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Green industrial policy, information asymmetry, and repayable advance

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Abstract

The energy transition requires the deployment of risky research and development programs, most of which are partially financed by public funding. Recent recovery plans, associated with the COVID-19 pandemic and the energy transition, increased the funding available to finance innovative low-carbon projects and called for an economic evaluation of their allocation. This paper analyzes the potential benefit of using repayable advance: a lump-sum payment to finance the project that is paid back in case of success. The relationship between the state and innovative firms is formalized in the principal-agent framework. Investing in an innovative project requires an initial observable capital outlay. We introduce asymmetric information on the probability of success, which is known to the firm but not to the state agency. The outcome of the project, if successful, delivers a private benefit to the firm and an external social benefit to the state. In this context a repayable advance consists in rewarding failure. We prove that it is a superior strategy in the presence of pure adverse selection. We investigate under what conditions this result could be extended in the presence of moral hazard. Implications for green industrial policy are discussed.

KEYWORDS
asymmetric information, conditional schemes, green innovation, public financing, repayable advance

1 | INTRODUCTION

We analyze the optimal way to subsidize a risky innovative project using scarce public funds. A project can generate both private and (external) social benefits, but it requires initial funding. The regulatory intervention is justified by the external social benefits.

Even though the model considered is general, the present work is motivated by green industrial policies aimed at promoting innovative low-carbon technologies. Subsidies are justified by both inadequate carbon pricing and knowledge externalities, likely to be large because of the immaturity and future growth of green technologies in the energy, mobility, and agricultural sectors (Greaker et al., 2018; Hepburn et al., 2020).[1] The recent political context (the recession risk after the pandemic, international tensions due to the Ukraine conflict, etc.) has triggered large recovery plans in many countries to accelerate the energy transition (the Inflation Reduction Act in the United States, the European Green Deal, etc.). The effectiveness and efficiency of these plans depend on the details of the allocation of funds to innovative firms. There are many pitfalls that may be encountered in this process (see Rodrik, 2014, for a critical analysis of the recovery plan in the United States following the 2007–2008 financial crisis). One of the pitfalls is the existence of windfall profits: the allocation of public money to projects that would have been launched anyway. The focus of the paper is on a particular scheme known as repayable advance, which is supposed to reduce this risk.

Sales contingent claims can be considered as being at the origin of repayable advances. They have been commonly used by European governments in aeronautics.[2] They consist of providing a lump sum to a firm investing in the production of a future product, the demand and cost being uncertain. A payback is to be repaid according to an agreed-upon schedule based on future sales. Kaivanto and Stoneman (2007) suggest that they could be used outside aeronautics to stimulate innovation in the presence of capital market failure: under some conditions, they provide a valuable financing alternative to equity and debt.[3] In France, they have been systematically used for promoting green technologies by The French Agency for The Ecological Transition (ADEME), following a recommendation in 2005 for a renewed industrial policy.[4] Their use has been encouraged by the European Commission for the financing of research and development (R&D) projects; guidelines for their implementation have been specified.[5] More generally, guaranteed loans are now part of the panoply of instruments commonly used to

[1]See Blackburn et al. (2020) for recent evidence of knowledge spillovers from pilot and demonstration projects.
[2]A typical example concerns the subsidies for the development of new aircraft by Boeing and Airbus; these so-called "reimbursable launch investments" are described in https://trade.ec.europa.eu/doclib/docs/2010/september/tradoc_146503.pdf.
[3]See Bolatto and Pignataro (2023) for a recent analysis of profit-sharing mechanisms to promote innovation under asymmetric information. Hall and Lerner (2010) provide a comprehensive discussion of the financing of innovation.
[4]Beffa,J.-L., Rapport à la Présidence de la République, available at https://www.vie-publique.fr/rapport/27089-pour-une-nouvelle-politique-industrielle.
[5]The EU Framework is available here: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52014XC0627(01)&from=EL. For a discussion of legal issues see Hargita et al. (2019).

stimulate green technologies (such as through the European Investment Bank for Europe or the Banque Publique d'Investissement in France). This paper leaves aside the issue of incomplete capital market to focus on the economic analysis of such instruments to mitigate windfall profits.

We develop a partial equilibrium model in which a firm invests a lump sum in a project that may succeed or fail, the probability of success depends on the type of the project and on the effort of the firm. Only successful projects generate private and social benefits. A public agency acting on behalf of the state may subsidize the firm. Without subsidies, some (low-type) projects would not be initiated while others (high type) would be. The agency can propose a couple of nonnegative subsidies that are conditional on success or failure. It needs to balance a selection bias (induce investments in projects in so much as they are socially valuable) with a risk for windfall profits (allocate funds to projects that would have been undertaken anyway) while at the same time motivating effort. We aim at clarifying under which conditions subsidizing failure, that is, using a repayable advance, might be optimal.

We derive the second-best optimal scheme using a linear quadratic specification for the effort function. We prove that in pure adverse selection situations the agency should only reward failure. This result is based on a simple intuitive mechanism, that does not appear in the existing literature. Given that high-type projects would be implemented without support, reducing their rent is done by subsidizing failure instead of success. We explore how this result may be extended in the presence of moral hazard when the uncertainly takes the form of a binomial or a uniform distribution on the types of the firm. We demonstrate that the balancing between reducing windfall profit and encouraging effort may result in a complex calibration between reward success and failure. These results provide an interesting characterization of the economics of repayable advance so as to justify its applicability in real cases.

Several articles in environmental economics discuss the issue of financing green projects under asymmetric information. Fischer (2005) provides an insightful analysis of the issue of "additionality" in the design of Clean Development Mechanism (CDM).[6] Mason and Plantinga (2013) consider the optimal design of contracts for carbon offsets with asymmetric information.[7] To our knowledge, the issue of windfall profits from innovative risky green projects has not been studied.[8]

From a more theoretical perspective, our analysis is related to the literature on mechanism design with both adverse selection and moral hazard.[9] In this respect our model features a risk-neutral principal and a risk-neutral agent, and constrained incentive schemes. The principal (the agency) is constrained to propose a single couple of nonnegative subsidies. A key element of our analysis is that some projects would be financed without the scheme, making the

[6]The empirical analysis in Zhang and Wang (2011) does cast some doubt about the additionality of Chinese CDM activities.

[7]Within the agricultural sectors, the design of agrienvironmental schemes raises similar issues (e.g., Engel et al., 2008; Wu & Babcock, 1996), and a related concern is the "stacking" of green payments: a farmer maybe rewarded twice for biodiversity and greenhouse gas reduction for the same action (Lankoski et al., 2015; Woodward, 2011).

[8]There is a large literature on the coordination between environmental and innovation policy in dynamic models, most notably endogenous growth models. Smulders et al. (2014) provide a survey, and Greaker et al. (2018) highlight that even with a long-lived patent green research subsidies are justified. There are also several articles on the influence of technical uncertainty on optimal R&D in green technologies (e.g., Baker & Adu-Bonnah, 2008; Goeschl & Perino, 2009). However, these papers do not analyze whether such R&D should be subsidized with pure subsidy or conditional schemes.

[9]Mixed models are covered in Chap. 7 in Laffont and Martimort (2002).

participation constraint dependent on the type. Some papers have introduced some of these restrictions (e.g., Lewis & Sappington, 2000a, 2000b; Quérou et al., 2015).

The article by Ollier and Thomas (2013) is the closest to the present work. There are several similarities and differences between our model and theirs which deserve detailed consideration to understand why we get different results. In both cases, assumptions on the effort cost function ensure that the probability of success is increasing with the type of the firm. Ollier and Thomas (2013) introduce an ex post participation constraint (or a limited liability constraint) and show that it leads to pooling. In our case, pooling is an exogenous assumption and subsidies must be nonnegative.[10] Most importantly, in their framework, there are no issues related to the selection of projects, because of the absence of a fixed cost, nor to the allocation of windfall profits to projects that would be implemented anyway, because of the absence of a private revenue. There is no need to finance low-profitability projects but only to motivate efforts which explains that, in their model, the principal should only reward success. This is the case in our setting when the moral hazard issue dominates; but we also show that there are some situations in which reward failure is optimal and others in which both subsidies are used. Rewarding failure could also be justified by the risk-aversion of the agent, as in the work of Gary-Bobo and Trannoy (2015) on students loans, but this justification is absent from our model since we consider risk-neutral actors (both the public agency and the firm).

The rest of the paper is organized as follows: In Section 2 the general model is introduced; Business-As-Usual (BAU) and first best are defined for the sake of comparison. In Section 3 we study the second-best optimal scheme, provide some general results, and completely solve the cases of pure adverse selection and pure moral hazard. The case in which both adverse selection and moral hazard prevail is solved for specific probability distributions over the types of the firm. Section 4 generalizes our results to two simple extensions: imperfect observability of the outcome of the project by the agency, and the introduction of an uncertain market phase in the deployment process of the project. Section 5 concludes with general considerations on green industrial policy and suggestions for possible extensions. In Appendix D, we apply our framework to a case study of a representative project submitted to ADEME. All proofs are in the appendix.

2 | THE MODEL

2.1 | The general setting

A firm may initiate a risky project, the decision is represented by a binary variable $\delta \in 0, 1$. If $\delta = 1$, the project is initiated and the firm incurs a fixed cost F. The project either succeeds or fails. In case of success, the firm gets a private revenue R, and a social external benefit b is generated. In case of failure neither private nor external benefits are created. If a project is not initiated, $\delta = 0$, the reference payoffs are zero, and no fixed cost is incurred. The probability of success depends on the type of the project θ and the effort of the firm e with θ and $e \in [0, 1]$:

[10]We do not analyze the optimal menu but a similar effect is at work in our model: without constraints the principal would propose a menu with a success subsidy that increases with the probability of success and a failure subsidy that decreases with the probability of success (we determine that menu in Appendix A.1). The failure subsidy should be negative for high-type projects which are not feasible because of our nonnegativity constraint (and their ex post participation constraint), which leads to pooling.

$p(e, \theta) \in [0, 1]$, and $p(0, \theta) = \theta$. The effort e induces a cost $f(e, \theta)$. Types are distributed according to the cumulative distribution function $G(\theta)$, continuously differentiable with $G'(\theta) = g(\theta)$.

The firm and the regulatory agency (henceforth the agency) know F, R, b, and the functions G, p, and f. Both entities observe whether a project is initiated and its outcome, that is, failure or success. The agency observes neither the type nor the effort of the firm.

