because the contribution of bank financing in a given market to global emission reductions is likely small, such that a local linear approximation of a potentially non-linear climate damage function is appropriate. For simplicity, we also omit that banks themselves may bear some of the avoided climate damage through physical risks (Campiglio et al., 2023).

For a social optimum that involves gradual or immediate financing, the first-order conditions require the following once we impose that the social optimum is symmetric:

$$\underbrace{\tau}_{\substack{\text{Climate}\\ \text{externality}}} \quad \underbrace{- \beta \tilde{N} c'(\tilde{N} l_1^{SO}) \psi \frac{D}{N}}_{\text{Learning gains to banks}} \geq \underbrace{\quad - r_1 \quad}_{\substack{\text{Initial return spread}\\ (= \text{loss})}}, \tag{21}$$

$$r - c(\tilde{N} l_1^{SO}) + \tau > r_D \tag{22}$$

Note that Equation 21 holds with equality (inequality) for a gradual-financing (immediate-financing) optimum and that both the left- and right-hand side are positive since $c' < 0$ and $r_1 < 0$.

Equations 21 and 22 illustrate that the climate externality works essentially as a premium on loan returns in both periods from a social point of view, reducing the negative return spread at $t = 1$ (r_1) and the amount of financing experience required to achieve bankability at $t = 2$. Therefore, the externality makes a no-financing optimum less and an immediate-financing optimum more likely and increases the amount of loan provision under a gradual-financing optimum.

Visually speaking, the concave section of the welfare function, defined as bank profits plus climate benefits, remains concave (due to diminishing returns to financing experience) but with a steeper upward slope so any potential peak for a gradual-financing optimum shifts to the right and reaches a higher value of welfare. If $\tau \geq -r_1$, then loans are socially desirable even if banks cannot learn over time. In this case, Equation 21 cannot hold with equality and, hence, it will always be socially optimal to serve the entire loan demand in both periods, no matter the losses to banks. As a result, the sum of bank profits and climate benefits (i.e., the social objective function) is no longer J-shaped and, instead, increases monotonically and concavely in L_1. If $\tau < -r_1$, then the climate externality shifts the bankability threshold to the left, and reduces the downward slope of welfare before this point is reached.

In contrast, banks do not consider the climate externality and their first-order conditions, as well as the potential Nash equilibria that arise, remain unchanged. Therefore, as in Section 5, we can express the minimum financing gap for a gradual-financing social optimum as follows:

$$\frac{l_1^{SO}}{l_1^{*NE}} = \frac{(c')^{-1}\left(\frac{r_1+\tau}{\beta\psi\frac{D}{N}\tilde{N}}\right)}{(c')^{-1}\left(\frac{r_1}{\phi\beta\psi\frac{D}{N}}\right)}. \tag{23}$$

which implies that the minimum financing gap between social optimum and market outcome increases monotonically in τ.[25]

[25]To see this, note that $(c')^{-1}$ takes negative input values and is monotonically increasing. If $\tau < -r_1$,

As a result, the climate externality exacerbates the potential market failures, but it does not fundamentally change the underlying model dynamics or the potential social optima and market outcomes. Therefore, the policy implications of such an externality in our model can be easily derived. First, all climate benefits of clean energy projects arise at the technology level and, hence, outside of the banking sector (unlike the learning spillovers). Therefore, the canonical first-best solution to this market failure is Pigouvian carbon pricing at the technology level, which improves the competitiveness of clean energy projects vis-a-vis fossil fuel incumbent technologies, and hence, the risk-return characteristics of these projects. Extant literature has shown that if such a carbon price is unfeasible or insufficient, green financial policies can be one (of many possible) second-best measures to increase welfare (Haas & Kempa, 2023). In our model, this can be reflected by setting de-risking measures s_1 and s_2 such that

$$s_1 = s_1^* + \tau$$

and

$$s_2 = \tau$$

where s_1^* is optimal de-risking in the absence of climate externalities. As a result, banks internalize the climate externalities of their lending decisions. If $\tau \geq -r_1$, then it is socially optimal to provide as many loans as possible, and the de-risking policy given above will achieve this, as de-risked early-stage loans are now profitable. If $\tau < -r_1$, then we are back to the previous result that an inferior Nash equilibrium with no financing may exist if no bank can unilaterally push past the bankability threshold and break even given s_1 and s_2. However, due to $s_2 = \tau$, this threshold is strictly lower than without the policy intervention, making it less likely, ceteris paribus, that public loan provision is required.

To quantitatively assess the role of a climate externality, we build on our numerical application in Section 7 and add estimated climate benefits of German offshore wind projects by replacing more CO_2-intensive power generation into the equation. The input parameters used are displayed in Table 2 and result in an estimate of $\tau = 0.23\%$ (for a step-by-step description, see Appendix F.6). This estimate almost exceeds $r_1 = -0.24\%$ even without learning gains, reinforcing immediate financing as the socially optimal outcome. At the same time, the Nash equilibrium without policy intervention remains the same no-financing outcome as in Section 7. However, if τ were internalized through $s_1 = s_1^* + \tau = 0.41\%$, early-stage loans are immediately profitable for banks, and the unique Nash equilibrium in the model is an immediate-financing outcome, with no further need for policy interventions. This illustrates that, as one would expect, climate exter-

then adding τ in the numerator leads to a less negative input value for the function and, hence, increases l_1^{SO}. If $\tau \geq -r_1$, then the social optimum is immediate financing and $l_1^{SO} = \frac{D}{N}$.

nalities of clean energy projects likely trump the potential benefits of financial learning through reducing banks' costs and unlocking profitable investments. Therefore, these results suggest that the financial policy interventions in our model are probably second-order compared to a carbon price.

Table 2: Parameters used to estimate the unpriced climate benefit of German offshore wind projects

#	Parameter	Value	Source
1	Carbon intensity (DE grid)	0.6265 tCO2e/MWh	Icha and Lauf (2024), Table 2; 2007–2018 average
2	Carbon intensity (DE offshore wind)	0.0073 tCO2e/MWh	Hengstler et al. (2021), Table 92
3	Capacity factor (DE offshore wind)	27.2%	Annual capacity factors calculated based on Umweltbundesamt (2024), Tables 3.1 & 4, averaged across 2009–2018 (generation commences in 2009)
4	Installed capacity	6,393 MW	Installed capacity through 2018 based on Umweltbundesamt (2024)
5	Total investment (incl. equity)	EUR 30.25 billion	Cumulative investment through 2018 (ZSW, 2024)
6	Social cost of carbon	84.95 EUR/tCO2e	Umweltbundesamt (2007); original value of EUR_{2007} 70 converted to EUR_{2021} based on Destatis (2024)
7	EU ETS price	10.74 EUR/tCO2e	European Environment Agency (2024); 2007–2018 average
8	τ	0.231% p.a.	Author calculations based on inputs above. Fore more details, see Appendix F.6

8.2 Uncertain demand growth

In our main setup, all parameters are known to banks and policymakers ex ante. However, the prospects of novel technologies in terms of deployment and resulting loan demand are uncertain. Therefore, we assume that the between-period demand growth in our model is a random variable with any distribution whose first and second moments exist. Let κ denote the bankability threshold for $\tilde{L}_{i,1}$ to ensure profitability at $t = 2$. Then expected profits are as follows:

$$\mathbb{E}[\pi \mid l_{i,1}, \tilde{L}_{i,1}] = \begin{cases} r_1 l_{i,1} + \beta(r - c(\tilde{L}_{i,1}) - r_D)\mathbb{E}[\psi]\frac{D}{N} & \text{if } \tilde{L}_{i,1} > \kappa \\ r_1 l_{i,1} & \text{otherwise.} \end{cases}$$

This setup reflects that with uncertain demand growth, first-period losses remain certain, but potential gains that could be obtained if demand growth occurs are uncertain. If we assume that banks are not risk-averse and simply maximize expected profits, it is straightforward to see that all first-order conditions will be equivalent to our main setup, with the only difference being that ψ is replaced by its expected value $\mathbb{E}[\psi]$. Therefore, a lower demand growth *expected by banks* will make it less likely that loan provision is socially optimal and, if it is, reduce the optimal loan amount in a gradual-financing outcome. In addition, if banks have a biased notion of $\mathbb{E}[\psi]$ (e.g., if the banking sector is too skeptical or bullish regarding the novel technology), this can lead to additional

deviations of the market outcome from the social optimum.

If banks are risk-averse, they will consider not just the mean but also the dispersion of the profit distribution, whose variance is given by

$$\mathbb{V}[\pi \mid l_{i,1}, \tilde{L}_{i,1}] = \begin{cases} \left(\beta(r - c(\tilde{L}_{i,1}) - r_D)\frac{D}{N}\right)^2 V[\psi] & \text{if } \tilde{L}_{i,1} > \kappa \\ 0 & \text{otherwise.} \end{cases}$$

If financing experience remains below the bankability threshold, profits are certain and the variance term takes the value of zero. Above the bankability threshold, a higher $\tilde{L}_{i,1}$ increases bank i's profit margin at $t = 2$ and hence the squared term that is multiplied by $\mathbb{V}[\psi]$, such that the variance of profits increases.

For simplicity, we assume that banks' utility from their profits is the expected profit minus a risk premium that scales in the variance of profits, which can be motivated through Expo-CARA preferences. The social planner then solves

$$max \sum_i \mathbb{E}[\pi]_i - \theta \mathbb{V}[\pi]_i$$

where $\theta > 0$ denotes the extent of banks' absolute risk aversion.

This results in the following first-order condition for optimal early-stage loan provision:

$$-\beta\Big(\underbrace{c'(\tilde{L}^{SO}_{i,1})l^{SO}_{i,2}}_{\substack{\text{Learning gain} \\ \text{to bank } i}} + \underbrace{\gamma \sum_{j \neq i} c'(\tilde{L}^{SO}_{j,1})l^{SO}_{j,2}}_{\text{Learning gain to peers}}\Big) - \underbrace{\theta\Big(\frac{\partial \mathbb{V}[\pi]_i}{\partial l_{i,1}} + \sum_j \frac{\partial \mathbb{V}[\pi]_j}{\partial l_{i,1}}\Big)}_{\text{Marginal risk premium on } l_{i,1}} = \underbrace{-r_1}_{\substack{\text{Initial return spread} \\ (= \text{loss})}} \tag{24}$$

The derivative of the variance of profits in this condition is analytically close to intractable as it involves the partial derivative of $(r - c(\tilde{L}_{i,1}) - r_D)^2$, a quadratic of a concave function with no specific functional form. However, if we rely on the common Wright's Law specification for $c(\cdot)$ and the parameters from our numerical application to German offshore wind from Section 7, Figure 8 shows that the variance scales almost linearly in $\tilde{L}_1 = \frac{\tilde{N}}{N} L_1$ over the relevant learning range. In our specific case, we assume that ψ follows a binary distribution and takes the value of our numerical application with a probability of 50% and otherwise equals zero (i.e., the ramp-up of German offshore wind collapses entirely).[26] Notably, the range below the bankability threshold (dotted line) is irrelevant because, as we laid out above, $\mathbb{V}[\pi]$ is zero below this threshold since the outcome at $t = 2$ (i.e., zero loans and profits) is known with certainty. At the threshold, the variance of profits is zero and then increases approximately linearly in L_1.

[26] Setting the probability to 50% is a conservative assumption because it maximizes the variance of ψ.

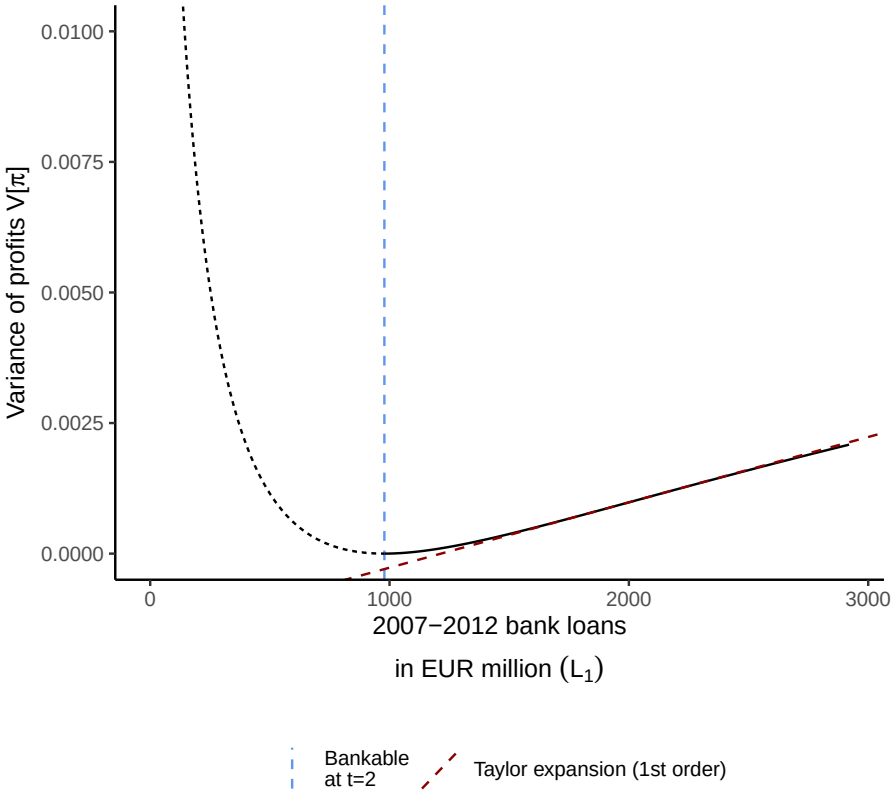


Figure 8: Variance of profits for our numerical application to German offshore wind

Assuming that $(r - c(l_{i,1} + \gamma L - i, 1) - r_D)^2$ can be approximated by a first-order Taylor expansion, its partial derivative with respect to $l_{i,1}$ is approximately equal to a constant gradient α. Using this approximation and imposing symmetry in the social optimum, we can rewrite the first-order condition from above to

$$-\beta \tilde{N} c'(\tilde{L}_i^{SO}) \mathbb{E}[\psi] \frac{D}{N} - \theta \tilde{N} \mathbb{V}[\psi] \left(\beta \frac{D}{N}\right)^2 \alpha = -r_1. \tag{25}$$

That is, the marginal risk premium is simply a product of exogenous parameters that detracts from second-period learning gains once banks learn enough to expect positive profits from later-stage loans. This risk premium increases quadratically in the discounted loan amount at stake $(\beta \frac{D}{N})$ and linearly in the absolute risk aversion of banks θ.

Generally, such a linearized risk premium is equivalent to a decrease in the learning rate that kicks in gradually once early-stage loan provision is high enough to ensure bankability, and grows with each additional early-stage loan. Specifically, it is clear that, *ceteris paribus*, under a higher risk premium, higher baseline marginal learning gains are required to make loan provision socially optimal. In addition, subtracting $\theta \mathbb{V}[\pi]$ from expected profits makes it less likely that the local optimum identified by the first-order condition above yields positive utility or, expressed differently, positive risk-adjusted returns. Hence, higher expected returns are required to make loan provision socially optimal. The changes to each bank's private optimization problem are analogous, with the exception that banks only consider the effect of additional investment on the variability

of their own second-period profits. This reduces the gap between market outcome and social optimum because uncertainty decreases effective learning gains and hence positive spillovers from one bank to all others.

Overall, these results support the notion of interpreting returns in our main setup as risk-adjusted returns – and immaturity costs c as risk-adjusted costs. In particular, a linearized risk premium as we have considered it in this section can be easily incorporated into a convexly decreasing cost function without changing any of our analytical results (as the combination of both functions will still be convex and there will be no discontinuity since the risk premium begins at zero and increases gradually). However, there are some additional policy implications if policy decisions can be adjusted once the uncertain outcome becomes visible at $t = 2$. In this case, any policy support at $t = 2$ may be withdrawn if the technology ramp-up fails. Such a risk of time inconsistency will increase $\mathbb{V}[\pi_i]$, conditional on the bankability threshold being surpassed, and, hence, exacerbate the risk premium placed on early-stage loans. Therefore, time inconsistency risks will reduce the effectiveness of policies announced for $t = 2$ but not for policy measures taken ex ante at $t = 1$ (i.e., early-stage loans and internalizing the experience spillover). At the same time, these early-stage measures now come at the risk of supporting a failing technology and incurring policy costs at $t = 1$ with nothing to show for it at $t = 2$, which may reduce policymakers' willingness to adopt such measures.

9 Conclusion

In this paper, we analyze bank loans for a novel clean energy technology in a partial equilibrium model where cumulative financing experience improves risk-adjusted returns over time and spills over between banks. We show that the positive learning externality leads to an undersupply of risky early-stage credit. This cooperation problem cannot be mitigated through public loan provision because public loans crowd out private investment and create no additional incentive for banks to provide risky early-stage loans. By contrast, introducing de-risking instruments, such as interest rate subsidies or credit guarantees, at an early stage can close the gap between the social optimum and a market equilibrium that involves some, albeit insufficient, early-stage loan financing. Second, the banking sector can remain stuck in an inferior Nash equilibrium featuring no loan financing due to a coordination problem. In this case, public loan provision serves to push the market to the preferable market equilibrium, which can be more cost-effective particularly if the public loan provider deliberately maximizes knowledge spillovers to commercial banks. However, public loan provision should always be paired with de-risking measures and should be phased out at a later stage when the novel technology has become bankable to minimize crowding-out issues. A numerical extension to loans for German offshore wind projects supports the policy relevance of these insights.

Since the findings presented here do not rely on market failures at the technology or consumer level, such as greenhouse gas emissions and research and development spillovers, they motivate financial policy intervention even if other first-best instruments, such as carbon pricing or renewable energy support schemes, are already in place. They can therefore guide policymakers in shaping the rules and mandates for public loan programs and state investment banks that are targeting clean energy projects, such as the clean finance initiatives established under the Inflation Reduction Act's National Clean Investment Fund in the United States. In addition, our model also echoes previous findings that if technology-level externalities, such as climate benefits, are not or insufficiently priced, such financial policies can be second-best measures to foster to reduce emissions (Haas & Kempa, 2023). Similar considerations apply to other technology-level externalities not modeled here, such as cost reductions in clean energy projects due to increased deployment.

While our model provides a clear framework to conceptualize the role of public loan provision for clean energy technologies, its simplicity also comes with limitations. First, assuming a perfectly inelastic loan demand and full substitutability of financing experience gained from banks' own loans and from observing loans by others exacerbates crowding-out issues in our model, which would decrease in demand elasticity and a lower extent of substitutability. We abstract away from how supply-demand dynamics might impact risk-adjusted returns, whereas public loan provision could also address an undersupply of credit due to market power for a decreasing demand curve and a finite N. These conservative assumptions make clear that the mobilization effect of public loans can be even larger in other setups, particularly if the experience spillovers they generate exceed those of commercial loans. In addition, while our model features a risk-adjusted return motivated by default risks and risk aversion, we do not account for within-portfolio correlations, uncertainties about key parameters other than the growth potential of the novel technology, or for systemic risks and bank heterogeneity.

