Venturing Brown to Subsidize Green Subsidies*

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Abstract

We study how brown (i.e., emitting) firm joint ventures (JVs) affect green innovation and optimal climate policy. Brown firms derive private benefits from climate-abatement technology, which both reduces their expected tax bill and their cost of capital (in the presence of a greenium). JVs of brown firms can lead to first-best investment in abatement technology with lower government subsidies because they mitigate the free ridership problems whereby non-innovating brown firms benefit from abatement innovation without paying innovation costs. The subsidy reduction is increasing in the brownness of the JV, the prevailing greenium, and the size of a sufficiently brown JV, with the latter two of these benefits being complementary. Overall, our findings suggest JVs as a new mechanism to harness brown firms' private benefits from certain green innovations to reduce the tax burden of optimal climate policy.

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"Substantial amounts of funds will be required for the green transition. To achieve the above aims, the contribution of the private sector to funding green investment will be key, also given current public finance constraints."

– European Central Bank[1]

1 Introduction

Climate change has become one of the most pressing global challenges of the twenty-first century (Nordhaus, 2019). Acemoglu, Aghion, Bursztyn, and Hemous (2012) shows how optimal climate policy should employ both carbon taxes and subsidize investment in clean technologies, yet debates over climate policy frequently turn on how intensively governments should subsidize "green R&D" versus relying on private-sector innovation (Nerlich et al., 2025).[2] Our paper lies at the intersection of this debate, examining how government subsidies can become more efficient when they leverage the preexisting incentives for private firms to conduct green innovation.

Private firms have vested interests in the success of certain green innovations. In particular, brown firms, defined as traditional high-emission companies, will disproportionately benefit from a breakthrough in carbon abatement technology via reductions in expected taxes, stranded asset risk, and cost of capital, i.e., "greenium" (Pástor, Stambaugh, and Taylor, 2021; Bolton and Kacperczyk, 2023). Consistent with brown firms internalizing these outsized benefits to certain green innovations, brown firms are actively developing green patents and products (Cohen, Gurun, and Nguyen, 2020; Chiu, Hsu, Li, and Tong,

[1] `https://www.ecb.europa.eu/press/economic-bulletin/articles/2025/html/ecb.ebart202501_03~90ade39a4a.en.html`.

[2] The department of energy of the United States committed $3.5 billion for the development of carbon abatement technology. See `https://www.hoganlovells.com/en/publications/doe-announces-over-35-billion-in-carbon-management-funding-opportunities`. The European governments also invest heavily on green technology; but there are urgent calls for large private investment additionally to achieve the desired target of carbon emission (Nerlich et al., 2025).

2025; Calel and Dechezleprêtre, 2016).

To the extent that the costs to brown firms innovating green are more concentrated than the benefits, however, a free ridership problem will result in underinvestment even among brown firms. One way brown firms offset this problem is through joint ventures (JVs) that coordinate carbon abatement innovations. For example, large energy firms have formed carbon capture and storage JVs such as Bayou Bend (by Chevron, Total, Equinor) and Northern Lights (by Equinor, Shell, Total).[3] These JVs help to internalize the positive externalities (i.e., knowledge spillover) in R&D, reducing free-riding and boosting innovations (Kamien, Muller, and Zang, 1992).

We develop a theoretical model to analyze how optimal government subsidies for carbon abatement R&D vary depending on the structure of brown-firm JVs. The model illustrates that brown firm JVs can actively fund carbon abatement innovation, leading to increased private-sector innovation and a diminished need for direct government support. Our model extends this key insight to shed further light on how governments can most effectively deploy taxpayer dollars to finance climate policy, specifically addressing questions such as: how the socially-optimal research subsidies depend on a JV's characteristics (i.e., its size and brownness) and the prevailing greenium? And, which JV structure yields the lowest research subsidies?

In the model, polluting firms – which differ in their "brownness" (i.e., carbon emission intensity absent of innovation)– organize into research JVs on carbon abatement technology while maintaining competition in the product market.[4] At $t = 0$ of our three-period model the government announces its policy mix of carbon taxes and research subsidies for the JV. At $t = 1$, the innovation stage, the JV determines funding for a continuum of carbon abatement projects. If at least one funded project succeeds, it leads to an innovation breakthrough,

[3]Other examples include Net Zero Teesside (BP, Eni, Equinor, Shell, Total), and Quest (Shell, Chevron, Marathon Oil), to name a few.

[4]Coordination on R&D while maintaining competition in the product market is compliant with the anti-trust laws in many jurisdictions.

generating positive externalities through knowledge spillovers that lower emission intensity across all firms, regardless of their participation in the JV. Finally, at $t = 2$, firms compete in the product market where their profits are affected by both carbon tax payments and their cost of capital, which incorporates a "greenium" - a higher cost of capital applied to firms with higher carbon emission intensity. As in Acemoglu, Aghion, Bursztyn, and Hemous (2012), we show that a constant carbon tax rate must be combined with a linear R&D subsidy achieves the first-best outcome. Our model extends Acemoglu, Aghion, Bursztyn, and Hemous (2012) to show how the optimal R&D subsidy depends on the the structure of the JV and the prevailing greenium.

