Subsidizing Less by Coordinating More: When Brown Firms Collaborate on Green Innovation[*]

Matthew Gustafson[†] Zhe Wang[‡]

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Abstract

We study climate policy when high-emission ("brown") firms collaborate in research joint ventures (JVs) on carbon abatement innovation. We show that less government subsidy is needed to achieve the first-best outcome when markets better internalize externalities—through a JV that is larger and composed of sufficiently brown firms or through a higher greenium in capital markets. We characterize the JV structure that minimizes required subsidies and show it does not arise under decentralized formation. However, it can be implemented by government coordination that makes each firm pivotal for the JV formation and allocates unreimbursed costs in line with firms' private innovation incentives. Our results highlight a role for active government coordination and inform the antitrust treatment of climate-motivated collaborations.

Keywords: Climate Policy, Green Innovation, Research Subsidies, Brown Firm Joint Ventures, Greenium, Antitrust

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[†] Smeal College of Business, Pennsylvania State University; Email: mtg15@psu.edu.

[‡] Smeal College of Business, Pennsylvania State University; Email: zxw192@psu.edu.

"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). Its causes and solutions both involve *externalities*: emissions impose global environmental costs not borne by individual firms, while innovation in mitigation technologies generates knowledge spillovers that lead to free-riding and underinvestment in green R&D. Because no single firm can efficiently address these twin externalities, both public-private collaboration and collaboration between private actors are important components to climate solutions. In particular, joint research and development (R&D) arrangements allow firms to share costs and partially internalize spillovers, making carbon abatement projects viable that no firm would undertake alone.

High-emission "brown" firms are especially important potential innovators. Brown firms stand to gain disproportionately from breakthroughs in carbon abatement technology, which lower their expected carbon tax burden, stranded-asset risk, and cost of capital (the "greenium") (Pástor, Stambaugh, and Taylor, 2021; Bolton and Kacperczyk, 2023). Consistent with these incentives, brown firms actively develop green patents and products (Calel and Dechezleprêtre, 2016; Cohen, Gurun, and Nguyen, 2024; Chiu, Hsu, Li, and Tong, 2025; Leippold and Yu, 2025) and have begun forming large-scale carbon abatement research joint ventures (JVs).[2]

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

[2] For example, large energy firms have formed carbon capture and storage JVs such as Bayou Bend (by

We study how climate policy can leverage the incentives of brown firms to participate in research JVs to develop carbon abatement technologies. An optimal climate policy mix typically combines carbon taxes, which price the pollution externality, with R&D subsidies, which address knowledge spillovers (Acemoglu, Aghion, Bursztyn, and Hemous, 2012). Yet ongoing policy debates increasingly focus on how aggressively to subsidize green R&D and how much governments can lean on the innovative capacity of the private sector, especially given fiscal constraints (Nerlich et al., 2025). Recent initiatives—such as the U.S. Department of Energy's multi-billion-dollar support for carbon management and large European green-technology programs—underscore both the scale of required investment and the need to leverage private capital.[3]

Our paper speaks directly to this debate by asking two questions. First, how do optimal subsidies for carbon abatement R&D depend on the size and composition of brown-firm research JVs and on the strength of the greenium in capital markets? Second, what JV structure minimizes the government's required subsidy while still achieving the socially optimal level of green innovation, and will such a coalition form voluntarily? By answering these questions in a tractable model, we show how "subsidizing less" becomes feasible when market players "coordinate more" on green innovations.

We develop a stylized model to answer these questions. 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 Stage 0 of our three-period model, the government announces its policy mix of carbon taxes and research subsidies. At Stage 1, the innovation stage, the JV determines funding for a continuum of carbon abatement projects. If at least one funded

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Chevron, Total, Equinor) and Northern Lights (by Equinor, Shell, Total). Other examples include Net Zero Teesside (BP, Eni, Equinor, Shell, Total), and Quest (Shell, Chevron, Marathon Oil).

[3] See Hughes (2025) and Nerlich et al. (2025).

[4] This setting follows the traditional research JV literature such as d'Aspremont and Jacquemin (1988) and Kamien, Muller, and Zang (1992). Coordination on R&D while maintaining competition in the product market is compliant with the anti-trust laws in many jurisdictions.

project succeeds, it leads to an innovation breakthrough, generating positive externalities through knowledge spillovers that lower emission intensity across all firms, regardless of their participation in the JV. Finally, at Stage 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. Similar to Acemoglu, Aghion, Bursztyn, and Hemous (2012), we show that a constant carbon tax rate combined with a linear R&D subsidy achieves the first-best outcome. Our model extends Acemoglu et al. (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). First, the subsidy falls as the greenium rises: 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. Second, the subsidy falls with the JV's brownness: a JV composed of browner firms internalizes more of the private gains from abatement—through larger reductions in carbon taxes and financing costs—and therefore requires less subsidization. Third, the subsidy falls with the JV's size (as long as constituents remain sufficiently brown): adding sufficiently brown firms increases the share of innovation benefits captured within the coalition, lowering the required subsidy.[5] Importantly, these effects interact: A larger JV size *complements* a higher greenium in reducing necessary subsidies.

Taken together, these results highlight a common theme: government support can be smaller when market forces internalize more of the externalities—either through the greenium or through a JV composed of firms with the strongest private incentives to abate. This insight then motivates our analysis of the *subsidy-minimizing* JV structure, which corresponds to the

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[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.

coalition a government would prefer if it aimed to reduce public spending while still achieving first-best innovation. We show that private innovation incentives are maximized when the JV includes all firms sufficiently brown to benefit from the abatement breakthrough, but not those green firms that would be harmed by the intensified competition that follows. Moreover, when the greenium is high, the optimal JV expands to include additional, and even greener, firms, because stronger capital-market penalties make abatement innovation privately attractive to a broader set of emitters.

Lastly, we study how the subsidy-minimizing JV can be implemented. We show that decentralized formation fails: because abatement knowledge spills over to all firms, each polluter prefers to stay outside and free-ride on any innovation funded by firms who join the JV. In contrast, the desired JV can be formed if the government makes a take-it-or-leave-it offer under which the coalition is created only if all selected firms join, and unreimbursed R&D costs are shared in proportion to each firm's private incentive to innovate. By making every firm pivotal and assigning lower cost shares to those with weaker incentives, this mechanism eliminates free-riding and yields voluntary participation by all targeted members.

Policy Implications. Because research JVs often involve collaboration among competitors, our results speak directly to ongoing debates about how antitrust policy should treat climate-motivated cooperation (OECD, 2021; Hearn et al., 2023; Hanawalt et al., 2024). Our analysis highlights that governments may benefit from doing more than simply relaxing antitrust scrutiny for climate R&D collaboration. Existing regimes—such as the U.S. National Cooperative Research and Production Act, the DOJ–FTC Antitrust Guidelines for Collaborations Among Competitors (2000)[6], and the EU's R&D Block Exemption and Horizontal Guidelines on Horizontal Cooperation Agreements (2023)[7]—primarily lower legal barriers for voluntary cooperation but do not solve the free-riding problem that prevents socially valuable climate JVs from forming. Our results suggest that, in addition to providing antitrust

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[6] `https://bit.ly/3LP8eLW`.

[7] `https://bit.ly/4p55xow`.

"safe harbors," governments may need to actively coordinate or catalyze the formation and composition of research JVs that would otherwise fail to emerge.

