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Public-private partnerships as a policy response to climate change

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ABSTRACT

The negative impacts of climate change on the environment and economic activities are increasingly obvious and relevant. Private response to this threat often proves to be inadequate. For example, empirical evidence reveals a sub-optimal investment by firms in energy efficiency projects capable of reducing energy costs and CO_2 emissions, as well as adaptation projects able to reduce the vulnerability of the ecosystem. On the other hand, past public programs that provided financial subsidies to the above-mentioned projects have proven to be not particularly cost-effective or able to enhance final performances.

In this paper, as an alternative to public subsidies, we propose and assess the opportunity to implement Public-Private Partnerships (PPPs) where the public regulator plays a more active role in the investment choice. Precisely, we model the decision-making process through a Nash bargaining procedure between public and private actors. We end up with two main results: (i) compared to public subsidies, the use of PPPs leads to higher outcomes/performances and allows governments to overcome incompleteness in contracts; (ii) PPPs are optimally chosen only when there is a fair allocation of the bargaining power between the two sides and when bargaining procedures are not perceived as being too lengthy or costly.

1. Introduction and background

Observations and direct measurements of the climate system over recent decades have provided evidence of global warming and long-term changes in the atmosphere, the ocean, the cryosphere, and the land surface (IPCC, 2013). Indeed, citing the IPCC report of 2013: "many of the observed changes are unprecedented over decades to millennia."

Some consequences of changes in the climate system are the increase of atmospheric carbon dioxide (CO_2), rising temperatures and altered precipitation patterns. These disturbances affect the community as a whole and, in particular, private households whose main sources of revenues are from land and water resources (farmers, foresters, fishermen, etc.). Detailed descriptions of climate change effects on land and water resources are provided in several institutional and academic analyses (USDA, 2012; European-Commission, 2009; Backlund et al., 2008; European-Forest-Institute et al., 2008; Sohngen and Mendelsohn, 1998). With a special focus on the agricultural and forest sectors, previous studies describe evidence of abiotic disturbances (changes in fire occurrence, changes in wind storm frequency and intensity) and biotic disturbances (frequency and consequences of pest and disease outbreaks).

Despite the growing public concern over climate change, actions undertaken by private firms and public institutions to deal with these threats are still highly inadequate. In this respect, it is relevant to mention the existence of both an "energy efficiency" and an "adaptation" gap. On the one hand, as evidence of the first gap, empirical analyses show that firms and individuals under-invest with respect to what would be optimal for the society in terms of energy-efficient equipment and technologies capable of reducing energy consumption and C02 emissions (Gillingham and Palmer, 2014; Brown, 2001; Jaffe and Stavins, 1994). On the other hand, according to the UNEP report of 2016, "the adaptation gap can be defined generically as the difference between the level of adaptation actually implemented and a societally set target or goal, which reflects nationally determined needs related to climate change impacts, as well as resource limitations and competing priorities." (UNEP, 2016).

The sub-optimal investment in energy-efficient technologies or adaptation projects by private firms and individuals may be explained by market failures. In such contexts, market failures can be caused by the presence of environmental externalities, market barriers, insufficient and incorrect information, credit constraints and incomplete financial markets (UNEP, 2016; Gillingham and Palmer, 2014; Jaffe and Stavins, 2005, 1994; Brown, 2001).

These failures motivate government intervention that can take several forms. Traditional tools to deal with the presence of

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environmental externalities are Pigouvian taxes or subsidies, while credit constraints may be addressed through government financing programs (Gillingham and Palmer, 2014). Past programs and policies promoted by public entities included economic incentives and subsidies with the main goals of both removing barriers for the development of innovative procedures and boosting private incentives to invest in adaptation or energy-efficient technologies (Gillingham and Palmer, 2014; Filatova, 2014; Zhang and Maruyama, 2001). However, the outcomes of such programs have often not been consistent with their initial targets and the debate about their capacity to improve welfare continues. Empirical analyses show that energy efficiency programs in most countries had not led to the desired outcomes and were not cost-effective (Gillingham and Palmer, 2014; Arimura et al., 2012; Rivers and Jaccard, 2011). Indeed, it is expected that government policies to promote private adaptation will not be as effective if they are not sufficiently linked to private strategies (Urwin and Jordan, 2008) and especially if they merely provide funds to cover ex-post damages provoked by catastrophic/systematic events (Skees and Barnett, 1999).

Public-Private Partnership (PPP) may represent, within these contexts, a valid alternative to traditional public policies. Brown (2001) describes PPPs in the energy sector as "industry-government alliances that involve joint technology road mapping, collaborative priorities for the development of advanced energy-efficient and low-carbon technologies, and cost sharing." Similarly, Agrawala and Fankhauser (2008) suggest the use of PPPs in climate change adaptation to obtain an efficient and fair allocation of risks and incentives among public and private actors. In the energy sector, most PPPs were developed with the intention of promoting energy-efficient technologies for housing, appliances, schools, commercial and public buildings, vehicles, etc. (Jaffe and Stavins, 2005, 1999; Sperling, 2001). PPPs have also been tested in the forest sector as a way to restore forest management (Knoot and Rickenbach, 2014; Sturla, 2012), and in the agricultural sector as a tool to develop innovative technologies and enhance the use of sustainable agricultural practices (Spielman et al., 2010). Moreover, the use of PPPs has been acknowledged as a contribution to climate change adaptation in the tourism sector (Wong et al., 2012) and in agriculture (Urwin and Jordan, 2008).