The question at stake for the agency is to propose a couple of nonnegative subsidies (s_1, s_2). For the sake of realism we restrict ourselves to nonnegative subsidies and simple schemes, that is, the agency cannot offer a menu of contracts, $(s_1(\theta), s_2(\theta))_\theta$.[11] The firm gets s_1 in case of success (probability $p(e, \theta)$) and s_2 in case of failure (probability $1 - p(e, \theta)$). Therefore, we refer to s_1 as rewarding success and to s_2 as rewarding failure. And without loss of generality, we certainly have:

$$0 \leq s_1 \leq b \quad \text{and} \quad 0 \leq s_2 \leq F. \tag{1}$$

For convenience we define the bonus as $s = s_1 - s_2$ so that $s \leq b$ and might even be negative. The failure subsidy s_2 can be reinterpreted as a repayable advance, that is, a loan only reimbursed in case of success.[12]

For a project of type θ, the profit of the firm is denoted π and the agency surplus v. Welfare w is the sum of the firm profit and the agency surplus. Capital letters Π, V, and W refer to expectation over θ. We have

$$\pi(\delta, e, \theta, s_1, s_2) = \delta[p(e, \theta)(R + s_1) + (1 - p(e, \theta))s_2 - (F + f(e, \theta))], \tag{2}$$

$$v(\delta, e, \theta, s_1, s_2) = \delta[p(e, \theta)(b - s_1) - (1 - p(e, \theta))s_2]. \tag{3}$$

$$w(\delta, e, \theta) = v + \pi = \delta[p(e, \theta)(R + b) - F - f(e, \theta)]. \tag{4}$$

The firm chooses δ and e to maximize π for each θ for a given couple (s_1, s_2), and the agency designs a scheme to maximize

$$V = \int_0^1 v(\delta, e, \theta, s_1, s_2) g(\theta)\, d\theta, \quad \text{s.t.} \;\; (\delta, e) = \operatorname{argmax} \pi(\delta, e, \theta, s_1, s_2).$$

2.2 | The specification of the effort cost function

We will make use of the following linear quadratic specification to be defined for $0 \leq e \leq 1$:

[11]Note that the optimal menu is not easy to characterize because of both the positivity constraints (the so-called limited liability constraint) and the participation of high-type firms which may fund the project by themselves. Indeed, high-type projects are initiated without subsidy if $R > F$. It resembles a situation of type-dependent outside opportunities that is known to modify the characteristics of the optimal menu (Jullien, 2000) with the important distinction that in our case the principal's payoff is also positive if a high-type project is funded independently. If both of these constraints (nonnegative subsidy, unilateral private funding) are removed, a standard optimal menu can be described (cf. Appendix A.1), and with a uniform distribution and our quadratic specification, it can even be explicitly written.

[12]A loan of s_2 € reimbursed in case of success and not in case of failure gives the net profit: $s_2 + p \times (-s_2) + (1 - p) \times 0 = (1 - p)s_2$.

$$p(e,\theta) = \theta + e(1-\theta), \tag{5}$$

$$f(e,\theta) = (1-\theta)\frac{\gamma}{2}e^2. \tag{6}$$

Since $0 \le e \le 1$ we have $\theta \le p(e,\theta) \le 1$. This formulation is motivated by considering that a project is constituted of a continuum of technical steps: for a project of type θ a share θ of steps have already been completed (in the lab) and $(1-\theta)$ steps remain to be completed (with the pilot) to guarantee success. A given level of effort has a larger impact on projects with an initially low probability of success, but it is more costly.[13]

The profit of a firm could be rewritten as

$$\pi(1,e,\theta,s_1,s_2) = [\theta(R+s_1) + (1-\theta)s_2 - F] + (1-\theta)\left[e(R+s_1-s_2) - \frac{\gamma e^2}{2}\right]. \tag{7}$$

The net benefit from effort is encompassed in the last bracketed term. The effort exerted by a firm does not depend on the type θ but only on the bonus s. It is

$$e(s) = \min\left\{\frac{R+s}{\gamma}, 1\right\}. \tag{8}$$

This property greatly facilitates the analysis because the effort of the firm will not depend on the information available to the firm. Observe that the property is also true for the effort that maximizes welfare: it is simply equal to $\min((R+b)/\gamma, 1)$.

The following technical assumption will be needed in some results. It ensures that all efforts considered are strictly lower than 1.

Assumption 1. The slope of the marginal cost of effort is larger than the marginal social benefit: $\gamma > R + b$.

2.3 | BAU, first best, Pigouvian solution

BAU refers to the situation in which there is no subsidy and firms are informed about their types, while first best refers to the allocation that maximizes welfare. For each project there are two choices: whether to initiate the project and the level of effort. BAU and first best could be described by threshold types, respectively, denoted θ^{BAU} and θ^{FB}, such that projects with a larger type are initiated, and by effort levels e^{BAU} and e^{FB} which, respectively, maximize π and

[13]Rewriting cost as a function of the probability of success gives, defining $\psi(p,\theta) = F + f(e(p,\theta),\theta)$ with $e(p,\theta)$ such that $p(e,\theta) = p$:

$$\psi(p,\theta) = F + \frac{\gamma}{2}\frac{(p-\theta)^2}{1-\theta} \quad \text{for } p > \theta, = 0 \text{ otherwise.}$$

The function $\psi(p,\theta)$ satisfies the technical assumptions in Ollier and Thomas (2013). It is increasing with respect to p and decreasing with respect to θ, and the cross derivative is negative (the marginal cost to increase the probability of success is decreasing with the type), which ensures that the probability of success is decreasing with the type, for a given bonus s.

w for initiated projects. These efforts depend on the type in the general model but not in the specification.

For BAU we have $e^{BAU} = R/\gamma$ and

$$\theta^{BAU} = \max\left\{\frac{1}{R}\frac{2F\gamma - R^2}{2\gamma - R}, 0\right\}. \tag{9}$$

And for the first best we have $e^{FB} = (R + b)/\gamma$ and

$$\theta^{FB} = \max\left\{\frac{1}{R + b}\frac{2F\gamma - (R + b)^2}{2\gamma - (R + b)}, 0\right\}. \tag{10}$$

The following assumptions make the problem interesting. They ensure that some projects are initiated without subsidy while some are not.

Assumption 2. Some projects are profitable without subsidies: $F < R$.

Assumption 3. Not all projects are initiated without subsidies: $R^2 < 2\gamma F$.

Note that $e^{FB} > e^{BAU}$ and $\theta^{FB} \le \theta^{BAU}$. Furthermore $\theta^{FB} \ge 0$ if and only if $(R + b)^2 \le 2F\gamma$ and, as b increases, θ^{FB} decreases from θ^{BAU} to 0.

The first best can be decentralized with $s_1 = b$ and $s_2 = 0$, which corresponds to a Pigouvian subsidy.[14] However, the agency surplus is not maximized with such a scheme and firms get a rent. If the agency were able to tax profits with a proportional tax then a 100% (pure) profit tax realigns the agency objective with social welfare ($V = W$ and $\Pi = 0$), and $s_1 = b$ both implements the first best, and maximizes the agency surplus ($V = W^{FB}$); information asymmetry is then irrelevant.[15]

3 | SECOND BEST

We consider three configurations: one with both adverse selection and moral hazard and the other two either with adverse selection only or with moral hazard only. The first configuration cannot be solved analytically but some general results can be obtained. The complete solution for the other two configurations is derived. We conclude the section coming back to solve the first configuration for specific probability distributions over the types of the firm.

3.1 | Some general results

The two subsidies influence both the selection of projects and the effort made by firms, but they are costly to the agency. The trade-off between rent extraction and efficiency is made both at

[14]The fixed cost F does not by itself justify the implementation of a subsidy because projects are infinitesimally small.
[15]Even though net profits are null (or infinitely small) firms would choose an optimal effort because they would maximize $(1 - \tau)\pi(\delta, e, \theta, b, 0)$ with τ the profit taxation rate. This result resonates with the fact that in a Ramsey optimal taxation framework the optimal corporate tax on pure profit is 100% (Munk, 1978).

the extensive margin (suboptimal number of projects) and the intensive margin (suboptimal effort), as stated by Proposition 1.

For any subsidy couple (s_1, s_2), there is a threshold project $\tilde{\theta}(s_1, s_2)$ such that all projects with a type above the threshold are initiated, and the effort chosen is $e(s)$ given by Equation (8). The threshold $\tilde{\theta}$ solves $\pi(e, \theta, s_1, s_2) = 0$, that is,

$$p(e, \tilde{\theta})(R + s_1 - s_2) + s_2 - (F + f(e, \tilde{\theta})) = 0. \tag{11}$$

The agency surplus is

$$V = \int_{\tilde{\theta}}^{1} [p(e, \theta)(b - s_1) - (1 - p(e, \theta))s_2] g(\theta)\, d\theta. \tag{12}$$

Subsidies s_1 and s_2 have three effects: (i) on the selection of projects via $\tilde{\theta}$, (ii) on the effort via the bonus $s = s_1 - s_2$, and (iii) on the total expected transfer to firms. As is usual in agency problems the agency trades-off efficiency with rents. It is illuminating to isolate the selection of projects from the precise design of subsidies. Instead of considering the two variables s_1 and s_2, we rewrite the profit of the firm and agency surplus as functions of s and $\tilde{\theta}$. Injecting Equation (11) into the expression (2) gives the profit of a firm as a function of s and $\tilde{\theta}$:

$$\pi = [p(e, \theta) - p(e, \widetilde{\theta})](R + s) - [f(e, \theta) - f(e, \widetilde{\theta})]. \tag{13}$$

And, with a slight abuse of notation, the agency surplus can be rewritten:

$$\begin{aligned} V(s, \widetilde{\theta}) = \int_{\widetilde{\theta}}^{1} \{ & [p(e, \theta)(R + b) - (F + f(e, \theta))] \\ & -[p(e, \theta) - p(e, \widetilde{\theta})](R + s) + [f(e, \theta) - f(e, \widetilde{\theta})]\} dG(\theta). \end{aligned} \tag{14}$$

To increase the bonus s while keeping the threshold type $\tilde{\theta}$ unchanged requires to increase s_1 and reduce s_2.[16] The change of the agency surplus is

$$\frac{\partial V}{\partial s} = \int_{\widetilde{\theta}}^{1} [p_e(R + b) - f_e] e'(s) dG(\theta) - \int_{\widetilde{\theta}}^{1} [p(e, \theta) - p(e, \widetilde{\theta})] dG(\theta). \tag{15}$$

There are two effects from such a change of s: effort is increased (first term) and the expected subsidy transferred to firms is increased (second term). The expected subsidy is increased because a high-type firm is more likely to succeed $p(e, \theta) > p(e, \widetilde{\theta})$ and get the s_1 subsidy. So any change of the scheme that transfers subsidy from failure to success while keeping constant the expected subsidy of the threshold firm has a positive effect on the expected subsidy of initiated projects. This gives the following proposition which characterizes the optimal second-best threshold θ^{SB}.

[16]A change of s that keeps $\tilde{\theta}$ fixed is equivalent to a change of s_1 and a corresponding change of s_2 with $ds = ds_1 - ds_2$, and from Equation (11) we get $p(e, \tilde{\theta}) ds_1 + (1 - p(e, \tilde{\theta})) ds_2 = 0$. A change of $\tilde{\theta}$ for a given s only necessitates a change of s_2 exactly offset by a change of $ds_1 = ds_2$.

Proposition 1. *The second-best optimal scheme* (s_1^*, s_2^*) *is such that the bonus* $s^* = s_1^* - s_2^*$ *is lower than* b*, the effort exerted by firms is then suboptimal and less projects are selected than in the first best* $\theta^{SB} > \theta^{FB}$.

Furthermore, if both subsidies are positive, they satisfy

$$\int_{\theta^{SB}}^{1} (1-\theta)\, dG(\theta)(b - s^*)\frac{1}{\gamma} = \int_{\theta^{SB}}^{1} [\theta - \theta^{SB}]\, dG(\theta)\left(1 - \frac{R + s^*}{\gamma}\right), \tag{16}$$

and θ^{SB} *solves*

$$p(e,\theta)(R+b) - [F + f(e,\theta)] = [1 - G(\theta)][p_\theta(e,\theta)(R + s^*) - f_\theta(e,\theta)]. \tag{17}$$

The proof is in Appendix A. Equation (16) exhibits the trade-off between efficiency and rent extraction, and is reminiscent of the equation satisfied by the optimal menu (cf. Appendix A.1). The left-hand side corresponds to the marginal benefit for the agency from larger effort: the probability of success is increased by $(1-\theta)$ and the agency gets the social benefit minus the bonus. The right-hand side is the marginal profit obtained from a larger bonus by high-type firms which is the difference between their probability of success and the one of the threshold firms. While Equation (16) describes the rent-efficiency trade-off at the intensive margin, Equation (17) describes it at the extensive margin, that is, the selection of project. The benefit from the marginal project (which should be null at the first best) is set equal to the rent created by the required increase of subsidies. Equation (16) is satisfied only if both subsidies are positive, it still gives hints to factors that will justify to set one of the two equal to zero: a larger γ reduces s until eventually $s_1 = 0$, a smaller support of θ justifies larger s, and possibly $s_2 = 0$.