Future research can address these limitations by extending our framework to multiple assets, incorporating additional uncertainties, and exploring how a falling loan demand curve and bank heterogeneity might moderate our findings presented. Given the signaling role of public green banks suggested by qualitative studies (Geddes et al., 2018; OECD, 2016a), scholars could also model borrower projects explicitly to explore how co-investing with commercial banks can increase the policy impact of public loan providers or how incorporating herding dynamics can affect the conclusions presented here. Nevertheless, the market failures arising in our simple framework already provide a clear rationale for financial measures in addition to other policy instruments that address the externality of emissions, which can explain the popularity of de-risking and public loan provision among policymakers.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT (version o1) for language and coding review purposes. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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Appendices

A Additional definitions

We introduce further definitions and conventions to make the subsequent proofs more concise:

- $\bar{L}_t \coloneqq \sum_{i=1}^{N} l_{i,t}$.
- $(l_1, l_2)_{i=1}^{N}$ denotes any kind of symmetric outcome where each bank provides l_1 in $t = 1$ and l_2 in $t = 2$.
- L denotes the $N \times 2$ matrix with elements $l_{i,t}$ in its i-th row and t-th column.
- L_{-i} and $\bar{L}_{-i,t}$ denote the corresponding matrix and sum, respectively, excluding bank i.
- $\mathcal{L}^{NE}$ denotes the set of existing Nash equilibria under the market outcome, given model parameters.
- The notation $|g$, $|s$, and $|gs$ after a variable denote the respective variable's value in the presence of a policy intervention (direct loan provision, de-risking subsidy, or a combination of the two, respectively). For instance, $l_1^{NE}|g$ denotes the symmetric Nash equilibrium with loan financing in $t = 1$ that results under direct loan provision.

As laid out in the main text, throughout the paper we assume that the initial return spread over the deposit rate and transaction cost is negative. For a full provision of early-stage financing, the return spread in $t = 2$ can become positive:

Assumption 1. *$r > r_D$, $r - \bar{c} < r_D$ and $r - c\left(\frac{\tilde{N}}{N}D\right) > r_D$, where $\tilde{N} \coloneqq 1 + \gamma(N-1) < N$.*

B Proofs for Proposition 1 (social optimum)

Using a more formal notation, Proposition 1 can be stated as

Proposition 1. *Let $l_1^* \coloneqq \tilde{N}^{-1}(c')^{-1}\left(-\frac{\bar{c}+r_D-r}{\beta\psi\frac{\tilde{N}}{N}D}\right)$ where $(c')^{-1}(\cdot)$ denotes the inverse function of c'.*[27] *Then*

$$(l_1^{SO}, l_2^{SO}) = \begin{cases} (\frac{D}{N}, \psi\frac{D}{N}) & \text{if } l_1^* \geq \frac{D}{N} \wedge \beta\left(r - c(\tilde{N}\frac{D}{N}) - r_D\right) > \bar{c} + r_D - r \\ (l_1^*, \psi\frac{D}{N}) & \text{if } l_1^* < \frac{D}{N} \wedge \beta\left(r - c(\tilde{N}l_1^*) - r_D\right)\psi\frac{D}{N} > (\bar{c} + r_D - r)\, l_1^* \\ (0, 0) & \text{otherwise} \end{cases}$$

[27] Note that c' is monotonically increasing, and hence $(c')^{-1}$ exists and is monotonically increasing.

Ceteris paribus, both l_1^* and the likelihood of the condition for $l_1^{SO}, l_2^{SO} > 0$ being satisfied increase monotonically in r, β, D, and ψ, and decrease monotonically $\bar{c}$ and N. For γ, the sign depends on the exact functional form of $c(\cdot)$ and the specific parameters.

Proof. See Appendices B.1 and B.2. □

B.1 First- and second-order conditions

The Lagrangian of the social maximization problem stated in Equation 10 is as follows:

$$\max_{l_{1,1},\dots l_{N,2}} \mathcal{Z} = \sum_{i=1}^{N} (r - \bar{c} - r_D) l_{i,1} + \beta \left(r - c(\gamma \bar{L}_{-i,1} + l_{i,1}) - r_D\right) l_{i,2} + \mu_{i,1} \left(\frac{D}{N} - l_{i,1}\right) + \mu_{i,2} \left(\psi \frac{D}{N} - l_{i,2}\right) + \mu_{i,3} l_{i,1} + \mu_{i,4} l_{i,2}.$$

Note that here we redefine the Lagrangian multipliers applying to $t = 2$ as the original multiplier divided by β. This does not affect results since $\beta \in (0, 1)$ but does simplify the first-order conditions (FOCs).

The resulting Karush-Kuhn-Tucker conditions tell us that, for each bank i, the following conditions have to hold in the social optimum:

$$-r_D + r - \bar{c} - \beta \left(c'(\tilde{L}_{i,1}^{SO}) l_{i,2}^{SO} + \gamma \sum_{j \neq i} c'(\tilde{L}_{j,1}^{SO}) l_{j,2}^{SO} \right) - \mu_{i,1} + \mu_{i,3} = 0 \tag{26}$$

$$-r_D + r - c(\tilde{L}_{i,1}^{SO}) - \mu_{i,2} + \mu_{i,4} = 0 \tag{27}$$

$$\mu_{i,1}(\frac{D}{N} - l_{i,1}^{SO}) = \mu_{i,2}(\psi \frac{D}{N} - l_{i,2}^{SO}) = \mu_{i,3} l_{i,1}^{SO} = \mu_{i,4} l_{i,2}^{SO} = 0 \tag{28}$$

$$\mu_{i,1}, \mu_{i,2}, \mu_{i,3}, \mu_{i,4} \geq 0. \tag{29}$$

Obviously, the upper and lower bound restrictions on $l_{i,1}^{SO}$ and $l_{i,2}^{SO}$ are mutually exclusive. Hence, the complementary slackness conditions expressed by Equation 28 imply that:

$$\mu_{i,u} > 0 \rightarrow \mu_{i,v} = 0 \; \forall \; (u, v) \in \{(1,3), (3,1), (2,4), (4,2)\}.$$

Keeping in mind that banks prefer no loan financing if the return spread is exactly zero, by Equation 27 we can rule out any scenario where $\mu_{i,2} = \mu_{i,4} = 0$. This gives us a simple rule for $l_{i,2}^{SO}$ given the optimal solution for all banks other than i, as expressed in Lemma 1 (see Section 3).

B.2 Social optimum under symmetry

For the reasons laid out in Section 4 and in line with the literature (Eslava & Freixas, 2021), we impose symmetry on the social optimum:

Assumption 2. *Let $(l_{i,1}^{SO}, l_{i,2}^{SO})$ be the solution to the maximization problem in Equation 10 for any bank i. Then*

$$l_{i,t}^{SO} = l_t^{SO} \; \forall \; i = 1, ..., N, \;\; t = 1, 2.$$

Based on Lemma 1, there are only six different ways that a given bank i can behave:

1. $l_{i,1}^{SO} = l_{i,2}^{SO} = 0$;
2. $l_{i,1}^{SO} = \frac{D}{N}, l_{i,2}^{SO} = \psi\frac{D}{N}$;
3. $l_{i,1}^{SO} \in \left(0, \frac{D}{N}\right), l_{i,2}^{SO} = \psi\frac{D}{N}$;
4. $l_{i,1}^{SO} \in \left(0, \frac{D}{N}\right), l_{i,2}^{SO} = 0$;
5. $l_{i,1}^{SO} = \frac{D}{N}, l_{i,2}^{SO} = 0$;
6. $l_{i,1}^{SO} = 0, l_{i,2}^{SO} = \psi\frac{D}{N}$.

Under symmetry, we can rule out the two cases involving $l_{i,1} > 0, l_{i,2} = 0$ because there is no point in providing early-stage financing if no one benefits from it in $t = 2$. Similarly, if all banks behave symmetrically, then $l_{i,1} = 0, l_{i,2} = \psi\frac{D}{N}$ cannot be optimal. This is because the absence of learning effects from $t = 1$ mean that financing provision in $t = 2$ results in negative profits. Therefore, one of the three following cases must apply:

- "Immediate financing": $(l_{i,1}^{SO}, l_{i,2}^{SO}) = (\frac{D}{N}, \psi\frac{D}{N}) \; \forall \; i = 1, ..., N$;
- "Gradual financing": $(l_{i,1}^{SO}, l_{i,2}^{SO}) = (l_1^{SO}, \psi\frac{D}{N}) \; \forall \; i = 1, ..., N$ with $l_1^{SO} \in (0, \frac{D}{N})$;
- "No financing": $(l_{i,1}^{SO}, l_{i,2}^{SO}) = (0, 0) \; \forall \; i = 1, ..., N$.

Furthermore, we can show that "immediate financing" and "gradual financing" are mutually exclusive as critical points of the Lagrangian:

Lemma 5. *Let $\mathcal{L}^*$ be the set of critical points satisfying the FOCs of the maximization problem in Equation 10. Under Assumption 2, it holds that*

- $(l_1, \psi\frac{D}{N}) \in \mathcal{L}^*$ *for* $l_1 \in (0, \frac{D}{N}) \implies (\frac{D}{N}, \psi\frac{D}{N}) \notin \mathcal{L}^*$
- $(\frac{D}{N}, \psi\frac{D}{N}) \in \mathcal{L}^* \implies (l_1, \psi\frac{D}{N}) \notin \mathcal{L}^*$ *for* $l_1 \in (0, \frac{D}{N})$

Proof. Due to symmetry, the FOCs in Equations 26-27 simplify to:

$$-r_D + r - \bar{c} - \beta\tilde{N}l_2^{SO}\left(c'(\tilde{N}l_1^{SO})\right) - \mu_{i,1} + \mu_{i,3} = 0 \tag{30}$$

$$-r_D + r - c(\tilde{N}l_1^{SO}) - \mu_{i,2} + \mu_{i,4} = 0. \tag{31}$$

Note that $c' < 0$ such that $-\beta\tilde{N} l_2^{SO} \left(c'(\tilde{N} l_1^{SO})\right)$ is nonnegative both under "immediate financing" and "gradual financing", $l_2^{SO} = \psi\frac{D}{N}$. Equation 30 therefore only differs in l_1^{SO} (and correspondingly $\mu_{i,1}$ and $\mu_{i,3}$) between the two outcomes. But if

$$\exists l_1 \in (0, \frac{D}{N}) : -\beta\tilde{N}\frac{D}{N}\left(c'(\tilde{N} l_1)\right) = r_D - (r - \bar{c})$$

then

$$-\beta\tilde{N}\frac{D}{N}\left(c'(\tilde{N}\frac{D}{N})\right) < r_D - (r - \bar{c})$$

as $c' < 0$ and $c'' > 0$. This is because $l_1 < \frac{D}{N}$ and hence the absolute value of $c'(\tilde{N}\frac{D}{N})$ must be smaller than the absolute value of $c'(\tilde{N} l_1)$ as the marginal learning gain decreases. By the same logic, Equation 30 cannot hold for $l_1^{SO} \in (0, \frac{D}{N})$ if it holds for $l_1^{SO} = \frac{D}{N}$. □

If Equation 30 holds for $\mu_{i,1} = \mu_{i,3} = 0$, this gives the following solution:

$$l_1^* \coloneqq \tilde{N}^{-1}(c')^{-1}\left(-\frac{r_D - r + \bar{c}}{\beta\tilde{N}\psi\frac{D}{N}}\right).$$

By Lemma 5 and Assumption 2, there can be at most two critical points of the Lagrangian: one at $(0,0)_{i=1}^N$ and one at either $(l_1^*, \psi\frac{D}{N})_{i=1}^N$ or $(\frac{D}{N}, \psi\frac{D}{N})_{i=1}^N$. Given the second-order condition (SOC) for an optimum at $(l_1, \psi\frac{D}{N})_{i=1}^N$ where $l_1 \in \{l_1^*, \frac{D}{N}\}$, it suffices to show that the objective function's value at this point exceeds the value at $(0,0)_{i=1}^N$. Since $\bar{\pi}_i(L = (0,0)_{i=1}^N) = 0$, then the SOC simply requires profits above zero:

$$N\left((r - \bar{c} - r_D)l_1 + \beta(r - c(\tilde{N} l_1) - r_D)\psi\frac{D}{N}\right) > 0. \tag{32}$$

Dividing by N and rearranging gives the condition in the Appendix version of Proposition 1.

Since $r - \bar{c} - r_D < 0$ by Assumption 1, this requires $r - c(\tilde{N} l_1) - r_D > 0$, which directly implies that $(l_1, \psi\frac{D}{N})_{i=1}^N$ also satisfies the FOC with respect to $l_{i,2}$:

Lemma 6. *Let $l_1 \in \{l_1^*, \frac{D}{N}\}$. If Equation 32 holds for l_1, then Equation 31 holds for $l_1^{SO} = l_1, \mu_{i,2} > 0$.*

Proof. For Equation 32 to hold, it must be that $r - c(\tilde{N} l_1) - r_D > 0$. Hence, Equation 31 can only hold if $\mu_{i,2} > 0$. □

Therefore, the conditions for a social optimum at $l_1 \in \{l_1^*, \frac{D}{N}\}$ given in the Appendix version of Proposition 1 only include the FOC with respect to $l_{i,1}$ and the SOC (which implies the FOC with respect to $l_{i,2}$). Taking partial derivatives of l_1^* and the respective SOC yields the comparative statics. For γ, there are two opposing effects since $\tilde{N}$ features in two different locations in the definition of l_1^*. On the one hand, $\gamma \uparrow$ implies more learning for the other banks (i.e., $(c')^{-1} \uparrow$). On the other hand, more spillovers also imply that

each individual bank has to provide fewer loans to achieve the same amount of overall experience $\tilde{N} l_1^{SO}$ (as $\gamma \uparrow$ implies $\tilde{N}^{-1} \downarrow$).

B.3 Isomorphism of the optimization problem

We can show that the optimization problems of the social planner and the individual bank i in our main setup are isomorphic to the same optimization problems assuming that an outside option is available and that interest on all deposits needs to be paid even if some are not used to finance loans. (Recall that our main setup assumes that r_D is only paid if banks actually use the deposits to issue loans).

The profit maximization problem of bank i in our main setup is as follows:

$$\max_{l_{i,1}, l_{i,2}} \pi_i = (r - \bar{c} - r_D) l_{i,1} + \beta \Big(r - c(l_{i,1} + \gamma \sum_{j \neq i} l_{j,1}) - r_D \Big) l_{i,2}. \tag{33}$$

Now suppose that in each period, bank i has a total amount of deposits X_t at its disposal where $X_1 \gg \frac{D}{N}$ and $X_2 \gg \psi \frac{D}{N}$ (i.e., issuing loans for the novel clean energy technology it not constrained by the availability of deposits in the banking sector, only by the available demand for loans). Bank i must pay interest to its depositors at a rate of r_D and can invest up to $\frac{D}{N}$ and $\psi \frac{D}{N}$ at $t = 1$ and $t = 2$ into loans to projects using the novel clean energy technology, exactly as in our main setup. In addition, it can also invest an unlimited amount of its deposits into a fully mature investment opportunity with risk-adjusted return $r_{rf} \geq 0$, which may represent a long-term government bond that is virtually risk-free or an interbank interest rate considered risk-free, such as the former LIBOR. Let the amount of deposits that bank i invests into this "outside option" be denoted as $m_{i,t}$. We assume that, net of any immaturity-related cost and risk premiums, the novel technology loans outperform the outside option (i.e., $r > r_{rf} > 0$). In this setup, the optimization problem of bank i would be

$$\max_{l_{i,1}, l_{i,2}, m_{i,1}, m_{i,2}} \pi_i = (r - \bar{c} - r_D) l_{i,1} + \beta \Big(r - c(l_{i,1} + \gamma \sum_{j \neq i} l_{j,1}) - r_D \Big) l_{i,2} + (r_{rf} - r_D)(m_{i,1} + \beta m_{i,2}) \tag{34}$$

subject to

$$0 \leq l_{i,t} + m_{i,t} \leq X_t \; \forall \; t = 1, 2.$$

Notably, banks incur costs of $r_D(X_1 + X_2)$ no matter what they use the deposits for. Since $r_{rf} > 0$, they will, therefore, always deploy all available deposits in the optimum and not leave any financial resources unused, such that the budget constraint is necessarily binding in the optimum (i.e., $m_{i,t} = X_t - l_{i,1} \; \forall \; t = 1, 2$).

Inserting the binding budget constraint for $m_{i,t}$ into the optimization problem and

rearranging terms then yields

$$\max_{l_{i,1},l_{i,2}} \pi_i = (r-\bar{c}-r_{rf})l_{i,1}+\beta\Big(r-c(l_{i,1}+\gamma\sum_{j\neq i} l_{j,1})-r_{rf}\Big)l_{i,2}+(r_{rf}-r_D)X_1+\beta(r_{rf}-r_D)X_2 \tag{35}$$

Notably, the last two terms only depend on exogenous parameters but not on the choice variables. Therefore, the two optimization problems in Equations 33 and 35 are isomorphic and yield the same first-order and second-order conditions with respect to $l_{i,1}$ and $l_{i,2}$. Comparing this adapted setup to our main setup immediately shows that the adapted optimization problem is equivalent to the original optimization problem if we replace r_D with r_{rf} in the latter and interpret profits as opportunity profits from financing the novel technology compared to the risk-free option (instead of interpreting them as absolute profits). Absolute profits then depend on $(r_{rf} - r_D)(X_1 + \beta X_2)$, that is, on the minimum profits that bank i obtains in the optimum if no loans to the novel technology are issued. These are determined by the relationship between r_{rf} and r_D. Optimal absolute profits when including the outside option are i) identical to opportunity profits in our main setup if $r_{rf} = r_D$, and lower (higher) for $r_{rf} < r_D$ ($r_{rf} > r_D$). As an extreme case, if $r_{rf} = 0$ – i.e. if there is no outside option at all –, banks lose an exogenously determined $r_D(X_1+\beta X_2)$ and choose $l_{i,1}$ and $l_{i,2}$ to minimize these losses and, if possible, strike positive present-value profits.

We can follow the same steps for the social planner's optimization problem

$$\max_{\{l_{i,1},l_{i,2}\}_{i=1}^N} \sum_i \pi_i$$

to show that this optimization problem is also isomorphic to the social optimization problem that includes an outside option.

C Proofs for Proposition 2 (market outcome)

Using formal notation, Proposition 2 can be stated as

Proposition 2. *Let* $l_1^{*NE} \coloneqq \tilde{N}^{-1}(c')^{-1}\left(-\frac{r_D+\bar{c}-r}{\beta\psi\frac{D}{N}}\right)$*, let* $\mathcal{L}^{NE}$ *be the set of possible Nash equilibria, and let* $\bar{l}_1 \coloneqq \min\{l_1^{*NE}, \frac{D}{N}\}$*. Then*

- $\mathcal{L}^{NE} = \{(0,0)_{i=1}^N\}$ *if* $\bar{l}_1 \leq 0$ *and otherwise* $\mathcal{L}^{NE} \in \mathcal{P}\left(\{(\bar{l}_1, \frac{D}{N})_{i=1}^N, (0,0)_{i=1}^N\}\right) \setminus \emptyset$;
- $(0,0)_{i=1}^N \in \mathcal{L}^{NE}$ *if and only if*

$$\nexists\, l_{i,1} \in \{\tilde{N}l_1^{*NE}, \frac{D}{N}\} \cap (0, \frac{D}{N}] : \beta(r - c(l_{i,1}) - r_D)\psi\frac{D}{N} > (r_D + \bar{c} - r)l_{i,1}; \tag{36}$$

- $(\bar{l}_1, \psi\frac{D}{N})_{i=1}^N \in \mathcal{L}^{NE}$ *if and only if*

$$\bar{l}_1 > 0 \wedge \beta(r - c(\tilde{N}\bar{l}_1) - r_D)\psi\frac{D}{N} > (r_D + \bar{c} - r)\bar{l}_1. \tag{37}$$

Furthermore, for any $(l_1, l_2)_{i=1}^N \in \mathcal{L}^{NE}$*, it must hold that* $l_1 \leq l_1^{SO}$*, with* $l_1 = l_1^{SO}$ *if and only if*

$$l_1^{SO} = 0 \vee \left(l_1^{SO} = \frac{D}{N} = l_1 = \bar{l}_1\right). \tag{38}$$

Proof. See Appendices C.2, C.3, C.4 and C.5. □

C.1 First-order conditions

The Lagrangian of the individual maximization problem of bank i stated in Equation 13 is as follows:

$$\begin{aligned}\max_{l_{i,1},l_{i,2}} \mathcal{Z} =&(r - \bar{c} - r_D)l_{i,1} + \beta\left(r - c(\gamma\bar{L}_{-i,1} + l_{i,1}) - r_D\right) l_{i,2} \\ &+ \mu_{i,1}\left(\frac{D}{N} - l_{i,1}\right) + \mu_{i,2}\left(\psi\frac{D}{N} - l_{i,2}\right) + \mu_{i,3}l_{i,1} + \mu_{i,4}l_{i,2}.\end{aligned}$$

Again, we simplify by redefining the Lagrangian multipliers applying to t = 2 as the original multipliers divided by β.