The added value of this paper is its contribution to a greater understanding of possible forms of public-private partnerships for energy efficiency and climate adaptation investments. The topic is extremely relevant for policy implications because, as is emphasized by several authors, most of these types of investments are in the hands of private actors that, in many cases, do not offer enough incentives to provide optimal levels of investment and effort (Tompkins and Eakin, 2012; Mees et al., 2012). The use of PPPs in such cases is suggested and encouraged by researchers and practitioners, but there is still a lack of awareness of the nature and functioning of such partnerships (Jaffe and Stavins, 2005). In this paper, we provide a first insight into the topic through a model of public-private bargaining.

The goal of this paper is to compare PPPs with public subsidies as policies that aim at enhancing investments and efforts by private agents in terms of adaptation and energy efficiency projects. The paper develops a theoretical model where a private firm must decide the level of investment in technologies that may reduce the subsequent operational and management costs. Some examples are the choice of a private firm to invest or not in energy-efficient machinery (co-generation plants) capable of reducing energy production costs, or the decision of a forest owner to invest in infrastructure and technologies (road networks, irrigation canals or machine technology) that facilitate adaptive management practices such as fire prevention systems, changes in species composition, maintenance and thinning treatments. Energy efficiency investments and climate adaptation treatments lead to higher private returns in the form of reduced uncertainty or lower costs but, at the same time, they generate positive spillovers for the society in the form of lower CO_2 emissions and the reduced vulnerability of the ecosystem to climate change. In comparing the two government policies, we consider that in the case of public subsidies, the transfer is contingent on the level of initial investment, whereas in the case of PPPs, a bargain must be struck between the private and public sectors to determine both the investment level and the optimal sharing of costs between the two sides.

On the basis of our analysis, we can put forward some results that may be useful for policy implications: (i) government interventions correct market failures and, as already intuited by some authors such as Tompkins and Eakin (2012), the adoption of PPPs may be particularly beneficial in a context of high uncertainty and incomplete contracts[1]; (ii) PPPs are always optimal with respect to public subsidies in terms of final outcomes, but they represent the best solution only when the decision-making process is not perceived to be too lengthy or costly; (iii) As already intuited by Mees et al. (2012), it is easier to achieve a successful adoption of governance arrangements involving public and private participants when the bargaining power is not excessively concentrated in one part and when private and social returns are similar.

The following sections are organized as follows. In Section 2, we present the model and study the first best case; thereafter, we consider that the private owner carries out the investment without any public help and we adopt this scenario as a benchmark. In Section 3 we introduce and compare the two possible types of public intervention in a context of incomplete contracts. In Section 4, we then propose a numerical example and a comparative statics analysis to determine which type of intervention is preferable depending on either the level of uncertainty or the bargaining power parameter. Finally, in Section 5, we conclude and discuss policy implications.

2. Methodology

In this section, we present a stylized model designed to deal with all of the relevant elements that characterize climate change and energy efficiency projects, including: their public/private nature, the high level of uncertainty, the presence of asymmetric information between public and private agents (moral hazard), and the risk aversion of private investors.

We consider these investments as quasi-public goods provided by private firms or individuals, but that generate some positive spillovers for society (Tompkins and Eakin, 2012). Then, since such projects are characterized by a high level of uncertainty, we include both exogenous and endogenous risks in the model. The first source of uncertainty depends on external factors and affects the payoff of the private agent because of the presence of risk aversion. The second source of uncertainty is related to the effort that the private agent may exert to include the new adaptation and/or energy-efficiency practices in the daily activities of the firm.

In the model we start by considering a private firm that owns a business that, in the absence of uncertainty, generates a certain level of revenue (R_0). W.l.o.g. and to simplify the notation, it is assumed that $R_0 = 0$ from now on.

In managing their activity, private agents may exert effort, for example, to reduce energy costs or to implement adaptation practices (e). This effort can generate additional revenue that is assumed to be equal to $Re + f(e)\epsilon$. In addition, such activities have a positive spillover for society that is assumed to be equal to $Se + f(e)\epsilon$. The expected revenue and social functions positively depend on the effort of the private agent and are further related to a parameter ϵ that is assumed to follow a random distribution with a mean equal to zero and a variance equal to σ_ϵ^2. This latter parameter reflects a certain degree of uncertainty that may be explained by the difficulty to either forecast climate change scenarios and future energy prices or to assess the expected effectiveness of adaptation action. A positive (negative) shock means that the

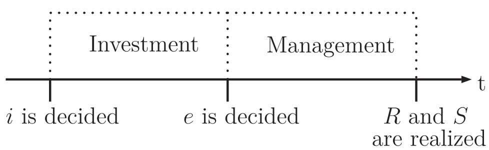
[1] Nevertheless, the government intervention may be limited in the presence of budget constraints (shadow cost of public funds).

implemented practices turned out to be more (less) necessary than expected. In such a situation, it is reasonable to expect that benefits would be much higher (lower) than forecasted, the more the agent was committed to implementing these cost-reducing or adaptation activities ($f_e > 0$).[2]

The level of effort e implies a disutility equals to $\psi(e)$. This function is assumed to be increasing and convex in e ($\psi_e > 0$, $\psi_{ee} \geq 0$). The private agent has the possibility to reduce this disutility cost by investing in technologies/appliances (i) that facilitate the implementation of adaptation or cost saving practices ($\psi_i < 0$) (Agrawala and Fankhauser, 2008; Jaffe and Stavins, 1999). We additionally assumed that $\psi_{ie} = \psi_{ei} \leq 0$, i.e., the marginal disutility of an effort decreases with the level of investment. This investment implies a monetary cost equal to $c(i)$ that follows the usual properties ($c_i > 0$, $c_{ii} \geq 0$).