Three key factors determine the optimal per unit subsidy of R&D expenditure (i.e., the cost reimbursement ratio). The optimal subsidy is decreasing in the: (i) Greenium: A higher greenium (i.e., the cost-of-capital advantage of greener firms) strengthens emitting firms' incentives to innovate to reduce emission, cutting the need for government subsidies. (ii) JV's brownness: A JV formed by browner firms has larger incentives to innovate in carbon abatement technology, as browner firms enjoy larger reductions in cost of capital and carbon tax payments compared to their greener counterparts, leading to less government support required. (iii) JV's size: When JVs add sufficiently brown firms – who privately benefit from the innovation – the JV internalizes a greater share of the total gains from innovation, reducing the need for government subsidies.[5] Importantly, these effects interact: A larger JV size amplifies the subsidy-reducing effect of the greenium by internalizing more firms' incentives to lower their cost of capital, thereby reducing the required subsidy.

We also explore the subsidy-minimizing design of brown JVs, which is what the government would select if it sought to government spending while achieving first-best green innovation. We show that private innovation incentives are highest when the JV includes all

[5]Including sufficiently green firms can reverse the effect, as greener firms face increased competition from more profitable brown firms adopting better technology, which weakens greener firms' incentive to support innovation.

firms brown enough so as to generate benefits from green innovation. Notably, this will not include all firms since some low-emitting firms lose more via increased competition than they gain due to the cost reducing benefits of green innovation to their high-emitting competitors. In addition, when the greenium is high, the JV should expand to include more, and greener, firms, as stronger cost-of-capital concerns make innovation more attractive to all emitting firms.

Our findings highlight the importance of the emitting (i.e., brown) firms, especially their JVs, as potential financiers of green innovation. These results also illustrate the importance of coordinated policy design. A well-structured JV can internalize the innovation externalities, reducing the need for direct government support. By pairing carbon taxation with targeted subsidies and optimizing JV composition, policymakers can achieve efficient and cost-effective green technology innovation.

Related Literature: Our work is related to the large literature on JVs or partnerships (see e.g., Hennart (1988); Podolny and Page (1998); Dyer and Singh (1998). Kamien, Muller, and Zang (1992) show that research joint venture cartelization, where firms share the benefit and costs of innovation while competing in the product market, can boost innovation. Similar ideas arise in many contexts, such as the formation of trade organizations (Hoberg and Neretina, 2023). In the context of global climate policy, Nordhaus (2015) propose "climate clubs" as a solution to free-riding in international climate policy, where member countries enforce strict carbon regulations and enjoy free trade, while non-members face trade sanctions.

We contribute to this literature by providing the first formal analysis of the opportunities brown firm JVs raise for funding climate policy and reduce government subsidies. The unique benefits that brown firms have in optimal climate policy are rooted in their disproportionate benefits to innovations such as carbon abatement, which in turn derive from their substantial exposure to climate risk (Cohen, Gurun, and Nguyen, 2020; Chiu, Hsu, Li, and Tong, 2025;

Calel and Dechezleprêtre, 2016). Thus, our study also relates to a large literature highlighting the consequences of climate policy or stranded asset risks on brown firms (McGlade and Ekins, 2015; Krueger et al., 2020; Chevallier et al., 2021; Dietz et al., 2021; van Benthem et al., 2022; Barnett, 2024).

Our work is also related to the literature of directed technological change, which is based on the long-established idea that the direction of innovation responds to profit incentives (Hicks, 1963, Binswanger, Ruttan, Ben-Zion, Janvry, Evenson, et al., 1978).[6] Particularly related are two papers examining the relationship between climate policies and green innovation. Acemoglu et al. (2012) show, among others, that the optimal climate policy involves both carbon taxes, which address the pollution externalities, and research subsidies, which address knowledge spillovers in green innovations. Gans (2012) illustrates that stricter carbon pricing policies increase innovations in carbon abatement technologies. We contribute to the literature by proposing brown firm JVs as major players in green innovation, and illustrating how climate policies can be designed according to the JVs' characteristics (namely, size and brownness).

We also contribute to the theoretical literature on the "greenium." Existing work proposes explanations for the greenium, including investors' preferences for holding environmental-friendly financial assets, motives to hedge against climate risks, and consumers' preferences for greener products (Heinkel, Kraus, and Zechner, 2001; Pástor, Stambaugh, and Taylor, 2021). Although there is some debate regarding the current size of the greenium across various markets (Bolton and Kacperczyk, 2021, 2023; Pástor, Stambaugh, and Taylor, 2022; Hsu, Li, and Tsou, 2023; Eskildsen, Ibert, Jensen, and Pedersen, 2024), our theory shows how the greenium can help drive green innovation. One important implication of our model is that brown firm JVs can leverage any existing greenium to drive green innovation, with

[6] Acemoglu (2002) formalized this idea in a broad array of applications, which as pointed out in the Popp (2019) survey, "spurred both new modeling efforts (e.g. Acemoglu, Aghion, Bursztyn, and Hemous, 2012, Lemoine, 2017) and empirical analyses (e.g. Acemoglu, Akcigit, Hanley, and Kerr, 2016) of directed technical change in an environmental setting."

a larger JV size *amplifying* the greenium's innovation-boosting effect. In this way, our findings reveal a novel implication of greenium: as private markets begin pricing it in, brown firm JVs emerge as an increasingly relevant policy instrument, underscoring the interplay between private market forces and public policy.