The resulting Karush-Kuhn-Tucker conditions that any Nash equilibrium must satisfy are as follows:

$$-r_D + r - \bar{c} - \beta c'(\tilde{L}_{i,1}^{NE})l_{i,2}^{NE} - \mu_{i,1} + \mu_{i,3} = 0 \tag{39}$$

$$-r_D + r - c(\tilde{L}_{i,1}^{NE}) - \mu_{i,2} + \mu_{i,4} = 0 \tag{40}$$

$$\mu_{i,1}(\frac{D}{N} - l_{i,1}^{NE}) = \mu_{i,2}(\psi\frac{D}{N} - l_{i,2}^{NE}) = \mu_{i,3}l_{i,1}^{NE} = \mu_{i,4}l_{i,2}^{NE} = 0 \tag{41}$$

$$\mu_{i,1}, \mu_{i,2}, \mu_{i,3}, \mu_{i,4} \geq 0. \tag{42}$$

C.2 Best response function

We can show that bank i's best response to an other-bank first-period investment level of $L_{-i,1}$ must be one of the following:

1. "Immediate financing" (IF): bank i finances the full amount of projects in both periods subject to its demand constraint.

2. "Gradual financing" (GF): bank i finances some but not all available projects in $t = 1$ and all projects in $t = 2$.

3. "Free-riding" (FR): bank i invests nothing in $t = 1$ but finances all available projects in $t = 2$.

4. "No financing" (NF): bank i does not invest in either period.

To specify the ranges of other-bank investment over which bank i best responds with each of the above investment plans, respectively, it is helpful to specify some threshold learning levels.

ξ is the amount of aggregate learning (net of spillover losses) that equates private marginal first-period losses to private marginal second-period gains (conditional on the bank investing the full $\psi\frac{D}{N}$ in the second period). It is defined implicitly by

$$-c'(\xi) = \frac{r_D + \bar{c} - r}{\beta\psi\frac{D}{N}}. \tag{43}$$

κ is the amount of aggregate learning at which per-unit gains from second-period investment turn positive. It is defined implicitly by

$$c(\kappa) = r - r_D. \tag{44}$$

η is the amount of aggregate learning at which the bank just breaks even when choosing an immediate investment plan $\left(\frac{D}{N}, \psi\frac{D}{N}\right)$. (Or, alternatively, it is the amount of aggregate learning at which second period per-unit profits begin to exceed first-period per-unit losses.) It is defined implicitly by

$$c(\eta) = r - r_D - \frac{r_D + \bar{c} - r}{\beta\psi}. \tag{45}$$

CF is defined as the multiplier of $\frac{D}{N}$ such that

$$(r - c(\xi) - r_D)\beta\psi\frac{D}{N} = (r_D + \bar{c} - r)\frac{D}{N} \cdot CF. \tag{46}$$

That is, $L = \frac{1}{\gamma}(\xi - \frac{D}{N} \cdot CF)$ is the amount of other-bank learning at which the gradual investment plan $(\xi - \gamma L, \psi\frac{D}{N})$ becomes profitable if feasible.

We can then make exact statements about the best response function using these threshold learning levels.

Lemma 7. *The best response function BR_i of bank i to other-bank first-period investment $L_{-i,1}$ can be defined as follows:*

- *If ξ does not exist, $r - c(\xi) - r_D < 0$ or $\xi - \frac{D}{N} \cdot CF \geq \kappa$,*

$$BR_i(L_{-i,1}) = \begin{cases} (0,0) & \text{if } L_{-i,1} \leq \frac{1}{\gamma}\kappa \\ (0, \psi\frac{D}{N}) & \text{otherwise} \end{cases} \tag{47}$$

- *If ξ exists, $r - c(\xi) - r_D > 0$ and $\xi - \frac{D}{N} \cdot CF < \kappa$, we need to distinguish two cases:*
  - *If $CF > 1$, η must exist and it must hold that $\eta - \frac{D}{N} < \kappa$ and $\eta < \xi$. Then,*

$$BR_i(L_{-i,1}) = \begin{cases} (0,0) & \text{if } L_{-i,1} \leq \frac{1}{\gamma}(\eta - \frac{D}{N}) \\ (\frac{D}{N}, \psi\frac{D}{N}) & \text{if } L_{-i,1} \in \left(\frac{1}{\gamma}(\eta - \frac{D}{N}), \frac{1}{\gamma}(\xi - \frac{D}{N})\right] \\ (\xi - \gamma L_{-i,1}, \psi\frac{D}{N}) & \text{if } L_{-i,1} \in \left(\frac{1}{\gamma}(\xi - \frac{D}{N}), \frac{1}{\gamma}\xi\right] \\ (0, \psi\frac{D}{N}) & \text{otherwise} \end{cases} \tag{48}$$

  - *If $CF \leq 1$, then*

$$BR_i(L_{-i,1}) = \begin{cases} (0,0) & \text{if } L_{-i,1} \leq \frac{1}{\gamma}(\xi - \frac{D}{N} \cdot CF) \\ (\xi - \gamma L_{-i,1}, \psi\frac{D}{N}) & \text{if } L_{-i,1} \in \left(\frac{1}{\gamma}(\xi - \frac{D}{N} \cdot CF), \frac{1}{\gamma}\xi\right] \\ (0, \psi\frac{D}{N}) & \text{otherwise} \end{cases} \tag{49}$$

Proof. This follows from Lemmas 8-22. □

Just by our functional form and parameter assumptions, we can already make some statements about ξ, κ and η.

Lemma 8. *ξ exists if and only if $-c'(0) \geq \frac{r_D + \bar{c} - r}{\beta\psi\frac{D}{N}}$. If it exists, it is uniquely defined as $\xi = (c')^{-1}(-\frac{r_D + \bar{c} - r}{\beta\psi\frac{D}{N}}) \geq 0$.*

Proof. **If**. Suppose $-c'(0) \geq \frac{r_D + \bar{c} - r}{\beta\psi\frac{D}{N}}$. By strict convexity of the cost function c, this means that marginal learning gains $-c'(L)$ must be strictly decreasing in learning L. By assumption, $\lim_{L\to\infty} -c'(L) = 0$ (marginal learning gains tend to zero). Since c' is continuous, a unique crossing point ξ must exist at which $-c'(\xi) = \frac{r_D + \bar{c} - r}{\beta\psi\frac{D}{N}}$.

Only if. Suppose there is a ξ such that $-c'(\xi) = \frac{r_D + \bar{c} - r}{\beta\psi\frac{D}{N}}$. Since c is only defined over non-negative learning levels, ξ has to be non-negative. Furthermore, by strict convexity of c, ξ has to be unique.

By the same token, it has to hold that $-c'(0) \geq -c'(\xi) = \frac{r_D + \bar{c} - r}{\beta\psi\frac{D}{N}}$. □

Lemma 9. *If ξ does not exist, $-c'(L) < \frac{r_D + \bar{c} - r}{\beta\psi\frac{D}{N}}$ for any learning level $L \geq 0$.*

Proof. Assume that ξ does not exist. By Lemma 8, this means that $-c'(0) < \frac{r_D + \bar{c} - r}{\beta\psi\frac{D}{N}}$. But by convexity of c, $-c'$ is decreasing, so for any $L \geq 0$, $-c'(L) \leq -c'(0)$. □

Lemma 10. *κ exists and is uniquely defined as $\kappa = c^{-1}(r - r_D) > 0$.*

Proof. By assumption, there is a level of aggregate learning $\kappa < \infty$ such that $r - c(L) - r_D > 0$ for all $L > \kappa$. (That is, sufficiently high learning levels will eventually make investments in the new technology profitable.)

Furthermore, by assumption $r - c(0) - r_D < 0$. Since c is strictly increasing and continuous, this implies that κ must be unique and strictly positive. □

Lemma 11. *η exists if and only if $\beta\psi(r - \underline{c} - r_D) > -(r - \bar{c} - r_D)$, where $\underline{c} = \lim_{l\to\infty} c(l)$. If it exists, it is uniquely defined as $\eta = c^{-1}(r - r_D - \frac{r_D + \bar{c} - r}{\beta\psi}) > \kappa > 0$.*

Proof. **If**. Suppose that $\beta\psi(r - \underline{c} - r_D) > -(r - \bar{c} - r_D)$. This is equivalent to $r - r_D - \frac{r_D + \bar{c} - r}{\beta\psi} > \underline{c}$. By assumption, $r - \bar{c} - r_D < 0$. Rewriting this shows that $c(0) = \bar{c} > r - r_D - \frac{r_D + \bar{c} - r}{\beta\psi}$. Since c is strictly decreasing and continuous, this implies that a unique $\eta > 0$ must exist that satisfies $c(\eta) = r - r_D - \frac{r_D + \bar{c} - r}{\beta\psi}$. Since $\frac{r_D + \bar{c} - r}{\beta\psi} > 0$,

$$c(\eta) = r - r_D - \frac{r_D + \bar{c} - r}{\beta\psi} < r - r_D = c(\kappa). \tag{50}$$

As c is strictly decreasing, this implies that $\eta > \kappa$. By Lemma 10, we know that $\kappa > 0$, so $\eta > 0$ as well.

Only if. Suppose there is a η that satisfies $c(\eta) = r - r_D - \frac{r_D + \bar{c} - r}{\beta\psi}$.

Since $\underline{c}$ is the infimum of c, and since c is strictly decreasing and continuous, we know that $\underline{c} < c(\eta) = r - r_D - \frac{r_D + \bar{c} - r}{\beta\psi}$. This inequality is equivalent to $\beta\psi(r - \underline{c} - r_D) > -(r - \bar{c} - r_D)$. □

Lemma 12. *CF exists and is uniquely defined by $CF = \frac{\beta\psi(r - c(\xi) - r_D)}{r_D + \bar{c} - r}$.*

Proof. This follows directly from rearranging the implicit definition *CF* in (46). □

Lemma 13. *Consider any investment plan (l_1, l_2) with $l_2 \in (0, \psi\frac{D}{N})$. Then, for any level of other-bank investment L, either $(l_1, 0)$ or $(l_1, \psi\frac{D}{N})$ will yield weakly higher profits.*

Proof. Take any own first-period investment l_1 and other-bank first-period investment L. Then, the bank's profits can be expressed as the following function of second-period investment l_2:

$$\pi_{l_1;L} = (r - \bar{c} - r_D)l_1 + \beta(r - c(l_1 + \gamma L) - r_D)l_2. \tag{51}$$

Obviously, if $r - c(l_1 + \gamma L) \leq r_D$, $l_2 = 0$ maximizes profits. Otherwise, $l_2 = \psi\frac{D}{N}$ maximizes profits. □

Corollary 1. *No investment plan (l_1, l_2) with $l_2 \in (0, \psi\frac{D}{N})$ can be a best response to any level of other-bank investment L.*

Proof. This follows directly from Lemma 13 paired with our assumption that banks will choose not to invest unless investment yields strictly positive profits. □

Lemma 14. *Consider any investment plan $(l_1, 0)$ with $l_1 > 0$. Then, for any level of other-bank investment L, the investment plan $(0, 0)$ will yield strictly higher profits.*

Proof. The proof is trivial: Consider an investment plan $(l_1, 0)$ and a level of other-bank investment L. Then, bank profits from this investment plan are

$$\pi(l_1, 0; L) = (r - \bar{c} - r_D)l_1 < 0 = \pi(0, 0; L). \tag{52}$$

□

Corollary 2. *If an investment plan (l_1, l_2) is a best response to any level L of other-bank investment and features positive first-period investment $l_1 > 0$, it has to hold that $l_2 = \psi\frac{D}{N}$.*

Proof. Follows directly from Lemmas 13 and 14. □

Lemma 15. *If ξ does not exist, no investment plan (l_1, l_2) with $l_1 > 0$ can be a best response to any level of other-bank investment.*

Proof. By Corollary 2, any best response investment plan with $l_1 > 0$ must feature $l_2 = \psi\frac{D}{N}$.

Now, suppose that ξ does not exist. Consider any level of other-bank learning $L \geq 0$, let $l_1 > 0$ and assume for contradiction that $(l_1, \psi\frac{D}{N})$ is the bank's best response to L.

This implies that l_1 must maximize

$$\pi_{\psi\frac{D}{N}}(l) = (r - \bar{c} - r_D)l + \beta(r - c(l + L) - r_D)\psi\frac{D}{N}, \tag{53}$$

that is, the bank's profits from first-period investment l conditional on investing $\psi\frac{D}{N}$ in the second period and given other-bank learning L.

Marginal profits from investing l_1 are then given by

$$\pi'(l_1) = (r - \bar{c} - r_D) - c'(l_1 + L)\beta\psi\frac{D}{N}. \tag{54}$$

By convexity of c, we know that $-c'(l_1 + L) \leq -c'(l_1)$ for any $L \geq 0$. Additionally, by Lemma 9, the fact that ξ does not exist implies that $-c'(l_1) < \frac{r_D + \bar{c} - r}{\beta\psi\frac{D}{N}}$ for any $l_1 \geq 0$. Combining this inequality with the expression for marginal profits π' shows that $\pi'(l_1) < 0$ for any $l_1 \geq 0$.

Since $\pi_{\psi\frac{D}{N}}(l_1)$ is differentiable everywhere, this means that bank profits must be strictly decreasing in l. Hence, $\pi_{\psi\frac{D}{N}}(0) > \pi_{\psi\frac{D}{N}}(l_1)$, which contradicts the requirement that l_1 maximize $\pi_{\psi\frac{D}{N}}(l_1)$. □

Corollary 3. *If there is an investment plan (l_1, l_2) with $l_1 > 0$ and a level of other-bank investment L to which (l_1, l_2) is a best response, ξ must exist.*

Proof. This is simply the contrapositive of Lemma 15. □

Lemma 16. *Suppose ξ exists and consider the subset of investment plans with positive second-period investment, $\mathcal{L} = \{(l_1, \psi\frac{D}{N}) \mid l_1 \in [0, \frac{D}{N}]\}$. Then, given a level of other-bank first period investment L, the investment plan $\mathbf{l} \in \mathcal{L}$ that maximizes a bank's profits features first-period investment*

$$l_1 = \begin{cases} \frac{D}{N} & \text{if } L \leq \frac{1}{\gamma}(\xi - \frac{D}{N}) \\ \xi - \gamma L & \text{if } \frac{1}{\gamma}(\xi - \frac{D}{N}) \leq L \leq \frac{1}{\gamma}\xi \\ 0 & \text{if } L > \frac{1}{\gamma}\xi \end{cases}$$

Proof. Define

$$\pi(l_1; L) = (r - \bar{c} - r_D)l_1 + (r - c(l_1 + \gamma L) - r_D)\psi\frac{D}{N} \tag{55}$$

as bank profits under other-bank investment of L conditional on investing $\psi\frac{D}{N}$ in the second period. Since c is strictly convex and twice continuously differentiable, this profit function is strictly concave and twice continuously differentiable in l_1. It is also strictly concave, strictly increasing and continuous in other-bank investment L.

The first-order conditions of the profit maximization problem immediately tell us that $l_1(L) = \xi - \gamma L$ is the unconstrained maximizer of $\pi(\cdot; L)$. Since it has to hold that $l_1 \in [0, \frac{D}{N}]$, this unconstrained solution is feasible as long as

$$L \in \left[\frac{1}{\gamma}(\xi - \frac{D}{N}), \frac{1}{\gamma}\xi\right]. \tag{56}$$

For $L < \frac{1}{\gamma}(\xi - \frac{D}{N})$, the upper boundary condition will be binding and optimal feasible first-period investment is $l_1 = \frac{D}{N}$. For $L > \frac{1}{\gamma}\xi$, the lower boundary condition will be binding and optimal feasible first-period investment is $l_1 = 0$. □

Lemma 17. *Suppose η and ξ exist and $\eta \leq \xi$. Then, any investment plan (l_1, l_2) with positive first-period investment $l_1 > 0$ is dominated by the zero investment plan $(0, 0)$ for any level of other-bank investment $L \leq \frac{1}{\gamma}(\eta - \frac{D}{N})$.*

Proof. Note that by the definition of η,

$$\pi(\frac{D}{N}, \psi\frac{D}{N}; \frac{1}{\gamma}(\eta - \frac{D}{N})) = 0. \tag{57}$$

Since banks only choose to invest under positive profits by assumption, $(0, 0)$ is the best response to $L = \frac{1}{\gamma}(\eta - \frac{D}{N})$. Since profits conditional on positive second-period investment are strictly increasing in other-bank investment, it has to hold that

$$\pi(\frac{D}{N}, \psi\frac{D}{N}; L) < 0 \tag{58}$$

for any $L < \frac{1}{\gamma}(\eta - \frac{D}{N})$. That means that $(0, 0)$ dominates $(\frac{D}{N}, \psi\frac{D}{N})$ for any such L. By Lemma 14, $(0, 0)$ also dominates any investment plan $(l_1, 0)$ with $l_1 > 0$.

That leaves only investment plans $(l_1, \psi\frac{D}{N})$ with $l_1 < \frac{D}{N}$ as potential alternatives with a positive profit. But since $\eta \leq \xi$, Lemma 16 implies that for any $L \leq \frac{1}{\gamma}(\eta - \frac{D}{N})$, $(\frac{D}{N}, \psi\frac{D}{N})$ dominates any other investment plan with positive second-period investment. Hence, it has to hold that for such an L,

$$\forall l_1 \geq 0 : \pi(l_1, \psi\frac{D}{N}; L) \leq \pi(0, 0; L) = 0. \tag{59}$$

□

Lemma 18. *Suppose there is an investment plan $(l_1, \psi\frac{D}{N})$ with $l_1 > 0$ that satisfies $\pi(l_1, \psi\frac{D}{N}; L) > 0$ for some $L \leq \frac{1}{\gamma}\kappa$. Then, for any level of other-bank learning $L < \frac{1}{\gamma}\xi$, there has to be an investment plan $(l_1', \psi\frac{D}{N})$ with $l_1' > 0$ such that $\pi(l_1', \psi\frac{D}{N}; L) > \pi(0, \psi\frac{D}{N}; L)$. Additionally, for any $L \geq \frac{1}{\gamma}\xi$, it has to hold that any investment plan $(l_1', \psi\frac{D}{N})$ with $l_1' \geq 0$ satisfies $\pi(l_1', \psi\frac{D}{N}; L) \leq \pi(0, \psi\frac{D}{N}; L)$.*

Proof. Let $l_1 \in (0, \frac{D}{N}]$, $L' \leq \frac{1}{\gamma}\kappa$ and $\pi(l_1, \psi\frac{D}{N}; L') > 0$.