A second implication concerns how antitrust authorities evaluate such collaborations once they arise. Under both the DOJ–FTC guidelines and the EU Horizontal Guidelines, competitor R&D alliances are typically assessed under a rule-of-reason framework that weighs efficiencies against potential harms. Our model indicates that, in the climate context, this assessment should pay particular attention to the incentives of JV members to undertake green innovation. These incentives depend on the JV's brownness, its size, and the prevailing greenium. Incorporating these features into rule-of-reason analysis—fully consistent with the flexibility allowed under current U.S. and EU guidance—can help identify when a research JV is more likely to advance climate-related innovation rather than create competitive concerns.

Related Literature. Our work is related to the literature on JVs or partnerships (see e.g., d'Aspremont and Jacquemin (1988); 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 how brown-firm research JVs can finance climate-related innovation and reduce the need for government subsidies. A key result is that the subsidy-minimizing JV does not form organically, implying a role for the government in actively coordinating its formation rather than merely relaxing antitrust scrutiny. 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, 2024; 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 idea that the direction of innovation responds to profit incentives (Hicks, 1963, Binswanger, Ruttan, Ben-Zion, Janvry, Evenson, et al., 1978).[8] Particularly related are two papers examining the relationship between climate policies and green innovation. Acemoglu et al. (2012) shows 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 this literature by positioning brown-firm research JVs as key engines of green innovation and showing how optimal climate policy—especially R&D subsidies—should be tailored to their size and brownness. Our model suggests not only that governments should leverage brown JVS as targets for subsidies aimed at climate abatement technology, but also that active government coordination of JV formation is itself an additional policy lever for addressing climate externalities, beyond carbon pricing and conventional subsidies.

Thus, we contribute to the active academic debate on how competition law should treat collaborations motivated by sustainability goals. Policy works such as OECD (2021), Hearn, Hanawalt, and Sachs (2023), and Hanawalt, Hearn, and Field (2024) discuss how environmental objectives can be integrated into competition enforcement and calls for up-

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[8] 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." In a more recent paper, Barnett, Brock, Zhang, and Hansen (2024) examine how the uncertainty pertaining to climate change and related R&D affects the optimal climate policy.

dating U.S. DOJ/FTC collaboration guidelines so that legitimate climate agreements are not chilled. Gasparini and Tufano (2025) provide empirical evidence on business climate alliances among financial institutions, finding that membership increased adoption of climate-aligned practices without clear traditional antitrust harms. Studies such as Xiong and Yang (2024) and Bond and Levit (2025) further highlight the potentially pro-competitive effects that corporate ESG initiatives can have. We contribute to this literature by proposing a novel channel, where the relaxation of antitrust scrutiny on research collaborations among brown firms can facilitate green innovation.

Finally, our study contributes to the literature studying the interaction between financial markets and climate policy. On the investor side, 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), and in particular to work that combines pro-social investment with formal climate regulation (Inderst and Opp, 2025; Döttling, Levit, Malenko, and Rola-Janicka, 2024). Inderst and Opp (2025) show that the private-market provision of ESG funds marketed to retail investors under a mandatory taxonomy can raise welfare in addition to optimally chosen environmental regulation when financial frictions are present. Döttling et al. (2024) show that shareholder democracy can reduce the government subsidies required to achieve a given level of public good provision (e.g., green innovation).[9] These papers highlight how investors' preferences and voting power can complement or substitute for climate policy in shaping real outcomes. We contribute to this line of work by studying how socially responsible investment—summarized in our framework by the equilibrium greenium—interacts with the design of brown-firm research JVs that minimize the first-best level of government subsidies.

On the cost-of-capital side, we contribute to the theoretical literature on the "greenium." Existing work proposes several mechanisms behind a greenium, including investors'

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

preferences for holding environmentally friendly financial assets, motives to hedge physical or regulatory climate risks, and consumers' preferences for greener products (Heinkel, Kraus, and Zechner, 2001; Pástor, Stambaugh, and Taylor, 2021). At the same time, there is active debate about the magnitude and robustness of the greenium across markets and asset classes (Bolton and Kacperczyk, 2021, 2023; Pástor, Stambaugh, and Taylor, 2022; Hsu, Li, and Tsou, 2023; Eskildsen, Ibert, Jensen, and Pedersen, 2024; Zhang and Shi, 2024; Garrett, Gibbons, and Shahrabi, 2025). In our model, the greenium is a key financial-market parameter that shapes firms' incentives to invest in abatement and thus the optimal mix of climate policies. While existing theory often interprets the greenium as a shadow carbon price or partial substitute for weak climate policy (e.g., Pedersen, 2025), we show that a higher greenium not only lowers the optimal research subsidy but also alters which firms should collaborate to innovate: the subsidy-minimizing coalition is a larger, greener JV when the greenium is stronger. Because JV size amplifies the innovation impact of a given greenium, brown-firm research JVs become an important mechanism through which private climate-risk pricing in capital markets is translated into additional green innovation.

The rest of the paper is organized as follows. Section 2 describes the model, Section 3 examines the first-best climate policies given a JV structure, the optimal JV structure that minimizes the government subsidy needed, and the formation mechanism of the JV, Section 4 discusses the policy implications, and Section 5 concludes.

2 Model Setup

We present a three-stage model featuring a social planner, a continuum of firms and downstream consumers. We introduce the three stages backwards.

2.1 Stage 2: Production, Emission and Consumption

There is a continuum of heterogeneous firms of measure one, each labeled with an "emission" type $e \in [0, \bar{e}]$. The types are distributed according to a density function $g(e)$ with full support. This type e measures the firm's brownness, i.e., carbon emissions per unit of output absent of any carbon abatement technology breakthroughs. There is a state $h \in \{0, 1\}$ indicating the existence of a breakthrough in a carbon abatement technology. If $h = 0$, there is no breakthrough. If $h = 1$, there is a breakthrough in abatement technology that reduces the total emission of a firm to a fraction $\rho \in (0, 1)$ of its initial value. Given the state h and production quantity q, a type-e firm's *net* carbon emission reads:

$$\big(h\rho + (1-h)\big)eq.$$

The social planner commits to a carbon tax policy with a tax rate $\tau(h)$ per unit of carbon emission. That is, the social planner can set the tax rate depending on the common carbon abatement state h. All firms are price takers in the product market, facing the same strictly convex production cost function $C(q)$. Given state h and carbon tax rate $\tau(h)$, each type-e firm chooses output $q = q(e, h)$ to solve:

$$\pi(e,h) \equiv \max_q \quad \underbrace{pq - C(q)}_{\text{production profit}} - \underbrace{(h\rho + (1-h))eq}_{\text{emission}} \underbrace{\tau(h)}_{\text{tax rate}} . \tag{1}$$

There is measure one of homogeneous price-taking consumers. Facing market price p, a representative consumer chooses consumption quantity Q to solve:

$$\max_Q \; U(Q) - pQ - k \underbrace{\int_0^{\bar{e}} (h\rho + (1-h))eq(e,h)g(e)\mathrm{d}e,}_{\text{total emission}}$$

where $U(Q)$ is a strictly concave utility function. The last term, which is independent of consumption, reflects the passive disutility from total emission by all firms, with $k > 0$ representing the intensity of disutility imposed by emission.