Lastly, our paper relates to the literature on socially responsible investment and governance (Oehmke and Opp, 2024; Green and Roth, 2021; Edmans, Levit, and Schneemeier, 2023; Goldstein, Kopytov, Shen, and Xiang, 2024), especially those combining pro-social investment and climate policies (Inderst and Opp, 2025; Döttling, Levit, Malenko, and Rola-Janicka, 2024). Inderst and Opp (2025) illustrate that the private market provision of ESG funds marketed to retail investors with a mandatory taxonomy can improve welfare on top of optimally chosen environmental regulation if there are financial frictions. Döttling et al. (2024) show that shareholder democracy can reduce the amount of government subsidy needed to achieve a targeted level of public good provision (e.g., green innovation).[7] We contribute to this literature by examining the interactions between socially-responsible investment (i.e., the resulting greenium) and the design of brown firm JV structure that minimizes the first-best government subsidies.

The rest of the paper is organized as follows. Section 2 describes the model; Section 3 examine the first-best climate policies given a JV structure, as well as the optimal JV structure that minimizes the government subsidy needed. Section 4 concludes.

2 Model Setup

We present a model with three key elements: (1) a continuum of firms with heterogeneous *brownness*, (2) cost-of-capital differing by emission intensity (*greenmium*), and (3) R&D

[7] Additionally, they show that if shareholders advocate for stronger pro-social policies, it may trigger political backlash, potentially undermining ESG initiatives.

investment in carbon abatement technology via a joint venture (JV), which is formed by emitting firms. The model features three stages:

- $t = 0$, carbon taxes and research subsidies policies announced
- $t = 1$, carbon abatement innovation
- $t = 2$, product market competition

We describe the model backwards.

2.1 Production Market ($t = 2$)

There is a continuum of heterogeneous firms with a total measure of one, each firm featured with a "brownness" parameter $e \in [0, \bar{e}]$. This brownness e measures the firm's carbon emissions per unit of output absent of any carbon abatement innovation. That is, if a firm with type-e produces q units of output, its carbon emissions are eq. An *innovation breakthrough* in carbon abatement technology reduces type-e firm's emission per unit of output from e to ρe, with $\rho \in (0, 1)$. Denote $h \in \{0, 1\}$ as the indicator of the innovation breakthrough, with $h = 1$ referring to a breakthrough. A type-e firm's total carbon emissions given output q and innovation outcome h is $\big(h\,\rho + (1-h)\big)e\,q$. Let the density of firm of type e to be $g(e)$, then $\int_0^{\bar{e}} g(e)\,de = 1$.

All firms are price takes and compete in the product market at $t = 2$. Given carbon tax per unit of emission, denoted as $\tau(e, h)$, each type-e firm chooses output $q(e, h)$ to maximize profit

$$\pi(e,h) = \max_{q(e,h)} \underbrace{p\,q(e,h)}_{\text{revenue}} - \underbrace{\frac{c_q\,q(e,h)^2}{2}}_{\text{production cost}} - \underbrace{(h\rho + (1-h))e\,q(e,h)}_{\text{emission}} \underbrace{\tau(e,h),}_{\text{carbon taxes}}$$

where the production cost function is quadratic with the marginal cost being $c_q > 0$.

There is a continuum of price-taking consumers with total measure one. A representative consumer chooses consumption Q to maximize utility

$$\max_{Q} u(Q) - p\,Q - k\,E,$$

where $u(Q) = bQ - \frac{dQ^2}{2}$ is a quadratic utility function with $b, d > 0$ and the term $p\,Q$ is the total price paid. The last term $k\,E$ is the social damage from total emission, where $k > 0$ and E is the total emission by all firms, with

$$E = \int_0^{\bar{e}} g(e)\,(h\rho + (1-h))\,e\,q(e,h)\,de.$$

The market clearing condition is

$$Q = \int_0^{\bar{e}} q(e,h)g(e)\,de.$$

2.2 Carbon Abatement Innovation ($t = 1$)

There exists a continuum of carbon abatement projects, each costing \$1 to fund. With probability $\lambda \in (0,1)$, a project succeeds, generating $\$R > 1$. With probability $1-\lambda$, the project fails, generating 0. The realization of success or failure are i.i.d. across projects. If at least one project funded succeeds, there is an innovation breakthrough, that is, $h = 1$; otherwise, $h = 0$. The direct profit from investing in a project is negative, that is, $\lambda R + (1-\lambda)0 - 1 = -(1-\lambda R) < 0$.[8] We thereby denote $\kappa = 1 - \lambda R$ as the R&D cost per project.

Firms can form a research JV, who can fund these carbon abatement projects. Suppose the fraction of type-e firms joining the JV is $\mu(e) \in [0,1]$. Then the mass of the JV is

$$m = \int g(e)\mu(e)\,de.$$

[8]The payoff R can be interpreted as patent proceeds. We assume R to be exogenous and low in value to highlight the knowledge spillover effect that patent protection is not sufficient to attribute all social benefit of innovation to the innovator, leading to underinvestment in innovation.

Consistent with the seminal paper on research JVs by Kamien, Muller, and Zang (1992), we allow the firms in the JV to coordinate on R&D by sharing the cost and benefit of the investment, while continuing to compete in the product market.[9] That is, the JV maximizes the discounted joint profit of all participating firms in the product market net of the direct R&D costs that is not reimbursed by the government subsidy. This JV structure is common in practice and is in compliance with anti-trust laws in many jurisdication including the United States and Europe.[10]

The JV's problem is to find the optimal units of carbon abatement projects to invest, x, to maximize

$$\max_{x} \quad \underbrace{\Pr(h=1;x)\int_0^{\bar{e}} \frac{\pi(e,h=1)}{1+r(e,h=1)} g(e)\mu(e)\,de}_{\text{joint profit with breakthrough}} + \underbrace{\Pr(h=0;x)\int_0^{\bar{e}} \frac{\pi(e,h=0)}{1+r(e,h=0)} g(e)\mu(e)\,de}_{\text{joint profit without breakthrough}}$$

$$- \quad \underbrace{x(1-\lambda R)}_{\text{direct R\&D cost}} \quad + \quad \underbrace{S(x)}_{\text{research subsidy}} \tag{1}$$