We finally assumed, as is plausible in real world cases, that the public regulator can observe and verify the level of investment, whereas it cannot verify either the effort or the final outcomes in the form of private and social benefits.

The timeline of the investment is illustrated in the following graph:



The expected profit of the private agent is equal to:

$$\pi = \mathbf{E}_\epsilon[eR + f(e)\epsilon - c(i) - \psi(i, e)] \tag{1}$$

We consider that the agent wants to maximize the expected utility and is risk-averse with constant risk aversion equal to $r > 0$. Thus, the objective function can be written in terms of the certainty-equivalent of a CARA utility function:

$$CE = Re - c(i) - \psi(i, e) - \frac{r}{2}f(e)^2\sigma_\epsilon^2 \tag{2}$$

The risk neutral principal is assumed to maximize the expected social welfare that is equal to:

$$w = \mathbf{E}_\epsilon[eS + f(e)\epsilon] = eS \tag{3}$$

In the next two sections, we compute first best results and we then solve the model under the benchmark case (private governance).

First Best Solution . As a first best scenario we consider the case where the levels of investment and effort are derived from the maximization of the total welfare function that is given by the difference between total private and social revenues minus investment and effort costs. The maximization problem is solved backward.

$$\max_e [e(R + S) - c(i) - \psi(i, e)]$$

The First-Order Condition (FOC) is as follows:

$$\frac{\mathrm{d}(W)}{\mathrm{d}e}: R + S = \psi_e(i, e^{fb}) \tag{4}$$

Second, we can derive the level of investment at the optimum:

$$\max_i [e^{fb}(R + S) - c(i) - \psi(i, e^{fb})]$$

Using the envelope theorem:

$$\frac{\mathrm{d}(W)}{\mathrm{d}i}: c_i(i^{fb}) = -\psi_i(i^{fb}, e^{fb}) \geq 0 \tag{5}$$

Thus, from the property of the ψ function, the higher e^{fb} is, the higher i^{fb} will be.

[2] In addition, the marginal impact of an increase in the level of effort on unexpected final outcomes is assumed to be either constant or decreasing in the level of effort ($f_{ee} \leq 0$). It is plausible to assume that the effect of e will be higher on expected rather than unexpected final outcomes.

Private governance . Under the benchmark scenario, private agents are responsible for financing and managing the investment, thus setting the optimal levels of effort and investment by maximizing their certainty equivalent. The maximization problem is still solved backward.

$$\max_e \left[Re - c(i) - \psi(i, e) - \frac{r}{2}f(e)^2\sigma_\epsilon^2\right]$$

The FOC is as follows:

$$\frac{\mathrm{d}CE}{\mathrm{d}e}: R = \psi_e(i, e^{pr}) + rf(e^{pr})f_e(e^{pr})\sigma_\epsilon^2 \tag{6}$$

Comparing Eq. (6) with Eq. (4), we can conclude that:

Lemma 1. *The level of effort under private governance is lower with respect to the first best case.*

Proof. By comparing the two FOCs related to the First Best Scenario and the Benchmark Private Governance, respectively:

$$R + S = \psi_e(i, e)$$
$$R = \psi_e(i, e) + rf(e)f_e(e)\sigma_\epsilon^2$$

we can conclude that benefits (left side) are higher under the first best scenario, while costs are lower. As a consequence, incentives to increase the level of effort are higher under the first best scenario. The exclusion of the social surplus from the private payoff as well as the presence of risk aversion explain this difference between e^{pr} and e^{fb}.□

Second, we can derive the level of investment at the optimum:

$$\max_i \left[e^{pr}R - c(i) - \psi(i, e^{pr}) - \frac{r}{2}f(e^{pr})^2\sigma_\epsilon^2\right]$$

Using the envelope theorem:

$$\frac{\mathrm{d}CE}{\mathrm{d}i}: c_i(i^{pr}) = -\psi_i(i^{pr}, e^{pr}) \geq 0 \tag{7}$$

By comparing Eq. (7) with Eq. (5), we can conclude that:

Lemma 2. *The level of investment under private governance (i^{pr}) is lower with respect to the first best case (i^{fb}).*

Proof. Comparing the two FOCs:

$$c_i(i) = -\psi_i(i, e^{fb})$$
$$c_i(i) = -\psi_i(i, e^{pr})$$

The only difference comes from e. According to Lemma 1, we know that $e^{fb} \geq e^{pr}$. Moreover, from the initial assumptions, we know that $c_i > 0$, $\psi_i < 0$ and $\psi_{ei} = \psi_{ie}$ is lower than zero. As a consequence, $\psi_i(i, e^{fb}) \leq \psi_i(i, e^{pr})$, implying that $-\psi_i(i, e^{fb}) \geq -\psi_i(i, e^{pr})$.□

Finally, we can study the effect of uncertainty and conclude that:

Lemma 3. *The higher the level of uncertainty on future outcomes is (σ_ϵ^2), the lower the levels of effort and investment under private governance will be (e^{pr} and i^{pr}).*

Proof. The FOCs of the agent's maximization problem are the following:

$$R = \psi_e(i, e^{pr}) + rf(e)f_e(e)\sigma_\epsilon^2$$
$$c_i(i^{pr}) = -\psi_i(i^{pr}, e^{pr}).$$

From the first equation, we can observe that the higher σ_ϵ^2 is, the higher the cost of a marginal increase in effort is, and the lower the level of e^{pr} at equilibrium will be. Moreover, from the second equation and knowing that the lower e is, the lower $-\psi_i(i, e)$ will be, we can conclude that the level of investment at equilibrium also decreases with σ_ϵ^2.□

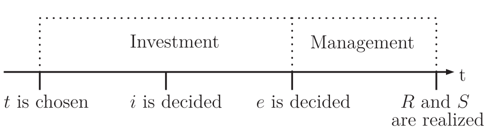
This last result confirms the intuition of Tompkins and Eakin (2012) that in a context of high uncertainty, there is a strong need for public intervention.

