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Screening green innovation through carbon pricing

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ABSTRACT

Effective climate change mitigation requires green innovation, but not all projects have equal social value. We examine the role of innovation heterogeneity in a model where the policy maker cannot observe innovation quality and directly subsidize the socially most valuable green innovations. We find that carbon pricing works as an innovation screening device; this creates a premium on the optimal carbon price, raising it above the Pigouvian level. We identify conditions for perfect screening and generalize results to screening policies under alternative intellectual property regimes and complementary policies. A calibration reveals that screening can justify a carbon price that is up to three times the Pigouvian price.

1. Introduction

The development and adoption of green technologies is of key importance to achieving climate targets. A comprehensive climate policy should thus not only include a carbon price to internalize the negative emission externalities, but also research and development (R&D) policies that reward innovations according to their social value. These instruments are implemented in markets with a substantial degree of heterogeneity. This heterogeneity is illustrated in Fig. 1, which displays the number of forward citations of climate change mitigation patents in manufacturing. It shows that the majority of patents receive zero or one citation, while over forty percent of all citations are accrued by fewer than two percent of all patents. Citations are generally considered a proxy for innovation quality and spillovers.[2] As such, the strong skew in citations indicates significant heterogeneity in the quality of emission mitigation patents and their social value.[3]

In light of this heterogeneity, the success of climate policies depends not simply on whether they lead to more innovation, but particularly on whether they generate the *right* innovation. Whereas emission prices conveniently incentivize the adoption of

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2 This is supported by empirical work that establishes the positive relationship of patent citations with measures of innovation spillovers (Jaffe et al., 2005) and private returns to innovation (Hall et al., 2005; Kogan et al., 2017), and motivates the practice of using citation-weighted patents as a measure of the quality-adjusted volume of innovation in the empirical literature on innovation and growth (see e.g., Bloom et al. 2013, Aghion et al. 2016).

3 The citation distribution and implied diversity of green innovation quality is not unique to the selected time period or technology: akin to Fig. 1, Popp et al. (2013) and Dechezleprêtre et al. (2017) report significant asymmetries and skewness in the quality of green innovation. The finding that both the private returns to innovation and knowledge spillovers from innovation are strongly skewed applies more generally to other technology fields; see Trajtenberg (1990), Scherer and Harhoff (2000) and Silverberg and Verspagen (2007).

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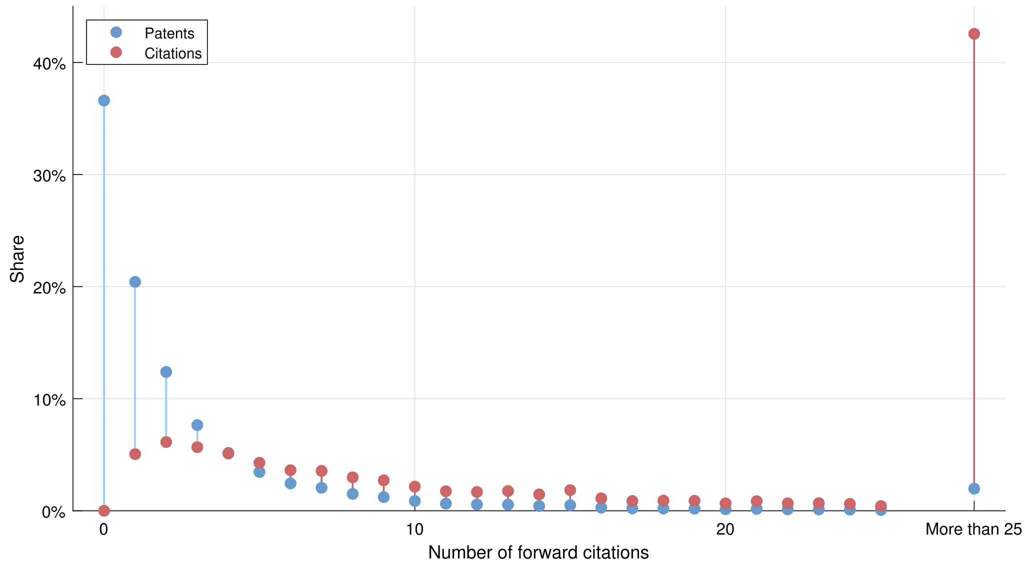

Fig. 1. 5-year citation distribution for green patents.
Notes: The figure uses European Patent Office (EPO) PATSTAT data and displays citation frequencies for the 86,238 patents registered in 2017 in the Y02P class in the Cooperative Patent Classification (CPC) system for the 'production and processing of goods' sector. The figure displays both the share of patents (blue bars) and the share of total citations (red bars) by citation bin. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

lowest-cost abatement technologies, R&D subsidies do not, by themselves, incentivize the development of the socially most valuable technologies. Instead, such subsidies rely either on the policy maker's ability to 'pick winners' by targeting support to the most valuable technologies, or alternatively amount to subsidies that are paid across the board and run the risk of being partly wasted on inferior projects.

This article explores a third alternative: a climate policy design that screens the most valuable innovations through a combination of subsidies, carbon pricing, and patent rights. We develop a model where innovators privately observe innovation cost and quality, and introduce green innovations to the market to sell to polluting firms. In addition to private returns, innovation may generate spillovers, which are greater for high-quality technologies.

As the main result, we show that the policy maker can use carbon prices to screen the most socially valuable innovations. The intuition is as follows. Across-the-board R&D subsidies reward the technologies that are the cheapest to develop, socially valuable or not. In contrast, high carbon prices generate demand for carbon abatement technologies, and more so for the most valuable high-quality innovations that can spread more widely and thus have the largest market.[4] Moreover, a higher carbon price alleviates the distortion due to positive mark-ups on abatement technologies created by the intellectual property rights system. These findings together imply that there exists a previously unidentified screening benefit to emission prices that gives rise to a 'carbon price premium', raising the optimal carbon price above the marginal emission damages.

Does the optimal policy resolve the problem of 'picking winners'? We show that in a special case the policy maker reaches the first-best using a combination of high carbon prices and intellectual property rights that perfectly screen in the socially most valuable innovations. This is possible when there are no innovation spillovers and when firms' energy use is perfectly inelastic. If these restrictive conditions are not satisfied, the first-best allocation is out of reach, and the policy maker must additionally rely on direct R&D subsidies. Still, we can show that the optimal policy reduces the need for direct subsidies vis-à-vis a naive policy that does not exploit the screening benefit of carbon prices.

Our core result, that the policy maker can use high carbon prices as an instrument for screening the socially valuable innovations, is generally maintained under alternative assumptions regarding the intellectual property rights system and complementary policies; we reassess the optimal carbon price under exogenous patent systems, patent buyouts, and uptake subsidies for the abatement technologies.

To quantify impacts, we calibrate the model to the European manufacturing sector. The results indicate that innovation heterogeneity can significantly increase optimal carbon prices: we find carbon prices close to three times the Pigouvian level,

[4] This intuition is consistent with empirical evidence for the positive relationship between innovation quality and private market value (Harhoff et al., 1999; Hall et al., 2005; Kogan et al., 2017). Particularly, Hall et al. (2005) find a positive relationship between firm valuation and patent citations, and Harhoff et al. (1999) and Kogan et al. (2017) establish a positive relationship between a patent's estimated economic value and the number of forward citations. In contrast to these articles, Abrams et al. (2013) find an inverted u-shaped relationship between economic value and forward citations. They explain this by widespread strategic patenting in high-value industries, aimed at discouraging follow-on innovation.

averaging around twice the value of the Pigouvian level. Our numerical analysis further establishes that innovation heterogeneity, coupled with the inability to 'pick winners', results in substantial welfare losses. A large share of these losses can be mitigated by implementing the optimal policy mix, including higher carbon prices.

Literature. A primary reason why most economists favor carbon pricing over command-and-control policies is its informational simplicity: carbon prices efficiently allocate abatement efforts in the presence of heterogeneity in abatement costs across sectors, firms and technologies. In contrast, R&D policies are informationally demanding, as they require policy makers to know which innovations should be incentivized. Despite the large literature scrutinizing the twin environmental and innovation market failures,[5] the policy implications of the substantial heterogeneity in green innovation have received strikingly little consideration.

Instead, the literature typically focuses on the case where innovators are homogeneous. In such a setting, a uniform R&D subsidy, if available, can accurately correct the positive externality from technology spillovers. Combining this R&D subsidy with an appropriate carbon price allows the policy maker to adequately address both market failures (Gerlagh et al., 2009, 2014; Acemoglu et al., 2012, 2016; Greaker et al., 2018).[6] Research has then focused on second-best environments, where instruments are either unavailable or constrained at suboptimally low levels. Contributions exploring second-best policy in the absence of green R&D subsidies includes Hart (2008), Gerlagh et al. (2009) and Greaker and Pade (2009). Fischer (2008) assesses policy under suboptimal carbon prices, while Popp (2006) and Fischer and Newell (2008), as well as the more recent work by Fischer et al. (2017), Hart (2019) and Fischer et al. (2021) provide a more general assessment of second-best policy exploring multiple policy constraints and alternative policy instruments.[7] Our primary contribution to this literature is the consideration of heterogeneity in innovation. As such, our results do not rely on restricting the levels of carbon prices or R&D subsidies. Instead, it is the presence of heterogeneous innovators combined with the inability to specifically tailor R&D subsidies to this heterogeneity that creates a demand for using the carbon price as a screening instrument. The screening effect we identify creates a carbon price premium that is new in the green innovation literature, but is related to the selection effect identified by Ahlvik and Liski (2022) in a setting where polluting firms can avoid carbon pricing by relocating production.

Innovation heterogeneity and the corresponding need to design an intellectual property right system that adequately encourages R&D under privately informed innovators are core features in the literature on general R&D policies (for instance, Scotchmer, 1999; Hopenhayn et al., 2006; Weyl and Tirole, 2012). In this innovation policy literature, the demand curve is typically exogenous, and the optimal patenting system strikes a balance between incentivizing high-quality innovation and mitigating under-supply of technology. Green innovation as we consider in this article is fundamentally different from the types of R&D analyzed in this literature, as demand is not exogenous but instead created by the environmental policy.[8] As such, the possibility to manipulate the policy-driven demand for innovation implies an additional policy tool which can be used to incentivize high-quality innovations.