To interpret, the third term is the direct R&D expense, while the fourth term is the research subsidy, which is a function of the R&D investment x. The first two terms stand for the joint product market profit for the participating firms under two different states: breakthrough ($h = 1$) and no breakthrough ($h = 0$). The probability of a breakthrough, $\Pr(h = 1; x)$, is an increasing function of x, and it can be shown that $\Pr(h = 1; x) = 1 - e^{-\lambda x}$. The term $\frac{\pi(e,h)}{1+r(e,h)}$ is type-e firm's product market profit discounted to $t = 1$, using the the cost of capital for the firm under innovation state h, namely, $r(e, h)$.

To capture *greenium*, we assume that the cost of capital increases in the the emission per unit of output of the firm:

$$r(e,h) = \alpha + \beta \cdot \underbrace{(h\rho + (1-h))\,e}_{\text{emission per unit of output}} \tag{2}$$

[9] This structure is called "research joint venture cartelization" in Kamien, Muller, and Zang (1992) and is shown to be effective in boosting innovation.

[10] See `https://bit.ly/4iIhpsI`. Also `https://bit.ly/3DA69jq`.

with $\beta > 0$ represents the magnitude of greenium. Though we do not endogenize greenium in our model, we follow Pástor, Stambaugh, and Taylor (2021) and interpret β as the average investor's preference for environmental-friendly securities.[11]

Lastly, there is *knowledge spillover* of innovation beyond the JV innovator. That is, if there is an innovation breakthrough in the JV, then all firms adopt the abatement technology, regardless of their participation in the JV. That is, all firms of type-e reduce their emission per unit of output from e to ρe after the breakthrough.

For simplicity, we focus on the following parameter ranges to ensure strictly positive output for each firm under the first best allocation. That is, the consumer's utility per unit of consumption (b) should be sufficiently high compared to the environmental costs (k) to justify positive output for all firms.

Assumption 1. $b > (\bar{e} + \frac{d(\bar{e}-\mathbb{E}(e))}{c_q})k$, where $\mathbb{E}(e) = \int_0^{\bar{e}} g(e)e\,de$.

We also impose an assumption on the social planner's discount rate, denoted as $r_{\text{SP}}(h)$, which requires that the social planner's discount rate is lower in good state of the world ($h = 1$, innovation breakthrough) than in bad state of the world ($h = 0$, no innovation breakthrough). This assumption ensures that the discounted social welfare is improved by the innovation breakthrough.

Assumption 2. $0 < r_{\text{SP}}(h = 1) \leq r_{\text{SP}}(h = 0)$.

3 Analysis

In Sections 3.1 and 3.2, we investigate the first-best climate policy, namely, carbon taxes and research subsidies, given the structure of a JV. In Section 3.3, we examine the optimal JV structure that minimizes the first-best research subsidy.

[11] Similar to Pástor, Stambaugh, and Taylor (2021), we can also interpret β as an average consumer's environmental preference, or consumer's motives to use green securities to hedge climate risks. Moreover, our qualitative results are unchanged if the cost of capital increases in total carbon emission instead of emission per unit of output.

3.1 First-Best Allocation

This section explores the first best allocation of output $q_{\text{FB}}(e,h)$ and carbon abatement innovation x_{FB}. We solve the problem backwards.

3.1.1 Output Choice at $t = 2$

At $t = 2$, after (possible) R&D success h, the social planner chooses $q_{\text{FB}}(e,h)$ for each type-e firm to maximize the consumer utility net of production costs and environmental damages, with the value function denoted as $W_{\text{FB}}(h)$:

$$\begin{aligned} W_{\text{FB}}(h) \quad &= \max_{q_{\text{FB}}(e,h)} \underbrace{u\big(Q_{\text{FB}}(h)\big)}_{\text{consumer utility}} - \underbrace{\int_0^{\bar{e}} g(e) c_q \frac{(q_{\text{FB}}(e,h))^2}{2}\, de}_{\text{production cost}} \\ &- \underbrace{k\Big(\int_0^{\bar{e}} g(e)\cdot(h\rho+(1-h))e\cdot q_{\text{FB}}(e,h)\, de\Big)}_{\text{environmental damage}} \\ &\text{where total output } Q_{\text{FB}}(h) = \int_0^{\bar{e}} q_{\text{FB}}(e,h) g(e)\, de \end{aligned}$$

The first order condition implies

$$\begin{aligned} q_{\text{FB}}(e,h) &= \frac{u'(Q_{\text{FB}}(h)) - k\,(h\rho+(1-h))\,e}{c_q}, \\ \text{where total output } Q_{\text{FB}}(h) &= \int_0^{\bar{e}} \frac{b - k\,(h\rho+(1-h))\,e}{d+c_q} g(e)\, de, \end{aligned}$$

These illustrate the tradeoff by the social planner: higher $q_{\text{FB}}(e,h)$ leads to higher consumer utility, but also higher production costs and environmental costs.