3.2 | Pure adverse selection

The problem of additionality and windfall profit appears in its simplest form in a pure adverse selection problem, in which no effort is exerted. This will make clear the driving force for the difference between our results and Proposition 4 of Ollier and Thomas (2013), in which they show that only success should be rewarded in the absence of fixed cost. We shall assume in that section that $\gamma = +\infty$, so $e = 0$ and $p = \theta$. The agency does not know the ex ante probability of success $p = \theta$ of a given project. The sole remaining purpose of the incentive scheme is to select projects to be initiated. Let us establish that the optimal second-best scheme consists in rewarding failure.

The threshold type $\tilde{\theta}$ at which expected profit is null is (from Equation 7 with $e = 0$):

$$\tilde{\theta}(s_1, s_2) = \frac{F - s_2}{R + s_1 - s_2}. \tag{18}$$

The agency surplus is

$$V(s_1, s_2) = \int_{\tilde{\theta}(s_1,s_2)}^{1} [\theta(b - s_1) - (1-\theta)s_2] g(\theta)\, d\theta. \tag{19}$$

The first best and BAU threshold types are, respectively, $\theta^{FB} = F/(R+b)$ and $\theta^{BAU} = F/R$. Decompose the problem of the agency in two steps:

Step 1: given a targeted threshold probability θ^t the agency minimizes the expected cost of the subsidy:

$$C(\theta^t) = \min_{s_1, s_2} \int_{\theta^t}^{1} [\theta s_1 + (1-\theta)s_2]\, dG(\theta), \quad \text{s.t. } \tilde{\theta}(s_1, s_2) = \theta^t.$$

Since subsidies are nonnegative all firms that invest accept the scheme. If the subsidy could be negative, then firms might be better off investing without subscribing to the scheme.

Step 2: the optimal choice of θ^t maximizes $V = b\int_{\theta^t}^{1} pg(p)\,dp - C(\theta^t)$. This will give the proposition that follows.

Lemma 1. *Whatever the targeted threshold type $\theta^t \leq \theta^{BAU}$, the scheme that minimizes the expected cost of the subsidy is*

$$s_1 = 0 \quad \text{and} \quad s_2 = (F - \theta^t R)/(1-\theta^t).$$

A firm of type $\theta > \theta^{BAU}$ gets a windfall profit.

The proof is in Appendix A.

The result of Lemma 1 is illustrated in Figure 1 in which expected payments with respect to the type are depicted. The dashed black line depicts welfare $\theta(R+b) - F$. The black line corresponds to the BAU profit without subsidy, and the red line profit with a flat subsidy $s_1 = s_2$. The red area corresponds to the total expected subsidy, and the dashed red line depicts a change of the subsidy line associated with an increase of s_2 and a reduction of s_1 that leaves the threshold firm unchanged. As can be seen such a change reduces the total expected subsidy by reducing the expected subsidy obtained by high-type firms. High-type firms succeed more frequently than the threshold type. They more frequently get the success subsidy, and less frequently the failure subsidy; the expected subsidy is then reduced by rewarding more failure and less success. It is optimal to reward only failure to limit windfall profit leaving θ^t is unchanged.

Proposition 2. *At the second-best optimal scheme, only failure is rewarded $s_1 = 0$, and $s_2 \geq 0$ is such that:*

(i) $s_2 = 0$ *and* $\theta^{SB} = \theta^{BAU}$ *if*

$$b \leq \frac{R^3}{F(R-F)} \int_{F/R}^{1} (1-\theta)g(\theta)\,d\theta. \tag{20}$$

(ii) *otherwise* $s_2 > 0$ *and* $\theta^{FB} \leq \theta^{SB} < \theta^{BAU}$ *with* θ^{SB} *defined by the following implicit equation:*

$$\theta^{SB} = \theta^{FB} + \frac{1}{g(\theta^{SB})} \frac{R-F}{b+R} \int_{\theta^{SB}}^{1} \frac{1-\theta}{(1-\theta^{SB})^2} dG. \tag{21}$$

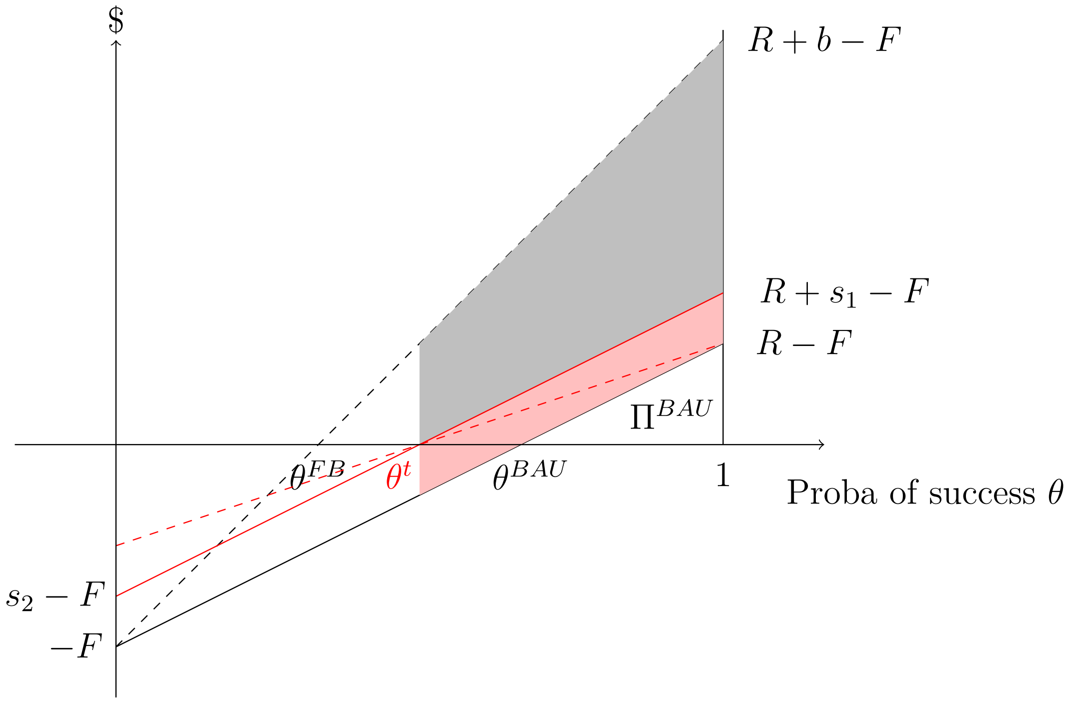

FIGURE 1 Expected subsidy as a function of the firm type: the black line depicts the firm's profit without subsidy (BAU) as a function of its type, the red line depicts the firm's profit with subsidy, the red area is equal to the total expected subsidy (weighted by $g(\theta)$). BAU, Business-As-Usual; FB, first best.

See Appendix B.2 for the proof. It is relatively straightforward to establish that a menu of subsidies cannot improve the situation whenever Assumption 1 holds. Whatever the initial subsidy couple proposed (s_1, s_2), there is no room for maneuver: the agency cannot propose another couple (s_1', s_2') that would be both more interesting to a firm of type $\theta > \tilde{\theta}(s_1, s_2)$ and less costly to the agency. The first condition is equivalent to $\theta s_1' + (1-\theta)s_2' > \theta s_1 + (1-\theta)s_2$ and the second to $\theta s_1' + (1-\theta)s_2' < \theta s_1 + (1-\theta)s_2$. Note that the above reasoning does not rest on the positivity constraints but on the risk neutrality of the principal and the agent.

Finally, it should be stressed that without positivity constraints the first best would be achieved ($\tilde{\theta} = \theta^{FB}$) with subsidies close to $s_2 = F$ and $s_1 = F - R < 0$. It can be seen graphically in Figure 1, further reducing s_1 below zero and increasing s_2 pivots the dashed line further toward the x-axis. Only types between θ^{FB} and θ^{BAU} subscribe to the scheme and get a negligible profit. Larger types $\theta > \theta^{BAU}$ do not accept the scheme and invest nonetheless.

3.3 | Moral hazard only

In a pure moral hazard setting the type of the project θ is known by the firm and the agency, but the agency can observe neither the effort nor its cost. We shall show that rewarding success only is the second-best solution and detail the corresponding scheme. The first best is not achieved.

We now describe the optimal second-best scheme (s_1, s_2) as a function of the type θ of the project. The agency should decide whether to ensure the deployment of a project as soon as $\theta \geq \theta^{FB}$ and whether to further motivate effort. First, if the agency ensures the deployment of a project, it is optimal to do so by rewarding success and not failure because it maximizes the effort of the firm. Second, three cases may occur: the optimal subsidy could be null for $\theta \geq \theta^{BAU}$, it could ensure a null profit to the firm for $\theta < \theta^{BAU}$, or it could be larger to further increase the effort. Let us denote $s_{1B}(\theta)$ as the subsidy that ensures a null profit, and $s_{1A}(\theta)$ as the subsidy that maximizes the agency surplus without the profit positivity constraint (note that $v(1, e(s_1), \theta, s_1, 0)$ is a quadratic function of s_1). It is easily seen that

$$s_{1B}(\theta) = \gamma \frac{\theta}{1-\theta}\left[\sqrt{1 + \frac{2F}{\gamma}\frac{1-\theta}{\theta^2}} - 1\right] - R \tag{22}$$

and

$$s_{1A}(\theta) = \frac{b-R}{2} - \gamma \frac{\theta}{2(1-\theta)}. \tag{23}$$

Note that $s_{1A}(\theta)$ is relevant only if $s_{1A}(\theta) \geq \max\{s_{1B}(\theta), 0\}$; otherwise the project is not initiated. The best of the three occurrences depends on the values of the parameters b, γ, R, and F. Since $s_{1A}(\theta)$ is increasing with b while $s_{1B}(\theta)$ is independent of b, for given values of γ, R, and F, there will be a critical value of b, denoted as $b^*(\theta)$, such that $s_{1A}(\theta)$ should be preferred for $b \geq b^*(\theta)$ while $s_{1B}(\theta)$ should be preferred if $b \leq b^*(\theta)$.

The following proposition holds.

Proposition 3. *At the second-best optimal scheme* $(s_1^*(\theta), s_2^*(\theta))$ *only success is rewarded* $(s_2^* = 0)$, *and a project is initiated if and only if* $\theta \geq \theta^{FB}$.

For all $\theta \geq \theta^{FB}$, *the optimal subsidy is conditional on success and equal to* $\max\{s_{1A}, s_{1B}, 0\}$, *with* s_{1A}, s_{1B} *given by Equations* (23) *and* (22).

If b *is sufficiently large and* F *small,* $s_1^* = s_{1A} > 0$ *and the firm gets a positive profit. Otherwise, the firm gets its BAU profit which is null for* $\theta < \theta^{BAU}$.

The proof is in Appendix B.3. We can interpret the choice of the agency as follows. If $\theta^{BAU} \leq \theta$, it may be worthwhile to induce more effort by selecting $s_{1A}(\theta)$ rather than $s_1 = 0$. If $\theta \leq \theta^{BAU}$, $s_{1B}(\theta)$ compensates the firm for its private loss while $s_{1A}(\theta)$ induces a larger effort and gives some profit to the firm. Both $s_{1A}(\theta)$ and $s_{1B}(\theta)$ are decreasing functions of θ but their ranking may not be monotonous with respect to θ. Figure 2 illustrates a situation in which the best scheme is to choose s_{1A} for low values of θ then s_{1B} up to $\theta = \theta^{BAU}$ and then $s_1 = 0$. As b decreases, it may be that the optimal sequence is $s_{1B}, s_{1A}, s_{1B}, s_1 = 0$. For low b it will be $s_{1B}, s_1 = 0$.