Our study also contributes to the recent literature on how government can more broadly design policies to screen the 'right' innovation and maximize welfare. This includes Acemoglu et al. (2018) and Akcigit et al. (2022), who consider optimal corporate taxes alongside R&D subsidies in contexts with firm dynamics and heterogeneity in research productivity and quality. In addition, Lach et al. (2021) study how government loan programs can be designed to screen projects that generate positive expected social returns but would not be otherwise funded.

The remainder of the article is structured as follows. Section 2 presents the analytical model. Section 3 presents a benchmark policy in which the policy maker can condition subsidies on innovation quality, and solves for the optimal combination of carbon and technology prices when subsidies are implemented across the board. Section 4 considers alternative intellectual property rights regimes and complementary technology uptake subsidies. The main model takes the size of the innovation spillover as exogenous; in Section 5 endogenizes these spillovers. Section 6 presents a numerical analysis, and Section 7 concludes.

2. Model

Final output and abatement. Consider the model as follows. A competitive market produces the numeraire output according to the production function, $Y(E)$, where E denotes energy use and $Y'(E) > 0$ and $Y''(E) < 0$. Energy has a cost per unit of $\xi > 0$. Emissions are a byproduct from energy use, and impose an external cost on society equal to $\Delta > 0$ per unit of emissions. For convenience, we assume that each unit of energy generates one unit of emissions. Emissions can be reduced through abatement A, such that total emissions equal $E - A$, with

$$A = \frac{1}{\beta} \int_{\mathcal{N}} \theta_i^{1-\beta} q_i^{\beta} di, \tag{1}$$

where $\mathcal{N}$ is the set of abatement inputs developed and sold by innovators, q_i denotes the quantity used of abatement input of technology i, θ_i a measure of input quality and we assume $\beta \in (0, 1)$. As we specify below, whether or not an innovation is developed

[5] See Popp et al. (2010), Popp (2019) for reviews of this literature.

[6] Both R&D subsidies and carbon pricing are widely used and even high carbon prices are observed in practice. In 2019, government support for business R&D amounted to 0.67 percent of GDP across the OECD on average (OECD, 2021). Globally, there are 57 carbon pricing initiatives either implemented or scheduled for implementation, with prices ranging from very low values ($\$1/tCO_2$ in Ukraine) to values that are above typical estimates for the Pigouvian level ($\$130/tCO_2$ in Sweden); see World Bank (2022).

[7] Further work also considers implications of unilateral policy making (Hémous, 2016; van den Bijgaart, 2017) and limited policy commitment (Laffont and Tirole, 1994, 1996; Montero, 2011; Datta and Somanathan, 2016; Harstad, 2020).

[8] This idea has strong empirical support, for instance Calel and Dechezleprêtre (2016), Calel (2020) establish a positive effect of carbon pricing on green patenting. See also Grubb et al. (2021) for a review.

depends on cost and returns; as such, $\mathcal{N}$ is endogenous. Firms purchase abatement inputs at a price p_i per unit. Technologies can be understood broadly; for instance they can represent carbon dioxide scrubbers with a new method for post-combustion carbon capture, or a new type of solar panels with improved structure.[9]

To incentivize emission mitigation, a policy maker can introduce a carbon price, τ.[10] Firms can then lower emission cost by either reducing energy use or adopting abatement technologies. Profit-maximizing firms will choose energy use such that the marginal benefit of energy equals its marginal cost: $Y'(E) = \xi + \tau$. The quantity of abatement inputs are chosen similarly so that the marginal emission cost savings due to abatement equal the price of the input: $\tau\theta_i^{1-\beta}q_i^{\beta-1} = p_i$. This expression can be rewritten to obtain the demand function for abatement inputs:

$$q_i = \left(\frac{\tau}{p_i}\right)^{\frac{1}{1-\beta}} \theta_i. \tag{2}$$

The demand function has the following characteristics. First, demand for abatement inputs is downward sloping; a high price p_i hinders the diffusion of the abatement technology. Second, demand is created by regulation. Specifically, it increases in the carbon price τ and is zero in the absence of environmental regulation: $q_i = 0$ if $\tau = 0$. Third, the quality of the abatement input, θ_i, influences demand, with a higher demand for high-quality inputs.

Innovation. Abatement technologies, and the inputs derived from them, are not readily available on the market. Instead, they must be developed by innovators. Once an innovation is made, innovators obtain intellectual property rights and produce abatement inputs at per unit cost $\phi > 0$, which we assume is common across inputs. Then, innovator profit from input sales is equal to

$$\pi_i = (p_i - \phi)q_i = (p_i - \phi)\left(\frac{\tau}{p_i}\right)^{\frac{1}{1-\beta}} \theta_i. \tag{3}$$

Innovator profit from input sales will be positive as long as the price exceeds production cost, $p_i > \phi$, and the carbon price is positive, $\tau > 0$.

Innovations may further generate social value through innovation spillovers. For instance, knowledge generated by one innovation may reduce the cost or increase the quality of subsequent innovation.[11] In the main model specification, we treat such spillovers as exogenous, and assume that they are linearly related to innovation quality: an innovation of quality θ_i generates a spillover with social value $\delta\theta_i$, with $\delta \geq 0$. In Section 5 we show that our results generalize to a model extension where spillovers generate social value by reducing others' innovation costs. As the achieved cost reductions will be greater if there is more innovation, the size of the spillover δ becomes endogenous to policy choices. In either setting, our assumptions imply a positive relationship between patents' private economic value and positive externalities through spillovers that is consistent with the empirical findings by Harhoff et al. (1999), Hall et al. (2005) and Kogan et al. (2017) (see also footnote 4).

From Eq. (3) we can solve the profit-maximizing price $p_M = \phi/\beta$, which is the same for all inputs regardless of their quality. If the innovator has full monopoly power in the intellectual property rights system, it would choose this price. However, a policy maker may, either through the intellectual property rights system or direct regulations, restrict the abatement input price to below that level. For example, in the absence of intellectual property rights protection, competition will reduce the input price to marginal cost: $p_i = \phi$. This prevents the innovator from obtaining positive returns to its innovation, but maximizes the (ex-post) spread. Intermediate prices $\phi < p_i < p_M$ imply that the policy maker gives more protection against patent infringement. In the remainder, we assume $p \leq p_M$ and, following (Gilbert and Shapiro, 1990), use p as a reduced-form for the strength of the intellectual property rights system. As we assume a common intellectual property rights system, $p_i = p$ for all inputs i.

The innovator will develop the technology whenever revenue exceeds the innovation cost, c_i, net of innovation subsidies s_i:[12]

$$\pi_i \geq c_i - s_i. \tag{4}$$

Innovations are then developed up to the point where the innovator breaks even.[13] We define z as the maximum innovation cost that innovators are willing to incur to develop the innovation. From Eqs. (3) and (4), this gives

$$z(\tau, p, s_i, \theta_i) = s_i + (p - \phi)\left(\frac{\tau}{p}\right)^{\frac{1}{1-\beta}} \theta_i. \tag{5}$$

[9] Our specification for abatement most directly represents a'scrubber-like' technology which reduces emission from fossil fuel combustion. Alternatively, one can interpret A as abatement achieved due to substitution towards renewable energy, with q_i resembling renewable energy inputs.

[10] In our model, a carbon price created by an emissions trading scheme or carbon tax are equivalent. We thereby abstract from the optimal choice amongst these pricing instruments; see for example Montero (2002b), Requate (2005) and Popp et al. (2010). We also abstract from imperfect competition in the output market, as studied by Montero (2002a).

[11] Empirical research suggests these spillovers are likely substantial. Myers and Lanahan (2022), for example, use R&D grants given out by the US Department of Energy and find that "*for every patent produced by grant recipients, three more are produced by others who benefit from spillovers.*" All in all, they estimate that only 25%–50% of the value generated by a patent is captured by the patenting firm. Similarly, Zacchia (2020) finds that the marginal social returns to R&D are about 112% of the marginal private returns.

[12] We do not explicitly consider the uncertainty inherent in the innovation process. Assuming that innovators are risk neutral, one can interpret c_i as the expected cost incurred to obtain one successful innovation.

[13] We model innovation in a static framework. As such, π_i captures total profits generated by the innovation, and likewise c_i and s_i represent total cost and subsidies. In a context where an innovation generates profits over multiple time periods, the cost, subsidies and profits can be treated as annualized values.

For notational simplicity, we suppress subscript i in the remainder.

The policy maker can incentivize innovation by offering greater direct subsidies s ('technology push'), allowing innovators to choose price p closer to the monopoly price p_M, or manipulating the demand for innovation by imposing a higher carbon price τ ('technology pull'). Eq. (5) demonstrates an important difference between these strategies to increase innovation. While a uniform subsidy rewards all innovators equally, a higher input or carbon price is *more* valuable for those innovations with high θ. A uniform increase in s thus encourages more innovations of all qualities, whereas a similar increase in p or τ in particular induces innovation in high quality technologies.[14]

Distributions and information. Our key assumption is that innovations are heterogeneous in quality θ and cost c, and that these parameters are known by innovators. We analyze both the case where also the policy maker can directly observe these parameters and condition policy on quality θ, and the case where it knows the distributions of θ and c, but cannot observe or condition policy on θ or c at the innovation level.[15]

We assume that $\theta \in [\underline{\theta}, \overline{\theta}]$ is distributed based on density function $g(\theta)$ with cumulative distribution function $G(\theta)$, satisfying the standard monotone hazard rate assumption and $0 \leq \underline{\theta} < \overline{\theta}$.[16] We assume that $c \in [0, \overline{c}]$ is distributed based on density function $f(c)$ and cumulative distribution $F(c)$, and innovation costs are assumed to be independent of θ, $g(\theta|c) = g(\theta)$. To avoid technical but uninteresting issues at the upper bound, we let $\overline{c} \to \infty$, implying that for any given finite subsidy level some innovations are left undeveloped.