3.1.2 R&D Investment at $t = 1$

At $t = 1$, the planner selects the investment in carbon abatement, x_{FB}, to maximize expected welfare, which is the expected welfare in $t = 2$ (i.e., $W_{\text{FB}}(h)$) discounted back to $t = 1$ using the

social planner's discount rate $r_{\text{SP}}(h)$, net of the R&D expenses:

$$\max_{x_{\text{FB}}} \quad \underbrace{\Pr(h=1;x_{\text{FB}})\,\frac{W_{\text{FB}}(h=1)}{1+r_{\text{SP}}(h=1)}+\Pr(h=0;x_{\text{FB}})\,\frac{W_{\text{FB}}(h=0)}{1+r_{\text{SP}}(h=0)}}_{\text{discounted output market welfare}}-\underbrace{x_{\text{FB}}(1-\lambda R)}_{\text{direct R\&D cost}}$$

$$\text{where } \Pr(h=1;x_{\text{FB}})=1-\Pr(h=0;x_{\text{FB}})=1-e^{-\lambda x_{\text{FB}}}.$$

The first order condition implies that

$$e^{-\lambda\, x_{\text{FB}}}=\frac{1-\lambda R}{\frac{W_{\text{FB}}(h=1)}{1+r_{\text{SP}}(h=1)}-\frac{W_{\text{FB}}(h=0)}{1+r_{\text{SP}}(h=0)}}.$$

At $t=1$, the social planner faces the following tradeoff: higher investment in R&D leads to higher probability of innovation breakthrough, which leads to higher social welfare due to less pollution. However, this is at the cost of higher R&D expenses.

3.2 First-Best Implementation with Climate Policies

We next show that the first-best outcome $\left(q_{\text{FB}}(e,h),x_{\text{FB}}\right)$ can be implemented via a combination of linear carbon taxes and linear research subsidies.

Proposition 1 (First-Best Implementation)**.** *The first-best outcome can be attained by:*

1. *A constant carbon tax rate, $\tau(e,h)=k$, set equal to the marginal environmental cost of emissions.*

2. *A linear research subsidy given to the JV, which is linear on the JV's R&D spending x, i.e., $S(x)=s\cdot x$. Specifically, the fraction of R&D cost reimbursed by the subsidy, $\frac{s}{1-\lambda R}$, must satisfy*

$$\frac{s}{1-\lambda R}\;=\;1-\frac{\displaystyle\int_0^{\bar{e}} g(e)\,\mu(e)\left(\frac{\pi(e,h=1\mid\tau=k)}{1+r(e,h=1)}-\frac{\pi(e,h=0\mid\tau=k)}{1+r(e,h=0)}\right)de}{\dfrac{W_{\text{FB}}(h=1)}{1+r_{\text{SP}}(h=1)}-\dfrac{W_{\text{FB}}(h=0)}{1+r_{\text{SP}}(h=0)}}. \tag{3}$$

As in Acemoglu et al. (2012), the first best outcome requires both carbon taxes and R&D subsidies, where the former corrects the pollution externalities and the latter corrects the underinvestment due to knowledge spillovers. Although we allow for all functional forms of tax rates and subsidy policies, Proposition 1 shows that a constant linear tax rate and a linear subsidy policy is sufficient to achieve the first best.

To interpret part 1, consider the product market at $t = 2$. By imposing a constant tax $\tau(e, h) = k$ per unit of emissions, each firm internalizes the marginal enviornmental damage from pollution in its output decision. In a competitive market with price-taking behavior, setting $\tau(e, h) = k$ ensures that the private cost of emissions equals the social cost, aligning each firm's production choice $q(e, h)$ with the first-best level conditional on the innovation outcome h.

To interpret part 2, consider the innovation stage at $t = 1$. Because R&D success benefits *all* firms regardless of their participation in the research JV, but only firms joining the JV pays the research costs, a subsidy is needed to bridge the gap between private and social returns on R&D. Specifically, equation (3) can be rewritten as

$$\frac{\text{Subsidy per unit of R\&D investment}}{\text{Total cost per unit of R\&D investment}} = 1 - \frac{\text{Private Benefit of R\&D for JV}}{\text{Social Benefit of R\&D}}$$

That is, the fraction of total R&D cost reimbursed by the subsidy (left-hand-side) has to bridge the difference between the gap between the social benefit of R&D and the private benefit of R&D due to the knowledge spillover beyond the JV innovator.[12]

From Proposition 1, the key to lowering the subsidy is increasing the JV's *private* benefit of the R&D outcome. For a type-e firm participating in the JV, denote its private benefit from R&D as $v(e, \beta)$:

$$v(e, \beta) = \frac{\pi(e, h = 1 \mid \tau = k)}{1 + r(e, h = 1)} - \frac{\pi(e, h = 0 \mid \tau = k)}{1 + r(e, h = 0)}, \tag{4}$$

[12] Algebraically, on the right hand side, the numerator in the fraction captures the difference in discounted private profits from $h = 1$ versus $h = 0$, while the denominator reflects the difference in social discounted welfare from $h = 1$ versus $h = 0$.