3. Public intervention

In the following sections we allow the public regulator to intervene in the project. We take into account a situation where contracts are partially incomplete since the government cannot verify the level of effort nor the final outcomes. However, the government can observe the investment *i*. Consistent with the literature on the topic (e.g., Hart, 1988), we consider that a contract is incomplete when some targets of the project cannot be part of the agreement because it may be hard to specify their values in advance and/or because, in the event of litigation, they cannot be adequately verified ex-post by a Court of Justice. This is the typical situation of climate change adaptation and energy efficiency projects where the pervasive uncertainty does not allow the principal to disentangle the effect of private contribution/effort to final outcomes from the impact of exogenous shocks (Agrawala and Fankhauser, 2008). We then consider two cases. At first, the government can participate in the initial investment stage by providing a subsidy to the private agent. This is the public policy that has been traditionally used by governments to encourage investment in these sectors, although it is often unsuccessful (Gillingham and Palmer, 2014; Filatova, 2014; Arimura et al., 2012; Rivers and Jaccard, 2011). Second, we discuss the establishment of a Public-Private Partnership where, as suggested by Mees et al. (2012), costs and responsibilities are shared between the public and the private sector. To approach this type of governance we adopt a bargaining model. In both cases, whenever the public regulator sustains monetary costs, the shadow cost of public funds (λ) is considered as a way to capture the distortion imposed on taxpayers to finance the investment.

3.1. Public subsidy

If ex-post outcomes are not verifiable, the government can only intervene through a subsidy that increases with the level of investment (ti).[3] The transfer choice allows the government to enhance the initial investment and to support the management stage. For a better understanding, the following graph summarizes the time-line of the project:



The problem is solved backward. Thus, the private agent first decides the level of effort:

$$\max_{e}\left[Re - c(i) - \psi(i, e) - \frac{r}{2}f(e)^2\sigma_\epsilon^2 + ti\right]$$

The FOC is as follows:

$$\frac{\mathrm{d}CE}{\mathrm{de}}\colon R = \psi_e(i, e^{ps}) + rf(e^{ps})f_e(e^{ps})\sigma_\epsilon^2 \tag{8}$$

Second, we obtain the level of investment at the optimum:

$$\max_{i}\left[e^{ps}R - c(i) - \psi(i, e^{ps}) - \frac{r}{2}f(e^{ps})^2\sigma_\epsilon^2 + ti\right]$$

Using the envelope theorem:

$$\frac{\mathrm{d}CE}{\mathrm{di}}\colon c_i(i^{ps}) = -\psi_i(i^{ps}, e^{ps}) + t \geq 0 \tag{9}$$

Finally, the public decides the optimal level of *t*:

$$\max_{t}[e^{ps}S - (1+\lambda)ti^{ps}]$$

$$\frac{\mathrm{dw}}{\mathrm{dt}}\colon \frac{de^{ps}}{di}\frac{di^{ps}}{dt}S - (1+\lambda)i^{ps} - (1+\lambda)t\frac{di^{ps}}{dt} = 0$$

[3] For simplicity we assume a linear transfer, but the analysis can be generalized to any set of transfers that increase with the investment level.

Considering that $\frac{de^{ps}}{di}$ and $\frac{di^{ps}}{dt}$ are greater than zero,[4] we can rewrite the level of transfer as:

$$t^{ps} = \frac{\frac{de^{ps}}{di}}{1+\lambda}S - \frac{i^{ps}}{\frac{di^{ps}}{dt}} \tag{10}$$

The level of transfer is greater than zero as long as $\frac{\frac{de^{ps}}{di}}{1+\lambda}S > \frac{i^{ps}}{\frac{di^{ps}}{dt}}$. Substituting the optimal value of *t* in Eq. (9), we obtain the equation to derive *i* at the optimum value of *t*, that is equal to:

$$c_i(i^{ps}) = -\psi_i(i^{ps}, e^{ps}) + \frac{\frac{de^{ps}}{di}}{1+\lambda}S - \frac{i^{ps}}{\frac{di^{ps}}{dt}} \tag{11}$$

By comparing Eq. (11) with Eq. (7), we can conclude that:

Proposition 1. *The level of investment and effort in the case of a positive public subsidy is higher with respect to the private benchmark case.*

Proof. Comparing the two FOCs:

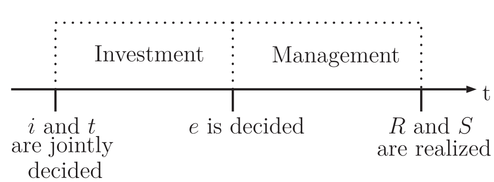
$$c_i(i) = -\psi_i(i, e^{pr})$$

$$c_i(i) = -\psi_i(i, e^{ps}) + \frac{\frac{de^{ps}}{di}}{1+\lambda}S - \frac{i^{ps}}{\frac{di^{ps}}{dt}}$$

Since the level of effort for a given level of investment is equal between the two cases, the only difference comes from $\frac{\frac{de^{ps}}{di}}{1+\lambda}\Delta S - \frac{i^{ps}}{\frac{di^{ps}}{dt}}$ that is equal to the level of transfer at equilibrium; it should therefore be positive or at least equal to zero. As a consequence, the marginal benefit is higher in the case of a public subsidy and, therefore, the level of investment at equilibrium as well. According to the properties of function ψ ($\psi_{ei} < 0$), we can also conclude that at equilibrium $e^{ps} > e^{pr}$.□