Welfare. A policy maker maximizes welfare, which is given by

$$W = Y(E) - (\xi + \Delta)E + \int_{\underline{\theta}}^{\overline{\theta}} \int_0^{z(\tau,p,s,\theta)} \Big(v(\tau,p)\theta - c \Big) f(c)dc \; g(\theta)d\theta. \tag{6}$$

The first two terms capture the benefits of energy use $Y(E)$, net of its private (ξ) and social (Δ) costs. The integral gives the social value of innovations, $v(\tau,p)\theta$, net of development costs, c, integrated over the entire mass of innovations that are developed ($c \leq z$). The social value of an innovation of quality θ is $v(\tau,p)\theta$, where

$$v(\tau,p) = \frac{\Delta}{\beta}\left(\frac{\tau}{p}\right)^{\frac{\beta}{1-\beta}} - \phi\left(\frac{\tau}{p}\right)^{\frac{1}{1-\beta}} + \delta. \tag{7}$$

The first term in (7) captures the social value of abatement generated by innovation. This value is equal to marginal emission damages Δ, multiplied by the abatement from the use of abatement input, $\theta^{1-\beta}q^{\beta}/\beta$, see Eq. (1), with equilibrium q given by Eq. (2). The second term subtracts the cost of producing the abatement inputs, which is equal to ϕq. The third term, δ, captures any positive spillovers from innovations that cannot be captured by the innovator.

The policy maker chooses carbon prices, abatement input prices and innovation subsidies to maximize welfare given by Eq. (6). In what follows, we make two different assumptions about the policy makers' constraints. In Section 3.1 we first consider a benchmark where the policy maker is able to *pick winners* by conditioning innovation subsidies on the true quality of innovation θ. In Section 3.2, we assume that the policy maker cannot condition on θ (or c) and thereby the policies must be designed to *screen winners*. This inability to condition on θ is due to unobservability of θ on part of the policy maker; equivalently, it could be due to institutional constraints that inhibit the policy maker from differentiating subsidies across innovators.[17] We assume throughout that carbon and abatement input prices are common to all firms and technologies. In Section 4 we further assess the generalizability of our results under alternative intellectual property rights regimes and complementary policies.

3. Optimal climate policy with innovation heterogeneity

We begin with some general insights. The optimal policy in which the policy maker chooses carbon price τ and abatement input price p to maximize social welfare, taking the innovation subsidy s, for now, as given. The carbon price that maximizes welfare (6) then satisfies

$$\frac{\partial W}{\partial \tau} = \underbrace{\frac{\Delta - \tau}{-Y''(E)}}_{\text{energy market effect}} + \underbrace{\int_{\underline{\theta}}^{\overline{\theta}} v'_{\tau}\theta F(z)g(\theta)d\theta}_{\text{diffusion effect}} + \underbrace{\int_{\underline{\theta}}^{\overline{\theta}} [v\theta - z]\, z'_{\tau} f(z)g(\theta)d\theta}_{\text{innovation effect } (\Omega_{\tau})} = 0, \tag{8}$$

[14] Whether this result, that carbon pricing disproportionally increases the number of high-quality, highly cited patents, holds empirically is an open question. Aghion et al. (2016) do report a larger elasticity of citation-weighted patents with respect to fuel prices compared to non-weighted patent counts, which is consistent with carbon pricing favoring high-citation patents.

[15] Although the innovator may not know the exact cost or quality ex-ante, it is reasonable that it has better information than policy makers do; innovators likely posses more technical expertise in and experience with anticipating cost and quality in highly specialized innovation projects. Innovation cost, c, should be understood broadly as the minimum reimbursement that the innovator would require to undertake the project. We follow the usual assumption in the literature (e.g., Scotchmer, 1999; Akcigit et al., 2022) that the policy maker cannot observe innovation costs, at least not fully.

[16] In order to keep the demanded quantity in Eq. (2) positive, we rule out socially harmful innovations and guarantee that innovations always have a non-negative quality. Note, though, that their ex-ante social value may still be negative because of the innovation costs (if $\pi + s < c$).

[17] Our assumption that policy maker cannot observe innovation costs c implies our analysis abstracts from research subsidy schemes that are conditioned on c such as R&D tax credits. Although we acknowledge that a part of R&D costs may be observable and verifiable, unobservable R&D cost components, including R&D effort and managerial input, likely remain and typically not all expenses can be claimed for tax credits. Indeed, in the majority of OECD countries, less than half of business R&D expenditures qualify for tax credits (OECD, 2021). See also Scotchmer (1999), Lach et al. (2021) and Akcigit et al. (2022) for similar assumptions.

where v'_τ denotes the partial derivative of $v(\tau, p)$ with respect to τ, and, likewise, z'_τ is the partial derivative of $z(\tau, p, s, \theta)$ with respect to τ. For notational simplicity, Eq. (8) and most of the remaining exposition will suppress the arguments of v, z and their derivatives.

The carbon price serves three potential purposes, captured by the three effects in Eq. (8). Consider a small increase in τ. First, this reduces energy use and corresponding climate damages; the first term is this *energy market effect* which depicts the reduction in the deadweight loss from energy-related carbon emissions. This term is positive if $\tau < \Delta$, and becomes zero under Pigouvian pricing, $\tau = \Delta$. Second, the social value of the innovation, $v\theta$, depends on how widely it is adopted. A higher carbon price can incentivize technology uptake and correct the distortion created by a patenting system that allows innovators to set abatement input prices above marginal cost. It may however also lead to excessive take-up of the abatement technology, especially if carbon prices are high to begin with, in which case this *diffusion effect* is negative. The second term gives this impact, aggregated over all technologies that enter the market. Third, a higher carbon price increases demand for abatement inputs, and thereby makes innovation more profitable. The benefits of encouraging innovation are given by the wedge between the social and private value of innovation $v\theta - z$, multiplied by the marginal effect of carbon pricing on innovation incentives z'_τ, aggregated over potential innovations. Here, $f(z)g(\theta)$ captures the density of innovators with innovation quality θ and cost $c = z$.

We rewrite this *innovation effect* to decompose it into an *average innovation effect* $\bar{\Omega}_\tau$ and an *innovation screening effect* Ω^s_τ:[18]

$$\Omega_\tau = \underbrace{\mathbb{E}\left[(v\theta - z) f(z)\right] \mathbb{E}[z'_\tau]}_{\text{average innovation effect } (\bar{\Omega}_\tau)} + \underbrace{Cov\left((v\theta - z) f(z), z'_\tau\right)}_{\text{innovation screening effect } (\Omega^s_\tau)}, \tag{9}$$

with $\mathbb{E}\left[z'_\tau\right] \equiv \int_{\underline{\theta}}^{\overline{\theta}} z'_\tau g(\theta) d\theta$ the expected value of z'_τ (over θ) and similarly $\mathbb{E}\left[(v\theta - z) f(z)\right] \equiv \int_{\underline{\theta}}^{\overline{\theta}} \left[v\theta - z\right] f(z) g(\theta) d\theta$.

Eq. (9) immediately highlights the implications of heterogeneity for the optimal carbon price: when heterogeneity implies a positive covariance between the effect of carbon pricing on innovation (z'_τ), and the wedge between the social and private benefit of the additional innovation ($v\theta - z$) with mass $f(z)$, the innovation screening effect Ω^s_τ will be positive, warranting a premium on the carbon price. In other words, carbon prices should be higher if they particularly incentivize the development of the socially most undervalued technologies.[19]

Similarly, the optimal input price satisfies

$$\frac{\partial W}{\partial p} = \underbrace{\int_{\underline{\theta}}^{\overline{\theta}} v'_p \theta F(z) g(\theta) d\theta}_{\text{diffusion effect}} + \underbrace{\int_{\underline{\theta}}^{\overline{\theta}} \left[v\theta - z\right] z'_p f(z) g(\theta) d\theta}_{\text{innovation effect } (\Omega_p)} \geq 0, \tag{10}$$

holding with equality if the constraint $p \leq p_M$ is not binding. As in Eq. (9), we can rewrite and decompose Ω_p into the average innovation effect $\bar{\Omega}_p$ and the innovation screening effect Ω^s_p:

$$\Omega_p = \underbrace{\mathbb{E}\left[(v\theta - z) f(z)\right] \mathbb{E}[z'_p]}_{\text{average innovation effect } (\bar{\Omega}_p)} + \underbrace{Cov\left((v\theta - z) f(z), z'_p\right)}_{\text{innovation screening effect } (\Omega^s_p)}, \tag{11}$$

where $\mathbb{E}[z'_p]$ is defined similarly to $\mathbb{E}[z'_\tau]$.

The welfare-maximizing input price optimally balances the cost and benefits of a marginal increase in p. First, such an increase has a negative impact on diffusion. Second, with positive carbon pricing, an abatement input price closer to the monopoly level p_M leads to higher profits, especially for high θ innovations. This increases innovation incentives, and creates gains equal to $(v\theta - z) f(z)$ for an input of type θ. The term z'_p then captures the effect of a marginal increase in p on the mass of type-θ innovations that will be made.

Eqs. (8)–(11) make explicit how the consideration of heterogeneity influences the optimal policy prescription. We have, however, not yet considered innovation subsidies as part of the policy mix. Below, we show that whenever innovation subsidies can be targeted, that is, conditioned on innovation quality θ, the innovation benefit of carbon and input prices are zero ($\Omega_\tau = 0, \Omega_p = 0$), and heterogeneity in innovation quality does not distort the optimal carbon and input prices. This result does not extend to the setting where only across-the-board innovation subsidies can be awarded. Even though such subsidies would ensure innovations are appropriately rewarded on average ($\bar{\Omega}_\tau = 0, \bar{\Omega}_p = 0$), the innovation screening effects in (9) and (11) remain.

3.1. *Picking winners: Targeted R&D subsidies*

We first consider a benchmark setting where the policy maker observes the type of each innovation, θ, and can condition R&D subsidies on this type: $s(\theta)$. The policy maker also chooses welfare-maximizing τ and p according to (8) and (10). From (6) we find

[18] Here, Cov denotes covariance and this expression exploits that, by definition, for any two variables X and Y, $Cov(X, Y) = \mathbb{E}[XY] - \mathbb{E}[X]\mathbb{E}[Y]$.