Finally, market clearing requires:

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

2.2 Stage 1: Carbon-Abatement Innovation

Abatement projects. There is a continuum of carbon-abatement projects to fund in Stage 1. These projects have the same unit cost of one, so that funding a mass x of projects costs x dollars. If funded, the project may fail (and generates zero) or succeed. For simplicity, we normalize the direct payoff from success (e.g., from patents) to be zero.[10] When funded, each project has an independent Poisson rate $\lambda > 0$ of success. In other words, the number of successes among a mass x of funded projects has a Poisson distribution of parameter λx. The state becomes $h = 1$ if at least one success occurs among the funded projects, and $h = 0$ otherwise. Therefore, in Stage 2, we have the state distribution:

$$\Pr(h = 1|x) = 1 - e^{-\lambda x}, \quad \Pr(h = 0|x) = e^{-\lambda x}.$$

We implicitly assume *knowledge spillover* of innovation: if there is an innovation breakthrough, then all firms enjoy the better state $h = 1$ and adopt the abatement technology, regardless of the source of breakthrough.

Research subsidies. The social planner chooses a linear research subsidy policy, which reimburses a certain fraction of the R&D costs and lowers the investor's effective funding cost.

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[10] Allowing the payoff to be R such that $0 \leqslant R < \frac{1}{\lambda}$ does not change the result qualitatively. We assume the payoff to be low in value to highlight the knowledge spillover effect that private payoffs from patent protection is not sufficient to attribute all social benefit of innovation to the innovator, leading to underinvestment in innovation.

Let the subsidy per unit of investment cost by a stand-alone type-e firm be $s(e)$, implying that an $s(e)$-fraction of the firm's investment cost is reimbursed by the government. Similary, denote the subsidy per unit of investment cost by a JV formed by a mass of firms as S. Our assumption of a linear R&D subsidy (a constant reimbursement rate per unit of eligible expenditure) mirrors common practice in both general and green innovation policy. [11]

Funding decision by an individual firm. An individual firm of size $\Delta > 0$ can independently fund a number of $x\Delta$ projects, with $x \geqslant 0$ being any finite number.[12] For firm type e under state h, denote $r(e, h) > 0$ as the discount rate (cost of capital). The discount rate displays *greenium*, that is, the cost of capital increases in the the emission per unit of output of the firm:

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

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.[13]

Then, given the total number $\tilde{x}$ of projects funded by all other players, this firm's

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[11] In most OECD countries, expenditure-based R&D tax incentives provide a proportional subsidy to each unit of qualifying R&D and now account for the majority of public support for business R&D. See `https://bit.ly/4o7IYOC`. Similarly, clean-energy and climate R&D programs, such as U.S. Department of Energy cost-share awards, typically require a fixed government cost share (e.g., 20–50% of project costs), effectively implementing a linear cost-reimbursement scheme. See `https://www.law.cornell.edu/cfr/text/2/910.130`.

[12] This means that the firm is deep-pocketed.

[13] 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.

individual problem reads:

$$\max_{x(e)} \quad \Pr(h=1|\tilde{x}+x(e)\Delta) \underbrace{\frac{\pi(e,1)}{1+r(e,1)}}_{\text{profit at } h=1} + \Pr(h=0|\tilde{x}+x(e)\Delta) \underbrace{\frac{\pi(e,0)}{1+r(e,0)}}_{\text{profit at } h=0} - \underbrace{x(e)(1-s(e)),}_{\text{R\&D cost after subsidy}} \tag{3}$$

where $x(e)$ is the intensity of R&D investment by this type-e firm so that $x(e)\Delta$ is the mass of projects funded, and $\pi(e,h)$ as the firm's production market profit in the second stage based on (1). Note that the firm's product market profit $\pi(e,h)$ at Stage 2 does not depend on its R&D investment $x(e)$ in Stage 1: this is due to the spillovers of abatement knowledge from the innovator to all other players.

Funding decision by a joint venture (JV). Alternatively, a mass of firms can form a research JV to fund any mass of projects. Suppose that the fraction of type-e firms joining the JV is $\mu(e) \in [0,1]$, so that the mass of the JV is:

$$m \equiv \int_0^{\bar{e}} g(e)\mu(e)\mathrm{d}e.$$

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 remaining competitive in the product market.[14] 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.[15]

Given the total number $\tilde{x}$ of projects funded by all other players, the JV's problem is

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

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

to find the optimal number of projects to invest, X, to solve:

$$\max_X \quad \Pr(h=1|\tilde{x}+X)\underbrace{\int_0^{\bar{e}}\frac{\pi(e,1)\mu(e)g(e)}{1+r(e,1)}\mathrm{d}e}_{\text{joint profit at } h=1}+\Pr(h=0|\tilde{x}+X)\underbrace{\int_0^{\bar{e}}\frac{\pi(e,0)\mu(e)g(e)}{1+r(e,0)}\mathrm{d}e}_{\text{joint profit at } h=0}$$
$$- \quad \underbrace{X(1-S).}_{\text{R\&D cost after subsidy}} \tag{4}$$

To interpret, 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, $\Pr(h = 1|\tilde{x}+X)$, is an increasing function of X. The Stage-2 profit $\pi(e, h)$ is discounted by rate $r(e, h)$, and the integral only includes the $\mu(e)$ fraction of firms within the JV. The third term is the R&D expense less the proportional research subsidy.

2.3 Stage 0: Social Planner's Choice

The social planner commits to the carbon tax policy $\tau(h)$ and the research subsidy rates at the outset. It aims to maximize social welfare at discount rate $r_P(h)$.

2.4 Timeline and Assumptions

The timeline is summarized as follows:

- Stage 0 (policy announcement), the social planner announces the carbon tax rate $\tau(h)$. It also announces the research subsidy rate for a type-e stand-alone investor, $s(e)$, and for the JV, S.

- Stage 1 (innovation), the JV and all firms outside of the JV decide simultaneously on the number of abatement innovation projects to fund.

- Stage 2 (production), given the realized innovation outcome, all firms act as price-takers and compete in the product market.

For simplicity, we make the following assumptions on the parameters.

Assumption 1 (Parameters)**.**

(i) The cost function satisfies $C(0) = 0$, $C'(q) > 0$ *and* $C''(q) > 0$ *for all* $q > 0$.

(ii) The utility function satisfies $U(0) = 0$, $U'(0) > 0$ *and* $U''(q) < 0$ *for all* $Q > 0$.

(iii) $\mathbb{E}[C'^{-1}(\bar{e} - e)k] < U'^{-1}(\bar{e}k)$.

(iv) $0 < r_P(1) \leqslant r_P(0)$.

Parts (i) and (ii) are common curvature assumptions on the cost function and utility function. Part (iii) says consumers' demand function are sufficiently high compared to the intensity of disutility k. This ensures strictly positive output for each firm under the first-best allocation. Part (iv) requires the social planner's discount rate to be lower in good state (innovation breakthrough) than in bad state (no breakthrough). This ensures that the discounted social welfare is improved with the breakthrough.

3 Analysis

3.1 Benchmark: No JV

We first consider a benchmark with no JV. This helps us highlight the free-rider problem and its consequences.

Lemma 1 (No JV)**.**

Suppose there is no JV, and research subsidy is $s(e) < 1$ *for all* $e \in [0, \bar{e}]$. *Then no carbon abatement project will be funded.*

Intuitively, for an infinitesimally small firm, the R&D cost is proportional to its size. In contrast, the private return is of the second order of its size, compounding the firm's negligible influence on the breakthrough probability with its negligible share of the industry-wide benefit. As the cost is of the first order while the benefit is of the second order, no firm invests in R&D. In other words, the knowledge spill-over creates free-riding incentives on all firms to the extent of no investment in equilibrium.