Note that bank profits from free-riding, $\pi(0, \psi\frac{D}{N}; L)$, are strictly increasing and continuous in L. Similarly, note that $\pi(l_1, \psi\frac{D}{N}; L)$ is strictly increasing and continuous in L, and that by strict concavity of c and $l_1 > 0$,

$$\forall L : \frac{\partial}{\partial L}\pi(0, \psi\frac{D}{N}; L) > \frac{\partial}{\partial L}\pi(l_1, \psi\frac{D}{N}; L). \tag{60}$$

The definition of κ implies that $\pi(0, \psi\frac{D}{N}; \frac{1}{\gamma}\kappa) = 0$. By $L' \leq \kappa$ and strict monotonicity of profits, this implies that

$$\pi(l_1, \psi\frac{D}{N}; \frac{1}{\gamma}\kappa) > \pi(0, \psi\frac{D}{N}; \frac{1}{\gamma}\kappa) = 0. \tag{61}$$

Define a bank's optimal first-period investment conditional on full second-period investment and given other-bank first-period investment L as

$$l_1^*(L) = \arg\max_{l_1} \pi(l_1, \psi\frac{D}{N}; L) \tag{62}$$

and optimal profits conditional on full second-period investment as $\pi^*(L) = \pi(l_1^*(L), \psi\frac{D}{N}; L)$.

Then,

$$\pi^*(\frac{1}{\gamma}\kappa) \geq \pi(l_1, \psi\frac{D}{N}; \frac{1}{\gamma}\kappa) > \pi(0, \psi\frac{D}{N}; \frac{1}{\gamma}\kappa) = 0. \tag{63}$$

This means that the best response to $L = \frac{1}{\gamma}\kappa$ must involve positive first-period investment $l_1' > 0$, since both alternative strategies $(0,0)$ and $(0, \psi\frac{D}{N})$ yield zero profits in this case. Hence, by Corollary 3, ξ must exist.

By Lemma 16, conditional on investing $\psi\frac{D}{N}$ in the second period, optimal first-period investment $l_1^*(L)$ is positive until $L = \xi$ and zero for $L \geq \xi$. That means that $\pi^*(L) = \pi(0, \psi\frac{D}{N}; L)$ for $L \geq \xi$.

Additionally, we know by the envelope theorem that

$$\frac{\partial}{\partial L}\pi^*(L) = \pi'(l_1, \psi\frac{D}{N}; L) \mid_{l_1 = l_1^*(L)} = -c'(L + l_1^*(L))\beta\psi\frac{D}{N}. \tag{64}$$

This is always positive by strict monotonicity of c, but strictly smaller than $\pi'(0, \psi\frac{D}{N}; L) = -c'(L)\beta\psi\frac{D}{N}$ for $L < \xi$ by strict convexity of c. Hence, it has to hold by continuity of π (which implies continuity of π^*) that $\pi(l^*(L), \psi\frac{D}{N}; L) > \pi(0, \psi\frac{D}{N}; L)$ for $L < \xi$, and simultaneously that $l_1^*(L) > 0$ for $L < \xi$. Conversely, it has to hold that $\pi(l_1', \psi\frac{D}{N}; L) \leq \pi(0, \psi\frac{D}{N}; L)$ for any l_1' and $L \geq \xi$. □

Lemma 19. *An interval of other-bank first-period investment within which a bank's best response is $(\frac{D}{N}, \psi\frac{D}{N})$ (immediate financing) exists if and only if η and ξ exist, $\eta - \frac{D}{N} < \kappa$, $\eta \leq \xi$ and $\xi \geq \frac{D}{N}$. If such an interval exists, it is given by $L \in (\frac{1}{\gamma}(\eta - \frac{D}{N}), \frac{1}{\gamma}(\xi - \frac{D}{N})] \cap [0, \frac{1}{\gamma}(\xi - \frac{D}{N})]$.*

Proof. **If**. Assume η and ξ exist and $\eta - \frac{D}{N} < \kappa$, $\eta < \xi$ and $\xi \geq \frac{D}{N}$.

First, note that $(\frac{D}{N}, \psi\frac{D}{N})$ *cannot* be a best response to any level of other-bank investment $L \leq \frac{1}{\gamma}(\eta - \frac{D}{N})$ or $L > \frac{1}{\gamma}(\xi - \frac{D}{N})$. The lower bound follows from Lemma 17 and the upper bound follows from Lemma 16: For $L > \frac{1}{\gamma}(\xi - \frac{D}{N})$, $(\frac{D}{N}, \psi\frac{D}{N})$ is dominated by $(\max\{0, \xi - \gamma L\}, \psi\frac{D}{N})$.

At the same time, $(\frac{D}{N}, \psi\frac{D}{N})$ *has* to be a best response to any level of other-bank investment inside that interval, i.e. for any $L \in (\frac{1}{\gamma}(\eta - \frac{D}{N}), \frac{1}{\gamma}(\xi - \frac{D}{N})]$:

By the definition of η and the fact that bank profits conditional on positive second-period investment are strictly increasing in other-bank first-period investment L, playing $(\frac{D}{N}, \psi\frac{D}{N})$ must yield positive profits as soon as $\frac{D}{N} + \gamma L > \eta$. This implies that playing

$(\frac{D}{N}, \psi\frac{D}{N})$ dominates playing $(0,0)$ for any other-bank first-period investment above $\underline{L} = \frac{1}{\gamma}(\eta - \frac{D}{N})$.

By $\eta - \frac{D}{N} < \kappa$ and the fact that $\kappa > 0$ (as per Lemma 10), we further know that there must be an $L' \in (\frac{1}{\gamma}\max\{0, \eta - \frac{D}{N}\}, \frac{1}{\gamma}\kappa)$ at which $\pi(\frac{D}{N}, \psi\frac{D}{N}; L') > 0$. By Lemma 18, this means that $(0, \psi\frac{D}{N})$ cannot be a best response to any level of other-bank first-period investment $L < \frac{1}{\gamma}\xi$.

Since we know from Lemma 13 that all investment plans (l_1, l_2) with second-period investment $l_2 > 0$ must be dominated by $(l_1, 0)$ or $(l_1, \psi\frac{D}{N})$, this rules out that an investment plan with zero first-period investment can be a best response to other-bank investment levels $\underline{L} < L < \frac{1}{\gamma}\xi$. By Corollary 2, this means that the best response over this interval of other-bank investment levels must feature full second-period investment $l_2 = \psi\frac{D}{N}$.

Then, we know from Lemma 16 that $(\frac{D}{N}, \psi\frac{D}{N})$ dominates all other investment plans with full second-period investment given other-bank investment of $L \leq \frac{1}{\gamma}(\xi - \frac{D}{N})$. Hence, $(\frac{D}{N}, \psi\frac{D}{N})$ must be the best response to any $L \in (\frac{1}{\gamma}(\eta - \frac{D}{N}), \frac{1}{\gamma}(\xi - \frac{D}{N})]$.

Finally, we know by $\xi \geq \frac{D}{N}$, that the interval must be non-empty, since this implies that $\xi - \frac{D}{N} \geq 0$.

Only if. It is straightforward to see that an interval of other-bank first-period investment within which a bank's best response is $(\frac{D}{N}, \psi\frac{D}{N})$ cannot exist if any one of the five conditions given in the lemma does not hold:

- Suppose ξ does not exist. Then, by Lemma 15, $(0, l_2)$ must be the unique best response to any level of other-bank investment, with $l_2 \in \{0, \psi\frac{D}{N}\}$. Trivially, this means $(\frac{D}{N}, \psi\frac{D}{N})$ cannot be the best response to any level of other-bank investment.

- Suppose η does not exist. Then, there is by definition no amount of learning at which investing $(\frac{D}{N}, \psi\frac{D}{N})$ is profitable. Since the outside option of not investing is always possible and results in zero profits, $(\frac{D}{N}, \psi\frac{D}{N})$ is dominated by $(0,0)$ and cannot be a best response to any level of other-bank investment.

- Suppose $\eta - \frac{D}{N} \geq \kappa$. Since bank profits under positive second-period investment are strictly increasing in other-bank first-period investment, this implies that at an other-bank first-period investment of $\frac{1}{\gamma}(\eta - \frac{D}{N})$,

$$\pi(0, \psi\frac{D}{N}; \frac{1}{\gamma}(\eta - \frac{D}{N})) \geq 0 = \pi(\frac{D}{N}, \psi\frac{D}{N}; \frac{1}{\gamma}(\eta - \frac{D}{N})). \tag{65}$$

  By strict concavity of c (decreasing learning gains), marginal profits are higher under $(0, \psi\frac{D}{N})$ than under $(\frac{D}{N}, \psi\frac{D}{N})$ for any level of other-bank learning. By continuity of c, this implies that profits from $(0, \psi\frac{D}{N})$ will exceed profits from $(\frac{D}{N}, \psi\frac{D}{N})$ for any level of other-bank investment $> \frac{1}{\gamma}(\eta - \frac{D}{N})$. Hence, $(\frac{D}{N}, \psi\frac{D}{N})$ is weakly dominated either by $(0,0)$ – for other-bank investment below $\frac{1}{\gamma}(\eta - \frac{D}{N})$ – or by $(0, \psi\frac{D}{N})$ – for

other-bank investment above $\frac{1}{\gamma}(\eta - \frac{D}{N})$. Since by assumption, banks will choose not to invest if they have an equally profitable strategy that does not involve first-period investment, this means that $(\frac{D}{N}, \psi\frac{D}{N})$ cannot be a best response to any level of other-bank first-period investment.

- Suppose $\eta > \xi$. Then, by Lemma 16, $(\frac{D}{N}, \psi\frac{D}{N})$ is dominated by $(\max\{0, \xi - \gamma L\}, \psi\frac{D}{N})$ for any level of other-bank investment $L > \frac{1}{\gamma}(\eta - \frac{D}{N})$.

- Suppose $\xi < \frac{D}{N}$. Then, any positive level of other-bank investment

$$L \geq 0 > \frac{1}{\gamma}(\xi - \frac{D}{N}). \tag{66}$$

By the same reasoning as above, this implies that $(\max\{0, \xi - \gamma L\}, \psi\frac{D}{N})$ dominates $(\frac{D}{N}, \psi\frac{D}{N})$ for any $L \geq 0$, so $(\frac{D}{N}, \psi\frac{D}{N})$ cannot be a best response.

□

Lemma 20. *An interval of other-bank first-period investment within which a bank's best response is $(\xi - \gamma L, \psi\frac{D}{N})$ (gradual financing) exists if and only if ξ exists, $r - c(\xi) - r_D > 0$ and $\xi - \frac{D}{N} \cdot CF < \kappa$. If it exists, it ranges exactly over other-bank investment $L \in [\frac{1}{\gamma}(\xi - \frac{D}{N}), \frac{1}{\gamma}\xi] \cap (\frac{1}{\gamma}(\xi - \frac{D}{N} \cdot CF), \frac{1}{\gamma}\xi]$.*

Proof. **If.** Assume ξ exists, $r - c(\xi) - r_D > 0$ and $\xi - \frac{D}{N} \cdot CF < \kappa$. By Lemma 12, $r - c(\xi) - r_D > 0$ also implies that $CF > 0$.

For notational convenience, define

$$\pi^*(L) = (r - \bar{c} - r_D)(\xi - \gamma L) + \beta(r - c(\xi) - r_D)\psi\frac{D}{N}. \tag{67}$$

That is, π^* are the profits from investment plan $(\xi - \gamma L, \psi\frac{D}{N})$ given other-bank investment L. By $r - \bar{c} - r_D < 0$, these profits are strictly (and linearly) increasing in other-bank investment L.

Now, note that by Lemma 16, $(\xi - \gamma L, \psi\frac{D}{N})$ *cannot* be a best response to $L < \frac{1}{\gamma}(\xi - \frac{D}{N})$ or $L > \frac{1}{\gamma}\xi$. Furthermore, $(\xi - \gamma L, \psi\frac{D}{N})$ cannot be a best response to $L \leq \frac{1}{\gamma}(\xi - \frac{D}{N} \cdot CF)$, since by the definition of CF,

$$\pi^*(\frac{1}{\gamma}(\xi - \frac{D}{N} \cdot CF)) = 0. \tag{68}$$

As $\pi^*(L)$ is strictly increasing in L, this implies that $\pi^*(L) < 0$ for $L < \frac{1}{\gamma}(\xi - \frac{D}{N} \cdot CF)$.

At the same time, $(\xi - \gamma L, \psi\frac{D}{N})$ *has* to be the best response to other-bank investment levels

$$L \in [\frac{1}{\gamma}(\xi - \frac{D}{N}), \frac{1}{\gamma}\xi] \cap (\frac{1}{\gamma}(\xi - \frac{D}{N} \cdot CF), \frac{1}{\gamma}\xi]. \tag{69}$$

To see why, note first that by Lemma 16, $(\xi-\gamma L, \psi\frac{D}{N})$ strictly dominates any $(l_1, \psi\frac{D}{N})$ with $l_1 \neq \xi-\gamma L$ for $L \in [\frac{1}{\gamma}(\xi - \frac{D}{N}), \frac{1}{\gamma}\xi]$. Given Corollaries 2 and 1, that only leaves $(0,0)$ and $(0, \psi\frac{D}{N})$ as potential best responses over that interval.

Returning to equation (68) and using again the fact that π^* is strictly increasing in L, it is clear that $\pi^*(L) > 0 = \pi(0,0;L)$ for any $L > \frac{1}{\gamma}(\xi - \frac{D}{N} \cdot CF)$, so $(\xi - \gamma L, \psi\frac{D}{N})$ strictly dominates $(0,0)$ for other-bank investment $L \in (\frac{1}{\gamma}(\xi - \frac{D}{N} \cdot CF), \frac{1}{\gamma}\xi]$.

This leaves the free-riding investment plan $(0, \psi\frac{D}{N})$ as potential alternative. To see why this cannot be a best response to any L in our interval, we need to distinguish between two different potential states of the world: $\kappa > \xi$, $\kappa = \xi$ and $\kappa < \xi$.

By the definition of κ and the fact that profits from free-riding – $\pi(0, \psi\frac{D}{N}; L)$ – are strictly increasing in other-bank investment L, profits from free-riding $\pi(0, \psi\frac{D}{N}; L) < 0$ for any $L < \frac{1}{\gamma}\kappa$, $\pi(0, \psi\frac{D}{N}; \frac{1}{\gamma}\kappa) = 0$ and $\pi(0, \psi\frac{D}{N}; L) > 0$ for any $L > \frac{1}{\gamma}\kappa$.

If $\kappa > \xi$, $\frac{1}{\gamma}\xi < \frac{1}{\gamma}\kappa$, so profits from $(0, \psi\frac{D}{N})$ must be negative for any $L < \frac{1}{\gamma}\xi$. Hence $(0, \psi\frac{D}{N})$ cannot be a best response to other-bank investment in our interval.

If $\kappa = \xi$, the above reasoning holds for all values on our interval except the upper boundary $\frac{1}{\gamma}\xi$. But since $\kappa = \xi$, the gradual investment plan $(\xi - \gamma\frac{1}{\gamma}\kappa, \psi\frac{D}{N}) = (0, \psi\frac{D}{N})$, i.e. gradual investment and free riding correspond to the same action.

Finally, if $\kappa < \xi$, we know from $\xi - \frac{D}{N} \cdot CF < \kappa$ that $\pi(\xi - \frac{1}{\gamma}\kappa, \psi\frac{D}{N}; \frac{1}{\gamma}\kappa) > 0$, with $\xi - \frac{1}{\gamma}\kappa > 0$. By Lemma 18, this means that $(0, \psi\frac{D}{N})$ cannot be a best response to any $L \leq \frac{1}{\gamma}\xi$.

Only if. Again, let us go through the conditions one by one:

- If ξ does not exist, then by Lemma 15, there can be no best response that involves positive first-period investment.

- If ξ exists, but $r - c(\xi) - r_D \leq 0$, it has to hold that $CF \geq 0$ by Lemma 12. Profits from the investment plan $(\xi - \gamma L, \psi\frac{D}{N})$ are strictly increasing in other-bank investment L, and $\pi(\xi - \gamma L, \psi\frac{D}{N}; \frac{1}{\gamma}(\xi - \frac{D}{N} \cdot CF)) = 0$. That means profits from investment plan $(\xi - \gamma L, \psi\frac{D}{N})$ will only be positive for other-bank investment $L > \frac{1}{\gamma}(\xi - \frac{D}{N} \cdot CF) \geq \frac{1}{\gamma}\xi$. But $L > \frac{1}{\gamma}\xi$ implies that $\xi - \gamma L < 0$, which is not a feasible level of first-period investment.

- If ξ exists and $r - c(\xi) - r_D > 0$, but $\xi - \frac{D}{N} \cdot CF \geq \kappa$, profits from the gradual investment plan $(\xi - \gamma L, \psi\frac{D}{N})$,

$$\pi^*(L) = (r - \bar{c} - r_D)(\xi - \gamma L) + \beta(r - c(\xi) - r_D)\psi\frac{D}{N} \tag{70}$$

  are negative at an other-bank investment of $L = \frac{1}{\gamma}\kappa$, since $\pi^*(\frac{1}{\gamma}(\xi - \frac{D}{N} \cdot CF)) = 0$ and π^* is strictly increasing in L. At the same time, $\pi(0, \psi\frac{D}{N}; L)$ are zero at $L = \frac{1}{\gamma}\kappa$ by definition.

By strict concavity of c, the marginal profits from any investment plan $(l_1(L), \psi\frac{D}{N})$ with $l_1(L) \geq 0$ must be weakly lower than the marginal profits from $(0, \psi\frac{D}{N})$ for any level of other-bank investment L. Since $\xi - \gamma L \geq 0$ for any $L \leq \frac{1}{\gamma}\xi$, and infeasible for any other L, that means that marginal profits from $(0, \psi\frac{D}{N})$ must be consistently higher than marginal profits from $(\xi - \gamma L, \psi\frac{D}{N})$. Since c is continuous, and hence profits are continuous as well, this implies that $(\xi - \gamma L, \psi\frac{D}{N})$ is dominated by $(0, \psi\frac{D}{N})$ for any other-bank investment $L \geq \frac{1}{\kappa}$.

At the same time, $(\xi - \gamma L, \psi\frac{D}{N})$ is dominated by $(0, 0)$ for any $L < \frac{1}{\gamma}(\xi - \frac{D}{N} \cdot CF)$, which implies that it is dominated by any $L < \frac{1}{\gamma}\kappa$.

Hence, $(\xi - \gamma L, \psi\frac{D}{N})$ can never be a best response.

□

Lemma 21. *If an interval of other-bank learning exists to which a bank's best response is $(\frac{D}{N}, \psi\frac{D}{N})$, there must be an interval of other-bank learning L to which a bank's best response is $(\xi - \gamma L, \psi\frac{D}{N})$.*

Proof. Assume there is an interval of other-bank learning to which a bank's best response is $(\frac{D}{N}, \psi\frac{D}{N})$. By Lemma 19, ξ must exist and this interval must end at a level of other-bank learning of $\bar{L} = \frac{1}{\gamma}(\xi - \frac{D}{N})$.