[19] Whether this is the case will depend on the levels of input prices p and subsidies s, as we will show in Section 3.2, the covariance term is positive under optimized p and across-the-board subsidies s.

that when the policy maker can type-target subsidies, it will choose $s(\theta)$ such that the marginal social value of type-θ innovation is equal to its marginal private cost:

$$\frac{\partial W}{\partial s(\theta)} = \upsilon\theta - z = 0. \tag{12}$$

The optimal targeted subsidies equate the social ($\upsilon\theta$) and private (z) value of innovation, and thus the innovation effects of carbon pricing are zero. In fact, when the right innovations are in the market, there is no reason to distort the energy choice by deviating from the Pigouvian pricing ($\tau = \Delta$), and similarly, there is no reason to distort the diffusion of the new technology by setting an abatement input price in excess of marginal cost ($p = \phi$). Innovations are then solely compensated through quality-dependent innovation subsidies, which equal the social value of the innovation. This result is summarized in the following proposition:

Proposition 1 (*Picking Winners*). *If the innovation subsidy can be targeted based on innovation quality θ, then the optimal combination of policies is*

$$\tau = \Delta, \qquad \textit{Pigouvian pricing}$$
$$p = \phi, \qquad \textit{No patent rights}$$
$$s(\theta) = \left[\left(\frac{\Delta}{\phi}\right)^{\frac{\beta}{1-\beta}}\left(\frac{\Delta}{\beta} - \Delta\right) + \delta\right]\theta, \qquad \textit{Targeted R\&D subsidy}$$

with zero average innovation and innovation screening effects: $\bar{\Omega}_\tau = \bar{\Omega}_p = 0$ and $\Omega^s_\tau = \Omega^s_p = 0$.

Proof. See Appendix A.1.1. □

The policy mix in Proposition 1 implements the first-best allocation. As such, Proposition 1 can be considered a direct application of Tinbergen rule, where one policy tool is used for each policy target. Carbon pricing τ corrects the negative externality of emissions, targeted subsidies $s(\theta)$ ensure that innovators capture the social value of innovations and, thus, develop those technologies for which the social value exceeds innovation costs. This allows intellectual property rights to be released for free, leading to competitive production of abatement inputs: $p = \phi$. As the targeted subsidies ensure that the 'right' innovations will enter the market, there is no further need for the carbon price or the intellectual property rights system to act as a screening device; under the optimal policy combination, the innovation screening effects, Ω^s_τ and Ω^s_p are zero.

3.2. Screening winners: Across-the-board innovation subsidies

In actuality, policy makers often lack ready and reliable information about innovator and product characteristics, which inhibits their ability to accurately tailor policies to the most valuable innovations. Alternatively, the inability to differentiate R&D subsidies may stem from institutional constraints; differentiated subsidies across innovators within an industry may be prohibited by law, or it may be prohibitively expensive to implement. The inability to differentiate innovation subsidies across innovations implies that the policy maker is unable to implement the first-best allocation using the policy mix as described in Proposition 1.

In this section, we identify the constrained optimal combination of across-the-board subsidies and carbon pricing. The optimal across-the-board subsidy, s, then satisfies the following first-order condition:

$$\frac{\partial W}{\partial s} = \int_{\underline{\theta}}^{\bar{\theta}} [\upsilon\theta - z]\, f(z)g(\theta)d\theta = 0. \tag{13}$$

The subsidy balances two effects. First, a higher subsidy incentivizes innovation, which has social value $\upsilon\theta$; the first term. Second, the cost of this marginal innovation is $c = z$; the second term. The innovation subsidy then strikes a balance between the social value and cost, averaged across all types θ, and taking into account the density of innovators at margin of innovating or not, $f(z)$.

In contrast to the type-targeted subsidy given by Eq. (12), the optimal across-the-board innovation subsidy is only correct 'on average'. Heterogeneity in innovation quality implies heterogeneity in the wedge between the social and private returns to innovation; this creates a benefit to using carbon prices and intellectual property rights to incentivize the development of the best innovations. Mathematically, this is highlighted by the fact that whereas Eq. (13) ensures $\mathbb{E}\left[(\upsilon\theta - z)f(z)\right] = 0$, and thus eliminates the average innovation effect $\bar{\Omega}_\tau$ in (9), the innovation screening effect Ω^s_τ remains positive: the optimal carbon price includes a premium because it rewards the most valuable, high quality innovations. Likewise, we find that the policy maker finds it optimal to assign patent rights to the innovator: the optimal p exceeds ϕ. Recall that with targeted R&D subsidies (Proposition 1), patents were not optimal, as they prevent the diffusion of new technologies. This result no longer holds under across-the-board subsidies.

Proposition 2 (*Screening Winners*). *If the innovation subsidy cannot be targeted based on innovation quality θ, then the optimal combination of policies satisfies the following:*

$$\tau > \Delta, \qquad \textit{Higher-than Pigouvian pricing}$$
$$p > \phi, \qquad \textit{Patent rights}$$
$$s = \left[\left(\frac{\tau}{p}\right)^{\frac{\beta}{1-\beta}}\left(\frac{\Delta}{\beta} - \tau\right) + \delta\right]\frac{\mathbb{E}[\theta f(z)]}{\mathbb{E}[f(z)]}, \qquad \textit{Across-the-board R\&D subsidy}$$

with innovation screening effects: $\Omega^s_\tau > 0, \Omega^s_p \geq 0$, and $\bar{\Omega}_\tau = \bar{\Omega}_p = 0$.

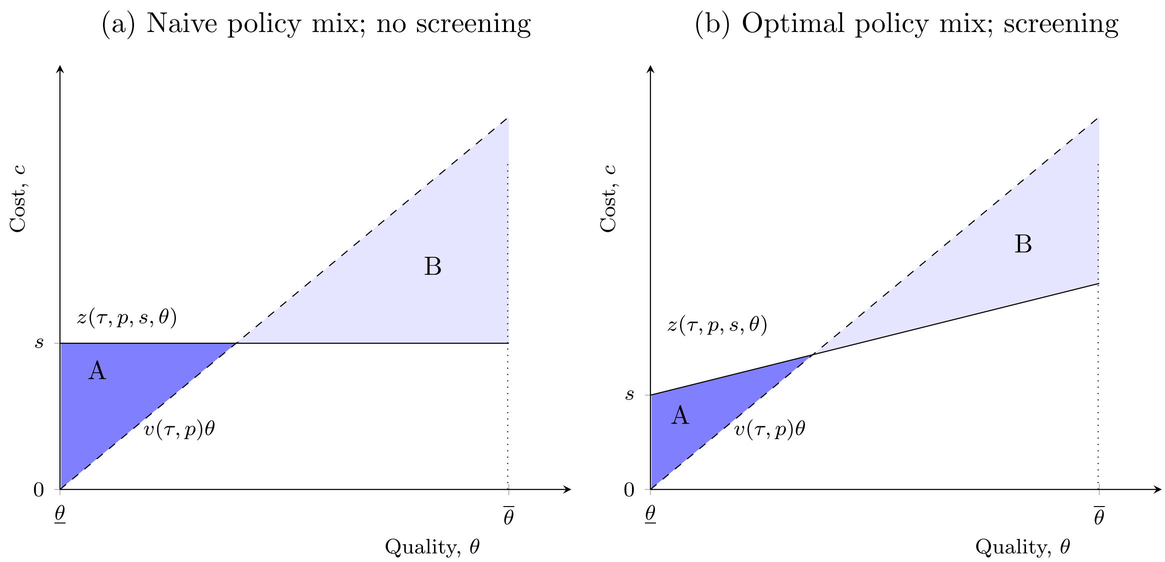

Fig. 2. Graphical illustration of screening in the model.
Notes. Solid line $z(\tau, p, s, \theta)$ is the cut-off for developing innovations (Eq. (5)). Dashed line $v(p, \tau)\theta$ is the cut-off for socially beneficial innovations (Eq. (7)). Area A: Socially unbeneficial innovations that are developed. Area B: Socially beneficial innovations that are not developed. Note that this Figure is an illustration, and uses a quantification distinct from the calibration in Section 6.

Proof. See Appendix A.1.2. □

Proposition 2 states our main result. When the policy maker cannot observe the true quality of innovation, it is optimal to set a carbon price that is above the Pigouvian level and set the abatement input price above marginal cost. This is despite the fact that the policy maker subsidizes innovation; whereas the implementation of an optimal across-the-board subsidy eliminates the average innovation effects $\bar{\Omega}_\tau$ and $\bar{\Omega}_p$, the innovation screening effect remains: $\Omega^s_\tau > 0$ and $\Omega^s_p \geq 0$.[20] This screening component then contributes to increasing the carbon price above marginal damages.

Fig. 2 illustrates the main results graphically. The policy mix partitions the type space into (i) innovations with cost below (or above) private returns, $c \leq z$ and (ii) innovations with cost below (or above) social returns, $c \leq v\theta$.

Fig. 2a considers a naive policy, which is defined as the policy mix that would be optimal if the policy maker naively ignores the innovation screening effects. One can straightforwardly show that this policy mix would constitute Pigouvian pricing and no patenting ($\tau = \Delta, p = \phi$), and R&D subsidies based on Eq. (13). This policy mix is equivalent to the 'picking winners' policy described in Proposition 1, with the across-the-board R&D subsidy equal to a weighted average of the targeted subsidy of Proposition 1. Under this naive policy mix, line z is horizontal and all innovations with cost below z are developed. This naive policy is costly, as it incentivizes the development of socially unbeneficial innovations (area A), yet fails to incentivize the development of some socially beneficial innovations (area B).

Fig. 2b shows how a policy mix as described by Proposition 2 alleviates this problem. With higher-than-Pigouvian carbon pricing and patent rights ($\tau > \Delta, p > \phi$), the slope of z increases and the areas A and B become smaller. The optimal carbon price balances this screening benefit against deadweight losses associated with deviations from the Pigouvian price (Eq. (8)) and suboptimal diffusion, and the optimal patenting balances the screening benefit against the distortion from market power (Eq. (10)).