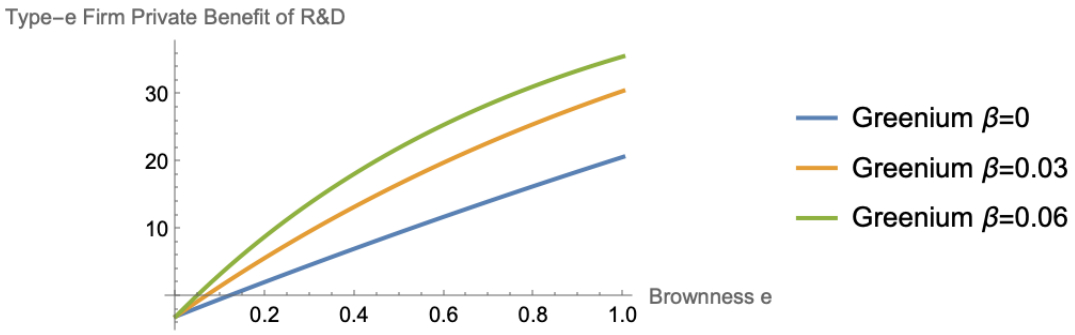


Figure 1: Type-e firm's private benefit $v(e, \beta)$ as an increasing function of brownness e and greenium β. Parameter choices are Parameters: $c_q = 1, k = 1, b = 10, d = 0.3, \rho = 1/2, \mathbb{E}(e) = 0.5, a = 0.15$. $e \in [0, 1]$.

which is the difference between the firm's discounted profit with innovation breakthrough ($h = 1$) v.s. without ($h = 0$). The existence of greenium implied by equation (2) indicates that this private benefit depends on the extent of greenium, β. Lemma 1 and Figure 1 shows that $v(e, \beta)$ increases in both brownness e and greenium β.

Lemma 1. *There exists $e^{max} > 0$ and $\beta^{max} > 0$ such that when $\bar{e} < e^{max}$ and $\beta < \beta^{max}$, a type-e firm's private benefit $v(e, \beta)$ as defined in equation (4) increases in brownness e and greenium β.*

Intuitively, an innovation breakthrough reduces emissions per unit of output by $(1 - \rho)e$. A browner firm (higher e) experiences a greater reduction in emissions per unit of output, leading to not only larger savings in carbon tax payments but also in cost of capital, which decline by $\beta(1 - \rho)e$. As a result, the profit boost from innovation is stronger for browner firms. When the prevailing greenium is higher (larger β), the cost-of-capital reduction $\beta(1 - \rho)e$ increases for all firms, amplifying the private gains from innovation breakthrough at any given emission level e.

For the rest of the paper, we maintain the assumptions that $\bar{e} < e^{max}$ and $\beta < \beta^{max}$. Lemma 1 thereby implies the next two corollaries (Corollary 1 and Corollary 2) regarding how the optimal subsidy rate s as defined in equation (3) changes with the JV's brownness and the prevailing greenium.

First, we examine how the optimal subsidy varies with the JV's brownness. Observe that $\mu(e)$, which represents the fraction of type-e firms joining the JV, uniquely determines the composition

of the JV. Consider an increase in brownness of the JV, which switches $\mu(e)$ from $\mu_1(e)$ to $\mu_2(e)$, such that the p.d.f. of a firm being type e conditional on the firm participating in the JV changes from $p_1(e) = \frac{\mu_1(e)g(e)}{\int_0^{\bar{e}} \mu_2(e)g(e)\,de}$ to $p_2(e) = \frac{\mu_2(e)g(e)}{\int_0^{\bar{e}} \mu_2(e)g(e)\,de}$, and that $p_2(e)$ first-order-stochastic-dominates (FOSD) $p_1(e)$. This change makes the expected brownness in the JV larger. Corollary 1 shows that this change also reduces the first-best subsidy needed.

Corollary 1. (Optimal Subsidy Decreases in JV Brownness)
If $\mu(e)$, which represents the fraction of type-e firms joining the JV, changes from $\mu_1(e) \in [0,1]$ $\mu_2(e) \in [0,1]$ such that $p_2(e) = \frac{\mu_2(e)g(e)}{\int_0^{\bar{e}} \mu_2(e)g(e)\,de}$ FOSD $p_1(e) = \frac{\mu_1(e)g(e)}{\int_0^{\bar{e}} \mu_2(e)g(e)\,de}$, while keeping the JV size constant at $m = \int_0^{\bar{e}} \mu_1(e)g(e)\,de = \int_0^{\bar{e}} \mu_2(e)g(e)\,de$. Then

1. *The JV is browner under $\mu_2(e)$ (i.e., average e is larger): $\int ep_2(e)\,de \geq \int ep_1(e)\,de$.*
2. *The optimal JV subsidy rate s, as defined by equation (3), is lower under $\mu_2(e)$.*

Intuitively, a browner JV implies that its member firms have higher baseline emissions, meaning they benefit more from an innovation breakthrough that reduces emissions per unit of output. Since the carbon tax is levied on emissions, firms with higher initial emissions experience larger absolute reductions in tax payments when adopting abatement technology. Additionally, because brown firms face cost of capital that are proportional to their brownness e, lowering emissions leads to a greater decline in their cost of capital, amplifying the private gains from innovation. As a result, a JV composed of browner firms benefits more from the abatement innovation, strengthening its incentives to invest in R&D and reducing the need for government subsidies.

Second, we explore how the optimal subsidy depends on the greenium.

Corollary 2. (Optimal Subsidy Decreases in Greenium) *The optimal subsidy rate s, as defined by equation (3), decreases when the greenmium β increases.*

Intuitively, a larger greenium increases the benefits of innovation for firms in the JV by amplifying the reduction in their cost of capital. With stronger financial incentives to lower emissions, firms are more willing to invest in the abatement technology. As a result, the need for government research subsidies decreases, as private incentives alone drive more innovation.

Next, we consider how the optimal subsidy varies with the size of the JV.