The first best cannot be achieved with an incentive scheme that respect the nonnegativity constraints but it can be with a negative subsidy s_2. At the first best welfare is maximized and the firm gets its BAU profit, otherwise it does not adhere to the scheme. The proof of this lemma is straightforward.

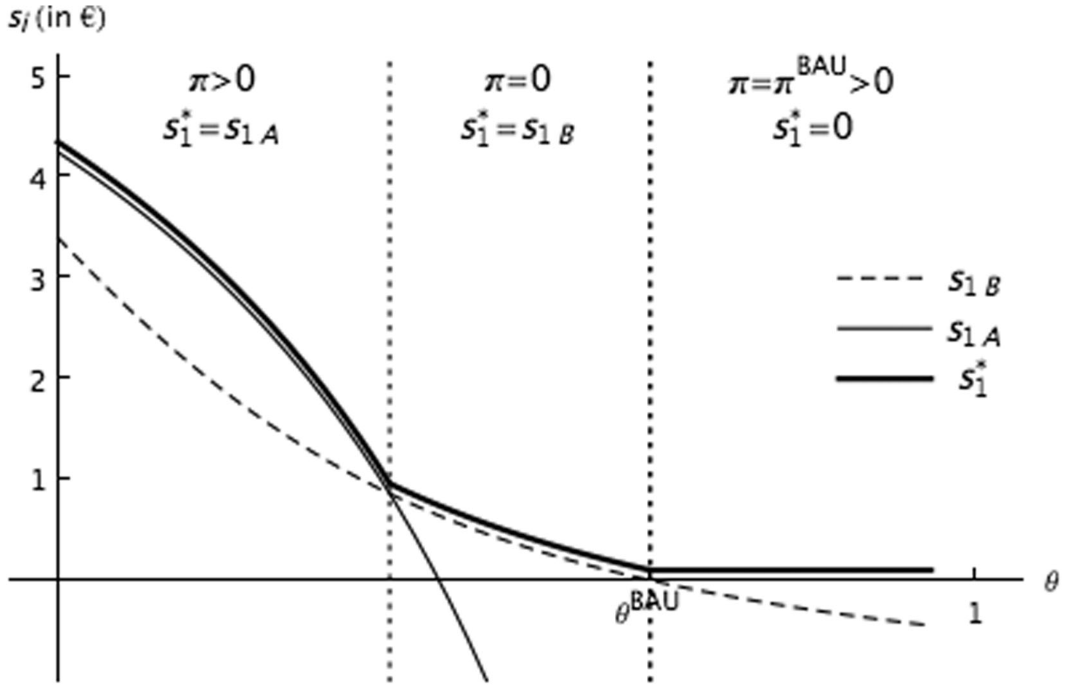

FIGURE 2 The optimal subsidy s_1^* ($s_2^* = 0$) with respect to θ for $R = 1.5, F = 1, \gamma = 12$, and $b = 10$ ($\theta^{FB} = 0$ so that all types should be initiated). BAU, Business-As-Usual; FB, first best.

Lemma 2. *The first best is obtained with an unconstrained scheme such that:*

- *if $\theta \leq \theta^{FB}$, no subsidy is proposed and the project is not initiated,*
- *if $\theta \geq \theta^{FB}$, the optimal scheme is such that $s_1 - s_2 = b$ and $\pi = \pi^{BAU}$.*

The agency surplus is $v = p(e, \theta)(b - (s_1 - s_2)) - s_2 = -s_2$, the subsidy s_2 is negative and could be interpreted as a tax on undue profit.

3.4 | Moral hazard and adverse selection with two specific distributions on θ

The derivation of the second-best optimal scheme may be quite complex. We derive the solution for two specific probability distributions on θ: either uniform or binomial. We shall explicitly rely on these two cases on applying our results to the financing of green projects (cf. Section 5).

Consider first the case of the uniform distribution. Using the result of Section 3.1 we see that with a uniform distribution over [0, 1] a simple and remarkable proposition holds.

Proposition 4. *With a uniform distribution of types θ over* [0, 1], $s_1^* = 0$ *and* $s_2^* > 0$*: failure only should be subsidized.*

The proof makes use of Equation (15) that holds if both subsidies are positive, injecting the expressions $p_e = 1 - \theta, f_e = (1 - \theta)(R + s), e' = 1/\gamma$ and $p(e, \theta) - p(e, \tilde{\theta}) = (\theta - \tilde{\theta})(1 - e)$ with $e = (R + s)/\gamma$ gives

$$\frac{\partial V}{\partial s} = \int_{\tilde{\theta}}^{1} (1 - \theta)(b - s)\frac{1}{\gamma} d\theta - \int_{\tilde{\theta}}^{1} (\theta - \tilde{\theta})\left(1 - \frac{R + s}{\gamma}\right) d\theta.$$

The first term represents the gains from increased efforts and the second term is the loss from increased rents (to high types). Thanks to Assumption 1 the difference between the two, in the case of a uniform distribution over [0, 1], is

$$\frac{\partial V}{\partial s} = \frac{1}{2}(1 - \tilde{\theta})^2 \frac{b - s}{\gamma} - \frac{1}{2}(1 - \tilde{\theta})^2\left(1 - \frac{R + s}{\gamma}\right) = \frac{1}{2}(1 - \tilde{\theta})^2\left[\frac{R + b}{\gamma} - 1\right] < 0.$$

Consequently V is linear with respect to s with a negative slope: the marginal loss due to increased rents dominates. The bonus s should then be kept at minimum, and the optimal second-best solution is such that $s_1 = 0$, and $s_2 > 0$. The length of the support of θ matters for this result, if it is shortened and concentrated around any $\theta \geq \theta^{FB}$, the situation is close to a moral hazard only and reward success is optimal. It is further investigated numerically in Section 5.

Consider now the case of a binomial distribution over two types: θ_L and θ_H with $\theta_L < \theta_H$. The probability of type θ_H is denoted as λ. The agency knows λ while the firm knows its type. We analyze the influence of λ over the optimal scheme. The following assumption is introduced to get the results.

Assumption 4. We take $(R + b) < \sqrt{2F\gamma}$ (i.e., $\theta^{FB} > 0$) and θ_L and θ_H such that $\theta^{FB} < \theta_L < \theta^{BAU}$ and $\theta^{BAU} < \theta_H$. The low-type firm would not initiate a socially valuable project, the high-type firm would even without subsidy.

To get intuition into the structure of the optimal second-best scheme, start with a situation in which the cost of effort γ is very high. Rewarding failure only is optimal. As γ decreases, for low values of λ it may become worthwhile to induce a low-type firm to make an effort through rewarding success, the incremental rent for the high-type firm being more than compensated. How do these two situations of rewarding success and rewarding failure combine together? As λ increases the balance between the benefit accruing from a higher effort from a low-type firm should exactly balance the increase in the rent of the high-type firm. The following lemma precisely defines the relationship between s_1 and s_2 for these intermediary situations.

Lemma 3. *If both subsidies are strictly positive the optimal scheme* (s_1^*, s_2^*) *satisfy*

$$s_1^* - s_2^* = b - \frac{\gamma\lambda(\theta_H - \theta_L)}{(1 - \theta_L) - 2\lambda(\theta_H - \theta_L)}(1 - e^{FB}), \tag{24}$$

and s_2^* *is such that the profit of the low-type firm is null, it solves*

$$s_2^* = F - \theta_L\left(R + \left(s_1^* - s_2^*\right)\right) - (1-\theta_L)\frac{\left(R + \left(s_1^* - s_2^*\right)\right)^2}{2\gamma}. \tag{25}$$

The proof is in Appendix C.2. We now characterize the optimal second-best scheme for all values of λ.

Proposition 5. *The optimal scheme (s_1^*, s_2^*) depends on three thresholds λ_1, λ_2, and λ_3 as follows:*

- *for $0 < \lambda \leq \lambda_1$: $s_1^* > 0$ and $s_2^* = 0$; $s_1^* = s_{1B}(\theta_L)$ given by Equation (22);*
- *for $\lambda_1 < \lambda < \lambda_2$: $s_1^* > 0$ and $s_2^* > 0$ given by Lemma 3;*
- *for $\lambda_2 < \lambda < \lambda_3$: $s_1^* = 0$ and $s_2^* > 0$ such that $\pi(1, e, \theta_L, 0, s_2^*) = 0$:*

$$s_2^* = R - \gamma + \gamma\left[1 - \frac{2}{\gamma}\frac{R-F}{1-\theta_L}\right]^{1/2}.$$

- *for $\lambda_3 < \lambda \leq 1$: $s_1^* = 0$ and $s_2^* = 0$.*

The profit of a low-type firm is always null, a high-type firm gets a windfall profit as long as $\lambda < \lambda_3$.

Proof in Appendix C.2.

4 | SIMPLE EXTENSIONS

4.1 | The outcome is imperfectly observable

There may be situations in which the agency does not perfectly observe the outcome of the project. This opens an opportunity for manipulation from the firm. If the agency were to reward failure, the firm may pretend that a success is a failure. In the following we limit ourselves to an extension of Section 3.2 (pure adverse selection) and show that as long as the agency receives an informative signal the solution is not qualitatively affected, though its efficiency is deteriorated (the threshold project is higher).

Let α_1 be the probability of observing a signal of failure if the project is a success and α_2 the probability of observing a signal of failure if the project fails. We assume that $\alpha_2 \geq \alpha_1$, a perfect signal corresponds to $\alpha_2 = 1$ and $\alpha_1 = 0$, and an uninformative signal corresponds to $\alpha_2 = \alpha_1$. The subsidy obtained by a firm is $\alpha_1 s_2 + (1-\alpha_1)s_1$ in case of success and $\alpha_2 s_2 + (1-\alpha_2)s_1$ in case of failure. The threshold project is then:

$$\tilde{\theta}(\alpha_1 s_2 + (1-\alpha_1)s_1, \alpha_2 s_2 + (1-\alpha_2)s_1),$$

and the expected total subsidy is

$$\int_{\tilde{\theta}}^{1} \{\theta[(1-\alpha_1)s_1 + \alpha_1 s_2] + (1-\theta)[(1-\alpha_2)s_1 + \alpha_2 s_2]\}\, dG(\theta).$$

Corollary 1. *If the success and failure of a project are not perfectly observable, the optimal scheme remains of the form $s_1 = 0$ and $s_2 > 0$. The second-best threshold type, the expected subsidy, the agency surplus, the welfare, and the profit of firms only depend on the ratio α_1/α_2.*

- If $\alpha_1 = 0$ (success is perfectly observed), then, whatever α_2, at the optimal second-best scheme, the threshold probability, welfare, and s_2 do not depend on α_2 and correspond to the perfect observability situation.
- Otherwise, with a uniform distribution, the threshold probability is higher and welfare and the agency surplus are lower than in the case with a perfect signal.

See Appendix B.4 for the proof.

4.2 | The final outcome is not known ex ante

In practice, R&D projects go through several stages from the lab to the market, and each of these stages could be subsidized and subject to informational asymmetry. Notably, in case of a success of a demonstration plant, the future revenue generated in the market through commercialization is likely to be better known by the firm than the public agency.