The inability to tailor R&D subsidies based on innovation quality implies that, generally speaking, the policy mix described by Proposition 2 implements a second-best optimum. Under specific conditions, however, the policy can implement the first-best which includes incentivizing the development of the 'right' innovations (i.e., eliminating areas A and B in Fig. 2). This is established in the proposition below:

Proposition 3 (*Implementing First-Best*). *The policy mix described in Proposition 2 implements the first-best allocation if and only if $\delta = 0$ and $Y''(E) \rightarrow -\infty$. If those conditions hold, the optimal policy sets*

$$\tau = \frac{\Delta}{\beta}, \qquad \textit{Higher-than-Pigouvian pricing}$$

$$p = p_M, \qquad \textit{Monopoly rights}$$

$$s = 0. \qquad \textit{No R\&D subsidy}$$

[20] While Ω^s_τ is strictly positive, Ω^s_p is strictly positive only if $p < p_M$. Assigning property rights such that $p = p_M$ maximizes firm profits, and thereby maximally exploits p to incentivize high-quality innovation. Yet, as the marginal effect of p on profits is zero at $p = p_M$, higher input prices cannot screen better innovations and thus $\Omega^s_p = 0$.

Proof. See Appendix A.1.3. □

The first-best is reached only if two conditions are met: $\delta = 0$ and $Y''(E) \to -\infty$. The first condition, $\delta = 0$, is that there are no innovation spillovers. If this is the case, innovators can capture the full social value of their innovation through a combination of monopoly patent rights (that allow for $p = p_M$), and higher-than-Pigouvian carbon price equal to $\tau = \Delta/\beta$. These high carbon prices are needed because a high input price decreases the technology take-up. The policy maker can correct this under-provision problem by setting a higher-than-Pigouvian carbon price. Such above-Pigouvian carbon prices however would normally create a distortion in energy demand. The second condition, $Y''(E) \to -\infty$, eliminates this distortion, as it implies the energy demand curve is vertical, and the market responds to regulation through abatement and innovation in abatement technologies, rather than by reducing energy use.[21] As the policy combination described in Proposition 3 ensures that the private and social value of innovation coincides, and thus perfectly screens innovation, no further R&D subsidies are required.

If these conditions are not met, the policy maker cannot fully rely on screening, but must complement the policy with R&D subsidies. A relevant question then is how the level of R&D subsidies in Proposition 2 compares to the average subsidy level when subsidies can be targeted, or to the level implemented by a naive policy maker as described above. In other words, does using carbon pricing to screen winners also reduce spending on R&D subsidies?[22]

It is not straightforward to answer this question. On the one hand, by leveraging the market to encourage the most socially beneficial innovations, the policy mix in Proposition 2 leaves less need for direct subsidies. On the other hand, the different mix of policies implies that, for each quality level θ, the marginal innovator now operates at a different cost level c, with a potentially different density $f(c)$. To draw unambiguous conclusions from a comparison of subsidy levels, additional assumptions on the distribution $f(c)$ must be made. For the proposition below, we make such an assumption:

Proposition 4 (*R&D Subsidies*)**.** *Denote optimal targeted subsidies in Proposition 1 by s^{target}, optimal subsidies in Proposition 2 by s^{opt}, and naive subsidies by s^{naive}. If $f(c)$ is non-increasing in c, then*

$$\mathbb{E}[s^{opt}] < \mathbb{E}[s^{target}] = \mathbb{E}[s^{naive}].$$

Proof. See Appendix A.1.4. □

Proposition 4 states that, on average, the targeted subsidies described in Proposition 1 exceed the across-the-board subsidies from Proposition 2 and also the subsidies implemented by a naive policy maker. This result holds under specific distributions for innovation cost c, including the uniform and exponential distribution.

4. Exogenous input prices and complementary policies

In reality, climate policy is generally determined separately from intellectual property rights policy. Therefore, the policy maker might not have the option to jointly optimize the carbon price τ and the patent regime, as proxied by the abatement input price p. Additionally, policy makers may have alternative strategies for rewarding innovation at their disposal. It may, for instance, subsidize the sales of abatement inputs, or offer the innovator to buy out their patent. In the following three subsections, we explore such alternative contexts and derive assumptions under which the innovation screening effect remains positive.

4.1. Exogenous abatement input prices

Our main result in Proposition 2 assumes that the policy maker can jointly and simultaneously optimize three policy instruments, subsidies s, carbon pricing τ, and patenting as proxied by the abatement input price p. The only constraint it faces in setting these instruments is that they are implemented across the board: they cannot be tailored to the specific innovator or input quality. Below we show that our main results regarding carbon pricing generalize to carry over to a setting where the abatement input price is exogenously set.

Proposition 5 (*Exogenous Input Price*)**.** *If the abatement input price is exogenously set and the innovation subsidy cannot be targeted based on the innovation quality θ, the optimal carbon price satisfies:*

- *If $p = \phi$, then $\tau = \Delta$ with a zero innovation screening effect: $\Omega^s_\tau = 0$,*
- *If $p = (\phi, p_M]$, then $\tau > \Delta$ with a positive innovation screening effect: $\Omega^s_\tau > 0$.*

Proof. See Appendix A.1.5. □

[21] Our results show that the channel through which the market responds to climate regulation (as studied by e.g., Calel, 2020 and Colmer et al., 2022) have important implications for the optimal policy. In Appendix A.1.3 we show that the assumption $Y''(E) \to -\infty$ can be relaxed if the policy maker subsidizes energy use E.

[22] We acknowledge that subsidy levels are not the only relevant metric in this context. A comparison of levels for instance does not account for the amount or quality of innovation incentivized though those subsidies.

The proposition states that whenever the intellectual property rights system is such that $p > \phi$, the optimal carbon price increases due to the positive screening effect. Put differently, it is optimal for the policy maker to use the carbon price as an innovation screening device, irrespective of the intellectual property rights system in place. The exception is the case with $p = \phi$. In this situation, no positive profits will be derived from innovation, and increasing the carbon price will thus not boost profits of the highest-quality inputs in particular. Therefore, the carbon price will not be able to contribute to the screening of the best innovations and should only be used to correct the environmental distortion (as $p = \phi$ already ensures the optimal diffusion of the technology).

4.2. Rewarding technology uptake

So far, the analysis has abstracted from policy tools that reward technology uptake. Examples of policies supporting technology diffusion in production processes include subsidies for solar panels, technology-specific carbon contracts for difference, as well as advance market commitments, which have gained renewed interest and application in the COVID pandemic (Kremer, 2000; Kremer et al., 2022), and are advocated as a potential tool for supporting negative emission technologies (Sarnoff, 2020).

To assess the implications of a similar measure in the context of our framework, we consider an abatement input subsidy σ, such that the cost per abatement input firms incur is $(1-\sigma)p$. We allow the policy maker to choose σ up to a maximum level: $\sigma \leq \bar{\sigma}$. This maximum $\bar{\sigma}$ reflects constraints for setting the subsidy. These constraints may be political or practical; high subsidies may be considered too costly for taxpayers, and sensitive to political capture. We maintain the assumption that the policy maker can set any $p \leq p_M$, where one can straightforwardly show that the subsidy does not change the monopoly price: $p_M = \phi/\beta$. We can then establish the following

Proposition 6 (*Abatement Input Subsidies*). *If the innovation subsidy cannot be targeted based on the innovation quality θ, and policy maker can implement an abatement input subsidy $\sigma \leq \bar{\sigma}$, then the optimal carbon and input price satisfy*

- *If $\sigma^{opt} \leq \bar{\sigma}$, then $\tau = \Delta$, $p = p_M$ and $\sigma = \sigma^{opt}$,*
- *If $\sigma^{opt} > \bar{\sigma}$, then $\tau > \Delta$, $p > \phi$ and $\sigma = \bar{\sigma}$,*

where σ^{opt} denotes the unconstrained optimal licensing price, which satisfies $\sigma^{opt} = 1-\beta$ if $\delta = 0$, and $\sigma^{opt} \in (1-\beta, 1)$ if $\delta > 0$. The innovation screening effects satisfy $\Omega_\tau^s = 0$ if $\delta = 0$ and $\sigma^{opt} \leq \bar{\sigma}$, and $\Omega_\tau^s > 0$ otherwise. Further, $\Omega_p^s = 0$ if $\sigma^{opt} \leq \bar{\sigma}$ and $\Omega_p^s \geq 0$ if $\sigma^{opt} > \bar{\sigma}$.

Proof. See Appendix A.1.6. □

The proposition establishes that if the constraint $\sigma \leq \bar{\sigma}$ is not binding, the optimal policy mix features a carbon price at the Pigouvian level and monopoly input prices. Although carbon prices are Pigouvian, market incentives are still heavily used to screen in the best innovations: in the empirically relevant case where spillovers are positive, the screening effect of taxes remains positive ($\Omega_\tau^s > 0$) and compensates for a negative diffusion effect ($\Gamma_\tau^s < 0$). Further, in Appendix A.1.6 we show that the allocation is not generally first-best; the policy mix characterized in Proposition 6 implement first-best only if $\sigma^{opt} \leq \overline{\sigma}$ and $\delta = 0$.

Strikingly, due to high optimal subsidy levels, the cost per abatement input cost firms incur is either equal to (if $\delta = 0$) or below (if $\delta > 0$) the marginal production cost. In effect, the taxpayer shoulders at least the full cost of technology diffusion. These high costs raise concerns about the practical and political feasibility of implementing the optimal input subsidy, thus highlighting the relevance of considering the constrained-optimum. If indeed such a constraint binds $\sigma = \bar{\sigma}$ and our previous results apply. In that case, we are back to the trade-off considered in Section 3: increasing the price level screens in the best technologies but at the cost of reduced uptake. For this reason, solely relying on intellectual property rights to screen innovation is insufficient, and it is optimal to additionally use carbon pricing for further screening.

4.3. Patent buyouts

A disadvantage of using intellectual property rights for rewarding innovation is that higher prices p reduce technology uptake. One proposal to enhance the diffusion of abatement technologies is for the government to buy patents and place them in the public domain (Kremer, 1998; Galasso et al., 2016). This would enhance the diffusion of green technologies by eliminating market power.