Corollary 3. (Effect of JV Size on Optimal Subsisdy) *Suppose* $\mu(e) < 1$ *for all* e. *Define the JV's total private benefit as*

$$\int_0^{\bar{e}} g(e)\,\mu(e)\left[\frac{\pi(e, h=1 \mid \tau = k)}{1 + r(e, h=1)} - \frac{\pi(e, h=0 \mid \tau = k)}{1 + r(e, h=0)}\right] de.$$

1. *If this integral is positive, scaling* $\mu(e)$ *by* $j > 1$ decreases *the optimal subsidy* s *as defined in equation (3).*

2. *If it is non-positive, scaling up the JV weakly* increases s.

Intuitively, expanding the JV to include more firms that directly benefit from R&D strengthens its incentive to innovate, as a larger share of the social benefits from the abatement technology is internalized within the JV. When more firms gain from lower carbon taxes and reduced cost of capital due to emissions reductions, the JV collectively values innovation more, reducing reliance on government subsidies. In contrast, if additional firms within the JV are negatively affected by R&D – such as greener firms facing increased competition from brown firms whose profitability were boosted by the innovation – the JV becomes more reluctant to invest in innovation. This weakened incentive necessitates a larger government research subsidy to compensate for the reduced willingness to pursue abatement technology.

Lastly, we examine the interacting effects of greenium and the JV's size on the optimal subsidy.

Corollary 4. (Interactions: Size Effect and Greenium Effect) *Suppose* $\mu(e) < 1$ *for all* e, *then scaling* $\mu(e)$ *by* $j > 1$ *strengthens the negative effect of* β *on* s, *i.e.* $\partial^2 s / \partial\beta\,\partial j < 0$.

That is, larger JV enhances the subsidy-reduction effect of larger greenium. Intuitively, this is because larger JV internalizes more benefits from cost-of-capital reductions.

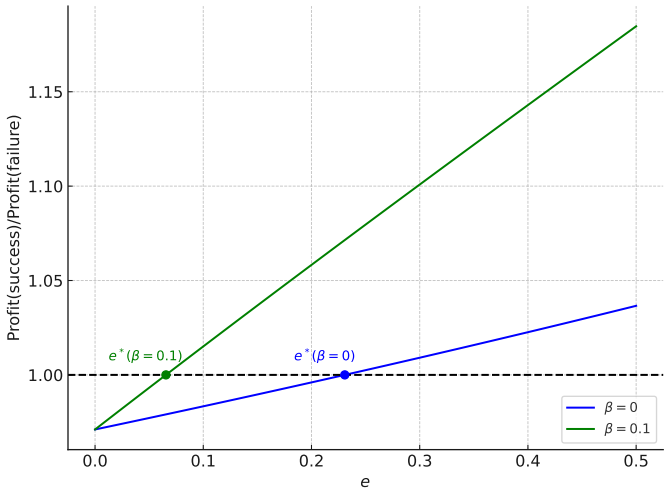


Figure 2: The cutoff type e^* as a greenium β. Parameter choices are Parameters: $c_q = 1, k = 1, b = 10, d = 0.3, \rho = 1/2, \mathbb{E}(e) = 1, a = 0.15$.

3.3 Optimal JV Structure to Minimize Subsidy

In this section, we investigate the optimal JV structure, $\mu^*(\cdot)$, that minimizes that the first-best research subsidy in equation (3).

Proposition 2 (Optimal JV Structure)**.** *Let $\mu^*(\cdot)$ be the optimal JV structure that minimizes first-best research subsidy defined by equation (3). Then*

1. *$\mu^*(\cdot)$ follows a cutoff structure: there exists a unique type e^* with zero private benefit of R&D, i.e., $v(e^*, \beta) = 0$, such that $\mu^*(e) = 1$ if $e \geq e^*$, and $\mu^*(e) = 0$ if $e < e^*$.*

2. *Moreover, $\frac{\partial e^*}{\partial \beta} < 0$.*

Part 1 of Proposition 2 implies that it is optimal to include only sufficiently brown firms into JV (those with brownness $e \geq e^*$). The reason is that browner firms benefit more from the abatement innovation. Part 2 states that when the prevailing greenium is larger, all emitting firms have larger incentive to innovate in abatement in order to reduce cost of capital, thereby the optimal JV should include more and greener firms. Figure 2 demonstrates how the cutoff e^* varies with greenium β.

3.4 Discussion: Formation of JV

We have focused our discussion on design of climate policy and optimal JV structure while assuming the JV is exogenously formed. In practice, such JV can be challenging to form due to potential free-riding issues. Since R&D costs may not be fully refunded by government subsidies, individual firms may prefer to let others bear the costs while still benefiting from the resulting technological advancements. This creates an incentive misalignment where some firms hesitate to join the JV, expecting others to contribute instead.

One solution is for the government to make take-it-or-leave-it offers to a selected set of firms, ensuring that if any firm rejects the offer, the JV and its associated research subsidy will not exist. This mechanism makes each firm pivotal to the formation of the JV, eliminating incentives to free-ride. Another approach is for firms to sign cooperative agreements that enforce participation, akin to cartelization, ensuring that all designated members share the R&D burden. Because forming the JV is collective welfare-improving for all selected firms, they have the incentive to sign the cooperative agreement and form this cartelization.