The lemma also implies that there must be a level of other-bank learning $L' \in [0, \frac{1}{\gamma}(\xi - \frac{D}{N})]$ such that $\kappa \geq L'$ and $\pi(\frac{D}{N}, \psi\frac{D}{N}; L') > 0$. Since $\pi(\frac{D}{N}, \psi\frac{D}{N}; L)$ is strictly increasing in L, this implies that $\pi(\frac{D}{N}, \psi\frac{D}{N}; \frac{1}{\gamma}\kappa) > 0$. Hence, we can conclude by Lemma 18 that $(0, \psi\frac{D}{N})$ cannot be a best response to any level of other-bank investment $L < \frac{1}{\gamma}\xi$.

Finally, we know that at $L = \bar{L}$, the gradual financing investment plan $(\xi - \gamma\bar{L}, \psi\frac{D}{N}) = (\frac{D}{N}, \psi\frac{D}{N})$, and $\pi(\frac{D}{N}, \psi\frac{D}{N}) > 0$. Since profits from $(\xi - \gamma L, \psi\frac{D}{N})$ are continuous in L, this implies that there must be an $\epsilon \in (0, \frac{D}{N})$ such that

$$\forall L \in [\bar{L}, \bar{L} + \epsilon] : \pi(\xi - \gamma L, \psi\frac{D}{N}; L) > 0. \tag{71}$$

Hence, an interval $[\bar{L}, \bar{L} + \epsilon]$ must exist in which $(0, 0)$ and $(0, \psi\frac{D}{N})$ are dominated. By Lemma 16, we finally know that $(\xi - \gamma L, \psi\frac{D}{N})$ must dominate all other investment plans with positive second-period investment if other-bank learning is inside that interval. That means $(\xi - \gamma L, \psi\frac{D}{N})$ must be the best response. □

Lemma 22. *If an interval of other-bank learning L exists to which a bank's best response is $(\xi - \gamma L, \psi\frac{D}{N})$, there must be an interval of other-bank learning to which the bank's best response is $(\frac{D}{N}, \psi\frac{D}{N})$ if and only if $CF > 1$ and $\xi > \frac{D}{N}$.*

Proof. Assume that a gradual financing best response exists. By Lemma 20, this implies that ξ exists, $r - c(\xi) - r_D > 0$ and $\xi - \frac{D}{N} \cdot CF < \kappa$.

If. Let $CF > 1$. Again by Lemma 20, this implies that the bank's best response to any $L \in [\xi - \frac{D}{N}, \xi]$ is $(\xi - \gamma L, \psi\frac{D}{N})$. $CF > 1$ also implies that at $L = \xi - \frac{D}{N}$ – where $\xi - \gamma L = \frac{D}{N}$ – $(\frac{D}{N}, \psi\frac{D}{N})$ is a best response. By our assumption that banks do not invest under zero profits, this requires that

$$\pi(\frac{D}{N}, \psi\frac{D}{N}; \frac{1}{\gamma}(\xi - \frac{D}{N})) > 0 \tag{72}$$

But since $\pi(\frac{D}{N}, \psi\frac{D}{N}; L)$ is continuous in L, and $\xi > \frac{D}{N}$, that means that there must also be an $L' \in [0, \frac{1}{\gamma}(\xi - \frac{D}{N}))$ such that $(\frac{D}{N}, \psi\frac{D}{N})$ dominates $(0, 0)$ for all $L \in [L', \frac{1}{\gamma}(\xi - \frac{D}{N})]$.

Finally, since $\kappa > 0$ by Lemma 10, and since $\kappa > \xi - \frac{D}{N} \cdot CF$, there must be a $L'' \in (\frac{1}{\gamma}(\xi - \frac{D}{N} \cdot CF), \frac{1}{\gamma}\kappa]$ such that $\pi(\frac{D}{N}, \psi\frac{D}{N}; L'') > 0$ or $\pi(\xi - \gamma L'', \psi\frac{D}{N}; L'') > 0$. Hence, by Lemma 18, $(0, \psi\frac{D}{N})$ cannot be a best response to any $L \in [L', \frac{1}{\gamma}(\xi - \frac{D}{N})]$.

Therefore, an interval where $(\frac{D}{N}, \psi\frac{D}{N})$ is the best response must exist.

Only if. Assume an interval of other-bank learning exists to which $(\frac{D}{N}, \psi\frac{D}{N})$ is a best response.

First, note that by Lemma 16, this requires that $\xi > \frac{D}{N}$. Otherwise, $(\xi - \gamma L, \psi\frac{D}{N})$ will dominate $(\frac{D}{N}, \psi\frac{D}{N})$ for any $L \geq 0 \geq \xi - \frac{D}{N}$.

By Lemma 19, we know that this plateau must range from $\frac{1}{\gamma}(\eta - \frac{D}{N})$ to $\frac{1}{\gamma}(\xi - \frac{D}{N})$. That implies that, at $L = \frac{1}{\gamma}(\xi - \frac{D}{N})$,

$$\pi(\xi - \gamma L, \psi\frac{D}{N}; L) > 0, \tag{73}$$

since then $\frac{D}{N} = \xi - \gamma L$.

This requires that $CF > 1$. Assume for contradiction that $CF \leq 1$. Then, $\xi - \frac{D}{N} CF \geq \xi - \frac{D}{N}$. By the definition of CF,

$$\pi(\xi - \gamma\frac{1}{\gamma}(\xi - \frac{D}{N} \cdot CF), \psi\frac{D}{N}; \frac{1}{\gamma}(\xi - \frac{D}{N} \cdot CF)) = 0 \tag{74}$$

Since $\pi(\xi - \gamma L, \psi\frac{D}{N}; L)$ is strictly increasing in L, this implies that

$$\pi(\xi - \gamma L, \psi\frac{D}{N}; L) \leq 0 \tag{75}$$

at $L = \frac{1}{\gamma}(\xi - \frac{D}{N})$, which contradicts (73). □

C.3 Symmetry of Nash equilibrium

We can show that any Nash equilibrium must be symmetric:

Lemma 23. *In any Nash equilibrium, it holds that*

$$\nexists i \in \{1, ..., N\} : l_{i,1} = 0 \wedge l_{i,2} > 0.$$

Proof. Let $l_{i,1} = 0$ in a Nash equilibrium. Assume for contradiction that $l_{i,2} > 0$. By Corollary 1, this implies that $l_{i,2} = \psi\frac{D}{N}$. Then, one of the following cases must hold:

- $\tilde{L}_{-i,1} = 0$. But by Assumption 1, this would imply that $r - c(\tilde{L}_{-i,1} + l_{i,1}) = r - \bar{c} < r_D$. Then, it is trivial to see that

$$\pi_i((L_{-i}, (0,0))) > \pi_i((L_{-i}, (0, l_{i,2}))).$$

  Hence, $(0, l_{i,2})$ cannot be a best response to L_{-i} for bank i, and therefore this strategy cannot be part of a Nash equilibrium.

- $\tilde{L}_{-i,1} > 0$. This implies that there is another bank j with $l_{j,1} > 0$ and, concomitantly, $l_{j,2} = \psi\frac{D}{N}$ and

$$\tilde{L}_{-j,1} = \gamma\bar{L}_{-i,-j,1} < \gamma\bar{L}_{-i,-j,1} + \gamma l_{j,1} = \tilde{L}_{-i,1}$$

  where $\bar{L}_{-i,-j,1}$ denotes the sum of first-period loans by all banks except i and j. It follows immediately that $\tilde{L}_{j,1} - \tilde{L}_{i,1} = (1-\gamma)l_{j,1} > 0$. Note that $l_{j,1} > 0$ requires by j's best response function that

$$r - \bar{c} - \beta c'(\tilde{L}_{j,1})\psi\frac{D}{N} \geq r_D,$$

  while $l_{i,1} = 0$ requires by i's best response function that

$$r - \bar{c} - \beta c'(\tilde{L}_{i,1})\psi\frac{D}{N} < r_D.$$

  But since $-\beta c'(\cdot)\psi\frac{D}{N}$ is strictly decreasing, $\tilde{L}_{i,1} < \tilde{L}_{j,1}$ implies that

$$r - \bar{c} - \beta c'(\tilde{L}_{i,1})\psi\frac{D}{N} > r - \bar{c} - \beta c'(\tilde{L}_{j,1})\psi\frac{D}{N} \geq r_D,$$

  which is a contradiction.

□

Lemma 24. *In any Nash equilibrium with $\bar{L}_1 \in (0, D]$, it holds that*

$$l_{i,1} \neq 0 \; \forall \; i = 1, ..., N.$$

Proof. $\bar{L}_1 \in (0, D]$ implies that there must be another bank j such that $l_{j,1} > 0$.

Assume for contradiction that there is a bank i such that $l_{i,1} = 0$. By Lemma 23, this implies that $l_{i,2} = 0$, which means that

$$\pi_i(L_{-i}, (0,0)) = 0.$$

Note that $l_{j,1} > 0$ implies that $l_{j,2} = \psi\frac{D}{N}$ by Corollary 2. Hence, bank j's profits must be

$$\pi_j(L_{-j}, (l_{j,1}, \psi\frac{D}{N})) = (r - \bar{c} - r_D)l_{j,1} + \beta\left(r - c(\tilde{L}_{-j,1} + l_{j,1}) - r_D\right)\psi\frac{D}{N}.$$

If the outcome is a Nash equilibrium, it has to hold by j's best response function that this yields positive profits.

Also, note that

$$\tilde{L}_{-j,1} - \tilde{L}_{-i,1} = \gamma\bar{L}_{-i,-j,1} - (\gamma\bar{L}_{-i,-j,1} + \gamma l_{j,1}) = -\gamma l_{j,1} < 0,$$

which means that $\tilde{L}_{-j,1} < \tilde{L}_{-i,1}$. But since $\pi_i(\cdot)$ is weakly increasing in $\tilde{L}_{-i,1}$, this means that if bank i were to switch from $(0,0)$ to adopting bank j's strategy $(l_{j,1}, \psi\frac{D}{N})$, then it must be the case that

$$\pi_i(L_{-i}, (l_{j,1}, \psi\frac{D}{N})) \geq \pi_j(L_{-j}, (l_{j,1}, \psi\frac{D}{N})) > \pi_i(L_{-i}, (0,0)).$$

By symmetry, $(l_{j,1}, \psi\frac{D}{N})$ must be feasible for bank i since it is feasible for bank j. Therefore, $(0,0)$ cannot be a best response of bank i to L_{-i}, and the outcome cannot be a Nash equilibrium. □

Lemma 25. *In any Nash equilibrium with $\bar{L}_1 \in (0, D]$ there is a $l_1^* \in \left(0, \frac{D}{N}\right]$ such that*

$$l_{k,1} = l_1^* \; \forall \; k = 1, ..., N.$$

Proof. In a Nash equilibrium with $\bar{L}_1 \in (0, D]$, it holds by Lemma 24 that $l_{i,1} > 0 \; \forall \; i$. Take any $i \neq j$ and assume for contradiction that $l_{j,1} > l_{i,1}$.

This implies that $\tilde{L}_{j,1} = \gamma\bar{L}_{-i,-j,1} + \gamma l_{i,1} + l_{j,1}$ and $\tilde{L}_{j,1} = \gamma\bar{L}_{-i,-j,1} + \gamma l_{j,1} + l_{i,1}$. Hence,

$$\tilde{L}_{j,1} - \tilde{L}_{i,1} = (1 - \gamma)(l_{j,1} - l_{i,1}) > 0.$$

Note that $l_{i,1}, l_{j,1} > 0$ implies by Corollary 2 that $l_{i,2} = l_{j,2} = \psi\frac{D}{N}$. Furthermore, $l_{j,1} > l_{i,1}$ implies that $l_{i,1} < \frac{D}{N}$. Since the outcome is a Nash equilibrium, i's best response function requires that

$$r_D = r - \bar{c} - \beta c'(\tilde{L}_{i,1})\psi\frac{D}{N}.$$

At the same time, $l_{j,1} > 0$ implies by j's best response function that

$$r_D \leq r - \bar{c} - \beta c'(\tilde{L}_{j,1})\psi\frac{D}{N}.$$

Combining both expressions yields the requirement that

$$-c'(\tilde{L}_{j,1}) \geq -c'(\tilde{L}_{i,1}).$$

However, since $-c'(\cdot)$ is strictly decreasing and $\tilde{L}_{j,1} > \tilde{L}_{i,1}$, this cannot hold. □

Lemma 26. *In any Nash equilibrium, it holds that*

$$l_{i,t} = l_t^* \; \forall \; i, t.$$

Proof. Simply note that $\bar{L}_1 \in [0, D]$, which means that one of the following cases has to hold:

- $\bar{L}_1 = 0$. Then, trivially, $l_{i,1} = 0 \; \forall \; i$, and $l_{i,2} = 0 \; \forall i$ by Corollary 2;
- $\bar{L}_1 \in (0, D]$. Then, by Lemma 25, $l_{i,1} = l_1^* \; \forall \; i$, and again by Corollary 2, $l_{i,2} = \psi \frac{D}{N}$.

□

C.4 Existence of Nash equilibria

Lemma 27. *Let* $l_1^{*NE} \coloneqq \tilde{N}^{-1}(c')^{-1}(-\frac{r_D - r + \bar{c}}{\beta \psi \frac{D}{N}})$. *Then the symmetric no-financing Nash equilibrium* $l_{i,t} = 0 \; \forall \; i, t$ *exists if and only if*

$$\nexists \, l_{i,1} \in \{\tilde{N} l_1^{*NE}, \frac{D}{N}\} \cap (0, \frac{D}{N}] : \beta \left(r - c(l_{i,1}) - r_D\right) \psi \frac{D}{N} > \left(r_D - r + \bar{c}\right) l_{i,1}.$$

Proof. **Only if**

By Assumption 1, the FOCs in Equation 39 and 40 hold for $l_{i,t} = 0 \; \forall \; i, t$ and $\mu_{i,3}, \mu_{i,4} > 0$. In other words, the symmetric no-financing outcome is always a critical point of the Lagrangian since both FOCs, in this case, reduce to $r - \bar{c} < r_D$.

By Lemma 7, $(l_{i,1}, l_{i,2}) = (0, \psi \frac{D}{N})$ cannot be a best response of bank i given $\bar{L}_{-i,1} = 0$. Therefore, by Lemma 7 the only possible best-response deviations for bank i from the symmetric no-financing outcome are

$$(l_{i,1}, l_{i,2}) = (\frac{D}{N}, \psi \frac{D}{N})$$

or

$$(l_{i,1}, l_{i,2}) = \left((c')^{-1} \left(-\frac{r_D - r + \bar{c}}{\beta \psi \frac{D}{N}} \right) - \tilde{L}_{-i,1}, \psi \frac{D}{N} \right)$$

which, given $\bar{L}_{-i,1} = 0$, can be rewritten as

$$(l_{i,1}, l_{i,2}) = \left(\tilde{N} l_1^{*NE}, \psi \frac{D}{N} \right).$$

Assume that the symmetric no-financing outcome is not a Nash equilibrium. Then, one of these two possible deviations must be optimal for bank i given $\bar{L}_{-i} = 0$, which by

the SOC requires that

$$\exists\, l_{i,1} \in \{\tilde{N} l_1^{*NE}, \frac{D}{N}\} \cap (0, \frac{D}{N}] : \pi_i \left(\bar{L}_{-i,1} = 0, (l_{i,1}, \psi \frac{D}{N}) \right) > \pi_i \left(\bar{L}_{-i,1} = 0, (0,0) \right) = 0.$$

Inserting the expression for $\pi_i \left(\bar{L}_{-i,1} = 0, (l_{i,1}, \psi \frac{D}{N}) \right)$ and rearranging gives us

$$\exists\, l_{i,1} \in \{\tilde{N} l_1^{*NE}, \frac{D}{N}\} \cap (0, \frac{D}{N}] : \beta \left(r - c(l_{i,1}) - r_D \right) \psi \frac{D}{N} > (r - \bar{c} - r_D) l_{i,1}.$$

If

If

$$\nexists\, l_{i,1} \in \{\tilde{N} l_1^{*NE}, \frac{D}{N}\} \cap (0, \frac{D}{N}] : \beta \left(r - c(l_{i,1}) - r_D \right) \psi \frac{D}{N} > (r_D - r + \bar{c})\, l_{i,1}$$

holds, then the SOC is violated for any $(l_{i,1}, l_{i,2}) \neq (0,0)$ that satisfies the best response function given by Lemma 7. Hence, the best response of bank i given $\bar{L}_{-i,1} = 0$ must be $(0,0)$. □

Lemma 28. *Let* $l_1^{*NE} \coloneqq \tilde{N}^{-1} (c')^{-1} \left(-\frac{r_D - r + \bar{c}}{\beta \psi \frac{D}{N}} \right)$. *Then the Nash equilibrium* $(l_1^{*NE}, \psi \frac{D}{N})_{i=1}^N$ *exists if and only if*

$$l_1^{*NE} \in (0, \frac{D}{N}] \wedge \beta \left(r - c(\tilde{N} l_1^{*NE}) - r_D \right) \psi \frac{D}{N} > (r_D - r + \bar{c})\, l_1^{*NE}. \tag{76}$$

Proof. **If**

First, we must show that $(l_1^{*NE}, \psi \frac{D}{N})_{i=1}^N$ satisfies the FOC for each bank i. Plugging this into Equation 39 yields

$$-r_D + r - \bar{c} - \beta c'(\tilde{N} l_1^{*NE}) \psi \frac{D}{N} - \mu_{i,1} + \mu_{i,3} = 0.$$

Assuming $l_1^{*NE} \in (0, \frac{D}{N}) \implies \mu_{i,3} = \mu_{i,1} = 0$ and given the definition of l_1^{*NE}, this reduces to

$$0 = 0.$$

Assuming $l_1^{*NE} = \frac{D}{N} \implies \mu_{i,3} = 0, \mu_{i,1} \geq 0$, the Equation still holds for $\mu_{i,1} = 0$, which does not violate the complementary slackness conditions. Hence, in both cases, the FOC is satisfied.

By Lemma 7, the only possible deviations for bank i from $(l_1^{*NE}, \psi \frac{D}{N})_{i=1}^N$ are $(0,0)$, $(0, \psi \frac{D}{N})$, and $(\frac{D}{N}, \psi \frac{D}{N})$. Then, the SOC requires that profits under these deviations are dominated by $(l_1^{*NE}, \psi \frac{D}{N})$.

First, note that

$$\beta \left(r - c(\tilde{N} l_1^{*NE}) - r_D \right) \psi \frac{D}{N} > (r_D - r + \bar{c})\, l_1^{*NE}$$

implies that bank i makes an above-zero profit in the potential Nash equilibrium. Hence $(0,0)$, which yields zero profits, cannot be an individually rational deviation from the potential Nash equilibrium.

For the other two deviations, it suffices to show that if $l_{i,2} = \psi\frac{D}{N}$, then for a given $L_{-i,1}$

$$\pi_i\left(\bar{L}_{-i,1}, (l_{i,1}, \frac{D}{N})\right) = (r - \bar{c} - r_D)l_{i,1} + \beta\left(r - c(l_{i,1} + \tilde{L}_{-i,1}) - r_D\right)\psi\frac{D}{N}$$

is strictly concave in $l_{i,1}$ since the first term is linear, hence weakly concave, in $l_{i,1}$ and $-c(\cdot)$ is strictly concave by the strict convexity of c. Therefore, any deviation from the critical point $(l_1^{*NE}, \psi\frac{D}{N})$ that still features $l_{i,2} = \psi\frac{D}{N}$ must result in strictly lower profits and cannot be a best response.