3.2. Public private partnerships

In a context of incomplete contracts, which means limited intervention capacity, PPPs may allow the public regulator to be more actively involved in a bargaining process with the private agent for decisions concerning the level of investment and the cost-sharing scheme. In the case of PPPs, the timeline of the projects is summarized by the following graph:



As usual, the problem is solved backward; the private agent thus first determines the level of effort. This level of effort is not verifiable by the public regulator. It can therefore not be a variable included in the bargaining process between the public and the private sector.

$$\max_{e}\left[eR - c(i) - \psi(i, e) - \frac{r}{2}f(e)^2\sigma_\epsilon^2\right]$$

The FOC is as follows:

$$\frac{\mathrm{d}CE}{\mathrm{de}}\colon R = \psi_e(i, e^{ppp}) - rf(e^{ppp})f_e(e^{ppp})\sigma_\epsilon^2 \tag{12}$$

[4] If not, optimal solutions for the levels of investment and transfer are equal to zero. This situation is not interesting in terms of our analysis.

As a second step, the level of i and t are chosen through the bargaining process between the public and the private agent. As in SubSection Section 3.1, the public subsidy is assumed to be linear with respect to the level of investment. To study the bargaining solution we used the Nash Approach (Osborne and Rubinstein, 2005). Precisely, according to the Nash procedure, the bargaining solution is derived from the maximization of Π that is equal to $[CE(i, e^{ppp}) - CE^{pr}(i^{pr}, e^{pr}) - C^p]^{\alpha}[w(i, e^{ppp}) - w^{pr}(i^{pr}, e^{pr}) - C^w]^{1-\alpha}$ where α $(1-\alpha)$ is the bargaining power of the private agent (public regulator). Moreover, we consider disagreement payoffs as being equal to payoffs under the private benchmark minus the corresponding disagreement costs that are equal to either C^p for the private agent or C^w for the public regulator. Disagreement may be costly for the two parts because it can, for example, lead to the delay of strategic decisions or significantly hinder the possibility of future strategic bargaining between the two sides. For the sake of simplicity, we will use the following terminology from now on: $dCE = CE(i, e^{ppp}) - CE^{pr}(i^{pr}, e^{pr}) + C^p$ and $dw = w(i, e^{ppp}) - w^{pr}(i^{pr}, e^{pr}) + C^w$.

Nash's bargaining maximization can be written as:

$$\max_{i,t}[dCE(i, t)]^{\alpha}[dw(i, t)]^{1-\alpha}$$

Applying the envelope theorem, first order conditions are as follows:

$$\frac{d\Pi}{di}: \alpha[dCE(i, t)]^{\alpha-1}[dw(i, t)]^{1-\alpha}[t - c_i(i) - \psi_i(i, e^{ppp})] +$$
$$+(1-\alpha)[dCE(i, t)]^{\alpha}[dw(i, t)]^{-\alpha}\left[\frac{de^{ppp}}{di}S - (1+\lambda)t\right] = 0$$
$$\frac{d\Pi}{dt}: \alpha[dCE(i, t)]^{\alpha-1}[w(e^{ppp})]^{1-\alpha}[i]$$
$$+ (1-\alpha)[dCE(i, t)]^{\alpha}[dw(i, t)]^{-\alpha}[-(1+\lambda)i] = 0$$

Designating $A = t - c_i - \psi_i(i, e^{ppp})$ and $B = \frac{de^{ppp}}{di}S - (1+\lambda)t$, we can rewrite first-order conditions as:

$$\frac{d\Pi}{di}: \frac{\alpha}{1-\alpha}\frac{dw(i, t)}{dCE(i, t)} = -\frac{B}{A}$$
$$\frac{d\Pi}{dt}: \frac{\alpha}{1-\alpha}\frac{dw(i, t)}{dCE(i, t)} = (1+\lambda)$$

Two equations leads to the following expression:

$$-B = A(1+\lambda)$$
$$-\frac{de^{ppp}}{di}S + (1+\lambda)t = t(1+\lambda) - c_i(1+\lambda) - \psi_i(i, e^{ppp})(1+\lambda)$$
$$(1+\lambda)c_{i^{ppp}} = \frac{de^{ppp}}{di^{ppp}}S - (1+\lambda)\psi_i(i^{ppp}, e^{ppp}) \tag{13}$$

The next proposition summarizes a first relevant result of the paper:

Proposition 2. *The levels of investment and effort in the case of PPPs are higher with respect to the case with a positive public subsidy. Moreover, the level of investment at equilibrium does not depend on the level of transfer.*

Proof. Comparing the two FOCs:

$$c_i(i) = -\psi_i(i, e^{ppp}) + \frac{\frac{de^{ppp}}{di}}{1+\lambda}S$$
$$c_i(i) = -\psi_i(i, e^{ps}) + \frac{\frac{de^{ps}}{di}}{1+\lambda}S - \frac{i^{ps}}{\frac{di^{ps}}{dt}}$$

Since the level of effort for a given level of investment is equal between the two cases, the only difference comes from the marginal benefit that is higher in the case of PPPs with respect to the case with a public subsidy. As a consequence, the level of investment and effort at equilibrium ($\psi_{ei} < 0$) are higher in the case of PPPs compared to the case with a public subsidy ($i_{ppp} > i_{ps}$, $e_{ppp} > e_{ps}$).□