In contrast, a JV reshapes the research incentives. A JV stipulates the investment decisions of the firms within, thereby internalizing the externality of breakthrough, even if partially. With its discrete size, it can collectively invest to significantly increase the chance of breakthrough and reap a sizable share of the product-market gains from breakthrough, generating stronger private incentives to innovate inside the JV than in the stand-alone benchmark.

In what follows, we show how a social planner can exploit these stronger incentives when designing research subsidies targeted at the JV. In Section 3.2, we characterize the first-best allocation and the associated optimal policy mix——carbon tax and research subsidy——taking the JV structure as given. Section 3.3 then studies how the JV's composition (its size and brownness) should be optimally designed to minimize the required research subsidy to achieve the first best. Section 3.4 explores how to implement a designed JV structure.

3.2 First-Best Allocation

This section explores the first-best allocation of output and carbon abatement investment, denoted as $q^{\dagger}(e, h)$ and $x^{\dagger}$, respectively. We solve the problem backwards.

3.2.1 Output Choice at Stage 2

At stage 2, with realized state $h \in \{0, 1\}$, the social planner chooses $q^\dagger(e, h)$ for each type-e firm to maximize the consumer utility net of production costs and environmental damages, with the social welfare denoted as $W^\dagger(h)$:

$$\begin{aligned} W^\dagger(h) = \max_{q^\dagger(e,h)} \quad & \underbrace{U\left(Q^\dagger(h)\right)}_{\text{consumer utility}} - \underbrace{\int_0^{\bar{e}} C(q^\dagger(e,h))g(e)\mathrm{d}e}_{\text{production cost}} \\ & \underbrace{- k(h\rho + (1-h)) \int_0^{\bar{e}} q^\dagger(e,h) e g(e)\mathrm{d}e}_{\text{environmental damage}} \\ \text{s.t.} \quad & Q^\dagger(h) = \mathbb{E}[q^\dagger(e,h)]. \end{aligned}$$

The first order condition implies:

$$C'(q^\dagger(e,h)) = U'(Q^\dagger(h)) - k(h\rho + (1-h))e,$$

which clearly illustrates the tradeoff the social planner faces: marginal cost on the left hand side, marginal utility, and marginal environmental costs on the right hand side. This, together with the market clearing condition, pins down the aggregate quantity $Q^\dagger$:

$$Q^\dagger(h) = \mathbb{E}\left[C'^{-1}\left(U'(Q^\dagger(h)) - k(h\rho + (1-h))e\right)\right]. \tag{5}$$

As is guaranteed by Assumption 1, $Q^\dagger > 0$ uniquely exists, and $q^\dagger(e, h) > 0$ for all e and $h \in \{0, 1\}$.

3.2.2 R&D Investment at Stage 1

At stage 1, the planner selects the investment in carbon abatement technology, $x^\dagger$, to maximize the expected welfare, which is the expected welfare $W^\dagger(h)$ in stage 2 discounted back to stage 1 using the social planner's discount rate $r_P(h)$, net of the R&D expenses:

$$\begin{aligned} \max_{x^\dagger} \quad & \underbrace{\Pr(h=1|x^\dagger)\,\frac{W^\dagger(1)}{1+r_P(1)} + \Pr(h=0|x^\dagger)\,\frac{W^\dagger(0)}{1+r_P(0)}}_{\text{discounted product market welfare}} - \underbrace{x^\dagger}_{\text{R\&D cost}} \\ \text{where} \quad & \Pr(h=1|x^\dagger) = 1 - \Pr(h=0|x^\dagger) = 1 - e^{-\lambda x^\dagger}. \end{aligned}$$

The first order condition implies that:

$$x^\dagger = \frac{1}{\lambda}\log\left(\frac{\lambda W^\dagger(1)}{1+r_P(1)} - \frac{\lambda W^\dagger(0)}{1+r_P(0)}\right). \tag{6}$$

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

3.2.3 Implementing the First Best

We next show that given any existing JV, the first-best outcome $\big(q^\dagger(e,h), x^\dagger\big)$ can be implemented via a combination of carbon tax and research subsidy.

Proposition 1 (First Best Implementation)**.**

Fix an existing JV featuring $\mu(\cdot)$*. The first-best outcome can be attained by a carbon tax rate* $\tau(h) = k$*, zero research subsidies given to stand-alone firms outside of the JV (i.e.,* $s(e) = 0$

for all e), and a research subsidy S targeted at the JV, where:

$$S = 1 - \frac{\displaystyle\int_0^{\bar{e}} \mu(e)g(e)\left(\frac{\pi(e,1)}{1+r(e,1)} - \frac{\pi(e,0)}{1+r(e,0)}\right)\mathrm{d}e}{\displaystyle\frac{W^\dagger(1)}{1+r_P(1)} - \frac{W^\dagger(0)}{1+r_P(0)}}. \tag{7}$$

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. Note that under the proposed research subsidy policy, firms outside of the JV do not innovate because they do not receive any subsidy and choose to free-ride on the JV.

To interpret the carbon tax rate, consider the product market at Stage 2. By imposing a constant tax $\tau(h) = k$ per unit of emissions, each firm internalizes the marginal environmental damage from pollution in its output decision. In a competitive market with price-taking behavior, setting $\tau(h) = k$ 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 the research subsidy, consider the innovation stage at stage 1. Because a R&D breakthrough 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 the private and the social returns on abatement R&D. Specifically, (7) can be rewritten as:

$$\text{Subsidy per unit of R\&D investment} = 1 - \frac{\text{JV's Private Benefit of R\&D}}{\text{Social Benefit of R\&D}}.$$

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

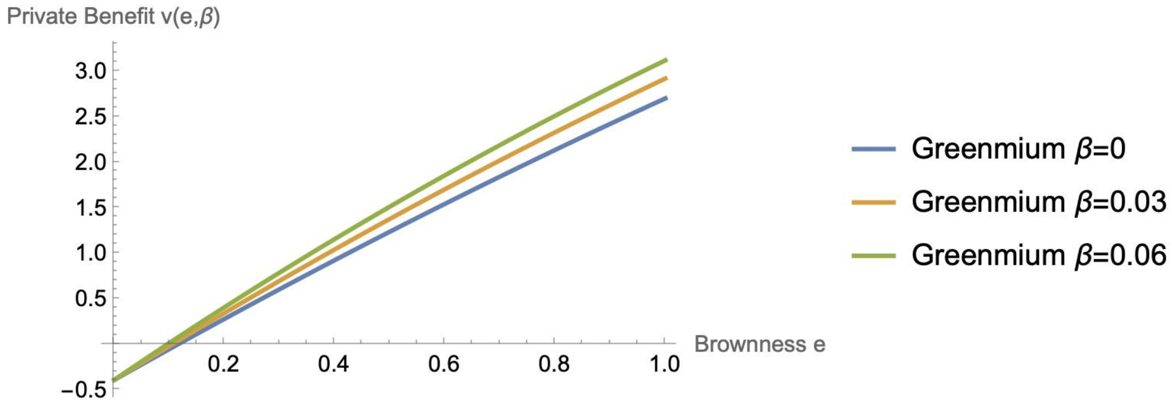

Figure 1: Type-e firm's private benefit $v(e, \beta)$ as an increasing function of brownness e and greenium β. Parameter choices are: $C(q) = 0.5q^2, U(Q) = 10Q - 0.3Q^2, k = 1, \rho = 1/2, \alpha = 0.15, e \sim U[0, 1]$.

benefit of R&D due to the knowledge spillover beyond the JV innovator.[16]

Proposition 1 then implies that the key to lowering the subsidy is to increase 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 $v(e, \beta)$:

$$v(e, \beta) \equiv \frac{\pi(e, 1)}{1 + r(e, 1)} - \frac{\pi(e, 0)}{1 + r(e, 0)}, \tag{8}$$

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

Lemma 2 (Monotonicity)**.**

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* $v(e, \beta)$ *increases in brownness* e *and greenium* β*.*

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[16] 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 $h = 0$.