4 Conclusion

This paper develops a theoretical framework to investigate how and when to subsidize green R&D JVs formed by carbon-intensive (brown) firms, particularly under a greenmium in capital markets. We demonstrate that a constant carbon tax, when paired with a linear R&D subsidy targeted at a joint ventures (JV), achieves the first-best outcome in carbon abatement technology innovation. While carbon taxes are necessary to correct pollution externalities, they alone cannot resolve the underinvestment in innovation caused by knowledge spillovers. The inclusion of an R&D subsidy specifically targeting brown firm JVs addresses this inefficiency, ensuring that firms have adequate incentives to invest in emissions-reducing technology. By structuring the policy mix appropriately, the government can achieve an efficient carbon abatement innovation goal while minimizing the public cost of innovation subsidies.

A key insight from our analysis is that the required R&D subsidy per unit of innovation depends on the JV charateristics and the prevailing greenium. First, it declines in the greenium, as higher financing advantages for greener firms strengthen private incentives to innovate, reducing the need for external support. Second, it decreases with the JV's brownness, as browner firms gain more from emissions reductions through both lower carbon tax liabilities and improved cost of capital, making them more willing to invest in carbon abatement innovation with minimal subsidies. Third, if the JV is sufficiently brown, an increase in its size further reduces the subsidy required. This occurs because additional brown firms internalize a greater share of the benefits from innovation, whereas an influx of greener firms may weaken innovation incentives due to increased product market competition from browner firms. Moreover, a larger JV size amplifies the subsidy-reducing effect of a larger greenium. When more firms participate in the JV, the benefits of lower financing costs from emissions reductions for more firms are internalized by the JV, further enhancing private incentives to invest in R&D. Our findings also have direct implications for the optimal design of the JV to minimize government subsidies for carbon abatement technology. To achieve the greatest reduction in required subsidies, a JV should be structured to include sufficiently brown firms. Additionally, when the greenium is high, a JV should expand to include more, and greener, firms.

Overall, our results underscore the importance of a strategic approach to policy design. A well-structured JV, combined with a carbon tax and a linear R&D subsidy, can internalize both pollution and innovation externalities, significantly reducing the need for direct government intervention. By carefully selecting JV participants and leveraging the effects of greenium and firm composition, policymakers can design market-based solutions that promote green innovation while maintaining economic efficiency.

Appendix: Proofs

Proof of Proposition 1.
Step 1 ($t = 2$, product market), for innovation outcome $h \in \{0, 1\}$, find optimal output $q(e, h)$ for each firm that maximizes flow profit $\pi(e, h|\tau(e, h))$, and then solve for the equilibrium $q(e, h)$. Let $q(e, h) = q_{\text{FB}}$ and solve for carbon tax rate $\tau(e, h)$, then we find that $\tau(e, h) = k$, the marginal environmental damage of emission.

Step 2 ($t = 1$, innovation), find the equilibrium JV abatement technology investment x that maximizes JV profit in equation (1) such where letting carbon tax rate being $\tau(e, h) = k$ and research subsidy being $S(x) = s\,x$. Find the optimal JV investment x and let $x = x_{\text{FB}}$, and solve for s.

□

Proof of Corollary 1.
The optimal subsidy rate s is defined as

$$\frac{s}{1-\lambda R} \;=\; 1 - \frac{\displaystyle\int_0^{\bar{e}} g(e)\,\mu(e) v(e,\beta)\,de}{\dfrac{W_{\text{FB}}(h=1)}{1+r_{\text{SP}}(h=1)} - \dfrac{W_{\text{FB}}(h=0)}{1+r_{\text{SP}}(h=0)}}. \tag{5}$$

Since $p_2(e)$ FOSD $p_1(e)$ and $\int_0^{\bar{e}} \mu_1(e) g(e)\,de = \int_0^{\bar{e}} \mu_2(e) g(e)\,de$ and also Lemma 1 implies that $v(e, \beta)$ increases with β, then we must have $\int_0^{\bar{e}} g(e)\,\mu_2(e) v(e,\beta)\,de \geq \int_0^{\bar{e}} g(e)\,\mu_1(e) v(e,\beta)\,de$. In addition, the term $\frac{W_{\text{FB}}(h=1)}{1+r_{\text{SP}}(h=1)} - \frac{W_{\text{FB}}(h=0)}{1+r_{\text{SP}}(h=0)} > 0$ due to Assumption 2. Therefore, s under $\mu_2(e)$ is smaller. □

Proof of Corollary 2.
Equation (5) and Lemma 1 implies that s is lower then β is higher. □

Proof of Corollary 4.
Replace $\mu(e)$ with $j\mu(e)$ in equation (5), then we have

$$\frac{\partial^2 s}{\partial\beta\,\partial j} = \frac{-1}{1-\lambda R} \frac{\displaystyle\int_0^{\bar{e}} g(e)\,\mu(e) \frac{\partial v(e,\beta)}{\partial\beta}\,de}{\dfrac{W_{\text{FB}}(h=1)}{1+r_{\text{SP}}(h=1)} - \dfrac{W_{\text{FB}}(h=0)}{1+r_{\text{SP}}(h=0)}},$$

which is negative because Lemma 1 implies that $\frac{\partial v(e,\beta)}{\partial\beta} > 0$.

□

Proof of Proposition 2.

For part 1, it can be shown that the ratio of discounted profit with innovation breakthrough over the discounted profit without,

$$\frac{\pi(e, h = 1 \mid \tau = k)}{r(e, h = 1)} / \frac{\pi(e, h = 0 \mid \tau = k)}{r(e, h = 0)},$$

is strictly increasing in browness e and greenium β. Also, the ratio is strictly below one when $e = 0$, and is above one when e is sufficiently high. Therefore, there is a cutoff structure with a unique cutoff e^*. Part 2 is implied by the ratio increasing in β.

□

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