As a first extension to model that dynamic, each project could be decomposed into two stages: a technical and a market stage. In the technical stage, a pilot plant is built to prove the concept of the innovation, a fixed cost F is incurred, and the project might succeed or fail with probability p. The decision whether to commercialize is made by the firm and depends on the revenue generated R which is a random variable, possibly negative. There is also asymmetry of information at the market stage: we take the extreme case in which the firm knows R while the agency does not. There is an ex ante probability distribution of $R, H(\cdot)$, conditional on the success of a preliminary technical stage. The environmental benefit now depends on the quantity actually produced and sold, it is a nondecreasing function of R: $b(R)$. Given that success has been observed by the agency, the remaining question is: should the agency subsidize the market stage. Define R^{FB} such that

$$R^{FB} + b(R^{FB}) = 0.$$

The following optimal repayable advance $s(R)$, which takes the form of a sales contingent claim, provides the first best:

$$s(R) = \begin{cases} 0 & \text{if } R < R^{FB}, \\ -R & \text{if } R^{FB} < R < 0, \\ 0 & \text{if } 0 < R. \end{cases} \tag{26}$$

Define $\bar{R}$ and $\bar{b}$ as the expected outcomes with the optimal market solution. That is,

$$\bar{R} = \int_{R^{FB}}^{R_{max}} (R + s(R))\, dH(R) \quad \text{and} \quad \bar{b} = \int_{R^{FB}}^{R_{max}} (b(R) - s(R))\, dH(R).$$

Our analysis of the project can be extended to a situation in which the final outcome is not known ex ante through substituting R and b by $\bar{R}$ and $\bar{b}$, respectively. The optimal scheme then consists of a couple of subsidies conditional on the technical outcome (s_1 in case of failure and s_2 in case of success) together with $s(R)$ being the optimal sales contingent claim.

5 | CONCLUSION

This article is concerned with public financing of risky R&D projects for the energy transition. Projects are formalized through a random process involving a sunk cost and leading to either success or failure. In case of success the project generates a private profit for the firm and a social benefit for society, that is, an externality. In the absence of a regulation to internalize the externality, a state agency may allow public subsidies to the project. The focus of the analysis concerns conditional schemes based on the observability of the outcome of the random process, that is, rewarding success and/or rewarding failure. We consider three issues: selection bias (a socially valuable project is not implemented by the firm), windfall profit (a profitable project obtains unnecessary public subsidies), and effort (the firm may not allocate the socially optimal resources to the project) under situations of adverse selection and moral hazard.

Our analysis provides an economic justification for using repayable advances in this context. We show how the benefit of doing this comes from balancing selection bias with windfall profit in pure adverse selection situations. In pure moral hazard situations, repayable advances have no bite and rewarding success is the optimal scheme. When the situation exhibits both adverse selection and moral hazard the benefit of repayable advance is possibly constrained by the fact that it does not encourage effort to succeed. The agency is stuck in the middle of two conflicting goals (encouraging effort and limiting windfall profit); a subtle balance between reward success and reward failure needs to be found. As illustrated through the case study detailed in the appendix, the nature of the uncertainty on the types of the firm may matter. While no subsidy would do almost as well in the case of a binomial distribution (two extreme peaks of uncertainty), looking for the optimal second-best contract is quite valuable in the case of a uniform distribution (large and flat uncertainty).

More generally our analysis justifies the importance of the empirical recommendations made by Rodrik (2014) for an agency in charge of monitoring a green policy. Let us review three of them briefly. Discipline: clarify ex ante objectives for the agency, build an evaluation protocol on what should or could be observed, making this an important aspect of the contracting process. Embeddedness: introduce reasonably simple conditional incentives along the life of the project but be aware of the risk of manipulation. Gaming: it plays an important role in our analysis, we formalize this issue and show how repayable advance may be used in some circumstances to mitigate its impact. We think that our formalization provides some helpful guidelines for structuring an efficient contracting process for green industrial policy.

From a theoretical standpoint, more work would be worthwhile. First, from a pure technical point, the robustness of our results should be tested with more general functional forms, in particular regarding the effort function. It would also be interesting to incorporate the dynamic aspects of innovation and to decompose a project into several technical steps that need to be completed. The timing of these steps and the determination of a stopping point, a time at which a project is abandoned, would be worth analyzing. To this end the burgeoning literature on experimentation with new ideas under asymmetric information could be inspiring (e.g., Bergemann & Hege, 1998, 2005). Second, in terms of the architecture of the formalization, the information structure may involve another party. Frequently, the state agency plays the role of a middleman between the firm and the banking system. Indeed, at first, the asymmetry of information is much more acute between the firm and the banking system (which induces a capital market failure) than between the firm and the state agency (which has much higher technical expertise than a bank). The formalization should explicitly analyze how the contractual arrangement between the state agency and the firm should evolve as the asymmetry between the bank and the firm reduces over time. It would connect our analysis on the characteristics of the contract with the literature on incomplete finance markets mentioned in the introduction (e.g., Kaivanto & Stoneman, 2007).

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DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no data sets were generated or analyzed during the current study.

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APPENDIX A: GENERAL SETTING

A.1 | Optimal menu without constraints

We provide a description of what would be the structure of a menu, with a general distribution of types, if the subsidies are not constrained to be positive, and firms cannot initiate the project without the regulator consent.

It is easier to work with the bonus $s(\theta)$ and consider $s_2(\theta)$ as a fixed transfer. The agency proposes a structured menu $(s(\theta), s_2(\theta))_{\theta\in(0,1)}$, a firm of type θ selecting the item $(s(\eta), s_2(\eta))$ has a profit $\pi(\theta, \eta) = p(e, \theta)(R + s(\eta)) + s_2(\eta) - (F + f(e, \theta))$, and the first-order condition necessary for self-selection is $p(e, \theta)s'(\theta) + s_2'(\theta) = 0$.

Using the standard methodology in contract design, denoting $\pi^m = \pi(\theta, \theta)$, its total derivative is $d\pi^m/d\theta = p_\theta(R + s) - f_\theta(e, \theta)$ which only depends on the bonus $s(\theta)$ and not $s_2(\theta)$. Thanks to this relationship and an integration by part the surplus of the agency can be written:

$$V = \int_{\tilde{\theta}}^{1}\left\{[p(e, \theta)(R + b) - (F - f(e, \theta))]g(\theta) - \frac{d\pi^m}{d\theta}[1 - G(\theta)]\right\}d\theta.$$

The optimal bonus $s(\theta)$ should be such that

$$p_e(b - s)\frac{de}{ds} = \frac{1 - G}{g}\frac{d}{ds}[p_\theta(e, \theta)(R + s) - f_\theta(e, \theta)]$$

and with our quadratic specification $s(\theta)$ solves

$$(1 - \theta)(b - s)\frac{1}{\gamma} = \frac{1 - G(\theta)}{g(\theta)}(1 - e(s)) = \frac{1 - G(\theta)}{g(\theta)}(\gamma - R - b)\frac{1}{\gamma}, \tag{A1}$$

which looks like Equation (16) satisfied by a simple scheme (s, s_2). We recover the usual result that $s = b$ for high types. The selection of projects is done with the choice of $s_2(\tilde{\theta})$ the profit of the $\tilde{\theta}$ firm being null.

A.2 | Proof of Proposition 1

The agency surplus is positive for $s_1 = s_2 = 0$, and if $s_1 - s_2 \geq b$ it is nonpositive, therefore, at the optimum scheme $s_1 - s_2 < b$.

Let us write the expression of the derivative of V with respect to s with our specification, from Equation (15):

$$\begin{aligned}\frac{\partial V}{\partial s} &= \int_{\tilde{\theta}}^{1}(1 - \theta)\,dG(\theta)\frac{b - s}{\gamma} - \int_{\tilde{\theta}}^{1}[\theta - \tilde{\theta}]\,dG(\theta)(1 - e)\\ &= \int_{\tilde{\theta}}^{1}(1 - \theta)\,dG(\theta)\frac{b - s}{\gamma} - \int_{\tilde{\theta}}^{1}[\theta - \tilde{\theta}]\,dG(\theta)\frac{\gamma - (R + s)}{\gamma}.\end{aligned} \tag{A2}$$

The first line makes use of $p_e(R + s) = f_e$ for all θ which cancels the influence of s via e on the second line of Equation (14). In the second line, f_e is replaced by $p_e(R + s)$ for all θ, and the third line makes use of Equation (8).

Concerning the selection of projects, several cases should be distinguished according to the sign of the two subsidies at the optimum:

(i) If $s_1 > 0$ and $s_2 > 0$: the derivative of V with respect to s, expressed in Equation (15), is null and Equation (16) is satisfied. θ^{SB} cancels the derivative of V, given by Equation (14), with respect to $\tilde{\theta}$ which gives (17).

(ii) If $s_1 \geq 0$ and $s_2 = 0$: then $s_1 < b$ and at θ^{SB}

$$0 = p(e, \theta^{SB})(R + s_1) - [F + f(e, \theta^{SB})] \quad \text{from Equation (11)} \tag{A3}$$

$$< p(e, \theta^{SB})(R + b) - [F + f(e, \theta^{SB})] \tag{A4}$$

$$< p(e^{FB}, \theta^{SB})(R + b) - [F + f(e^{FB}, \theta^{SB})], \tag{A5}$$

therefore, $\theta^{SB} > \theta^{FB}$ less projects are selected than at the first best.

(iii) If $s_1 = 0$ and $s_2 > 0$: the above method cannot be applied, the first-order condition should be considered. The threshold $\tilde{\theta}$ cannot be chosen independently from the bonus $s = -s_2$, and s_2 cancels the derivative of V given by Equation (12) so

$$p(e, \widetilde{\theta})(b + s_2) - s_2 = \int_{\widetilde{\theta}}^{1} [p_e(b - s_2)e' + (1 - p)]dG(\theta)/[-\partial\widetilde{\theta}/\partial s_2]$$

and injecting Equation (11) the left-hand side is $p(e, \widetilde{\theta})(R + b) - [F + f]$ which is then strictly positive, since $\partial\tilde{\theta}/\partial s_2 < 0$, and together with the fact that $e < e^{FB}$ implies that $\theta^{SB} < \theta^{FB}$.

Second-order condition: Formally, from Equation (15), the agency surplus is quadratic with respect to s with a second-order coefficient:

$$\int_{\tilde{\theta}}^{1} [(\theta - \tilde{\theta}) - (1 - \theta)]g(\theta)\, d\theta - \int_{\tilde{\theta}}^{1} (\theta - \tilde{\theta})[g(\theta) - g(1 + \tilde{\theta} - \theta)]\, d\theta, \tag{A6}$$

the sign of which depends on the shape of G and the threshold $\tilde{\theta}$.

APPENDIX B: PURE ADVERSE SELECTION OR MORAL HAZARD SITUATIONS

B.1| Proof of Lemma 1

Consider a change of the subsidy couple that keeps θ^t unchanged: $\theta^t ds_1 + (1 - \theta^t)ds_2 = 0$. For $\theta > \theta^t$ the effect of this change on the expected subsidy received by the firm of type θ is $(\theta - \theta^t)(ds_1 - ds_2)$, which is negative if $ds_2 > 0$. Therefore, to reduce $C(\theta^t)$ the agency should increase s_2 and reduce s_1.

B.2| Proof of Proposition 2

The threshold probability as a function of s_2 is $\tilde{\theta}(0, s_2)$, the derivative of welfare with respect to s_2 is

$$-[\tilde{\theta}b - (1-\tilde{\theta})s_2]g(\tilde{\theta})\frac{\partial\tilde{\theta}}{\partial s_2} - \int_{\tilde{\theta}}^{1}(1-\theta)g(\theta)\,d\theta, \tag{B1}$$

the first term is the benefit from the marginal project, the second term is the increased subsidy to all more profitable projects. The derivative of the threshold probability is

$$\frac{\partial\tilde{\theta}}{\partial s_2} = \frac{1-\tilde{\theta}}{R-s_2} = \frac{(1-\tilde{\theta})^2}{R-F},$$

the derivative of welfare could then be rewritten:

$$[\tilde{\theta}(R+b) - F]g(\tilde{\theta})\frac{(1-\tilde{\theta})^2}{R-F} - \int_{\tilde{\theta}}^{1}(1-\theta)g(\theta)\,d\theta. \tag{B2}$$

At $s_2 = 0\tilde{\theta} = F/R$ and the derivative of welfare is negative if

$$[F(R+b) - FR]g(F/R)\frac{1}{R}\frac{(1-F/R)^2}{R-F} \leq \int_{\tilde{\theta}}^{1}(1-\theta)g(\theta)\,d\theta,$$

point (i) follows. Otherwise, the optimal subsidy cancels the derivative of welfare, and point (ii) describes the first-order condition.