Below, we consider the implications of such a proposal for the optimal policy mix of carbon price τ, abatement input prices p and across-the-board subsidies s. More specifically, we allow the policy maker to make a take-it-or-leave-it offer T to the innovators, who in turn decide whether to take the offer and sell their patent to the government, or refuse it and retain their patent. Those patents that are sold are then placed in the public domain, implying the corresponding inputs will be available at marginal cost ϕ. As before, we assume that due to the lack of information or regulatory restrictions, the policy maker cannot (directly or indirectly) condition this offer on innovation quality θ. The innovator then accepts the offer if they expect to make less money by keeping the patent and licensing:

$$T \geq \pi = (p-\phi)\left(\frac{\tau}{p}\right)^{\frac{1}{1-\beta}}\theta, \tag{14}$$

where π is profits as specified in (3). Expression (14) shows that the scheme suffers from adverse selection: innovators are only willing to sell the low-quality innovations, and prefer to keep the revenue from producing and selling the high-quality innovations. We can establish the following:

Proposition 7 (*Patent Buyouts*). *Define θ^* such that $T = \pi$ for $\theta = \theta^*$, and assume that $p = \phi$ in the interval $[\underline{\theta}, \theta^*]$. It is then optimal to set T^* such that the policy maker allows for patenting ($p > \phi$) in the interval $[\theta^*, \overline{\theta}]$, where $\underline{\theta} \leq \theta^* < \overline{\theta}$. In addition $\tau > \Delta$ with innovation screening effects $\Omega^s_\tau > 0$ and $\Omega^s_p \geq 0$.*

Proof. See Appendix A.1.7. □

In the proof of the proposition, we formally show that patent buyouts strike a balance between two effects. On the one hand, buyouts are beneficial, because by placing patents in the public domain, they encourage technology diffusion. On the other hand, buyouts incentivize the development of low-quality innovations with negative social value. Hence, in spite of adverse selection it may be beneficial for the government to buy a subset of patents. Nevertheless, the government never wants to buy all the patents, as this would prevent using market instruments for screening, leading to excessive development of technologies with negative social value.

5. Endogenous spillovers

Our main model specification assumes innovation spillovers $\delta\theta_i$ are directly proportional to θ_i, with the proportionality δ taken as an exogenous parameter. In reality, the size of spillovers are likely endogenous, and directly or indirectly influenced by policy. For instance, if one innovation reduces the cost of others' innovation, spillovers materialize through continued development of such technologies which, in turn, depends on the stringency of climate policies (Fischer, 2008; Greaker et al., 2018).

In this subsection we present a generalization of our model to endogenous spillovers, and show that our main result is robust to this extension. Specifically, we assume that the cost of innovation is decreasing in aggregate 'knowledge', which we assume is proportional to aggregate innovation quality:

$$\hat{c} = c - \kappa\Theta, \tag{15}$$

where $\hat{c}$ denotes innovation cost net of the spillover, $\Theta \equiv \int_{\underline{\theta}}^{\overline{\theta}} \int_0^z \theta f(c) dc g(\theta) d\theta$ is the aggregate quality of the innovations that are developed and $\kappa \geq 0$ is a parameter determining the size of the spillover. We assume atomistic innovators who take Θ as given. With the spillover, the maximum innovation cost innovators are willing to incur now satisfies

$$z = s + (p - \phi)\left(\frac{\tau}{p}\right)^{\frac{1}{1-\beta}} \theta + \kappa\Theta. \tag{16}$$

The spillover increases the incentives to innovate given policies s, p and τ, and quality θ. Further, with endogenous spillovers, an increase in the subsidy s not only directly incentivizes innovation, but also indirectly affects incentives through the knowledge spillover, $\kappa\Theta$. Still, as the spillover benefits all innovators equally, a uniform subsidy incentivizes the development of all technologies regardless of their quality. Likewise, as in the main model, any increase in taxes or prices, particularly incentivizes innovation for high θ.[23]

In Appendix A.1.8 we show that welfare W and the social value of innovation $v\theta$ can then again be expressed by Eqs. (6) and (7), but with z now given by (16) and δ endogenous and equal to

$$\delta(\tau, p, s) = \kappa \int_{\underline{\theta}}^{\overline{\theta}} F(z) g(\theta) d\theta. \tag{17}$$

Eq. (17) states that under endogenous spillovers, δ, the value of the spillover generated per quality θ, is equal to κ multiplied by the mass of innovations that are developed. This is intuitive: under our specification, an innovation of quality θ generates cost savings equal to $\kappa\theta$ for each innovation that is developed.

We can then again determine the optimal policy mix. With endogenous spillovers, the carbon price and input price that maximize welfare again satisfy Eqs. (8) and (10), respectively. The derivatives v'_τ, z'_τ, v'_p and z'_p however change: they now account for the fact that a change in the carbon tax and input price affects the size of the spillover. Likewise, the first-order condition that characterizes the welfare-maximizing across-the-board subsidy now contains an additional element:

$$\frac{\partial W}{\partial s} = \int_{\underline{\theta}}^{\overline{\theta}} v'_s \theta f(z) g(\theta) d\theta + \int_{\underline{\theta}}^{\overline{\theta}} [v\theta - z] \, z'_s f(z) g(\theta) d\theta = 0. \tag{18}$$

With exogenous spillovers, the welfare gain from an increase in the innovation subsidy was equal to the value net of innovation cost of the additional innovation generated. When spillovers are endogenous, the additional innovation increases the spillovers generated by those innovations which were already developed prior to the subsidy increase; this is because more innovations now benefit from the accompanying cost savings. This increase in spillovers is captured through the term $v'_s = \delta'_s$.[24] Acknowledging that this mechanism constitutes benefits of increased innovation rather than diffusion, we define the innovation effects Ω_τ and Ω_p as including this effect of policy on the size of the pre-existing spillovers.[25] We can then again prove our main result:

[23] It is relevant to note that it is not clear from the outset that (16) implies a unique solution for z. Specifically, there may exist multiple equilibria, as the decision to innovate by one innovator, will induce further innovation as spillovers reduce innovation cost (see definition for Θ). The proposition we derive below therefore derives conditions that hold for any *local* optimum.

[24] This effect is also present in the v'_τ and v'_p under endogenous spillovers.

[25] And hence the diffusion effects as excluding this term. See Appendix A.1.8 for a formal definition and derivations.

Table 1
Summary of parameterization.

Parameter		Target
Elasticity of technology abatement	β	Varying between 0.1 and 0.9
Parameters from the literature		
Benefits of use	$Y(E)$	Linear energy demand with initial demand elasticity of −0.21
Social cost of carbon	Δ	\$100/tCO_2
Energy price	ξ	\$28/tCO_2
Innovation quality distribution	$G(\theta)$	Non-parametric 5-year citation distribution for Y02P patents
Targeted parameters		
Abatement input production cost	ϕ	\$1 million average value per citation π/θ
Innovation spillovers	δ	One-to-one ratio of spillover δ to private value π
Innovation cost distribution	$F(c)$	Uniform distribution, semi-elasticity of emissions consistent with data

Proposition 8 (*Endogenous Spillovers*)**.** *Suppose spillovers are endogenous. If the innovation subsidy cannot be targeted based on innovation quality θ, then the optimal carbon tax and input price satisfy $\tau > \Delta$ and $p > \phi$, with innovation screening effects: $\Omega_\tau^s > 0$ and $\Omega_p^s \geq 0$.*

Proof. See Appendix A.1.9. □

This generalization establishes that our main result can also be obtained under endogenous spillovers. It is however important to highlight that while this generalization captures the endogeneity of innovation spillovers to policy interventions, it does so in a static framework. As such, this specification does not capture the sequential nature of technological spillovers in which past innovations affect future innovation costs (akin to Gerlagh et al., 2014 and Acemoglu et al., 2016). We consider a dynamic framework with innovation heterogeneity to be beyond the scope of our current paper, yet an important future extension of our current work. Such an extension would allow for an assessment of how the innovation screening effect changes over time and, with it, the optimal time profile of carbon prices, intellectual property rights and subsidies.

6. Numerical analysis

The theoretical framework establishes that innovation heterogeneity, combined with the absence of targeted R&D subsidies, gives rise to a premium that raises optimal carbon prices above the Pigouvian level. To assess the economic significance of this premium, we perform a stylized calibration of the model to the European manufacturing sector. The aim of the numerical analysis is to assess the size of our effects using parameterization consistent with real-life observations. Below we briefly summarize our calibration approach; Table 1 lists the calibrated parameters and we present the full calibration details and justification for parameter choices in Appendix B.

6.1. Calibration

We proxy quality θ by the number of citations per patent and nonparametrically calibrate $G(\theta)$ to the citation distribution of climate change mitigation technologies presented in the 'production and processing of goods' sector (see Fig. 1). We calibrate the production function such that the price elasticity of energy demand is consistent with empirical estimates, demand is linear and baseline energy demand matches the 2010–2019 average EU industrial emissions. The social cost of carbon Δ is set to \$100/tCO_2.

In the model, parameter β has two potentially countervailing effects on the size of the innovation screening effect. First, it governs the carbon price elasticity of demand for abatement inputs, with demand being more responsive to prices for β closer to one (see Eq. (2)). As such, this parameter strongly influences the sensitivity of profits to carbon prices, and thus the potential strength of carbon pricing as screening instrument. Second, for a given dispersion in quality θ, a lower β implies a greater dispersion in abatement generated by each input (see Eq. (1)), which suggests greater potential benefits from screening for lower β. Instead of pinning down a single value, we consider a wide range for β, between 0.1 and 0.9.

The remaining parameters ϕ and δ, as well as the innovation cost distribution $F(c)$ are calibrated such that the model matches empirical estimates of (i) the private value per citation π/θ, (ii) the ratio of social to private value of a patent, and (iii) predicted emission reductions from Pigouvian policies. For consistency, we re-calibrate these parameters for each β.