Only if

Assume that the Nash equilibrium $(l_1^{*NE}, \psi\frac{D}{N})_{i=1}^N$ exists. By Corollary 2, this then implies that

$$l_1^{*NE} \neq 0$$

and, given the demand constraint and the nonnegativity condition,

$$l_1^{*NE} \in (0, \frac{D}{N}].$$

However, if the Nash equilibrium $(l_1^{*NE}, \psi\frac{D}{N})_{i=1}^N$ exists, then by Lemma 7 this implies above-zero profits. □

Lemma 29. *The Nash equilibrium $(\frac{D}{N}, \psi\frac{D}{N})_{i=1}^N$ exists if and only if*

$$r - \bar{c} - \beta\psi\frac{D}{N}c'(\tilde{N}\frac{D}{N}) \geq r_D \wedge \beta\psi\left(r - c(\frac{\tilde{N}}{N}D) - r_D\right) \geq r_D - r + \bar{c}.$$

Proof. **If**

For this part of the proof, we follow the same steps as above for Lemma 28: For

$$r - \bar{c} - \beta\psi\frac{D}{N}c'\left(\tilde{N}\frac{D}{N}\right) \geq r_D$$

the FOC with respect to $l_{i,1}$ is satisfied and $l_1^{*NE} \geq \frac{D}{N}$. In other words, a deviation from the potential Nash equilibrium to $l_{i,1} = l_1^{*NE}$ would violate the demand constraint. By the strict concavity of profits given $l_{i,2} = \psi\frac{D}{N}$, deviating from the critical point l_1^{*NE} to $l_{i,1} = 0$ must yield strictly lower profits. By Lemma 7, the only remaining best response

is $(0,0)$, which cannot be optimal since

$$\beta\psi(r - c\left(\frac{\tilde{N}}{N}D\right) - r_D) \geq r_D - r + \bar{c}$$

implies profits above zero under the potential Nash equilibrium. Hence, the Nash equilibrium exists.

Only if

First, assume that profits of bank i under $(\frac{D}{N}, \psi\frac{D}{N})_{i=1}^{N}$ are nonpositive. Since we assume that $(0,0)$ is preferred for zero profits, this directly implies that the best response must be $(0,0)$.

Alternatively, assume that

$$r - \bar{c} - \beta\psi\frac{D}{N}c'\left(\tilde{N}\frac{D}{N}\right) < r_D.$$

By Lemma 7, this implies that the best response cannot be $(l_{i,1}, l_{i,2}) = (\frac{D}{N}, \psi\frac{D}{N})$. □

Lemma 30. *Let $\mathcal{L}^{NE}$ be the set of Nash equilibria and let $l_1^{*NE} < \frac{D}{N}$. Then $(\frac{D}{N}, \psi\frac{D}{N})_{i=1}^{N} \notin \mathcal{L}^{NE}$ if $(l_1^{*NE}, \psi\frac{D}{N})_{i=1}^{N} \in \mathcal{L}^{NE}$ and vice-versa.*

Proof. By Lemma 29, $(\frac{D}{N}, \psi\frac{D}{N})_{i=1}^{N} \notin \mathcal{L}^{NE}$ requires that

$$r - \bar{c} - \beta\psi\frac{D}{N}c'\left(\tilde{N}\frac{D}{N}\right) \geq r_D,$$

whereas, by Lemma 28, $(l_1^{*NE}, \psi\frac{D}{N})_{i=1}^{N} \in \mathcal{L}^{NE}$ requires that

$$r - \bar{c} - \beta\psi\frac{D}{N}c'\left(\tilde{N}l_1^{*NE}\right) = r_D.$$

As $l_1^{*NE} < \frac{D}{N}$ and $c'' > 0$, these conditions are mutually exclusive as

$$-\beta\psi\frac{D}{N}c'\left(\tilde{N}\frac{D}{N}\right) < -\beta\psi\frac{D}{N}c'(\tilde{N}l_1^{*NE}).$$

□

Lemma 31. *Let $\mathcal{L}^{NE}$ be the set of Nash equilibria. Then if $(0,0)_{i=1}^{N} \notin \mathcal{L}^{NE}$, it holds that*

$$(l_1^{*NE}, \psi\frac{D}{N})_{i=1}^{N} \in \mathcal{L}^{NE} \vee (\frac{D}{N}, \psi\frac{D}{N})_{i=1}^{N} \in \mathcal{L}^{NE}.$$

Proof. By Lemma 27, $(0,0)_{i=1}^{N} \notin \mathcal{L}^{NE}$ requires that

$$\exists\, l_{i,1} \in \{\tilde{N}l_1^{*NE}, \frac{D}{N}\} \cap (0, \frac{D}{N}] : \beta\left(r - c(l_{i,1}) - r_D\right)\psi\frac{D}{N} > (r_D - r + \bar{c})\, l_{i,1}.$$

This condition holds under two cases:

Case 1:

$$\exists\, l_{i,1} = \tilde{N} l_1^{*NE} \in (0, \frac{D}{N}] : \beta \left(r - c(l_{i,1}) - r_D\right) \psi \frac{D}{N} > \left(r_D - r + \bar{c}\right) l_{i,1}.$$

Since this implies that $l_1^{*NE} \in (0, \frac{D}{N})$, both conditions in Lemma 28 are satisfied such that $(l_1^{*NE}, \psi\frac{D}{N})_{i=1}^{N} \in \mathcal{L}^{NE}$.

Case 2:

$$\tilde{N} l_1^{*NE} \notin (0, \frac{D}{N}] \wedge \beta\psi \left(r - c(\frac{D}{N}) - r_D\right) \frac{D}{N} > \left(r_D - r + \bar{c}\right) \frac{D}{N}.$$

By Lemma 7, the latter expression (i.e., that bank i can obtain positive profits unilaterally) requires that

$$r - \bar{c} - \beta\psi \frac{D}{N} c'(\frac{D}{N}) > r_D.$$

Since $\tilde{N} l_1^{*NE}$ is implicitly defined by

$$r - \bar{c} - \beta\psi \frac{D}{N} c'(\tilde{N} l_1^{*NE}) = r_D$$

and $c'' > 0$, this implies that $\tilde{N} l_1^{*NE} > \frac{D}{N}$.

Now, we need to distinguish two further cases:

Case 2a: $l_1^{*NE} \leq \frac{D}{N}$.

We know that

$$\beta \left(r - c(\frac{D}{N}) - r_D\right) \psi \frac{D}{N} > \left(r_D - r + \bar{c}\right) \frac{D}{N}$$

and that $l_1^{*NE} \leq \frac{D}{N}$ while $\tilde{N} l_1^{*NE} > \frac{D}{N}$. Then it directly follows that

$$\beta \left(r - c(\tilde{N} l_1^{*NE}) - r_D\right) \psi \frac{D}{N} > \left(r_D - r + \bar{c}\right) l_1^{*NE}$$

since $c' < 0$ and by Assumption 1, $r_D - r + \bar{c} > 0$. Hence, both conditions in Lemma 28 are satisfied such that $(l_1^{*NE}, \psi\frac{D}{N})_{i=1}^{N} \in \mathcal{L}^{NE}$.

Case 2b: $l_1^{*NE} > \frac{D}{N}$.

Again, we can directly conclude that

$$\beta \left(r - c(\tilde{N} \frac{D}{N}) - r_D\right) \psi \frac{D}{N} > \left(r_D - r + \bar{c}\right) \frac{D}{N}.$$

Hence, both conditions in Lemma 29 are satisfied such that $(\frac{D}{N}, \psi\frac{D}{N})_{i=1}^{N} \in \mathcal{L}^{NE}$.

□

C.5 Early financing gap

Lemma 32. *Let $\mathcal{L}^{SO}$ be the set of socially optimal solutions and $\mathcal{L}^{NE}$ be the set of Nash equilibrium solutions. Then, if $(0,0)_{i=1}^{N} \in \mathcal{L}^{SO}$, then $\mathcal{L}^{NE} = \{(0,0)_{i=1}^{N}\}$.*

Proof. By the social planner's SOC, $(0,0)_{i=1}^{N} \in \mathcal{L}^{SO}$ implies that, for any $\bar{L}_1 \in [0, D]$, $\tilde{L}_1 \in \left[0, \frac{\tilde{N}}{N} D\right]$,

$$0 \geq (r - \bar{c} - r_D)\bar{L}_1 + \beta(r - c(\tilde{L}_1) - r_D)\psi D.$$

Dividing both sides of this inequality by N, it is immediately clear that this is equivalent to

$$0 \geq (r - \bar{c} - r_D)l_1 + \beta(r - c(\tilde{L}_1) - r_D)\psi \frac{D}{N} \tag{77}$$

for any $l_1 \in \left[0, \frac{D}{N}\right], \tilde{L}_1 \in \left[0, \frac{\tilde{N}}{N} D\right]$.

Now, assume for contradiction that there is a different Nash equilibrium. This implies that there is at least one bank i for which $l_{i,1} \in \left(0, \frac{D}{N}\right]$ and $\tilde{L}_{-i,1} \in \left[0, \frac{\tilde{N}-1}{N} D\right]$. However, by bank i's best response function, this would require that

$$0 < (r - \bar{c} - r_D)l_{i,1} + \beta \left(r - c(\tilde{L}_{-i,1} + l_{i,1}) - r_D\right) \psi \frac{D}{N}.$$

Since $L_{-i,1} + l_{i,1} \in \left[0, \frac{\tilde{N}}{N} D\right]$, this would contradict the condition in Equation 77. □

Lemma 33. *Let the unique socially optimal solution be such that $\bar{L}_1^{SO} \in (0, D)$. Let $\mathcal{L}^{NE}$ be the set of Nash equilibrium solutions. Then, for any $L \in \mathcal{L}^{NE}$ and $N > 1$, it must hold that $\bar{L}_1 < \bar{L}_1^{SO}$.*

Proof. Assume for contradiction that $\bar{L}_1 \geq \bar{L}_1^{SO}$. By Lemma 26 (symmetry of the Nash equilibrium), this implies that $l_{i,1} = l_1 = \frac{\bar{L}_1}{N} \in \left(0, \frac{D}{N}\right] \ \forall\ i$. It also requires that there is at least one bank i with $l_{i,1}^{SO} \leq l_1$ and $\bar{L}_{-i,1} = \bar{L}_1 - l_1 \in \left[0, \frac{N-1}{N} D\right]$. Let i be this bank.

The bank's best response function implies that

$$-c'(\gamma \bar{L}_{-i,1} + l_1) \geq \frac{r_D - r + \bar{c}}{\beta} \frac{N}{\psi D},$$

where the condition holds with strict inequality if and only if $l_1 = \frac{D}{N}$. On the other hand, the FOCs for bank i in the social planner's problem tell us that

$$-c'(\gamma \bar{L}_{-i,1}^{SO} + l_{i,1}^{SO}) \leq \frac{r_D - r + \bar{c}}{\beta} \frac{N}{\psi D} \frac{1}{\tilde{N}},$$

where the condition holds with strict inequality if and only if $l_{i,1}^{SO} = 0$.

As $N > 1$, we know that

$$\frac{r_D - r + \bar{c}}{\beta}\frac{N}{\psi D} > \frac{r_D - r + \bar{c}}{\beta}\frac{N}{\psi D}\frac{1}{\tilde{N}},$$

and hence that

$$-c'(\gamma \bar{L}_{-i,1} + l_1) > -c'(\gamma \bar{L}^{SO}_{-i,1} + l^{SO}_{i,1}).$$

Since $c(\cdot)$ is strictly decreasing and convex, $-c'(\cdot)$ is strictly decreasing. This implies that $\gamma \bar{L}_{-i,1} + l_1 < \gamma \bar{L}^{SO}_{-i,1} + l^{SO}_{i,1}$. Rearranging yields

$$\bar{L}_1 + \frac{1}{\gamma}(l_1 - l^{SO}_{i,1}) < \bar{L}^{SO}_1.$$

Since $l_1 - l^{SO}_{i,1} \geq 0$, this implies that $\bar{L}_1 < \bar{L}^{SO}_1$, which contradicts $\bar{L}_1 \geq \bar{L}^{SO}_1$. □

Lemma 34. *Let $(\frac{D}{N}, \psi\frac{D}{N})_{i=1}^N$ be the unique socially optimal solution. Let $\mathcal{L}^{NE}$ be the set of Nash equilibrium solutions. Then, $(\frac{D}{N}, \psi\frac{D}{N})_{i=1}^N \in \mathcal{L}^{NE}$ if and only if*

$$-c'(\frac{\tilde{N}}{N}D) \geq \frac{r_D - r + \bar{c}}{\beta}\frac{N}{\psi D}. \tag{78}$$

Proof. If $(\frac{D}{N}, \psi\frac{D}{N})_{i=1}^N$ is the solution to the social maximization problem, the SOC implies that total profits exceed zero, i.e.,

$$\beta\left(r - c(\tilde{N}\frac{D}{N}) - r_D\right)\psi\frac{D}{N} > (r - \bar{c} - r_D)\frac{D}{N}$$

which satisfies the second condition in Lemma 29. The condition stated above is then simply the first condition in Lemma 29 restated. □

D Proofs for Propositions 3 and 4 (stand-alone policy interventions)

Using a more formal notation, Propositions 3 and 4 can be stated as follows:

Proposition 3. *Let $l^{SO}_1 \in (0, \frac{D}{N})$, let $s^*_1 := -\beta\gamma(N-1)\psi\frac{D}{N}c'(\tilde{N}l^{SO}_1) > 0$, and let $\mathcal{L}^{NE}|s$ be the set of possible Nash equilibria for a given $s_1, s_2 \geq 0$ and $g_1, g_2 = 0$. Then, it holds that*

- $(l^{SO}_1, l^{SO}_2)_{i=1}^N \in \mathcal{L}^{NE}|s \;\forall\; s_1 = s^*_1, s_2 \geq 0$;

- $(0,0)_{i=1}^{N} \in \mathcal{L}^{NE}|s \;\forall\; s_1 = s_1^*, s_2 \geq 0$ *if and only if*

$$\begin{aligned} &\nexists\, l_{i,1} \in \{\tilde{N} l_1^{SO}, \frac{D}{N}\} \cap (0, \frac{D}{N}] : \\ &\beta\left(r - c(l_{i,1}) - r_D + s_2\right)\psi\frac{D}{N} \geq \left(\bar{c} + r_D - r - s_1^*\right) l_{i,1}; \end{aligned} \tag{79}$$

- $(0,0)_{i=1}^{N} \in \mathcal{L}^{NE}|s \;\forall\; s_1 = s_1^*, s_2 = 0$ *if*

$$(0,0) \in \mathcal{L}^{NE}|s \text{ for } s_1, s_2 = 0 \wedge r - r_D \leq c(\frac{D}{N}); \tag{80}$$

- $\mathcal{L}^{NE}|s = \{(l_1^{SO}, l_2^{SO})_{i=1}^{N}\} \;\forall\; s_1 = s_1^*, s_2 > \bar{c} + r_D - r.$

Proof. See Appendix D.2. □

Proposition 4. *Let $l_1^{SO} \in (0, \frac{D}{N})$, and let $\mathcal{L}^{NE}|g$ be the set of possible Nash equilibria for a given $g_1, g_2 \geq 0$ and $s_1, s_2 = 0$. Let $l_1^{*NE}|g \coloneqq (c')^{-1}\left(-\frac{\bar{c}+r_D-r}{\beta\psi\frac{D-g_2}{N}}\right) - \frac{\gamma^g}{\tilde{N}} g_1$, and let $g_1^* \coloneqq \frac{1}{\gamma^g} c^{-1}(r - r_D)$. Then, it holds that*

- $\mathcal{L}^{NE}|g \in \mathcal{P}\left(\left\{\left(\max\{0, \min\{l_1^{*NE}|g, \frac{D-g_1}{N}\}\}, \psi\frac{D-g_2}{N}\right)_{i=1}^{N}, (0,0)_{i=1}^{N}\right\}\right) \setminus \emptyset;$
- $(0,0)_{i=1}^{N} \notin \mathcal{L}^{NE}|g \;\forall\; g_1 \in (g_1^*, D), g_2 \in [0, \psi D);$
- $l_1^{*NE}|g$ *decreases in* g_2*;*
- *The parameter space for which* $\left(\max\{0, \min\{l_1^{*NE}|g, \frac{D-g_1}{N}\}\}, \psi\frac{D-g_2}{N}\right)_{i=1}^{N} \in \mathcal{L}^{NE}|g$ *decreases in* g_2*.*

Proof. See Appendix D.3. The comparative statics for $l_1^{*NE}|g$ follow directly from its definition, keeping in mind that $(c')^{-1}$ is monotonically increasing. □

D.1 First-order conditions

The first-order conditions for the maximization problem by bank i given in Equation 15 are as follows:

$$r - \bar{c} - r_D + s_1 - \beta c'\left(\gamma \sum_{j \neq i} l_{j,1}^{NE} + \gamma^g g_1 + l_{i,1}^{NE}\right) l_{i,2}^{NE} - \mu_{i,1} + \mu_{i,3} = 0 \tag{81}$$

$$r - c\left(\gamma \sum_{j \neq i} l_{j,1}^{NE} + \gamma^g g_1 + l_{i,1}^{NE}\right) - r_D + s_2 - \mu_{i,2} + \mu_{i,4} = 0 \tag{82}$$

$$\mu_{i,1}(\frac{D}{N} - l_{i,1}^{NE} - \frac{g_1}{N}) = \mu_{i,2}(\psi\frac{D}{N} - l_{i,2}^{NE} - \frac{g_2}{N}) = \mu_{i,3} l_{i,1}^{NE} = \mu_{i,4} l_{i,2}^{NE} = 0 \tag{83}$$

$$\mu_{i,1}, \mu_{i,2}, \mu_{i,3}, \mu_{i,4} \geq 0. \tag{84}$$

Considering Equations 81-82, $\forall s_1, s_1, g_1, g_2 \geq 0$, we could simply redefine $r^* \coloneqq r + s_2$, $r_D^* \coloneqq r_D - s_1 + s_2$, and $\bar{c}^* \coloneqq c(\gamma^g g_1)$ and $c^*(x) = c(x + \gamma^g g_1)$. We would then face the same maximization problem as before and follow the steps in Appendix C.3 to derive that any resulting Nash equilibrium under the policy intervention must be symmetric and take the shape of a no-financing, gradual-financing, or immediate-financing equilibrium. In addition, it is now also possible that $(0, \psi\frac{D-g_2}{N})_{i=1}^N$ is a Nash equilibrium if the policy intervention alone suffices to ensure bankability at $t = 2$. Nevertheless, the existence of this additional outcome does not affect the logical steps that underlie the symmetry of the Nash equilibrium:

Lemma 35. *Let $\mathcal{L}^{NE}|gs$ be the set of possible Nash equilibria for a given $s_1, s_2, g_1, g_2 \geq 0$. Then for any $(l_1^{NE}, l_2^{NE}) \in \mathcal{L}^{NE}|gs$ it holds that*

$$l_{i,t}^{NE} = l_t^{NE} \; \forall \; i = 1, ..., N, t \in \{1, 2\}.$$

Proof. Analogous to Lemma 26 with the redefined maximization problem. □

D.2 De-risking subsidy

Lemma 36. *Let $l_1^{SO} \in (0, \frac{D}{N})$. Then, $s_1^* \coloneqq -\beta\gamma(N-1)\psi\frac{D}{N}c'(\tilde{N}l_1^{SO}) < r_D - r + \bar{c}$.*

Proof. If $l_1^{SO} \in (0, \frac{D}{N})$, then by Equation 26 it holds that:

$$r - r_D - \bar{c} - \beta c'(\tilde{N}l_1^{SO})\psi\frac{\tilde{N}}{N}D = 0.$$

Recalling that $\tilde{N} \coloneqq 1 + \gamma(N-1)$, we can rewrite this as

$$-\beta c'(\tilde{N}l_1^{SO})\psi\frac{D}{N} - \beta c'(\tilde{N}l_1^{SO})\gamma(N-1)\psi\frac{D}{N} = r_D - r + \bar{c}.$$