B.3| Proof of Proposition 3

•*First step*: The project is initiated if and only if $\theta \geq \theta^{FB}$.

If $\theta < \theta^{FB}$, the joint surplus of the agency and the firm are negative whatever the subsidy scheme that triggers initiation, therefore the agency is not willing to make the firm initiate the project and no subsidies are required.

If $\theta \geq \theta^{FB}$, the agency can set $s_1 = b$ and $s_2 = 0$, the project is initiated and the agency surplus is null. Therefore, the agency can obtain a positive surplus for $\theta > \theta^{FB}$ with an optimal scheme that triggers the initiation of the project.

•*Second step*: $s_2^* = 0$.

Let us consider that $\theta > \theta^{FB}$. The regulator maximizes its surplus (Equation 3) subject to the nonnegativity constraints on profit (Equation 2) and subsidy s_1 and s_2. The Lagrangien is

$$\mathcal{L} = v(1, \theta, e(s_1 - s_2), s_1, s_2) + \mu_0\pi + \mu_1 s_1 + \mu_2 s_2.$$

With μ_0 the Lagrange multiplier associated with the initiation constraint, μ_i the multiplier associated with the nonnegativity constraint of s_i, $i = 1, 2$. At the optimum[17]:

$$p_e(e,\theta)[b - (s_1 - s_2)]e' - (1-\mu_0)p + \mu_1 = 0, \tag{B3}$$

$$-p_e[b - (s_1 - s_2)]e' - (1-\mu_0)(1-p) + \mu_2 = 0. \tag{B4}$$

And the corresponding slackness conditions. Summing the two equations gives

[17]The derivative of the profit of the firm with respect to s_i does not directly involve e' by an envelop argument.

$$\mu_1 + \mu_2 + \mu_0 - 1 = 0. \tag{B5}$$

At least one of the μ_i is positive, otherwise $\mu_0 = 1$ and $s_1^* - s_2^* = b$. The agency surplus is then $-(1-p)s_2^* < 0$, which cannot be optimal. Consequently, $\mu_1 + \mu_2 > 0$ and $\mu_0 < 1$ (from Equation B5). Then, from Equation (B4)

$$\mu_2 = (1-\mu_0)(1-p) + p_e\left[b - \left(s_1^* - s_2^*\right)\right]e' > 0$$

and $s_2^* = 0$.

•*Third step*: Expressions of the optimal subsidy.

There are four possible cases: (i) $s_1^* = 0$ and $\pi > 0$, (ii) $s_1^* = 0$ and $\pi = 0$, (iii) $s_1^* > 0$ and $\pi > 0$, or, (iv) $s_1^* > 0$ and $\pi = 0$.

Case (i) corresponds to "BAU" no subsidy is used and the project is implemented with suboptimal effort. Case (ii) corresponds to a situation in which the project is not profitable and it is not worth subsidizing it.

In case (iii) $s_1^* > 0$ and $\pi > 0$ then $p_e[b - s_1^*]e' = p$, and in case (iv) $s_1^* > 0$ and $\pi = 0$ then $p_e[b - s_1^*]e' - p = -\mu_0 p \leq 0$.

The subsidy $s_{1A}(\theta)$ defined by Equation (23) is the solution of $p_e[b - s_1^*]e' = p$, if positive. And $s_{1B}(\theta)$ is the solution of $\pi(1, \theta, e(s_1), s_1, 0) = 0$, if positive. Replacing e by $(R + s_1)/\gamma$ in Equation (2) gives a second-order equation in $(R + s_1)$ with one positive root given by Equation (22).

If $s_1^* > 0$ and $\pi > 0$ then $s_1^* = s_{1A}$, and if $s_1^* > 0$ and $\pi = 0$ then $s_1^* = s_{1B}$. Furthermore, by the concavity of v, if both expressions s_{1A} and s_{1B} are positive the optimal subsidy is the larger of the two, otherwise it is null.

Ranking of the subsidies:

Some properties of the subsidies should be noted: $s_{1B}(\theta^{FB}) = b$ if $\theta^{FB} > 0$ and $s_{1B}(\theta^{BAU}) = 0$, while $s_{1A} < b$ for all θ.

From the two expressions (23) and (22) the sign of the difference $s_{1B} - s_{1A}$ is the sign of

$$\begin{aligned}
&\frac{\theta}{1-\theta}\left[\sqrt{1 + \frac{2F}{\gamma}\frac{1-\theta}{\theta^2}} - 1\right] - \frac{R}{\gamma} - \left[\frac{b-R}{2\gamma} - \frac{1}{2}\frac{\theta}{1-\theta}\right] \\
&= \sqrt{x^2 + \frac{2F}{\gamma}(1+x)} - \frac{b+R}{2\gamma} - \frac{1}{2}x \quad \text{with } x = \frac{\theta}{1-\theta},
\end{aligned}$$

the sign of which is the sign of the second-degree polynomial:

$$P(x) =_{def} [4x^2 + 8\phi(1+x)] - [\beta + x]^2 = 3x^2 - (2\beta - 8\phi)x + (8\phi - \beta^2), \tag{B6}$$

in which $\beta = (b+R)/\gamma < 1$ (by Assumption 1) and $\phi = F/\gamma$ which is lower than R/γ (by Assumption 2) and larger than $(R/\gamma)^2/2$ (by Assumption 3). And we have $\theta^{FB} > 0$ if and only if $2\phi > \beta^2$ (from Equation 10). The full characterization of the possible cases is cumbersome. However, despite our three assumptions, there is still a lot of room for maneuver in the choice of parameters. The two following corollary provide conditions on parameters F, b, R, and γ such that only s_{1B} is used for all θ. The third provides conditions so that s_{1A} is used.

Corollary B.1. *If $F > (b+R)^2/2$, that is, $\theta^{FB} > 0$, then $s_{1A} < s_{1B}$ for all θ so that the optimal subsidy is* $\max\{s_{1B}(\theta), 0\}$ *for all $\theta \in [0, 1]$, and the firm gets no extra profit.*

Proof. The discriminant of $P(x)$ (Equation B6) is $16[\beta^2 - 2\beta\phi - 6\phi + 4\phi^2]$ which is negative if $\phi > \beta^2/2$, and $P(0) = 8\phi - \beta^2 > 0$ so that $P(x) > 0$ for all x and $s_{1B} > s_{1A}$. □

Corollary B.2. *If $F > \gamma(1 - \sqrt{3}/2)(\simeq 0.134\gamma)$, then for all b such that $(R+b) < \gamma$ and all types $\theta > \theta^{FB}$, the optimal subsidy is* $\max\{s_{1B}(\theta), 0\}$ *and the firm gets no extra profit.*

Proof. The discriminant of $P(x)$ has the sign of $\beta^2 - 2\beta\phi - 6\phi + 4\phi^2$ which is increasing with respect to β (since $\phi < 1$) and therefore lower than $1 - 8\phi + 4\phi^2$ which is equal to $4(1-\phi)^2 - 3$ which is negative if and only if $\phi > 1 - \sqrt{3}/2$ □

Corollary B.3. *If $F < (R+b)^2/(8\gamma)$, then, $\theta^{FB} = 0$ and the optimal subsidy is equal to s_{1A} for small θ, for larger θ the optimal subsidy switches to s_{1B} and eventually to* 0.

If F is slightly larger than $(R+b)^2/(8\gamma)$, then $\theta^{FB} = 0$ and the optimal subsidy is equal to s_{1B} for small θ, for intermediate θ the optimal subsidy switches to s_{1A}, then switches back to s_{1B} and eventually to 0.

Proof. First, $F < (R+b)^2/(8\gamma) < (b+R)^2/2$ so that $\theta^{FB} = 0$ for F below or slightly larger than $(R+b)^2/(8\gamma)$. Second, we have

$$P(0) = 8\frac{F}{\gamma} - \frac{(R+b)^2}{\gamma^2} < 0$$

So $P(0) < 0$ gives that $s_{1B}(0) < s_{1A}(0)$ and so $s_1^* = s_{1A}(0)$ for small θ. Then, we know that $P(\cdot)$ has a unique positive root (the other is negative), so that for θ below that root (actually $x = \theta/(1+\theta)$ is the argument of P) s_{1A} is used, then $s_{1B}(\theta)$ until it is null.

If F is slightly larger than the threshold, then $P(0) > 0$, but one can show that $P'(0) < 0$ so that the first root of $P(\cdot)$ is close to zero, the optimal subsidy switches from s_{1B} to s_{1A} from there, and then back to s_{1B} after the second root of $P(\cdot)$. □

B.4| Proof of Corollary 1

Let us denote $\sigma_1 = \alpha_1 s_2 + (1-\alpha_1)s_2$ and $\sigma_2 = \alpha_2 s_2 + (1-\alpha_2)s_2$ the subsidies obtained in case of success and failure, respectively.

•*For unconstrained subsidies*: With the couple of subsidy, $s_1 = F - \alpha_2 R/(\alpha_2 - \alpha_1)$ and $s_2 = F + (1-\alpha_2)R/(\alpha_2 - \alpha_1)$, the expected subsidies are $\sigma_1 = F$ and $\sigma_2 = F - R$ which implement the first best.

•*For nonnegative subsidies*:

(1) $s_1 = 0$ and $s_2 > 0$: The reasoning of Lemma 1 can be reproduced: an increase of σ_2 coupled with a reduction of σ_1 that leaves $\tilde{\theta}$ unchanged reduces the total expected subsidy. Consequently it is optimal to set $s_1 = 0$ and $s_2 > 0$.

(2) Then, with $s_1 = 0$, $\sigma_1 = x\sigma_2$ with $x = \alpha_1/\alpha_2$ and the threshold probability is $\tilde{\theta}(x\sigma_2, \sigma_2)$, the regulator surplus is

$$V(x\sigma_2, \sigma_2) = \int_{\tilde{\theta}}^{1} [\theta(b - x\sigma_2) - (1 - \theta)\sigma_2]\, dG(\theta)$$

and welfare is $W(\tilde{\theta}(x\sigma_2, \sigma_2))$.

(3) If $\alpha_1 = 0$: then $x = 0$ and the surplus of the regulator, the profit of firms, and total welfare could all be written as functions of σ_2 without any other dependence on α_2. The optimum second-best scheme is then similar to the scheme described by Proposition 2 with $\alpha_2 s_2$ being independent of α_2.