6.2. Results

Fig. 3 shows the optimal carbon price τ, abatement input price p, average innovation subsidy $\mathbb{E}[s]$ and welfare relative to first-best. Our main result are the blue curves, which in Figs. 3a–c show the optimal policy mix when the innovators accurately observe cost c and quality θ, and the policy maker can only use across-the-board subsidies (Proposition 2). For comparison, we display two other cases. The solid black line displays the benchmark case where policy makers can 'pick winners' and condition innovation subsidies on heterogeneous quality θ (Proposition 1). In this case, the innovation subsidies ensure all innovations are rewarded according to their social value, and the carbon price is used solely for the purpose of internalizing the environmental externality. The dashed

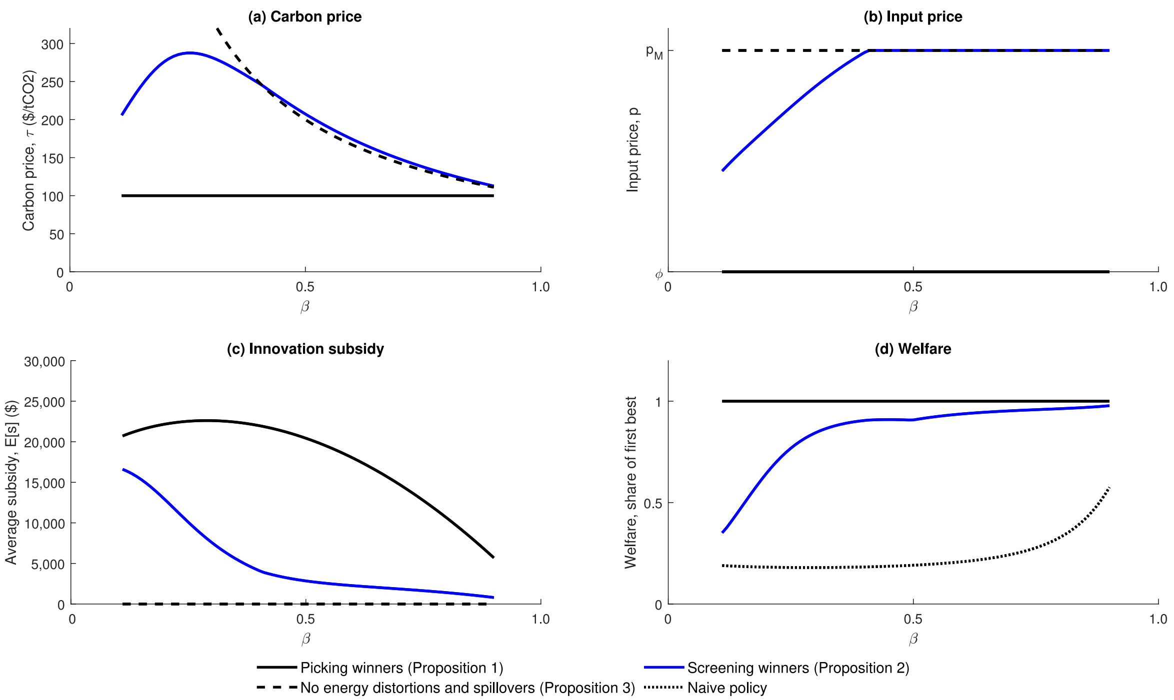

Fig. 3. Optimal policies in the numerical calibration.
Notes: The figure displays optimal policies in three settings. When the policy maker is able to pick winners by using targeted subsidies (Proposition 1), when the policy maker cannot pick winners and uses across-the-board subsidies (Proposition 2), a policy that leads to first-best under in the absence of energy demand distortions and innovation spillovers (Proposition 3), and a naive policy as defined in Section 3.2. Panel (a) is the carbon price τ in \$/tCO$_2$, (b) is the input price relative to the monopoly price $p_M = \phi/\beta$ and unit cost ϕ, panel (c) is the average innovation subsidy in \$, $\mathbb{E}[s]$, and (d) is welfare, as defined in eq. Eq. (6), relative to the first-best level. Note that in Panels (a)–(c) dotted and black lines overlap; in panel (d), dashed and black lines overlap. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

black line shows the case described in Proposition 3, where a first-best allocation can be achieved without targeted subsidies if energy demand distortions and innovation spillovers are absent.[26]

We find that innovation heterogeneity can substantially increase the optimal carbon prices when subsidies cannot be targeted. The optimal carbon price may be close to three times the Pigouvian level for intermediate levels of β, with a maximum of $\$288/tCO_2$ at $\beta = 0.25$. The mean carbon price across β is $\$202/tCO_2$, or just over twice the Pigouvian level. Innovation heterogeneity rationalizes abatement input prices in excess of marginal cost. Fig. 3b depicts the abatement input price relative to the monopoly price and unit cost and shows that awarding monopoly rights ($p = p_M$) is optimal for $\beta \geq 0.41$. Higher carbon and abatement input prices increase profits from innovation. As a consequence, lower innovation subsidies are required. Fig. 3c shows that the average innovation subsidy is reduced by 12.4%–80.2% relative to the case when targeted subsidies are available.

While innovation heterogeneity and the need for screening may substantially increase optimal carbon prices above the Pigouvian level, it is relevant to highlight that energy demand distortions considerably limit the size of this carbon price premium. This is best understood when comparing the blue curves to the black dashed curves in Fig. 3a. These dashed curve displays the optimal policy mix as described by Proposition 3, which assumes no energy demand distortions and no innovation spillovers.[27]

Fig. 3d shows welfare implications. Two results stand out. First, the welfare loss from being unable to 'pick winners' can be large. If the policy maker only has access to across-the-board subsidies, the maximum attainable welfare is 35.1%–97.8% (mean 85.7%) of welfare in the first-best allocation. Second, while large, this welfare loss is limited as the policy maker takes advantage of the innovation screening effect of carbon pricing. If the policy maker would have instead implemented the naive policy mix, which constitutes a Pigouvian carbon price, abatement input prices equal to marginal cost ϕ and an across-the-board innovation subsidy equal to the average optimal innovation subsidy under 'picking winners', the maximum attainable welfare relative to first-best is 18.0%–57.5% (mean 23.6%). Hence, Fig. 3d highlights that adjusting the policy mix to take advantage of the innovation screening effect can dramatically reduce the welfare loss vis-à-vis a naive policy.

[26] A third case is the naive policy with Pigouvian carbon prices, abatement input prices equal to marginal cost ϕ, and across-the-board innovation subsidies which coincide with the *average* subsidy under the picking winners policy (see Section 3.2 and Proposition 4).

[27] The additional absence of innovation spillovers ($\delta = 0$) explains why for lower carbon prices, part of the dashed curve lies below the blue curve. Fig. C.1 in Appendix C shows optimal policies for $\delta = 0$; in this case, the blue line is indeed always below the dashed line.

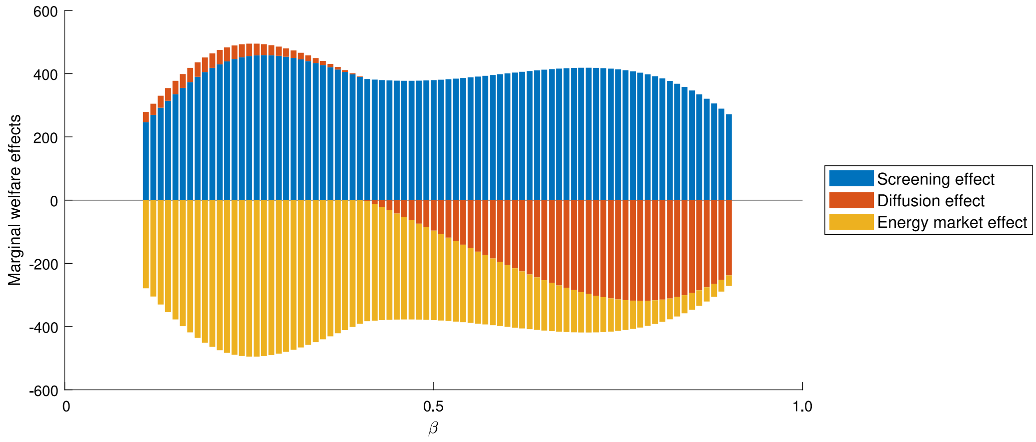

Fig. 4. Decomposition of the optimal carbon price.
Notes: The figure displays the energy market effect (yellow), diffusion effect (red), and innovation screening effect (blue), see decomposition in Equation Eq. (8). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 4 decomposes the premium into three effects, as in Eq. (8). These effects add up to zero under the optimal policy. The screening effect, shown by the blue bars, represents the increase in welfare due to a marginal increase in the carbon price, which encourages the development of high-quality innovations. The diffusion effect, indicated by red bars, is the welfare impact from a marginally higher carbon prices increasing the take-up of abatement technologies. This effect is positive for low β when the policy mix implies technology spreads too little from the social point of view, and turns negative for high β when the technology take-up cost exceeds the environmental benefit.[28] The diffusion effect reaches zero when $\tau = \Delta/\beta$ ($\tau = \$244/tCO_2$ when $\beta = 0.41$), which is also the point as of which it is optimal to assign monopoly abatement input prices, see Fig. 3. The energy market effect (yellow) depicts the marginal deadweight loss in the energy market due to excessively high carbon prices. As the optimal carbon price approaches the social cost of carbon for higher β, the energy market effect converges towards zero.

7. Concluding comments

Climate policies are implemented in markets with sizeable heterogeneities across firms. Heterogeneity in abatement costs is the primary reason why the theory of environmental policy design argues in favor of carbon prices over command-and-control instruments; prices allow the market to allocate abatement to those firms with the lowest marginal abatement cost. This paper considers a second type of heterogeneity, namely, in the quality of green innovations. We establish that in this context carbon prices also have an important benefit, as they act as a screening instrument for high-quality innovation. This screening benefit justifies a premium on the carbon price.

In this light, the high carbon prices recently observed in the EU Emissions Trading System, with the allowance price for the first time surpassing 100 €/tCO_2 in February 2023, may not only have contributed to increasing green innovation overall, but particularly reinforced high-quality projects. In fact, we find that this screening benefit can justify carbon prices that substantially exceed marginal damages. As such, these prices may be justified even under a lower social cost of carbon (Drupp et al., 2022).