As $c' < 0$, both terms on the left-hand side are strictly positive. The second term on the left-hand side is equal to s_1^*. Therefore, $s_1^* < r_D - r + \bar{c}$. □

Lemma 37. *Let $l_1^{SO} \in (0, \frac{D}{N})$, $s_1^* \coloneqq -\beta\gamma(N-1)\psi\frac{D}{N}c'(\tilde{N}l_1^{SO}) > 0$, and $\mathcal{L}^{NE}|s$ be the set of possible Nash equilibria for a given $s_1, s_2 \geq 0$ and $g_1, g_2 = 0$. Then, $(l_1^{SO}, l_2^{SO}) \in \mathcal{L}^{NE}|s \; \forall \; s_1 = s_1^*, s_2 \geq 0$.*

Proof. Imposing symmetry by Lemma 35 and inserting $s_1 = s_1^*, g_1 = g_2 = 0$ into Equation 81 yields:

$$r - \bar{c} - r_D - \beta\gamma(N-1)l_2^{NE}c'(\tilde{N}l_1^{NE}) - \beta c'(\tilde{N}l_1^{NE})l_2^{NE} - \mu_{i,1} + \mu_{i,3} = 0.$$

Note that this equals the FOC for the social optimum, such that we can replace (l_1^{NE}, l_2^{NE})

with (l_1^{SO}, l_2^{SO}). We can further set $l_2^{SO} = \psi\frac{D}{N}$, which directly follows from $l_1^{SO} \in (0, \frac{D}{N})$:

$$r - \bar{c} - r_D - \beta\tilde{N}\psi\frac{D}{N}c'(\tilde{N}l_1^{SO}) - \mu_{i,1} + \mu_{i,3} = 0.$$

Note that this is identical to Equation 26 at $l_2^{SO} = \psi\frac{D}{N}$. By the Appendix version of Proposition 1, $l_1^{SO} \in (0, \frac{D}{N})$ then implies that this satisfies the FOCs of banks. By the Appendix version of Proposition 1, the SOC of above-zero profits (Equation 32) must hold, which by symmetry implies above-zero profits for each bank i. Hence, both conditions in Lemma 28 are met and $(l_1^{SO}, l_2^{SO}) \in \mathcal{L}^{NE}|s$. □

Lemma 38. *Let $l_1^{SO} \in (0, \frac{D}{N})$, $s_1^* \coloneqq -\beta\gamma(N-1)\psi\frac{D}{N}c'(\tilde{N}l_1^{SO}) > 0$, and $\mathcal{L}^{NE}|s$ be the set of possible Nash equilibria for a given $s_1, s_2 \geq 0$ and $g_1, g_2 = 0$. Then, $(0,0) \in \mathcal{L}^{NE}|s \;\forall\; s_1 = s_1^*, s_2 \geq 0$ if and only if*

$$\nexists\, l_{i,1} \in \{\tilde{N}l_1^{SO}, \frac{D}{N}\} \cap (0, \frac{D}{N}] : \tag{85}$$

$$\beta\left(r - c(l_{i,1}) - r_D + s_2\right)\psi\frac{D}{N} > \left(r_D - r + \bar{c} - s_1^*\right)l_{i,1}. \tag{86}$$

Proof. This simply reflects the condition in the Appendix version of Proposition 2 for the adjusted maximization problem allowing for $s_1, s_2 \geq 0$. Note that under $s_1 = s_1^*$ and for $l_{j,1} = 0 \;\forall\; j \neq i$, the loan financing amount, for which bank i's FOC with respect to $l_{i,1}$ holds with equality, is $\tilde{N}l_1^{SO}$. In other words, this is the amount of loan financing (net of spillover losses) in the social optimum. Then, the remaining proof can be derived by the same steps as for Lemma 27. □

Lemma 39. *Let $l_1^{SO} \in (0, \frac{D}{N})$, $s_1^* \coloneqq -\beta\gamma(N-1)\psi\frac{D}{N}c'(\tilde{N}l_1^{SO}) > 0$, and $\mathcal{L}^{NE}|s$ be the set of possible Nash equilibria for a given $s_1, s_2 \geq 0$ and $g_1, g_2 = 0$. Then, it holds that $(0,0) \in \mathcal{L}^{NE}|s \;\forall\; s_1 = s_1^*, s_2 = 0$ if*

$$r - c(\frac{D}{N}) \leq r_D.$$

Proof. Inserting $s_2 = 0$ into the condition in Lemma 38 for the existence of a zero-financing Nash equilibrium yields

$$\beta\left(r - c(l_{i,1}) - r_D\right)\psi\frac{D}{N} > \left(r_D - r + \bar{c} - s_1^*\right)l_{i,1}.$$

By Lemma 36, the right-hand side is positive if $l_{i,1} > 0$. But by $r - c(\frac{D}{N}) \leq r_D$, the left-hand side is nonpositive for all $l_{i,1} \in [0, \frac{D}{N}]$. Hence, the condition in Lemma 38 is satisfied as the inequality condition cannot hold for any $l_{i,1} \in [0, \frac{D}{N}]$. □

Lemma 40. *Let $l_1^{SO} \in (0, \frac{D}{N})$, $s_1^* \coloneqq -\beta\gamma(N-1)\psi\frac{D}{N}c'(\tilde{N}l_1^{SO}) > 0$, and $\mathcal{L}^{NE}|s$ be the set of possible Nash equilibria for a given $s_1, s_2 \geq 0$ and $g_1, g_2 = 0$. Then, it holds that $\mathcal{L}^{NE}|s = \{(l_1^{SO}, l_2^{SO})\} \;\forall\; s_1 = s_1^*, s_2 > r_D + \bar{c} - r$.*

Proof. By the Appendix version of Proposition 2, if $l_1^{SO} \in (0, \frac{D}{N})$, then

$$\mathcal{L}^{NE} \in \left\{ \{(0,0)_{i=1}^N\}, \{(0,0)_{i=1}^N, (l_1^{*NE}, \psi\frac{D}{N})_{i=1}^N\}, \{(l_1^{*NE}, \psi\frac{D}{N})_{i=1}^N\} \right\}.$$

The same steps can be followed for the re-defined maximization problem under policies in Equation 15 such that

$$\mathcal{L}^{NE}|s \in \left\{ \{(0,0)_{i=1}^N\}, \{(0,0)_{i=1}^N, (l_1^{*NE}|s, \psi\frac{D}{N})_{i=1}^N\}, \{(l_1^{*NE}|s, \psi\frac{D}{N})_{i=1}^N\} \right\}.$$

By Lemma 37, it holds that

$$(l_1^{SO}, \psi\frac{D}{N})_{i=1}^N \in \mathcal{L}^{NE}|s \; \forall \; s_1 = s_1^*, s_2 \geq 0.$$

By Equation 82, the FOC with respect to $l_{i,2}$ requires that

$$r - c(\gamma \sum_{j \neq i} l_{j,1}^{NE}|s + \gamma^g g_1 + l_{i,1}^{NE}|s) - r_D + s_2 - \mu_{i,2} + \mu_{i,4} = 0$$

which, since $c(\cdot) \leq \bar{c}$, can only hold for $g_1 = 0, s_2 > r_D - (r - \bar{c})$ if $\mu_{i,2} > 0$—i.e., for $l_{i,2}^{NE}|s = \psi\frac{D}{N}$. Hence, $(0,0)_{i=1}^N \notin \mathcal{L}^{NE}|s$. □

D.3 Public loan provision

Lemma 41. *Let $l_1^{SO} \in (0, \frac{D}{N})$, and let $\mathcal{L}^{NE}|g$ be the set of possible Nash equilibria for a given $g_1, g_2 \geq 0$ and $s_1, s_2 = 0$. Let $l_1^{*NE}|g \coloneqq (c')^{-1}\left(-\frac{\bar{c}+r_D-r}{\beta\psi\frac{D-g_2}{N}}\right) - \frac{\gamma^g}{N}g_1$. Then*

$$\mathcal{L}^{NE}|g \in \mathcal{P}\left(\left\{\left(\max\{0, \min\{l_1^{*NE}|g, \frac{D-g_1}{N}\}\}, \psi\frac{D-g_2}{N}\right)_{i=1}^N, (0,0)_{i=1}^N\right\}\right) \setminus \emptyset.$$

Proof. By Lemma 35, every solution in $\mathcal{L}^{NE}|g$ must be symmetric. By Lemma 2, $l_1^{SO} < \frac{D}{N}$ implies that $l_1^{*NE} < \frac{D}{N}$, but the demand constraint $l_{i,1} \leq \frac{D-g_1}{N}$ can still bind for very low values of γ^g and very high values of g_1.

Under public loan provision, the FOC with respect to $l_{i,2}$ now requires that

$$r - c(\tilde{L}_{i,1}^{NE}|g + \gamma^g g_1) - r_D - \mu_{i,2} + \mu_{i,4} = 0.$$

The deterministic rule for $l_{i,2}^{NE}|g$ then becomes

$$l_{i,2}^{NE}|g = \begin{cases} 0, & \text{if } r - c(\tilde{L}_{i,1} + \gamma^g g_1) \leq r_D \\ \psi\frac{D-g_2}{N}, & \text{otherwise.} \end{cases} \tag{87}$$

Therefore, $\gamma^g g_1 \geq c^{-1}(r - r_D)$ implies that $l_2^{NE}|g = \psi\frac{D-g_2}{N}$.

Similarly, the best response function derived under the steps followed for Lemma 7 changes as follows:

$$\mathrm{BR}_i(L_{-i})|g = \begin{cases} \left(\frac{D-g_1}{N}, \psi\frac{D-g_2}{N}\right) & \text{if } r - \bar{c} - \beta c'\left(\gamma L_{-i,1} + \gamma^g g_1 + \frac{D-g_1}{N}\right)\psi\frac{D-g_2}{N} > r_D \wedge \\ & \quad r - c(\gamma L_{-i,1} + \gamma^g g_1 + \frac{D-g_1}{N}) > r_D \wedge \\ & \quad \pi_i(L_{-i}, (\frac{D-g_1}{N}, \psi\frac{D-g_2}{N})) > 0 \\ \left(l_{i,1}^*|g, \psi\frac{D-g_2}{N}\right) & \text{if } \exists l_{i,1} \in [0, \frac{D-g_1}{N}) : \\ & r - \bar{c} - \beta c'\left(\gamma L_{-i,1} + \gamma^g g_1 + l_{i,1}\right)\psi\frac{D-g_2}{N} = r_D, \\ & \pi_i(L_{-i}, (l_{i,1}, \psi\frac{D-g_2}{N})) > 0 \\ \left(0, \psi\frac{D-g_2}{N}\right) & \text{if the prior conditions are not satisfied and} \\ & r - c(\gamma L_{-i,1} + \gamma^g g_1) > r_D \\ (0,0) & \text{otherwise} \end{cases}$$

with

$$l_{i,1}^*|g = (c')^{-1}\left(\frac{r_D - r + \bar{c}}{\beta\psi\frac{D-g_2}{N}}\right) - \gamma L_{-i,1} - \gamma^g g_1.$$

Steps to derive the possible Nash equilibria are the same as in Appendix C.2 with one important difference. By Equation 87, it is now possible that $(0, \psi\frac{D-g_2}{N})_{i=1}^N \in \mathcal{L}^{NE}|g$ if $\gamma^g g_1 > c^{-1}(r - r_D)$.

Deriving the symmetric amount of loan financing that solves the FOC with respect to $l_{i,1}$ yields

$$\tilde{N}l_1^{*NE}|g = (c')^{-1}\left(\frac{r_D - r + \bar{c}}{\beta\psi\frac{D-g_2}{N}}\right) - \gamma^g g_1$$

which, subject to the nonnegativity and the demand constraint, leads to the possible definitions of $\mathcal{L}^{NE}|g$ in Lemma 41.

□

Lemma 42. *Let $l_1^{SO} \in (0, \frac{D}{N})$ let $\mathcal{L}^{NE}|g$ be the set of possible Nash equilibria for a given $g_1, g_2 \geq 0$ and $s_1, s_2 = 0$. Then the parameter space, for which $\left(\min\{l_1^{*NE}|g, \frac{D-g_1}{N}\}\}, \psi\frac{D-g_2}{N}\right)_{i=1}^N \in \mathcal{L}^{NE}|g$, decreases in g_2.*

Proof. Based on the best-response function $BR_i(L_i)|g$ above, a Nash equilibrium with $l_1^{NE}|g > 0$ requires that

$$r - \bar{c} - \beta c'\left(\tilde{N}l_1^{NE}|g + \gamma^g g_1\right)\psi\frac{D - g_2}{N} \geq r_D.$$

As $c' < 0$, this is, ceteris paribus, less likely to hold for $g_2 \uparrow$.

The FOC with respect to $l_{i,2}$ does not depend on g_2, while bank profits π_i, ceteris paribus, also decrease weakly monotonically in g_2, making the profitability condition in

the best-response function less likely to hold as well. Therefore, all three conditions for a Nash equilibrium with $l_1^{NE}|g > 0$ are either less likely to hold or unaffected by $g_2 \uparrow$.

□

Lemma 43. *Let $l_1^{SO} \in (0, \frac{D}{N})$, and let $\mathcal{L}^{NE}|g$ be the set of possible Nash equilibria for a given $g_1, g_2 \geq 0$ and $s_1, s_2 = 0$. Let $g_1^* \coloneqq \frac{c^{-1}(r-r_D)}{\gamma^g}$. Then, if $g_1 > g_1^*$, it holds that $(0,0) \notin \mathcal{L}^{NE}|g$.*

Proof. This follows directly from Equation 87 since $g_1 > g_1^*$ implies that $l_2^{NE}|g = \psi\frac{D-g_2}{N}$. Importantly, this is a sufficient but not a necessary condition for $(0,0) \notin \mathcal{L}^{NE}|g$ because a value for g_1 that is (slightly) below g_1^* might still enable an individual bank i to reach positive profits by deviating unilaterally from the $(0,0)$ Nash equilibrium. □

Lemma 44. *Let $l_1^{SO} \in (0, \frac{D}{N})$, let $g_2 = 0$, let $l_1^{*NE}|g \in \mathcal{L}^{NE}|g$ and $l_1^{*NE} > 0$. Then, it holds that*

- *$Nl_1^{*NE}|g + g_1 < Nl_1^{*NE}$ if and only if $\gamma^g < \frac{\tilde{N}}{N}$*
- *$Nl_1^{*NE}|g + g_1 = Nl_1^{*NE}$ if and only if $\gamma^g = \frac{\tilde{N}}{N}$*
- *$Nl_1^{*NE}|g + g_1 > Nl_1^{*NE}$ if and only if $\gamma^g > \frac{\tilde{N}}{N}$*

Proof. First, we note that, by Proposition 2,

$$l_1^{SO} < \frac{D}{N} \implies l_1^{*NE} < \frac{D}{N}$$

and that, by definition, $g_2 = 0$ implies that

$$l_1^{*NE}|g = l_1^{*NE} - \frac{\gamma^g}{\tilde{N}}g_1.$$

Therefore, the total amount of early-stage loans in this policy-induced gradual-financing Nash equilibrium $Nl_1^{*NE}|g + g_1$ equals

$$Nl_1^{*NE}|g + g_1 = Nl_1^{*NE} - \frac{N\gamma^g}{\tilde{N}}g_1 + g_1 = Nl_1^{*NE} + \Big(1 - \frac{N\gamma^g}{\tilde{N}}\Big)g_1.$$

Then,

$$Nl_1^{*NE}|g + g_1 > Nl_1^{*NE}$$

requires that

$$1 > \frac{N\gamma^g}{\tilde{N}}$$

which we can rewrite as

$$\gamma^g < \frac{\tilde{N}}{N}$$

and similarly for $Nl_1^{*NE}|g + g_1 < Nl_1^{*NE}$ and $Nl_1^{*NE}|g + g_1 = Nl_1^{*NE}$.

□

E Proofs for Lemmas 3 and 4 (policy costs & policy mix)

E.1 Comparing the de-risking subsidy and public loan provision for addressing the coordination problem

Lemma 45. *Let $l_1^{SO} \in (0, \frac{D}{N})$, $g_1 = g_1^* + \epsilon, g_2 = s_1 = 0$, and $s_2 = r_D + \bar{c} - r + \epsilon$, where $\epsilon > 0$ is an infinitesimally small positive constant. Then, it holds that*

$$g_1^* < \beta^g r_D^g D \implies PC(g_1) < PC(s_2) \; \forall \; r_D^g = r_D, r^g = r, \beta^g \geq 0, g_2 \geq 0, l_1^{NE}|g \geq 0$$

Proof. If the characteristics of the public loan provider and private banks are identical and ϵ is negligible, then

$$PC(s_2) \approx (r_D + \bar{c} - r)\beta\psi D r_D$$

$$PC(g_1) = (r_D + \bar{c} - r)g_1 - \beta\left(r - c(g_1 + \gamma N l_1^{NE}|g) - r_D\right) g_2.$$

Since g_2 can always be set to zero if second-period public loans are nonprofitable (i.e., if $r - c(g_1 + \gamma N l_1^{NE}|g) \leq r_D$), this implies that

$$PC(g_1) \leq (r_D + \bar{c} - r)g_1$$

such that any $g_1 < \beta\psi D r_D$ satisfies $PC(g_1) < PC(s_2)$.

□

E.2 Policy mix

Using formal notation, Lemma 4 can be stated as follows:

Lemma 46. *Let $l_1^{SO} \in (0, \frac{D}{N})$, $\mathcal{L}^{NE}|gs$ be the set of possible Nash equilibria given $g_1 = g_1^* + \epsilon$, and $s_1 = s_1^*, g_2 = s_2 = 0$. Then, it holds that*

- $\mathcal{L}^{NE}|gs = \left\{\left(\max\left\{0, \min\{\frac{D-g_1}{N}, l_1^{SO} - \frac{\gamma^g}{N} g_1\}\right\}, \psi\frac{D}{N}\right)_{i=1}^{N}\right\}$;
- $l_1^{NE}|g < l_1^{NE}|gs < l_1^{SO}$.

Proof. Note that the FOC with respect to $l_{i,2}$ in Equation 82 is unaffected by $s_1 = s_1^*$. Hence, Lemma 43 equally applies such that $(0,0)_{i=1}^{N} \notin \mathcal{L}^{NE}|gs$ for $g_1 = g_1^* + \epsilon$.