Intuitively, an innovation breakthrough reduces emission 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 2 thereby implies the next two corollaries (Corollary 1 and Corollary 2) regarding how the first-best subsidy rate S as defined in (7) changes with the JV's brownness and the prevailing greenium.

First, we examine how the first-best 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. Now consider an increase in brownness of the JV without changing its size. That is, suppose we change a JV with composition $\mu(e)$ into $\hat{\mu}(e)$ such that $\int_0^{\bar{e}} \mu(e)g(e)\mathrm{d}e = \int_0^{\bar{e}} \hat{\mu}(e)g(e)\mathrm{d}e = m$. However, the new JV is "browner" in the sense that $\hat{g}(e|JV) \equiv \frac{\hat{\mu}(e)g(e)}{m}$ first-order-stochastic-dominates (FOSD) $g(e|JV) \equiv \frac{\mu(e)g(e)}{m}$. Corollary 1 shows that this change also reduces the first-best subsidy needed.

Corollary 1 (Subsidy and JV Brownness)**.**
If the JV changes its composition from $\mu(e)$ *to* $\hat{\mu}(e)$ *such that* $\int_0^{\bar{e}} \mu(e)g(e)\mathrm{d}e = \int_0^{\bar{e}} \hat{\mu}(e)g(e)\mathrm{d}e = m$ *and* $\hat{g}(e|JV) = \frac{\hat{\mu}(e)g(e)}{m}$ *dominates* $g(e|JV) = \frac{\mu(e)g(e)}{m}$ *in the FOSD order. Then*

(i) The JV becomes browner on average: $\int e\hat{g}(e|JV)\mathrm{d}e \geqslant \int eg(e|JV)\mathrm{d}e$.

(ii) The first-best subsidy rate S*, defined in* (7)*, is reduced.*

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 using the 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 first-best subsidy depends on the greenium.

Corollary 2 (Subsidy and Greenium)**.**
The first-best subsidy rate S, defined in (7)*, decreases in the greenium β.*

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 first-best subsidy varies with the size of the JV.

Corollary 3 (Subsidy and JV Size)**.**
Suppose $\mu(e) < 1$ for all e. Uniformly scaling up $\mu(e)$ to $j\mu(e)$ for some $j > 1$ will decrease (resp. increase) *the first-best subsidy S if and only if the JV's total private benefit $\int_0^{\bar{e}} \mu(e)v(e,\beta)g(e)\mathrm{d}e$ is* positive (resp. negative)*.*

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 first-best subsidy.

Corollary 4 (JV Size and Greenium)**.**
Suppose $\mu(e) < 1$ *for all* e*. Uniformly scaling up* $\mu(e)$ *to* $j\mu(e)$ *for some* $j > 1$ *will strengthen the negative effect of greenium* β *on* S*, i.e.* $\frac{\partial^2 s}{\partial\beta\partial j} < 0$.

That is, a larger JV enhances the subsidy-reduction effect of a larger greenium. Intuitively, this is because a larger JV internalizes more benefits from cost-of-capital reductions, thereby reducing the required subsidy even further. In another word, a larger JV size and a higher greenium *complement* each other in reducing subsidies.

Taken together, Corollaries 1 to 4 highlight a common theme: less government support is needed when market forces internalize more of the externalities—either through the greenium or through a JV composed of firms with the strongest private incentives to abate. This observation motivates our next step, where we characterize the subsidy-minimizing JV structure, i.e., the coalition a government would favor if it wished to limit public spending while still achieving the first-best level of green innovation.

3.3 Optimal JV Structure to Minimize Subsidy

In this section, we investigate the optimal JV structure, $\mu^*(\cdot)$, that minimizes the first-best research subsidy in (7). Note that since the first-best carbon tax rate is fixed at $\tau(h) = k$, this JV structure also minimizes the total net expenditure by the social planner (i.e., total subsidies minus total taxes).

Proposition 2 (Optimal JV Structure)**.**

Let $\mu^*(\cdot)$ *be the optimal JV structure that minimizes the first-best research subsidy defined by Equation (7). Then*

(i) $\mu^*(\cdot)$ *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* $e \geqslant e^*$*, and* $\mu^*(e) = 0$ *if* $e < e^*$*.*

(ii) The cutoff type e^* *decreases in greenium* β*.*

(iii) The optimal JV size $m^* = \int_{e^*}^{\bar{e}} g(e)\mathrm{d}e$ *increases in greenium* β*.*

(iv) Under the optimal JV structure, the research subsidy rate $S^* < 1$*.*

Part (i) of Proposition 2 implies that it is optimal to include only sufficiently brown firms into JV (those with brownness $e \geqslant e^*$). The reason is that browner firms benefit more from the abatement innovation. Part (ii) and (iii) state that when the prevailing greenium is larger, all emitting firms have stronger private incentives to innovate in abatement in order to reduce their cost of capital, thereby the optimal JV should include more and greener firms. Therefore, the optimal JV size is larger. Part (iv) states that since the social planner has taken advantage of JV's private incentives to innovate, the required R&D reimbursement rate is less than 100%.

Figure 2 demonstrates Proposition 2. The vertical axis in Figure 2 is $v(e, \beta)$, which is a type-e firm's private benefit from a breakthrough. The cutoff type e^* is the type e at which $v(e, \beta) = 0$. The optimal JV should include all types with $e \geq e^*$, as those types strictly benefit from the breakthrough (those with $v(e, \beta) \geq 0$). Moreover, higher greenium (higher β), lower e^*, implying that the optimal JV should include additional greener firms when greenium is higher.