Finally, from the FOCs we can derive the level of transfer at equilibrium:

$$\alpha[e^{ppp}S - (1+\lambda)ti - w(i^{pr}, e^{pr}) + C^w] = (1+\lambda)(1-\alpha)$$
$$\times\left[e^{ppp}R - c(i) - \psi(i, e) - \frac{r}{2}f(e^{ppp})^2\sigma_{\epsilon}^2 + ti - CE(i^{pr}, e^{pr}) + C^p\right]$$
$$\alpha[e^{ppp}S - w(i^{pr}, e^{pr}) + C^w] = +(1+\lambda)ti + (1+\lambda)(1-\alpha)$$
$$\times\left[e^{ppp}R - c(i) - \psi(i, e) - \frac{r}{2}f(e^{ppp})^2\sigma_{\epsilon}^2 - CE(i^{pr}, e^{pr}) + C^p\right]$$
$$\alpha[w^{pr}(i^{ppp}, e^{ppp}) - w^{pr}(i^{pr}, e^{pr}) + C^w] = +(1+\lambda)ti$$
$$+ (1+\lambda)(1-\alpha)[CE^{pr}(i^{ppp}, e^{ppp}) - CE^{pr}(i^{pr}, e^{pr}) + C^p]$$

Designating respectively, $Df(w) = w^{pr}(i^{ppp}, e^{ppp}) - w^{pr}(i^{pr}, e^{pr}) + C^w$ and $Df(CE) = CE^{pr}(i^{ppp}, e^{ppp}) - CE^{pr}(i^{pr}, e^{pr}) + C^p$, the value of t can be written as:

$$t^{ppp} = \frac{\alpha Df(w) - (1-\alpha)(1+\lambda)Df(CE)}{i^{ppp}(1+\lambda)} \tag{14}$$

Looking at Eq. (14), we can conclude that the level of transfer depends on the allocation of the bargaining power, on disagreement costs and on differences between public and private payoffs, respectively, computed at the optimal PPP outcomes minus public and private payoffs under the benchmark private scenario. The level of transfer can be either higher or equal with respect to the case with a public subsidy depending on the allocation of the bargaining power and on disagreement costs.

The effects of α, C^w and C^p on t^{ppp} are directly observable looking at Eq. (14) and are summarized by the following corollary:

Corollary 1. *Looking at* Eq. (14), *we can conclude that the higher α or C^w is, the higher the public transfer in favor of the private agent will be; however, the same level of transfer decreases with increasing values of C^p.*

Results from the previous paragraphs will be discussed in the next section with the help of a numerical example.

4. A numerical example

To better understand the main results of the previous paragraphs, we decided to provide a practical example by assigning a specific form to cost functions that we introduced. Precisely, we consider: $c(i) = \frac{i^2}{2}$, $\psi(i, e) = \frac{e^2}{2i}$ and $f(e) = \sqrt{e}$. Considering these cost functions, we solve the problem under the four scenarios:

First Best Solution . For a given value of i, the level of effort is equal to:

$$e^{fb} = (R + S)i$$

Second, we can derive the level of investment at the optimum and, consequentially, the level of effort:

$$i^{fb} = \frac{(R+S)^2}{2}$$
$$e^{fb} = \frac{(R+S)^3}{2}$$

Private Governance .

For a given value of i, the level of effort is equal to:

$$e^{pr} = \left(R - \frac{r}{2}\sigma_{\epsilon}^2\right)i$$

Second, we can derive the level of investment at the optimum and, consequentially, the level of effort:

$$i^{pr} = \frac{\left(R - \frac{r}{2}\sigma_\epsilon^2\right)^2}{2}$$

$$e^{pr} = \frac{\left(R - \frac{r}{2}\sigma_\epsilon^2\right)^3}{2}$$

It is easy to verify that both i^{pr} and e^{pr} are lower than the first best solutions.

Public Subsidy .

For a given value of i, the level of effort is equal to:

$$e^{ps} = \left(R - \frac{r}{2}\sigma_\epsilon^2\right)i$$

Second, we can derive the level of investment for a given level of t:

$$i^{ps} = \frac{\left(R - \frac{r}{2}\sigma_\epsilon^2\right)^2}{2} + t$$

From the government's maximization problem, we can derive the value of t:

$$t^{ps} = \frac{\left(R - \frac{r}{2}\sigma_\epsilon^2\right)\left(S - (1+\lambda)\frac{R - \frac{r}{2}\sigma_\epsilon^2}{2}\right)}{2(1+\lambda)}$$

We can easily verify that $t > 0$ if $S > (1+\lambda)\frac{R - \frac{r}{2}\sigma_\epsilon^2}{2}$. Substituting the optimal value of t, we can derive the values at equilibrium of i and e:

$$i^{ps} = \frac{\left(R - \frac{r}{2}\sigma_\epsilon^2\right)\left(S + (1+\lambda)\frac{R - \frac{r}{2}\sigma_\epsilon^2}{2}\right)}{2(1+\lambda)}$$

$$e^{ps} = \frac{\left(R - \frac{r}{2}\sigma_\epsilon^2\right)^2\left(S + (1+\lambda)\frac{R - \frac{r}{2}\sigma_\epsilon^2}{2}\right)}{2(1+\lambda)}$$

It is easy to verify that if $t > 0$, then $i^{fb} > i^{ps} > i^{pr}$ and $e^{fb} > e^{ps} > e^{pr}$.

Public Private Partnership .