By $l_1^{SO} \in (0, \frac{D}{N})$ and Equation 11, we know that

$$-\beta\psi\frac{D}{N}c'(\tilde{N}l_1^{SO})\left(1 + \gamma(N-1)\right) = r_D + \bar{c} - r.$$

Under the given policy mix, the FOC with respect to $l_{i,1}$ from the individual bank's profit maximization in Equation 81 then yields

$$-\beta\psi\frac{D}{N}c'(\tilde{N}l_1^{*NE}|gs+\gamma^g g_1)+s_1^*=r_D+\bar{c}-r.$$

Inserting the definition of s_1^* then gives us

$$-\beta\psi\frac{D}{N}\left(c'(\tilde{N}l_1^{*NE}|gs+\gamma^g g_1)+\gamma(N-1)c'(\tilde{N}l_1^{SO})\right)=r_D+\bar{c}-r.$$

Since bank i takes g_1 as exogenous, combining this with the FOC from the social maximization problem requires

$$\tilde{N}l_1^{SO}=\tilde{N}l_1^{*NE}|gs+\gamma^g g_1.$$

Note that by the Appendix version of Proposition 1, $l_1^{SO}\in(0,\frac{D}{N})$ implies strictly positive overall profits. Given the definition of g_1, this implies that

$$\tilde{N}l_1^{SO}>\gamma^g g_1$$

because for $\bar{L}_1=0, g_1=g_1^*+\epsilon$, the return spread at $t=2$ is zero, and banks make zero profits in both periods. Therefore,

$$l_1^{SO}-\frac{\gamma^g}{\tilde{N}}g_1>0$$

such that $l_1^{*NE}|gs\in(0,l_1^{SO})$. However, the above is based on the FOC with respect to $l_{i,1}$ holding with equality (i.e., the critical point that is unconstrained by the non-negativity and the demand constraint on $l_{i,1}$). Even if $l_1^{SO}<\frac{D}{N}$, this does not guarantee that $l_1^{*NE}|gs<\frac{D-g_1}{N}$. For instance, if we assume that $\gamma^g\to 0$, then $g_1^*\to D$ such that $\frac{D-g_1}{N}\to 0$. Therefore, we cannot rule out that the demand constraint given g_1 is binding, which is reflected in the expression for $l_{i,1}$ in Lemma 46.

Regarding the second statement in Lemma 46, $l_1^{NE}|gs<l_1^{SO}$ follows directly from

$$l_1^{NE}|gs=l_1^{SO}-\frac{\gamma^g}{\tilde{N}}g_1$$

since $\gamma^g, g_1, \tilde{N}>0$.

By the Appendix version of Proposition 4, the maximum value $l_1^{NE}|g$ can take for any g_1 is $(c')^{-1}\left(-\frac{\bar{c}+r_D-r}{\beta\psi\frac{D-g_2}{N}}\right)-\frac{\gamma^g}{\tilde{N}}g_1$. Given $g_2=0$, this is equivalent to $l_1^{*NE}-\frac{\gamma^g}{\tilde{N}}g_1$, where l_1^{*NE} is the unconstrained symmetric solution to the market outcome FOC with respect to $l_{i,1}$ in the absence of any policy intervention. From the Appendix version of Proposition 2, it follows that

$$l_1^{*NE}<l_1^{SO}.$$

This implies that

$$l_1^{*NE}-\frac{\gamma^g}{\tilde{N}}g_1<l_1^{SO}-\frac{\gamma^g}{\tilde{N}}g_1$$

which is equivalent to

$$l_1^{NE}|g < l_1^{NE}|gs.$$

□

Lemma 47. *Let* $l_1^{SO} \in (0, \frac{D}{N})$, $l^{NE}|gs = l_1^{SO} - \frac{\gamma^g}{\tilde{N}g_1}$ *given* $g_1 = g_1^* + \epsilon$, $s_1 = s_1^*, g_2 = s_2 = 0$ *and let* $r_D^g = r_D$, $r^g = r$. *Then,* $\gamma^g < \frac{\tilde{N}}{N}$ *implies that*

$$\sum_i \pi_i(l_1^{SO}, \frac{\psi D}{N}; l_{-i,1} = l_1^{SO})) > \sum_i \pi_i(l^{NE}|gs, \frac{\psi D}{N}; l_{-i,1} = l^{NE}|gs) + (r^g - \bar{c} - r_D^g)g_1.$$

Proof. As laid out in the proof for Lemma 46, financing experience is equivalent between the social optimum and the market outcome given g_1 and s_1 unless the policy-induced Nash equilibrium given g_1 and s_1 is subject to the adjusted demand constraint $l_{i,1} \leq \frac{D-g_1}{N}$. Hence,

$$\tilde{N}l_1^{SO} = \tilde{N}l_1^{*NE}|gs + \gamma^g g_1$$

and, in consequence,

$$c(\tilde{N}l_1^{SO}) = c(\tilde{N}l_1^{*NE}|gs + \gamma^g g_1).$$

As banks provide $\frac{\psi D}{N}$ at $t = 2$ in the social optimum and the market outcome given the policy interventions, profits of banks at $t = 2$ must be the same under both outcomes, while $g_2 = 0$ ensures that there are no costs/profits of public loans to consider at $t = 2$. So we can restrict our attention to first-period profits (i.e., losses).

As $r^g = r$ and $r_D^g = r_D$, we can then rewrite first-period profits of banks given symmetry

$$(r - \bar{c} - r_D)(Nl_1^{*NE}|gs + g_1).$$

Then,

$$(r - \bar{c} - r_D)(Nl_1^{*NE}|gs + g_1) < (r - \bar{c} - r_D)Nl_1^{*SO}$$

requires that

$$Nl_1^{*SO} < Nl_1^{*NE}|gs + g_1.$$

Note that the direction of the inequality flips as $r - \bar{c} - r_D < 0$.

Now we can follow the exact same steps as for Lemma 44 to show that $Nl_1^{*SO} < Nl_1^{*NE}|gs + g_1$ is given if and only if $\gamma^g < \frac{\tilde{N}}{N}$, which nests the special case of $\gamma^g = \gamma$ since $\frac{\tilde{N}}{N} > \gamma$ by definition.

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F Additional information for the numerical application

F.1 Loan demand D and between-period growth ψ

We estimate D based on observed total investments in German offshore wind between 2007–2012 taken from ZSW (2024) and convert them to 2021 EUR using the producer price index from Destatis (2024). The resulting values are displayed in Figure 9. Since these values include both equity and debt financing, we multiply the sum of investments between 2007–2012 by an average debt share of 62% for three early-stage German offshore deals, of which two closed in 2010 and one in 2011, reported by Kitzing and Weber (2015).

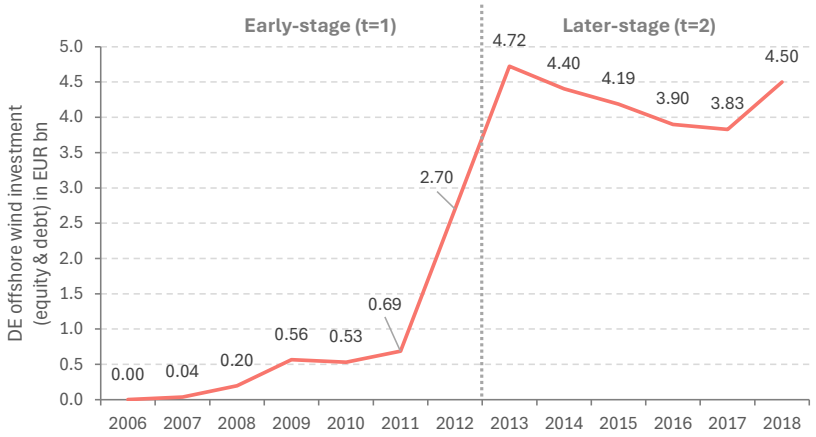


Figure 9: Annual investments in German offshore wind based on ZSW (2024) in 2021 EUR

To estimate loan demand in the 2013–2018 period, which implies ψ, we follow the same approach for 2013–2018 investments. However, we use a later-stage debt share of 73% estimated by IRENA (2023) for German offshore wind projects closing in 2020.[28] Then, ψ is calculated as the ratio of 2013–2018 to 2007–2012 loan demand.

F.2 Number of banks N

We rely on BloombergNEF data for transactions financing utility-scale renewable energy projects (BNEF, 2022), which is a leading data source for RE deals and commonly used research on renewable energy finance (Cárdenas Rodríguez et al., 2015; Gumber et al., 2024; Waidelich & Steffen, 2024). Specifically, we count the number of lenders appearing on at least three transactions financing new-build offshore wind projects in Germany through 2018. The resulting lenders are listed in Table 3. Since we treat the EIB and

[28] Unfortunately, IRENA (2023) do not provide values for earlier years that would perfectly correspond to the end of our later-stage period.

KfW as part of the policy interventions, they are excluded from our estimate of N and the table. Note that we subset lenders based on repeated activity because one-time lenders may have no interest in accumulating technology-related financing experience.

Table 3: Banks active on at least three offshore wind deals in Germany through 2018 in the renewable energy asset finance database by BloombergNEF, excluding KfW (and its subsidiary KfW IPEX) and the European Investment Bank.

	Bank	DE offshore wind deals in BNEF
1	Commerzbank AG	7
2	DSK Hyp AG	7
3	Societe Generale SA	7
4	Sumitomo Mitsui Banking Corp	7
5	Natixis SA	6
6	Banco Santander SA	5
7	Landesbank Hessen-Thueringen Girozentrale	5
8	Cooperatieve Rabobank UA	4
9	Deutsche Bank AG	4
10	ING Bank NV	4
11	ABN AMRO Bank NV	3
12	Hamburg Commercial Bank AG	3
13	MUFG Bank Ltd	3
14	NRW Bank	3
15	Rabobank NA	3

F.3 Profit margin at full maturity $r - r_D$

When assessing bank loan profitability, one must distinguish between the net interest margin (i.e., banks net interest revenue relative to their interest-earning assets) and the return on asset as a profitability measure, which is the net interest margin minus overhead and loan loss provisions (Demirguc-Kunt & Huizinga, 1999). For Germany, the average net interest margin of banks between 2007 and 2018 averaged 0.87% and remained relatively stable across our modeling period, as data from the World Bank's Global Financial Development Database (World Bank, 2022) in Figure 10 illustrates. By contrast, banks' returns on assets were more volatile in the 2007–2012 period due to the ramifications of the Financial Crisis in 2008/2009 but remained remarkably stable at 0.2% between 2012 and 2018. Therefore, we estimate the profit margin at full maturity $r - r_D$, net of all transaction costs and loan loss provisions that are unrelated to the financial immaturity of offshore wind, at 0.2%.

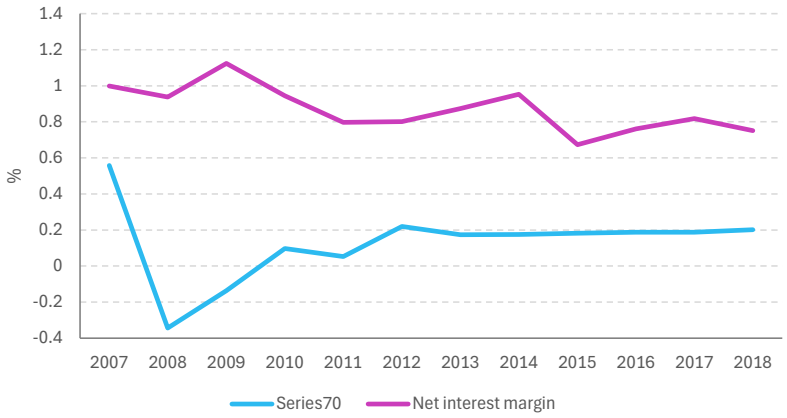


Figure 10: Net interest margin and pre-tax return on assets of German banks from World Bank (2022)

F.4 Deriving the learning curve $c(\cdot)$

As laid out in Section 7, we use three data points to estimate the pace of cost reductions for lenders to German offshore wind projects. First, Kitzing and Weber (2015) report debt margins for three German offshore wind deals (Globaltech I, Meerwind, and Borkum West, which closed in 2011, 2011, and 2010, respectively; see their Table 2). The debt shares of the three deals (58%, 69%, and 59%) average to 62%. Based on values, Kitzing and Weber (2015) estimate the cost of debt at 5.21%, which consists of the 10-year German government bond rate (1.66%) plus a 0.3% swap premium and a debt margin of 3.25% above this risk-free rate. As this is calibrated based on deals closing in 2010–2011, we use this data point for 2010.

Second, IRENA (2023) conduct a survey of expert estimates regarding financing conditions of different technologies and markets. For German offshore wind transactions in 2020, they estimate a debt share of 73% and a cost of debt of 1.6%. As their data does not include debt margins, we convert this cost of debt into a debt margin estimate consistent with Kitzing and Weber (2015) by subtracting the 2020 average of the ten-year German government bond rate of -0.51% (OECD, 2025) and the 0.3% swap premium, which gives us a debt margin of 1.81% for 2020.

Lastly, IRENA (2023) also conduct a benchmarking exercise, in which they produce formula-based estimates that reproduce their survey results as best as possible. In their approach, the cost of debt includes a debt margin that is market maturity-dependent based on a technology's share in installed electricity generation capacity and takes values between 3.25% for completely immature markets and 1.5% for fully matured markets. Importantly, IRENA (2023) classify Germany as an intermediate but not fully matured market, as only Denmark and the United Kingdom are classified as mature markets for offshore wind (see the Supplementary Information of Calcaterra et al., 2024). Therefore,

this benchmarking methodology aligns well with the estimates by Kitzing and Weber (2015) and, hence, provides us with a lower bound of 1.5%, to which debt margins may convert. Notably, this value at full maturity is about 1.5 times higher than the 1% debt margin, to which solar photovoltaics and onshore wind in Germany have converged throughout the 2010s (Egli et al., 2018), reflecting the higher risk levels of offshore wind projects.

Based on the data points above, we can define an immaturity-related component of the overall debt margin, which took a value of $DS_{2010} = 3.25\% - 1.5\% = 1.75\%$ for offshore wind deals in Germany closing around 2010, decreased to $DS_{2020} = 1.81\% - 1.5\% = 0.31\%$ by 2020 and would vanish entirely in the long run. These data points can be used to fit a Wright's Law learning curve, but this requires a definition of the accumulated financing experience in a given year. Notably, our model assumes that it takes up to six years (the length of one period) for all financial learning gains to materialize. In the two-period model, learning gains materialize at the end of the period, but in reality, financing experience is more likely to accumulate gradually over the years. Therefore, we calculate the cumulative financing experience in year a as $\frac{1}{6}$ times the debt investment in year $a-1$, $\frac{2}{6}$ times the investment in year $a-2$ and so on. Lending from at least six years ago enters the annual experience entirely as all learning gains have materialized. Combined with the adjustment for spillovers, we can then translate the annual debt investments L_a (calculated as observed investment from ZSW (2024) times the period-specific debt share) into year-specific financing experience as follows:

$$\tilde{L}_a = \sum_{k<a} \frac{\tilde{N}}{N} L_k \times \min\{1, \frac{a-k}{6}\}$$

Using this year-specific financing experience that is consistent with the logic of our two-period model, we can then calibrate the following learning curve

$$DS(\tilde{L}_a) = DS_{2010} \left(\frac{\tilde{L}_a}{\tilde{L}_{2010}} \right)^{-b}. \tag{88}$$

with our data points for 2010 and 2020, respectively, and the estimated financing experience net of spillovers in 2010 ($\tilde{L}_{2010} = 0.028$ billion), which results in an estimate of $b = 0.344$ and the following Wright's Law curve:

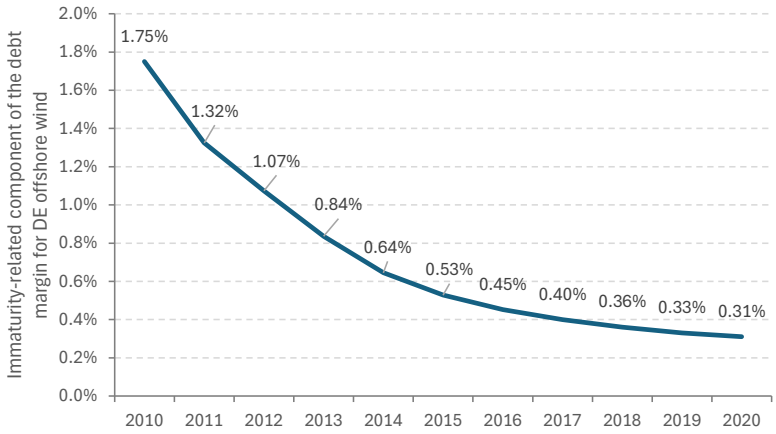


Figure 11: Estimated learning curve for immaturity-related component of the debt spread

With this estimate of how fast cost reductions occurred that were passed through to consumers, we can now estimate the part of cost reductions that improved bank margins, assuming a typical pass-through rate of approximately 80% for German bank loans to non-bank customers (Heckmann-Draisbach & Moertel, 2020). By doing so, we can estimate that for a cost reduction of 1.75% that would be ultimately passed through to projects, there is a $1.75\% \times \frac{1-0.8}{0.8} = 0.44\% = \bar{c}$ cost reductions that banks do not pass through to improve their margins, particularly given that initial returns do not compensate for the risks involved (which is supported by the interview results of Geddes et al. (2018) for offshore wind deals prior to 2012). By assuming that this cost reduction component that is not passed through shrinks at the same pace in financing experience as the observable debt margins, we get the following learning curve for the six-year period t:

$$c(\tilde{L}_t) = \bar{c} \left(\frac{\tilde{L}_t + \tilde{L}_{2010}}{\tilde{L}_{2010}} \right)^{-b} . \tag{89}$$

where again $b = 0.344$. Importantly, this assumes that the immaturity-related cost starts at the value derived from 2010 (our first empirical estimate available) and cannot exceed this value even if no loans are provided. This is because a Wright's Law curve requires a non-zero starting point. However, since $\tilde{L}_{2010}$ is equivalent to the experience generated from only EUR 110 million of bank loans (i.e., roughly 4% of the estimated 2007–2012 loan demand), the implications for the model are only minor. Importantly, our learning curve $c(\cdot)$ produces a remaining immaturity cost of around 0.14% for the empirically observed 2007–2012 loan provision of $D = 2.92$ billion, meaning that even if banks go all in during the first period, their best-possible profit margin in the later-stage period is only $0.2\% - 0.14\% = 0.06\%$, which is conservative.

F.5 Converting annual returns into profits per period

Notably, all estimates of financial returns we use in our numerical application (r, c, r_D) are annual rates. For the sake of simplicity, we calculate total profits per period by multiplying annual profits by the number of years per period instead of compounding them across years. Given the small margins in our application, this has negligible effects on the results. For instance, if the entire $D = 2.92$ billion were invested with a profit margin of 0.06%, then multiplying annual profits by six (the number of years per period) yields a profit of EUR 10.51 million, whereas compounding the return over six years yields EUR 10.53 million.

F.6 Estimating the climate externality of loans to offshore wind projects

We use estimates of German offshore wind's emission intensity from Hengstler et al. (2021) and the average emission intensity of the German grid throughout 2007–2018 estimated by Icha and Lauf (2024), implying an emission reduction of 0.6192 tCO_2e per MWh of generation replaced by offshore wind electricity. To estimate the annual generation of offshore wind projects financed throughout our modeling period, we take the average capacity factor of 27.2% through 2018 and the installed capacity through 2018 of 6,393 MW (Umweltbundesamt, 2024), resulting in 15.2 TWh and 9.4 megatons of CO_2e of emission reductions per year. We monetize these emission reductions using the social cost of carbon estimate of EUR 84.95 used by the German Federal Environmental Agency during the 2007–2012 period (Umweltbundesamt, 2007) and subtract the average 2007–2018 EU Emissions Trading System price of EUR 10.74 (EEA, 2024), reflecting that some of the external effects were already priced. This approach results in roughly EUR 700 million of monetized emission reductions per year. Divided by the EUR 30.25 billion of investments in German offshore wind through 2018 (debt and equity combined), this implies an annual social return of 2.31% per EUR of investment.[29]

However, the 2.31% rests on the aggressive assumption that not a single offshore wind farm would have been built without securing debt financing. Therefore, we use a far more conservative value by assuming that, on average, only 10% of emission reductions can be causally attributed to debt financing provision, resulting in $\tau = 0.231\%$.

[29]Note that dividing only by debt financing would falsely attribute any emission reduction share of equity investments to debt financing.