Note that although we restrict attention to research subsidies targeted only at the JV (and not stand-alone firms), this is without loss of generality. Because the JV partially

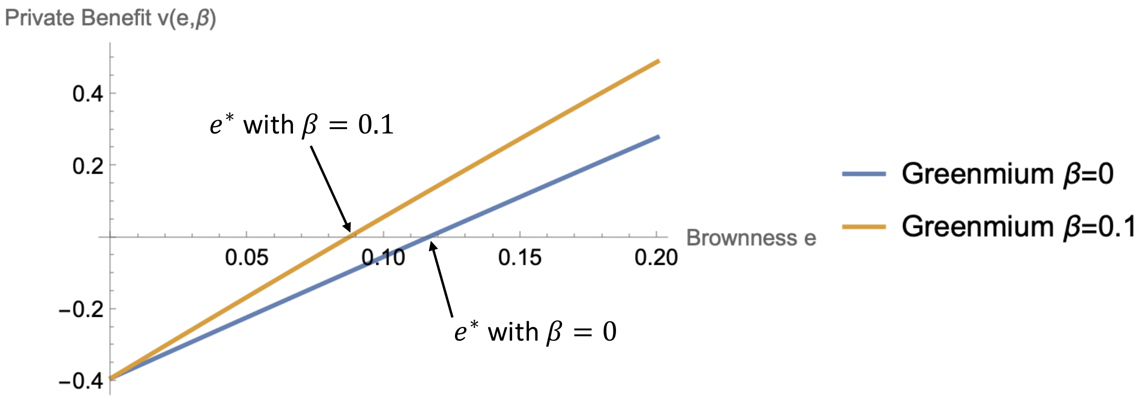

Figure 2: The cutoff type e^* as a function of greenium β. Parameter choices are: $C(q) = 0.5q^2, U(Q) = 10Q - 0.3Q^2, k = 1, \rho = 0.5, \alpha = 0.15, e \sim U[0, 1]$.

internalizes the benefits of innovation, it requires a subsidy of only $S^* < 1$. In contrast, stand-alone firms require full cost reimbursement (i.e., $s(e) = 1$) to engage in any investment. Thus, subsidizing the JV is strictly more cost-effective than subsidizing stand-alone firms.

3.4 Endogenous Formation of JV

We have so far analyzed climate policy and the optimal JV structure under the assumption that JV membership is *exogenously* given. This is meant to capture settings in which a JV is already in place for reasons outside our model—for example, pre-existing collaborative relationships, supply-chain links, or complementarities in expertise—rather than being formed specifically to internalize the knowledge spillovers we study.

By contrast, when a JV must form *endogenously* to internalize such spillovers, we face a fundamentally different problem. In these environments, the optimal JV that minimizes the first-best research subsidy, as characterized in Proposition 2, may be difficult to achieve organically because free-riding in JV participation can prevent the socially desired coalition from forming. Since R&D costs for JV members may not be fully refunded by the subsidies (that is, $S < 1$), individual firms may prefer to let others bear the investment 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.

To capture the endogenous formation of the JV, we revise the timeline in subsection 2.4 by adding Stage 0.5 between Stage 0 and Stage 1.

- Stage 0 (policy announcement), the social planner announces the carbon tax rate $\tau(h)$. It also announces the research subsidy rate for a type-e stand-alone investor, $s(e)$, and for the JV, S.
- **Stage 0.5 (JV formation)**, the social planner first announces a recommended JV composition $\mu(e)$ and a cost-sharing rule $l(e)$, where $l(e)$ denotes the fraction of the unreimbursed investment costs allocated to a type-e JV member such that $\int_{e\in\mu} l(e)g(e)\mathrm{d}e = 1$, where μ denotes the set of types included in the JV. All firms invited to the JV then simultaneously decide whether to join, taking $l(e)$ as given.
- Stage 1 (innovation), the JV and all firms outside of the JV decide simultaneously on the number of abatement innovation projects to fund.
- Stage 2 (production), given the realized innovation outcome, all firms act as price-takers and compete in the product market.

To analyze each selected firm's incentive to join the JV in Stage 0.5, consider a type-e firm. Suppose both the subsidy rate targeted at the JV, S, and the subsidy rate for stand-alone firms, $s(e)$, are less than 100%. The firm's payoff from joining the JV with structure $\mu(\cdot)$, given other selected firms have agreed to join, is

$$\Pr(h=1|join)\frac{\pi(e,1)}{1+r(e,1)} + (1-\Pr(h=1|join))\frac{\pi(e,0)}{1+r(e,0)} - X(1-S)l(e),$$

where the first two terms represent the expected product market profit. The third term is the unreimbursed investment costs allocated to this firm, where $X(1-S)$ is the JV's total unreimbursed investment costs, and $l(e)$ is the firm's allocated share.

In contrast, if not joining the JV, the firm does not pay the investment costs, nor does it receive the JV subsidy S. It does not receive the subsidy $s(e)$ for stand-alone firms either, because it would not make any investment as a stand-alone firm given that $s(e) < 1$. Meanwhile, the firm enjoys the same amount of product market profit conditional on the innovation outcome h due to the knowledge spillovers beyond the JV members. Therefore, the firm's payoff if not joining the JV is

$$\Pr(h=1|\textit{not join})\frac{\pi(e,1)}{1+r(e,1)} + (1-\Pr(h=1|\textit{not join}))\frac{\pi(e,0)}{1+r(e,0)}.$$

Then, the benefit from joining the JV relative to not joining is the difference between the two terms above:

$$B(e) \equiv (\Pr(h=1|\textit{join}) - \Pr(h=1|\textit{not join}))\, v(e,\beta) - X(1-S)l(e), \tag{9}$$

and the firm chooses to join if and only if $B(e) \geq 0$. Intuitively, the first term of $B(e)$ is the expected increase in the firm's private benefit from the innovation breakthrough, while the second term is the investment costs that is not reimbursed.

We now consider two distinct scenarios in Stage 0.5.

- **Scenario 1: decentralized formation.** Each selected firm decides on whether to join without the social planner's interference.
- **Scenario 2: coordinated formation.** The social planner makes a take-it-or-leave-it (TIOLI) proposal, such that the JV can only be permitted to be established if *all* selected firms agree to join.

The next proposition shows that in Scenario 1 (decentralized formation), any JV structure with subsidy rate $S < 1$ could not be formed due to the free-riding motives.

Proposition 3 (No JV with Decentralized Formation)**.**
Suppose under Scenario 1 (decentralized formation), any JV structure with subsidy rate $S < 1$ *can not be formed. That is, there exists an unique Nash equilibrium where no firm joins the JV.*

Intuitively, a firm that joins the JV must bear strictly positive investment costs because the cost reimbursement rate is less than full. Yet the benefit from joining is negligible: as an infinitesimal firm, its participation changes the breakthrough probability only by a negligible amount, while knowledge spillovers ensure that even an outsider can free-ride on any breakthrough generated by JV members. Hence, in equilibrium, no firm finds it profitable to join the JV. Formally, in Equation 9, the first term is zero because $\Pr(h = 1|join) = \Pr(h = 1|not\ join)$, while the second term is strictly negative because $S < 1$; so the net profit from joining, $B(e)$, is negative.

The no-JV result in Proposition 3 is driven by the severe free-riding issue in JV formation. One way for the social planner to curb the free-riding issue is to make a TIOLI proposal that renders each firm *pivotal* to the JV's formation. This is precisely the setup in Scenario 2 (coordinated formation): if any selected firm refuses to join, the JV is not established, even if all other selected firms accept. In another word, a rejecting firm faces a world in which all potential investors are stand-alone firms and no project is funded, so $\Pr(h = 1|not\ join) = 0$. Therefore, in Scenario 2 (coordinated formation), the net profit from joining in Equation 9 becomes

$$B(e) \equiv \Pr(h = 1|join)v(e, \beta) - X(1 - S)l(e). \tag{10}$$

A type-e firm agrees to join a JV if and only if $B(e) \geq 0$. Note that $\Pr(h = 1|join)v(e, \beta)$

captures the type-e firm's private benefit from the abatement investment, while $X(1-S)l(e)$ measures the firm's private investment cost if joining the JV. Therefore, the firm joins the JV if and only investing in abatement through the JV is a *positive-NPV* project given the cost-sharing rule.