For a given value of i, the level of effort is equal to:

$$e^{ppp} = \left(R - \frac{r}{2}\sigma_\epsilon^2\right)i$$

Second, we can derive the level of investment and effort at equilibrium:

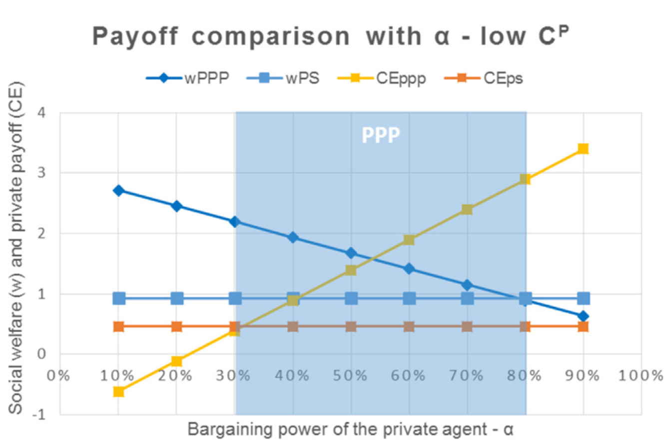


Fig. 1. Comparative statics analysis with respect to α - low C^p.

$$i^{ppp} = \frac{\left(R - \frac{r}{2}\sigma_\epsilon^2\right)\left(S + (1+\lambda)\frac{R - \frac{r}{2}\sigma_\epsilon^2}{2}\right)}{1+\lambda}$$

$$e^{ppp} = \frac{\left(R - \frac{r}{2}\sigma_\epsilon^2\right)^2\left(S + (1+\lambda)\frac{R - \frac{r}{2}\sigma_\epsilon^2}{2}\right)}{1+\lambda}$$

It is easy to verify that $i^{fb} > i^{ppp} > i^{ps}$ and $e^{fb} > e^{ppp} > e^{ps}$. Distortions with respect to the first best solutions are derived from the role of λ, from the risk aversion and from the non-verifiability of e.

The level of transfer at equilibrium is equal to:

$$t^{ppp} = \frac{\alpha Df(w) - (1-\alpha)(1+\lambda)Df(CE)}{i^{ppp}(1+\lambda)}$$

4.1. Comparative statics and discussion

In this paragraph, based on the previous example, first, considering public intervention, we compare private and public payoffs with different distributions of the bargaining power and, second, we show how i, and e may vary across scenarios with the increase of uncertainty (σ_ϵ^2).

Payoffs and bargaining power In the following graphs we illustrate the welfare (w) and private (CE) payoffs under the two regimes (Public Subsidy and PPP) considering a change in α.[5] In the first graph, we consider a PPP where the disagreement cost for the private agent is low ($C^p = 0$), while in the second graph we consider the case where the disagreement cost is high ($C^p = 400$) Fig. 1.

From the first figure, we can observe that the choice of a PPP is profitable for both the public and the private sectors if α is between 30% and 80%, meaning that the bargaining power should not be too much in favor of either the public or the private sector. From the second figure, we can observe that the choice of PPP is profitable for both the public and the private sector only for a value of α approximately between 70% and 90%, meaning that if private agents have higher disagreement costs, then it would be more difficult for them to decide to start a partnership with the public sector Fig. 2.

Final outcomes and uncertainty In the following graphs we show the investment and the effort choices, respectively, under the three regimes (Private Governance, Public Subsidy and PPP) considering a change in σ_ϵ^2. We maintain the parameters used in the previous comparative statics, except for the value of S that was previously equal to 16, whereas in these graphs, it takes the value of 4. This change is not essential for our results, but it is made to better emphasize the fact that presence of higher uncertainty may lead to a greater involvement of the public sector Fig. 3.

It is emphasized in both graphs that a higher level of uncertainty makes the public intervention more effective and necessary in terms of final outcomes. We have deliberately chosen a level of social surplus that in the absence of or with a low level of uncertainty makes the intervention of the public regulator through a public subsidy ineffective. In both graphs, we can then observe that an increase in the level of uncertainty makes the level of investment and effort in the presence of public intervention higher compared to the private benchmark case. As already highlighted in the previous paragraphs, outcomes in the PPP scenario are always higher with respect to both the private benchmark and the public subsidy regime Fig. 4.

These comparative statics highlight a relevant result of the paper that confirms the intuition of Tompkins and Eakin (2012) and Mees et al. (2012) that the stronger the uncertainty related to the real effectiveness of these projects is on the long term, the more necessary and effective the public involvement in these risky projects will be.

[5] To draw up this graph, we consider the following functions and the following values for the parameters: $c(i) = \frac{i^2}{2}$ $\psi(e) = \frac{qe^2}{2i}$, $S = 16$, $R = 8$ $\lambda = 0$, $q = 80$, $C^w = 400$, $C^p = 0$ (first graph), $C^p = 400$ (second graph).

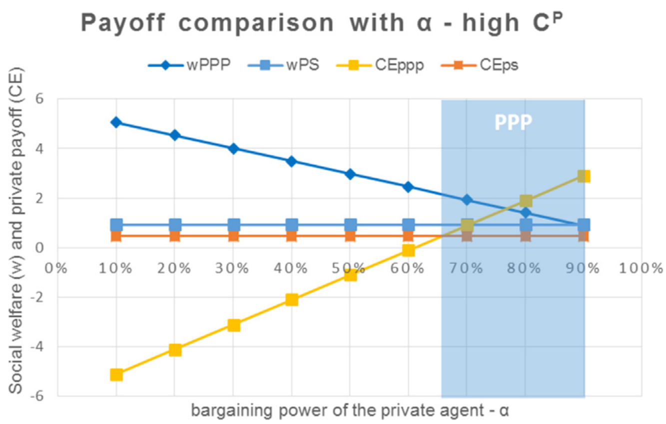


Fig. 2. Comparative statics analysis with respect to α - high C^p.