(4) Otherwise, for $\alpha_1 > 0$: then $x > 0$,

(4.1) Let us prove that θ^{SB} is increasing with respect to x, to do so we first write the first-order condition:

- the total derivative of the threshold type w.r.t. σ_2 is

$$\frac{d\tilde{\theta}}{d\sigma_2} = -\frac{1 - (1 - x)\tilde{\theta}}{R - (1 - x)\sigma_2},$$

the first-order condition satisfied at the optimal scheme is

$$[\tilde{\theta} - \theta^{FB}]g(\tilde{\theta})\frac{1 - (1 - x)\tilde{\theta}}{R - (1 - x)\sigma_2} = \int_{\tilde{\theta}}^{1} [\theta x + (1 - \theta)]\, dG(\theta)$$

and with a homogeneous distribution it gives

$$\tilde{\theta} = \theta^{FB} + \frac{R - (1 - x)F}{R + b}\frac{1}{2(1 - x)}\left[1 - \frac{x^2}{(1 - (1 - x)\tilde{\theta})^2}\right].$$

- θ^{SB} increases with respect to x (brutal calculations): The right-hand side of the first-order condition above side is a decreasing function of $\tilde{\theta}$, and it is increasing with respect to x: Its derivative is

$$\frac{(1 - \tilde{\theta})}{2(R + b)}\frac{2Fx + R[(1 - \tilde{\theta})^2 - x\tilde{\theta}(1 + \tilde{\theta})]}{(1 - (1 - x)\tilde{\theta})^3},$$

the sign of which is the sign of $2Fx + R[(1 - \tilde{\theta})^2 - x\tilde{\theta}(1 + \tilde{\theta})]$ which is positive (using that $\tilde{\theta} < F/R$).

(4.2) The effect of x on the regulator surplus at the optimal scheme, by an envelope argument, it is

$$\frac{\partial V}{\partial s_1}(x\sigma_2, \sigma_2)\sigma_2,$$

which is negative.

Welfare is decreasing with respect to $\tilde{\theta}$ as long as $\tilde{\theta} > \theta^{FB}$, so it is decreasing with respect to x.

APPENDIX C: BINOMIAL DISTRIBUTION

C.1 | Proof of Lemma 3

To alleviate notation the probability $p(e, \theta_L)$ and $p(e, \theta_H)$ are denoted with subscripts: $p_L(e)$ and $p_H(e)$, and the profits π_L and π_H.

If both s_1^* and s_2^* are positive, then low-type projects are implemented (otherwise one would apply Proposition 3 to high type) and their profits are null (otherwise the subsidies could be reduced). The regulator surplus is then

$$v(s_1, s_2) = (1-\lambda)[p_L(b - s_1) - (1-p_L)s_2] + \lambda[p_H(b - s_1) - (1-p_H)s_2] \tag{C1}$$

and the optimal scheme satisfies the following equation:

$$\frac{\partial v}{\partial s_1}\frac{\partial \pi_L}{\partial s_2} - \frac{\partial v}{\partial s_2}\frac{\partial \pi_L}{\partial s_1} = 0,$$

that is,

$$\frac{\partial v}{\partial s_1}(1-p_L) - \frac{\partial v}{\partial s_2}p_L = 0,$$

which gives, denoting $s^* = s_1^* - s_2^*$:

$$\begin{aligned}\lambda[p_H(1-p_L) + (1-p_H)p_L] &= \left[(1-\lambda)\tfrac{\partial p}{\partial e}(e, \theta_L) + \lambda\tfrac{\partial p}{\partial e}(e, \theta_H)\right](b - s^*)e',\\ \lambda[p_H - p_L] &= [(1-\lambda)(1-\theta_L) + \lambda(1-\theta_H)](b - s^*)\tfrac{1}{\gamma},\\ \lambda(\theta_H - \theta_L)(\gamma - (R + s^*)) &= [(1-\lambda)(1-\theta_L) + \lambda(1-\theta_H)](b - s^*),\end{aligned}$$

which then gives Equation (24). Equation (25) corresponds to $\pi_L = 0$.

C.2 | Proof of Proposition 5

The solution $s_1^* = s_2^* = 0$ corresponds to the situation in which L firms do not enter. The regulator surplus in that situation is

$$V_1(\lambda) = \lambda p_H b.$$

In all other situations, if one of the optimal subsidies is positive, L firms do enter (from Proposition 3, if only H firms enter then it is optimal to set $s_1 = s_2 = 0$). The regulator surplus when L firms enter is

$$V_2 = (1-\lambda)[p_L(b - s_1) - (1-p_L)s_2] + \lambda[p_H(b - s_1) - (1-p_H)s_2]$$

that can be equivalently defined as a function of $s = s_1 - s_2$ and s_2:

$$V_2(\lambda, s, s_2) = (1-\lambda)[p_L(b - s) - s_2] + \lambda[p_H(b - s) - s_2]$$

and the constraint $s_1 \geq 0$ is then $s + s_2 \geq 0$.

The problem of the regulator can be decomposed in two steps: first maximize V_2 and then compare the maximum obtained with V_1.

Let us consider the maximization of V_2 subject to $\pi_L \geq 0, s_2 \geq 0$, and $s + s_2 \geq 0$ and denote $s^{**}(\lambda)$ and $s_2^{**}(\lambda)$ the solution, and $s_1^{**} = s^{**} + s_2^{**}$. The problem can be simplified by transforming the three constraints $\pi_L \geq 0, s_2 \geq 0$, and $s + s_2 \geq 0$ into two constraints on s, by parameterizing everything by s.

•*At the maximum* $\pi_L = 0$: by contradiction, if $\pi_L > 0$ then $s_2^{**} = 0$ and s_1^{**} is larger than s_{1B} (which cancels π_L, it is defined by Equation 22) and solves

$$\left[(1-\lambda)\frac{\partial p_L}{\partial e} + \lambda\frac{\partial p_H}{\partial e}\right](b - s_1)e' = (1-\lambda)p_L + \lambda p_H,$$

then $\partial p_L/\partial e(b - s_1^{**})e' > p_L$ that is $s_1^{**} < s_{1A}(\theta)$ (given by Equation 23) which is lower than $s_{1B}(\theta)$ when $(R + b) \geq 2\sqrt{2F\gamma}$ (proof of Proposition 3), a contradiction.

• *We can then define* $s_2(s)$:

$$s_2(s) = F - \max_e [p(e, \theta_L)(R + s) - f(e, \theta_L)],$$

it is decreasing with respect to s with $s_2'(s) = -p_L$. And $s_1(s) = s + s_2(s)$ is strictly increasing with respect to s ($s_1' = 1 - p$).

- For $s = -R, s_2(-R) = F$ and the associated s_1 is $F - R < 0$.
- At $s = s_{1B}$, the profit $\pi_L(e, s_{1B}, 0)$ is null so that $s_2(s_{1B}) = 0$, and $s > s_{1B} \Leftrightarrow s_2(s) < 0$. Note also that $s_{1B} < b$.
- At $s = 0, s_2(0)$ is positive equal to $-\pi_L(e, 0, 0)$.
- Define $\underline{s}$ the solution of $s + s_2(s) = 0$, it is between $-R$ and 0. The corresponding s_2 is such that $\pi_L(e, 0, s_2) = 0$.

The regulator's objective is then equivalent to the maximization of

$$\max_s V_2(\lambda, s, s_2(s)) \quad \text{s.t. } \underline{s} \leq s \leq s_{1B}.$$

The derivative of the objective function with respect to s is

$$\begin{aligned}
\mathcal{V}(\lambda, s) &= \left[(1-\lambda)\frac{\partial p_L}{\partial e} + \lambda\frac{\partial p_H}{\partial e}\right](b - s)\frac{1}{\gamma} - \lambda[p_H - p_L] \\
&= [(1-\lambda)(1-\theta_L) + \lambda(1-\theta_H)](b - s)\frac{1}{\gamma} - \lambda(\theta_H - \theta_L)\left(1 - \frac{R + s}{\gamma}\right) \\
&= [(1-\theta_L) - \lambda(\theta_H - \theta_L)](b - s)\frac{1}{\gamma} - \lambda(\theta_H - \theta_L)\left(1 - \frac{R + b}{\gamma} + \frac{b - s}{\gamma}\right) \\
&= [(1-\theta_L) - 2\lambda(\theta_H - \theta_L)](b - s)\frac{1}{\gamma} - \lambda(\theta_H - \theta_L)(1 - e^{FB}) \quad \text{using}\left(e^{FB} = \left(\frac{R + b}{\gamma}\right)\right) \\
&= (\theta_H - \theta_L)[(\underline{\lambda} - \lambda)(b - s)/\gamma - \lambda(1 - e^{FB})],
\end{aligned}$$

in which

$$\underline{\lambda} = \frac{1-\theta_L}{2(\theta_H-\theta_L)}.$$

This derivative is strictly decreasing with respect to s as long as $\lambda < \underline{\lambda}$ (V_2 is strictly concave), and, for $\lambda > \underline{\lambda}$ it is negative, and thus V_2 is maximized at $s^{**} = \underline{s}$.

The derivative is also decreasing with respect to λ, with $\forall\, s \in [\underline{s}, s_{1B}]$, $\mathcal{V}(0, s) = (1-\theta_L)(b-s)/\gamma > 0$ and $\mathcal{V}(\underline{\lambda}, s) < 0$.

At $\lambda = 0$: $s^{**}(0) = s_1^{**}(0) = s_{1B}(\theta_L)$ and $s_2^{**}(0) = 0$, and, $\forall\, \lambda > \underline{\lambda}, s^{**}(\lambda) = \underline{s}$: $s_1^{**}(\lambda) = 0$ and $s_2^{**}(\lambda) = s_2(\underline{s})$ the solution of

$$p_L(e)R + (1-p_L)s_2 = F + f_L(e).$$

And we can define:

- λ_1 the solution of $\mathcal{V}(\lambda, s_{1B}(\theta_L)) = 0$,
- λ_2 the solution of $\mathcal{V}(\lambda, \underline{s}) = 0$.

Then the optimal solution as a function of λ is such that

- $0 \le \lambda < \lambda_1$: $s^{**}(\lambda) = s_1^{**}(\lambda) = s_{1B}$ and $s_2^{**}(\lambda) = 0$,
- $\lambda_1 \le \lambda < \lambda_2$: $s^{**}(\lambda) \in (\underline{s}, s_{1B})$, $s_1^{**}(\lambda) > 0$ and $s_2^{**}(\lambda) > 0$,
- $\lambda_2 \le \lambda \le 1$: $s^{**}(\lambda) = \underline{s}$, $s_1^{**}(\lambda) = 0$ and $s_2^{**}(\lambda) = s_2(\underline{s}) > 0$.

Then, the regulator should compare V_2 and V_1, the difference $V_2 - V_1$ is decreasing with respect to λ and positive for $\lambda = 0$ and negative for $\lambda = 1$ (by Proposition 3). There is then a λ_3 so that $\lambda > \lambda_3$ implies $s_1^{**}(\lambda) = s_2^{**}(\lambda) = 0$.

APPENDIX D: A CASE STUDY

We had the opportunity to review a large number of projects of ADEME as well as the corresponding contracts. We discuss the relevance of our model using one such contract. The proposal concerned the R&D of a new lithium battery for electric vehicles. It was submitted in 2012 in the open call for innovation in mobility launched by ADEME. The proposal described several steps to be carried out: technical steps followed by market steps. The technical steps started from the proof of concept and proceeded to the development of a product ready for commercialization. They described the team (which involved a partnership with other institutions) and also provided a time schedule, cost figures, and benchmarks over a 3-year period. The market steps estimated the potential market and revenues for the firm over the next 5 years, that is, the geographical scope (local, national, etc.) and the quantities, prices, and costs. The market steps also provided estimates of the social benefits, such as carbon abatements and other environmental and employment benefits.

The agency had selected the proposal in view of the criteria outlined in the open call. The contractual arrangement was negotiated with the firm leading the project. A global subsidy was provided to cover part of the costs of the technical steps, a fraction as a pure subsidy, and a fraction as a repayable advance. The total subsidy is to be transferred from the agency to the firm in several releases, each conditioned on the success of a technical step (go/no go). If all technical steps are realized and no profitable commercialization is expected, the total subsidy remains with the firm. If the product is commercialized, the reimbursement depends on the number of units actually sold over a 5-year period.