The next proposition charaterizes the implementation of the optimal JV structure obtained in Proposition 2.

Proposition 4 (Implementation of Optimal JV in Coordinated Formation)**.**
(i) Under Scenario 2 (coordinated formation), the optimal JV structure $\mu^*(\cdot)$ specified in Proposition 2, which includes all firms with $v(e,\beta) \geq 0$ (or, $e \geq e^*$) in the JV, can be implemented by the social planner's TIOLI proposal that includes a cost-sharing rule

$$l(e) \quad = \quad \frac{v(e,\beta)}{\int_{e^*}^{\bar{e}} v(e,\beta)g(e)\mathrm{d}e} \tag{11}$$

for a type-e firm.
(ii) The cost share $l(e)$ increases in brownness e.

Proposition 4 shows that the optimal JV structure in Proposition 2 is implementable via a TIOLI proposal that establishes the JV only if *all* invited firms agree to join. By making each invited firm pivotal for JV formation, this proposal mitigates the free-riding problem in JV participation.

The proposal also features a brownness-contingent cost-sharing rule $l(e)$, which assigns a larger share of the unreimbursed investment cost to browner firms. Intuitively, firms with higher emissions e enjoy a larger private benefit from the breakthrough (a higher $v(e,\beta)$) and are therefore willing to bear a greater fraction of the investment cost. Interestingly, Equation 11 shows that the share of cost born by a type-e investor is equal to its *private benefit share*, which is the ratio of its own private benefit from a breakthrough, $v(e,\beta)$, to the JV's total private benefit, $\int_{e^*}^{\bar{e}} v(e,\beta)g(e)\mathrm{d}e$.

Finally, note that imposing the JV participation constraint—that each invited firm must voluntarily join—does not increase the minimized first-best subsidy rate S^*, which was obtained in Proposition 2 without such a constraint. The reason is as follows. Under S^*, the JV optimally chooses the first-best investment level $x^\dagger > 0$, implying that such a level of investment is a positive-NPV project for the JV as a whole given the subsidy. Hence there exists a sharing rule for the unreimbursed investment cost such that each JV member's investment is also a positive-NPV project individually, so that all participation constraints can be satisfied without raising S^*.

Taken together, our analysis with the implementation of the optimal JV structure shows that government coordination is essential for JV formation: absent such coordination, the optimal JV structure cannot be implemented.

4 Policy Implications

Because research JVs by design bring together competing firms, our results naturally connect to the growing debate on how antitrust policy should handle climate-motivated collaboration (OECD, 2021; Hearn et al., 2023; Hanawalt et al., 2024). Existing instruments—such as the U.S. National Cooperative Research and Production Act, the DOJ–FTC Antitrust Guidelines for Collaborations Among Competitors (2000)[17] , and the EU's R&D Block Exemption and Horizontal Guidelines on Horizontal Cooperation Agreements (2023)[18]—are largely designed to clarify what kinds of joint R&D are acceptable and to reduce antitrust exposure for firms that voluntarily choose to cooperate. They do not, however, address the underlying coordination failure that we identify: even when a brown-firm JV would be socially desirable and subsidy-minimizing, no individual firm finds it optimal to initiate or join because

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[17] `https://bit.ly/3LP8eLW`.

[18] `https://competition-policy.ec.europa.eu/system/files/2023-07/2023_revised_horizontal_guidelines_en.pdf`.

abatement knowledge spills over to all. Our analysis therefore points to a complementary role for government policy. In addition to offering antitrust "safe harbors," policymakers may need to *proactively* help assemble or steer the membership of climate-oriented research JVs—using, for example, take-it-or-leave-it participation schemes and cost-sharing rule designs that make firms pivotal in the formation of the coalition.

A further implication concerns how these collaborations should be assessed once they exist. Under both the DOJ–FTC guidelines and the EU Horizontal Guidelines, cooperative R&D among competitors is typically reviewed under a rule-of-reason framework that balances potential efficiency gains against possible anticompetitive effects. Our model suggests that, in the climate context, this balancing exercise ought to pay explicit attention to the *innovation incentives* of JV members. In particular, we show that the strength of members' incentives to undertake green R&D is shaped by three characteristics: the JV's overall "brownness," its size, and the prevailing greenium. JVs that are sufficiently brown, include the right set of participants, and operate in an environment with a high greenium are more likely to undertake substantial abatement innovation for reasons that are aligned with social objectives rather than collusive ones. Incorporating information on these dimensions into rule-of-reason analysis—within the flexibility already available in current U.S. and EU guidance—can therefore help distinguish research JVs that are likely to advance climate-related innovation from those that may raise more conventional competition concerns.

5 Conclusion

We study climate policy when high-emission ("brown") firms collaborate in research joint ventures (JVs) to develop carbon-abatement technologies. In our framework, climate change involves two layers of externalities—emissions and knowledge spillovers from green R&D—so collaboration among competitors can, in principle, help internalize innovation benefits. We show that a constant carbon tax rate combined with a linear R&D subsidy can implement the first best, and that the first-best subsidy depends critically on the structure of the brown-firm JV and on financial-market conditions. Specifically, the required per-unit subsidy is lower when the greenium (the capital-market penalty for emissions) is higher, when the JV is composed of browner firms, and when it includes more of the firms that gain most from abatement.

We then characterize the subsidy-minimizing JV. The optimal coalition consists of all firms that are sufficiently brown to benefit from the abatement breakthrough, but not greener firms that would be hurt by intensified post-innovation competition. As the greenium rises, this threshold shifts and the optimal JV expands to include additional, and even greener, firms because stronger capital-market penalties make abatement R&D privately attractive to a broader set of emitters. Crucially, this coalition does not form on its own: given knowledge spillovers, each firm prefers to free-ride on others' investment. However, the optimal JV can be implemented by government coordination that makes each firm pivotal for the JV formation and allocates unreimbursed costs in line with firms' private innovation incentives. These findings imply that governments can subsidize less by coordinating more—using policy tools to shape who collaborates, rather than only how much to pay.

Our analysis has clear implications for antitrust and climate policy. Because brown-firm research JVs involve collaboration among competitors, they sit squarely in the ESG–antitrust debate. Our results provide a micro-founded rationale for when such collaborations are likely to be socially desirable—namely, when JV brownness, size, and the prevailing greenium align private incentives with social goals—and suggest that these characteristics are natural inputs into rule-of-reason assessments of climate-oriented R&D alliances.

At the same time, our framework is deliberately stylized. We treat the JV as if it can costlessly implement the efficient research effort, abstracting from potential internal governance conflicts. We also assume that collaboration at the innovation stage does not facilitate collusion in product markets, even though R&D cooperation can, in practice, create channels for anticompetitive coordination. Both simplifications imply that our stated social benefits of brown-firm JVs should be viewed as upper bounds. Relaxing these assumptions—by incorporating JV governance frictions and explicit product-market collusion—would be a natural direction for future work.