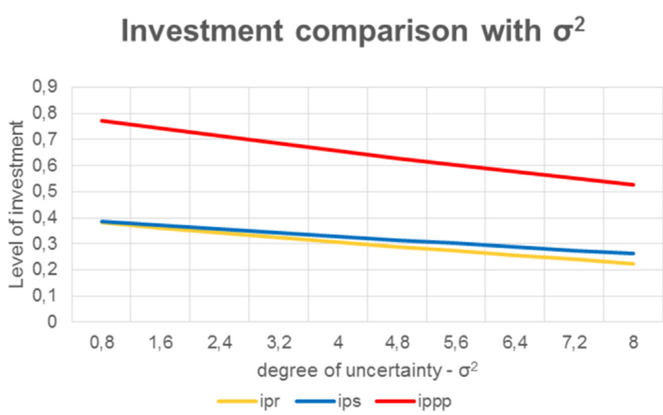


Fig. 3. Comparative statics analysis with respect to σ_ε^2.

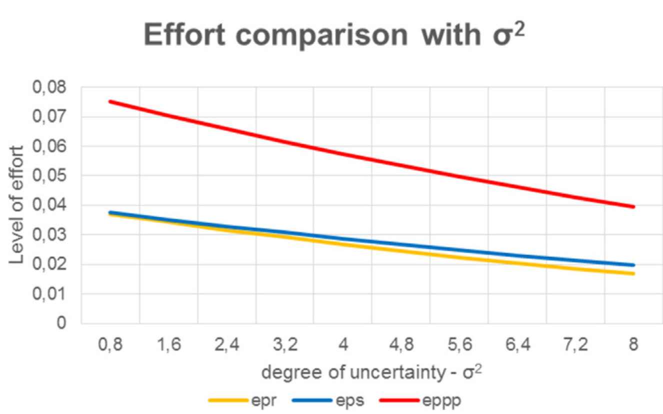


Fig. 4. Comparative statics analysis with respect to σ_ε^2.

5. Conclusion and policy implications

Our findings are related to the optimal method of government participation to support private investment with social spillovers. In this paper, we developed the model with the idea in mind of a climate change project. Precisely, the project involves two stages that are connected through an externality parameter (investment and management), final payoffs are uncertain, and society receives a benefit from its termination. For instance, there is an initial investment in technologies/plants that can facilitate subsequent energy cost savings or adaptation practices whose payoffs are uncertain but also beneficial for society.

As a major finding, we show that in such contexts where contracts based on contractible outcomes are often not feasible due to the high level of future uncertainty, PPPs may represent an interesting option to eliminate the presence of contract incompleteness, enhance performances and overcome operational constraints (Tompkins and Eakin, 2012; Agrawala and Fankhauser, 2008). Several academic and institutional documents exist that suggest the use of PPPs in the energy, forestry, agriculture and tourist sectors to enhance innovative and/or clean investments (Knoot and Rickenbach, 2014; Sturla, 2012; Wong et al., 2012; Spielman et al., 2010; Brown, 2001; Sperling, 2001). With this paper, we demonstrate if and why PPPs may improve welfare within such contexts. In fact, we are able to show that PPPs as opposed to public subsidies lead to higher levels of final outcomes (investment and effort) thanks to direct government involvement in the decision-making process that places more emphasis on the social returns of the project in the final outcomes. This result is even more relevant in a context of budget constraints (high level of λ). Indeed, if governments are not able to provide relevant public subsidies, they can eliminate the problem by using a PPP that, as a public policy, is more cost efficient.

However, in this paper, we go even further and explain potential obstacles that could limit the use of PPPs. For example, we show that in most cases, when the bargaining power is not well balanced between the two sides, a PPP is not implementable. Moreover, we demonstrate that high levels of cost in the case of disagreement may further limit the use of PPPs. Concerning the construction of the optimal public-private governance to manage these projects, our findings confirm the main intuitions of Mees et al. (2012) and provide some useful policy implications. Indeed, according to our analysis, governments should: avoid implementing many PPPs with small private firms, instead preferring a single PPP with an organization of firms with a stronger bargaining power; and decrease the costs and timing of bargaining procedures to encourage firms to enter the partnership.

This is a first step to understanding what the optimal mix of public and private governance would be in order to carry out and manage climate change projects that involve monetary investment and management activities. A first development of the current analysis would be to consider PPPs with the possibility of ex-post transfers, as in Auriol and Picard (2009) (such transfers may cover potential damages caused by catastrophic/systematic events). This type of contractual scheme can substantially reduce risk perception by private agents, further enhancing investment in risky technologies.

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Appendix: glossary of terms

The entries in this glossary are taken or adapted from definitions provided by authoritative sources, such as institutional reports or academic papers.

Description	Definition	Source
Climate change	A change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods.	IPCC (2013)
Energy efficiency investment	Energy efficient technologies capable of decreasing energy costs and improving the well-being of the population by reducing pollutant emissions.	Brown (2001)
Adaptation investment	In human systems, the process of adjustment to actual or expected climate and its effects in order to moderate harm or exploit beneficial opportunities. In natural systems, the process of adjustment to actual climate and its effects; human intervention may facilitate adjustment to expected climate.	UNEP (2016)
Energy efficiency gap	Under-investment with respect to what would be optimal for the society in terms of energy-efficient equipment and technologies capable of reducing energy consumption and C02 emissions	Gillingham and Palmer (2014); Jaffe and Stavins (1994)
Adaptation gap	The adaptation gap can be defined generically as the difference between the level of adaptation actually implemented and a societally set target or goal, which reflects nationally determined needs related to climate change impacts, as well as resource limitations and competing priorities.	UNEP (2016)

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