D.1 | Formalization of the project and calibration of the model

The proposal will be formalized as a two-stage process: a technical stage with a specified threshold to be achieved for the project to go on, and a market stage if the project is successful. Let us start with the market stage and rely on the extension detailed in Section 4.2. We need to specify the probability distribution $H(\cdot)$ over the revenue R and the agency benefit $b(R)$.[18] We may think of R as a function of a fixed commercialization cost plus a unit margin multiplied by the quantity of units sold; and b as related to the avoided emissions multiplied by the social cost of carbon, so that it will also be proportional to the quantity. The uncertainty of R and b comes from uncertainty about the quantity sold. We assume that the information available in the proposal made by the firm can be formalized as R being uniformly distributed over a segment $[R^-, R^+]$ and $b = (1 + R)/2$. We take $R^- = -0.5$ and $R^+ = 2.5$ which gives b uniformly distributed over $b^- = 0.25$ and $b^+ = 1.75$.

The probability distribution $H(\cdot)$ may be seen as the common state of information when the proposal is made. After the technical stage the firm updates its belief and, the agency does not, but it will eventually observe the realized value of R. Since $R^{FB} = -1/3 < R(BAU) = 0$ it is socially valuable to encourage the firm to initiate commercialization even if it is not privately profitable. Using the results of Section 4.2, the agency should provide a repayable advance $s_3(R)$ such that

$$s_3(R) = \begin{cases} S_3 & \text{if } R < -1/3, \\ -R & \text{if } -1/3 < R < 0, \\ 0 & \text{if } 0 \leq R. \end{cases} \tag{D1}$$

Using the formulas (Section 4.2) we get $\bar{R} = 1.042$ and $\bar{b} = 0.965$ and we are back to the standard model analyzed in Section 3.

To complete the calibration we first need to set the fixed cost F, and the parameter γ. We shall assume that $F = 1$ (used as a normalization factor for R and b), and $\gamma = 10$. F can be directly obtained from the proposal. Estimating γ is much more difficult. Its value is related to the risk of managerial and budget gaming (Collins et al., 1987). By setting $\gamma = 10$ we assume that this risk exists.

We derive that $\theta^{BAU} = 0.958$ and $\theta^{FB} = 0.442$. The project is profitable for the firm only for high types ($\theta > \theta^{BAU}$), while it is socially valuable for a much larger range of types ($\theta > \theta^{FB}$).

To complete the calibration we need the distribution $G(\cdot)$ of the types θ. We will be using the two specific distributions of Section 3.4., and compare the results. For the uniform distribution we take $\theta_L = 0.5$ for the lower bound of the interval of the support of the types and vary the upper bound, which we denote θ_{max}. For the binomial distribution we take $\theta_L = 0.5$ and $\theta_H = 0.98$ and vary λ.

The calibration is summarized in Table D1.

D.2 | The second-best optimal contract

Consider first the case of a uniform distribution of types on the interval $[\theta_L, \theta_{max}]$. If the range of types were the interval $[0, 1]$, Proposition 4 would apply: the second-best scheme only

[18]For simplicity timing is not explicitly considered so that all financial values in the original contract are discounted to obtain yearly equivalents.

rewards failure. With a value of θ_{max} close to θ_L, it would be beneficial to only reward success since the situation is close to a pure moral hazard one. The optimal scheme (s_1^*, s_2^*) is depicted in Figure D1a as a function of θ_{max}. It depends on two thresholds with approximate values $\theta_{max1} = 0.52, \theta_{max2} = 0.7$. As θ_{max} increases the solution first only rewards success, second rewards both success and failure, finally rewards only failure. The associated effort, the firm

TABLE D1 Calibration of the model.

Parameter	Value
F	1
$\bar{R}$	1.042
$\bar{b}$	0.965
γ	10
θ^{BAU}	0.958
θ^{FB}	0.442
θ_L	0.5
θ_H	0.98

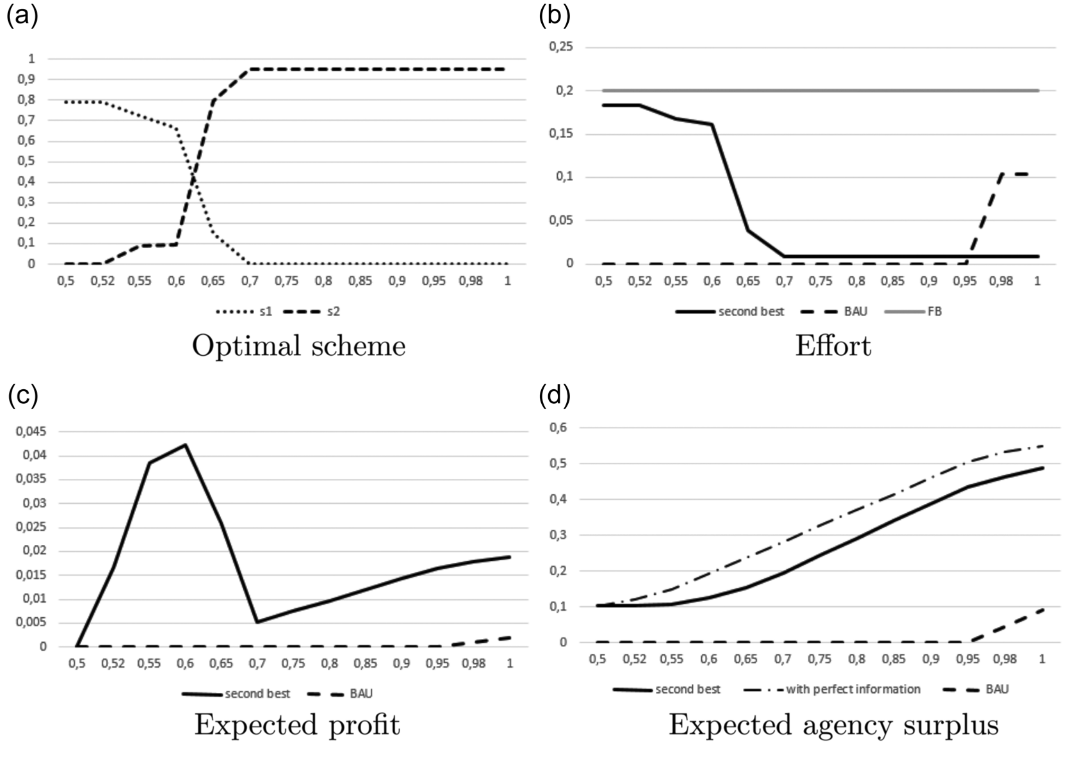

FIGURE D1 The results with a uniform distribution of types as a function of θ_{max}. (a) Optimal scheme, (b) effort, (c) expected profit, and (d) expected agency surplus. BAU, Business-As-Usual; FB, first best.

profit, and the agency surplus are depicted in Figure D1b–d. For the sake of comparison, the BAU respective outcomes are also reported in these figures. The expected agency surplus obtained in the case the agency knows the type of the firm is also reported; it allows quantifying the losses due to the asymmetry of information relative to using the second-best contract and BAU.

Consider now the case of the binomial distribution of types over $\theta_L = 0.5$ and $\theta_H = 0.98$ with λ standing for the probability of the high type. The optimal scheme (s_1^*, s_2^*) as a function of λ is depicted in Figure D2a. There are three thresholds with approximate values $\lambda_1 = 0.02$, $\lambda_2 = 0.2$, and $\lambda_3 = 0.4$. As λ increases the scheme first rewards only success, second rewards both success and failure, third rewards only failure, and finally no subsidies. The associated effort, the firm profit, and the agency benefit are depicted in Figure D2b–d, respectively.

We may compare the results. The optimal second-best contracts give more weight to limiting windfall profit as θ_{max} or λ increase. The efforts of the firm decrease accordingly. The rents of the firm appear the highest when the agency is somewhat stuck in the middle, using a contract which rewards both success and failure. These results are quite intuitive. What is not is the expected agency surplus: with a uniform distribution, the second-best contract greatly

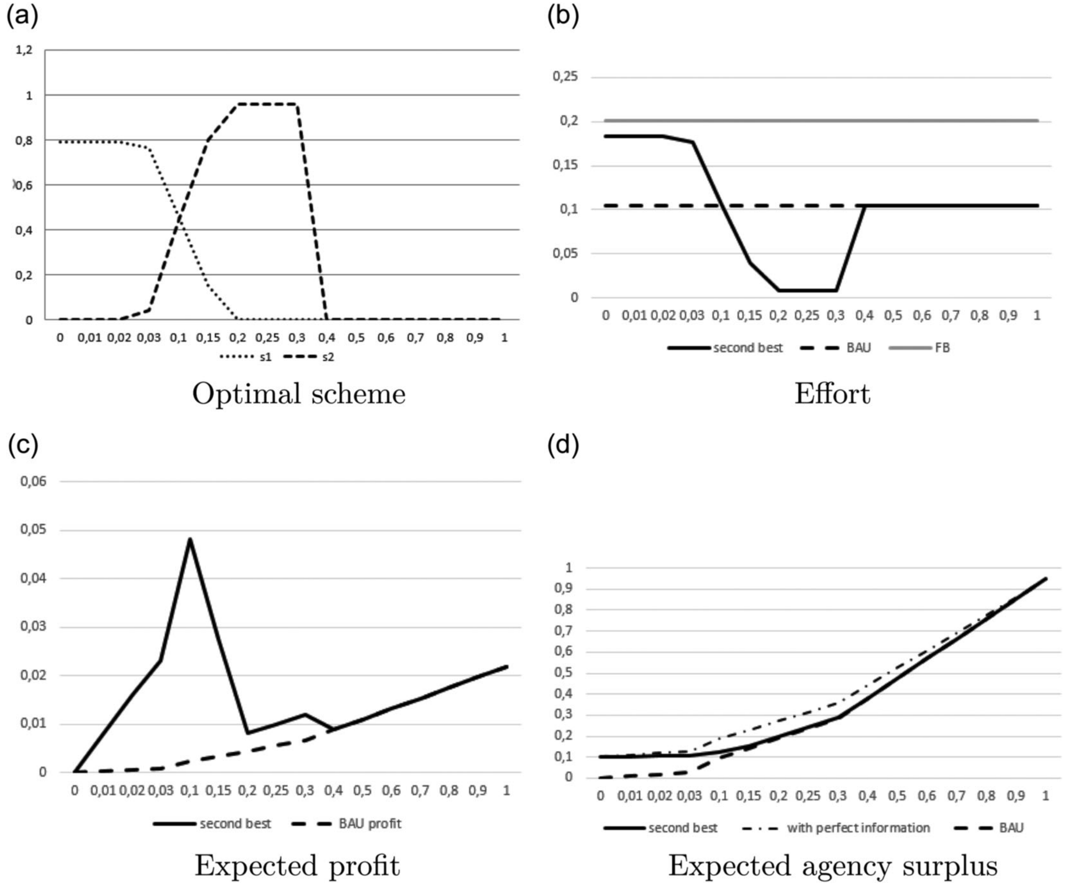

FIGURE D2 The results with a binomial distribution of types as a function of λ. (a) Optimal scheme, (b) effort, (c) expected profit, and (d) expected agency surplus. BAU, Business-As-Usual; FB, first best.

improves its surplus over BAU while it does not in the case of the binomial distribution (using the outcome with perfect information as a benchmark). This comes from the fact that, in the uniform case, with BAU, some high-type firms initiate the project if and only if $\theta_{max} > \theta^{BAU} = 0.958$, while, in the binomial case, the high-type firm would launch the project whatever the value of λ. Consequently BAU is more favorable to the agency in the binomial case than in the uniform one; which translates into the fact that it is much worthwhile to design a second-best contract in the first case while it is not in the second one. This observation has an interesting implication for designing public policy.

We expect that small changes in the calibration would not substantially affect the structure of the results. This suggests that our qualitative interpretation is fairly robust.