Appendix: Proofs

Proof of Lemma 1.
Take the derivative of (3) w.r.t. $x(e)$:

$$-(1-s(e))+\Delta\lambda e^{-\lambda(\tilde{x}+\Delta x(e))}\left(\frac{\pi(e,1)}{1+r(e,1)}-\frac{\pi(e,0)}{1+r(e,0)}\right).$$

Since there is no JV and each individual firm has $\Delta \to 0$, we take the limit to arrive at $-(1-s(e))<0$. Therefore, no project is funded. $\square$

Proof of Proposition 1.
Step 1 (stage 2, product market), for innovation outcome $h \in \{0,1\}$, find optimal output $q(e,h)$ for each firm that maximizes flow profit $\pi(e,h|\tau(h))$, and then solve for the equilibrium $q(e,h)$. Let $q(e,h)=q^\dagger$ and solve for the carbon tax rate $\tau(h)$, then we find that $\tau(h)=k$, the marginal environmental damage of emission. Part (iii) of Assumption 1 ensures the first-best output is positive.

Step 2 (stage 1, innovation), find the equilibrium JV abatement technology investment X that maximizes JV profit in Equation (4) such where letting the carbon tax rate being $\tau(h)=k$ and research subsidy being SX. Find the optimal JV investment X and let $X=x^\dagger$, and solve for S. $\square$

Proof of Lemma 2.
In the competitive equilibrium, $p=U'(Q(h))=k(h\rho+1-h)e+C'(q(e,h))$, and $Q(h)=\mathbb{E}[q(e,h)]$. These conditions pin down $Q(h)$ and $q(e,h)$ for all e,h. The profit of a type-e firm is:

$$\pi(e,h)=q(e,h)(U'(Q(h))-k(h\rho+1-h)e)-C(q(e,h)),$$

and the private benefit is:

$$\begin{aligned} v(e,h) \quad = \quad & \frac{C(C'^{-1}(U'(Q(0))-ke))-(U'(Q(0))-ke)C'^{-1}(U'(Q(0))-ke)}{1+\alpha+\beta e} \\ & -\frac{C(C'^{-1}(U'(Q(1))-\rho ke))-(U'(Q(1))-\rho ke)C'^{-1}(U'(Q(1))-\rho ke)}{1+\alpha+\rho\beta e}. \end{aligned}$$

Taking the derivative of $v(e,h)$ w.r.t. e and evaluating at $e=\beta=0$, we have

$$\frac{k}{1+\alpha}(C'^{-1}(U'(Q(0)))-\rho C'^{-1}(U'(Q(1)))).$$

Because $Q(1) > Q(0)$, $U' < 0$, $C'' > 0$ and $\rho < 1$, we conclude that the derivative is strictly positive. Due to continuity, there exists $e_e^{\max}$ and $\beta_e^{\max}$ such that the derivative is positive for all $e \in [0, e_e^{\max}]$ and $\beta \in [0, \beta_e^{\max}]$.

Taking the derivative of $v(e, h)$ w.r.t. β, dividing by e, and evaluating at $e = \beta = 0$, we have

$$\frac{1}{(1+\alpha)^2}\left(F(U'(Q(0))) - \rho F(U'(Q(1)))\right),$$

where the function $F(x) \equiv xC'^{-1}(x) - C(C'^{-1}(x))$. Note that $F'(x) = C'^{-1}(x) > 0$. Because $Q(1) > Q(0)$, $U' < 0$ and $\rho < 1$, we conclude that the above expression is strictly positive. Due to continuity, there exists $e_\beta^{\max}$ and $\beta_\beta^{\max}$ such that the derivative is positive for all $e \in [0, e_\beta^{\max}]$ and $\beta \in [0, \beta_\beta^{\max}]$. Finally, set $e^{\max} \equiv \min\{e_e^{\max}, e_\beta^{\max}\}$ and $\beta^{\max} \equiv \min\{\beta_e^{\max}, \beta_\beta^{\max}\}$. □

Proof of Corollary 1.
The first-best subsidy rate S is defined as

$$S = 1 - \frac{\displaystyle\int_0^{\bar{e}} g(e)\mu(e)v(e,\beta)\mathrm{d}e}{\dfrac{W^\dagger(1)}{1+r_P(1)} - \dfrac{W^\dagger(0)}{1+r_P(0)}}. \tag{12}$$

Since $\hat{g}(e|JV)$ FOSD $g(e|JV)$ and $\int_0^{\bar{e}} \mu(e)g(e)\mathrm{d}e = \int_0^{\bar{e}} \hat{\mu}(e)g(e)\mathrm{d}e$ and also Lemma 2 implies that $v(e, \beta)$ increases with β, then we must have $\int_0^{\bar{e}} g(e)\hat{\mu}(e)v(e,\beta)\mathrm{d}e \geqslant \int_0^{\bar{e}} g(e)\mu(e)v(e,\beta)\mathrm{d}e$. In addition, the term $\frac{W^\dagger(1)}{1+r_P(1)} - \frac{W^\dagger(0)}{1+r_P(0)} > 0$ due to part (iv) of Assumption 1. Therefore, S under $\hat{\mu}(e)$ is smaller. □

Proof of Corollary 2.
Equation 12 and Lemma 2 implies that S is lower when β is higher. □

Proof of Corollary 4.
Replace $\mu(e)$ with $j\mu(e)$ in Equation (12), then we have

$$\tfrac{\partial^2 S}{\partial\beta\,\partial j} = \frac{-\displaystyle\int_0^{\bar{e}} g(e)\,\mu(e)\frac{\partial v(e,\beta)}{\partial\beta}\,de}{\dfrac{W^\dagger(h=1)}{1+r_P(h=1)} - \dfrac{W^\dagger(h=0)}{1+r_P(h=0)}},$$

which is negative because Lemma 2 implies that $\frac{\partial v(e,\beta)}{\partial\beta} > 0$.

□

Proof of Proposition 2.
For part (i), it can be shown that the ratio of discounted profit with innovation breakthrough over the discounted profit without,

$$\frac{\pi(e,1)}{1+r(e,1)}\Big/\frac{\pi(e,0)}{1+r(e,0)},$$

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 (ii) is implied by the ratio increasing in β. Part (iii) is implied by part (ii). Part (iv) is due to the fact that all firms included in the JV have positive $v(e, \beta)$.

□

Proof of Proposition 4.

To see part (i), observe first that $\int_{e^*}^{\bar{e}} l(e)g(e)\mathrm{d}e = 1$, implying that 100% of the unreimbursed investment costs are shared among the JV members. Second, we verify that each selected firm is willing to join the JV under the cost-sharing rule. A type-e firm's net profit from joining given all other selected firms agree to join is captured by Equation 10. With the first-best investment $x^\dagger$, the first-best probability of a breakthrough, $\Pr(h = 1|x^\dagger)$, and the optimal JV subsidy rate S^*, the profit from joining can be simplifed as

$$B(e) = v(e,\beta)\left(\Pr(h=1|x^\dagger) - \frac{x^\dagger}{\frac{W^\dagger(1)}{1+r_P(1)} - \frac{W^\dagger(0)}{1+r_P(0)}}\right).$$

The first term $v(e, \beta)$ is positive for all firms with $e \geq e^*$ (i.e., all firms in the JV). The second term is also positive, because the planner's optimization result as in Equation 6 shows that $x^\dagger > 0$ generates a higher social welfare than zero investment, implying that the NPV of investing $x^\dagger$ in the abatement technology, expressed as $\Pr(h = 1|x^\dagger)\left(\frac{W^\dagger(1)}{1+r_P(1)} - \frac{W^\dagger(0)}{1+r_P(0)}\right) - x^\dagger$, is positive. Therefore, $B(e) \geq 0$ for all $e \geq e^*$, that is, all selected firms are willing to join the JV.

Par (ii) is implied by Lemma 2.

□

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