We establish our theoretical results under the assumption that the policy maker is unable to accurately target green innovation subsidies to the highest-value projects; if such targeting were feasible, appropriate innovation subsidies would eliminate the need for further screening. In reality, some targeting is present but likely imperfect. For instance, the innovation support for low-carbon technologies that is expected to be awarded though the EU Innovation Fund is primarily awarded through grants which are evaluated by experts (European Commission, 2023); the Inflation Reduction Act makes similar provisions (Bistline et al., 2023). Our analysis highlights that as long as the social and private return to innovation remains greatest for those high-quality innovations that are most sensitive to carbon prices, there exists a screening benefit to carbon prices, and correspondingly a premium on the optimal price.

CRediT authorship contribution statement

Lassi Ahlvik: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Inge van den Bijgaart:** Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

[28] Diffusion may be below-optimal because innovating firms use market power. Similarly, diffusion might be excessive from the social point of view if carbon prices exceed the Pigouvian level.

Appendix A. Proofs and derivations

A.1. Proofs

We introduce some definitions and expressions that will be used in several proofs. For notational simplicity, the exposition in this section will suppress the arguments of $v(\tau,p)$ and $z(\tau,p,s,\theta)$.

The proofs will use $k \equiv (p-\phi)\left(\tau/p\right)^{\frac{1}{1-\beta}}$ which is equal to the profit per unit of quality θ. This allows us to write the maximum innovation costs such that the innovator will innovate as $z = s + k\theta$. It is straightforward to verify that $k'_\tau = 0$ and thus $z'_\tau = 0$ if $\tau = 0$ or $p = \phi$, and $k'_\tau > 0$ and $z'_\tau > 0$ whenever $\tau > 0$ and $p > \phi$. Similarly, $k'_p = 0$ and thereby $z'_p = 0$ if $\tau = 0$ or $p = p_M$, and $k'_p > 0$ and $z'_p > 0$ if $\tau > 0$ and $p \in [\phi, p_M)$. As it is never optimal for the innovator to set $p > p_M$, we consider only solutions with $p \in [\phi, p_M]$.

In addition, we rewrite (8)–(11) as follows. First, define $\Gamma_\tau \equiv \int_{\underline{\theta}}^{\overline{\theta}} v'_\tau \theta F(z)g(\theta)d\theta$ as the diffusion effect of τ. This allows us to write the necessary condition (8) as

$$\frac{\partial W}{\partial \tau} = \frac{\Delta - \tau}{-Y''(E)} + \Gamma_\tau + \Omega_\tau = 0. \tag{A.1}$$

From here, we use (7), to write

$$\Gamma_\tau = \left[\Delta - \tau\frac{\phi}{p}\right]\frac{1}{(1-\beta)\tau}\left(\frac{\tau}{p}\right)^{\frac{\beta}{1-\beta}}\int_{\underline{\theta}}^{\overline{\theta}} \theta F(z)g(\theta)d\theta, \tag{A.2}$$

and observe that the sign of Γ_τ is equal to the sign of $[\Delta - \tau\phi/p]$.

Similarly, define $\Gamma_p \equiv \int_{\underline{\theta}}^{\overline{\theta}} v'_p \theta F(z)g(\theta)d\theta$ as the diffusion effect of p. This allows us to write the necessary condition (10) as

$$\frac{\partial W}{\partial p} = \Gamma_p + \Omega_p \geq 0. \tag{A.3}$$

and holding with strict equality if $p < p_M$. Next, using (7), we can write Term Γ_p as:

$$\Gamma_p = -\left[\Delta - \tau\frac{\phi}{p}\right]\frac{1}{(1-\beta)p}\left(\frac{\tau}{p}\right)^{\frac{\beta}{1-\beta}}\int_{\underline{\theta}}^{\overline{\theta}} \theta F(z)g(\theta)d\theta, \tag{A.4}$$

or, by (A.2), $\Gamma_p = -\Gamma_\tau \tau/p$. The sign of Γ_p is opposite to the sign of the term in brackets, and opposite to Γ_τ.

A.1.1. Proof of Proposition 1

The optimal p must satisfy (A.3). With $s(\theta)$ satisfying (12), the innovation effects are zero: by (11), $\Omega_p = \bar{\Omega}_p = \Omega^s_p = 0$. From (A.4), this implies $p = \phi\tau/\Delta$.

The optimal τ must satisfy (A.1). With $s(\theta)$ satisfying (12), the innovation effects are zero: by (9), $\Omega_\tau = \bar{\Omega}_\tau = \Omega^s_\tau = 0$. Similarly, with $p = \phi\tau/\Delta$, $\Gamma_\tau = 0$ (see (A.2)). By (A.1) this implies $\tau = \Delta$. From here it follows $p = \phi$.

From (12) and the definitions of v from (7) and z from (5) we obtain the result for the optimal targeted subsidy:

$$s = \left[\left(\frac{\tau}{p}\right)^{\frac{\beta}{1-\beta}}\left(\frac{\Delta}{\beta} - \tau\right) + \delta\right]\theta. \tag{A.5}$$

The optimal subsidy result is then obtained by plugging $\tau = \Delta$ and $p = \phi$ into (A.5). □

A.1.2. Proof to Proposition 2

From (13), the optimal uniform subsidy implies $\mathbb{E}[(v\theta - z)f(z)] = 0$. From (9) and (11) it follows that the average innovation effects in Ω_τ and Ω_p are zero, and only the innovation screening effects remain: $\Omega_\tau = \Omega^s_\tau$ and $\Omega_p = \Omega^s_p$.

Next, define $\tilde{z} \equiv z(\tau,p,s,\tilde{\theta})$, with $\tilde{\theta}$ such that $v\tilde{\theta} - \tilde{z} = 0$: as both $v\theta$ and z are linear in θ, $\tilde{\theta}$ is uniquely defined. Then subtracting $\tilde{z}'_\tau \mathbb{E}[(v\theta - z)f(z)]$ from Ω_τ as defined in (8), gives

$$\Omega_\tau = \int_{\underline{\theta}}^{\overline{\theta}} (v\theta - z)(z'_\tau - \tilde{z}'_\tau)f(z)g(\theta)d\theta, \tag{A.6}$$

where we exploit the fact that, by (13), the optimal uniform subsidy is defined by $\mathbb{E}[(v\theta - z)f(z)] = 0$. In turn, we subtract $\mathbb{E}[(v\tilde{\theta} - \tilde{z})(z'_\tau - \tilde{z}'_\tau)f(z)]$ from (A.6). This gives

$$\Omega_\tau = k'_\tau[v-k]\int_{\underline{\theta}}^{\overline{\theta}} (\theta - \tilde{\theta})^2 f(z)g(\theta)d\theta, \tag{A.7}$$

where we exploit that $v\tilde{\theta} - \tilde{z} = 0$ by the definition of $\tilde{\theta}$. The integral contains a squared term and is thus necessarily positive. Therefore the sign of Ω_τ is equal to the sign of $k'_\tau[v-k]$.

Following steps similar to those used to derive (A.7), we can write Ω_p as

$$\Omega_p = k'_p[v-k]\int_{\underline{\theta}}^{\overline{\theta}} (\theta - \tilde{\theta})^2 f(z)g(\theta)d\theta, \tag{A.8}$$

or $\Omega_p = (k'_p/k'_\tau)\Omega_\tau$. As the integral term is positive, the sign of Ω_p is equal to the sign of $k'_p(v-k)$. If $p < p_M$, this is equal to the sign of Ω_τ. For $p = p_M$, $\Omega_p = k'_p = 0$.

Proof: $p > \phi$. Proof by contradiction. Assume $p = \phi$, then $z'_\tau = 0$ (and $k'_\tau = 0$) and by (A.7), $\Omega_\tau = 0$. We show that this leads to a contradiction with the first-order conditions (8), (10) and (13) which the optimal policy must necessarily satisfy. With $p = \phi$, (A.2) becomes:

$$\Gamma_\tau = \left[\Delta - \tau\right]\frac{1}{(1-\beta)\tau}\left(\frac{\tau}{\phi}\right)^{\frac{\beta}{1-\beta}}\int_{\underline{\theta}}^{\overline{\theta}} F(z)\theta g(\theta)d\theta.$$

Combining this with (A.1) and $\Omega_\tau = 0$ it follows that $\tau = \Delta$. With $\tau = \Delta$ and $p = \phi$, (A.4) implies $\Gamma_p = 0$. Eq. (A.3) then requires $\Omega_p = 0$ (with strict equality because $p = \phi < p_M$). Yet, at $p = \phi$ and $\tau = \Delta$, $v - k = \frac{1-\beta}{\beta}\Delta^{\frac{1}{1-\beta}}\phi^{-\frac{\beta}{1-\beta}} + \delta > 0$ which, using (A.8), gives $\Omega_p > 0$ and implies (A.3) cannot hold; a contradiction.

Proof: $\tau > \Delta$. Proof by contradiction. Assume $\tau \leq \Delta$. Then $\Gamma_\tau > 0$ by (A.2) and $\Gamma_p < 0$ by (A.4). Eqs. (A.1) and (A.3) then require $\Omega_\tau < 0$ and $\Omega_p > 0$, which cannot be simultaneously true; a contradiction.

Proof: $\Omega_\tau > 0, \Omega_p \geq 0$. Proof by contradiction. By $\tau > \Delta$ and (A.1), $\Gamma_\tau + \Omega_\tau > 0$. Suppose $\Omega_\tau < 0$. Then $\Gamma_\tau > 0$. Yet this would imply $\Omega_p < 0$ and $\Gamma_p \leq 0$, which implies (A.3) is not satisfied. Similarly, if $\Omega_\tau = 0$, then (A.1) requires $\Gamma_\tau > 0$. In turn, this implies $\Omega_p = 0$ and $\Gamma_p < 0$ which is inconsistent with (A.3). Hence, $\Omega_\tau > 0$ from which follows $\Omega_p > 0$ if $p < p_M$ and $\Omega_p = 0$ if $p = p_M$.

Proof: $\overline{\Omega}_\tau = \overline{\Omega}_p = 0$, $\Omega^s_\tau > 0$, and $\Omega^s_p \geq 0$. By (13), $\overline{\Omega}_\tau$ and $\overline{\Omega}_p$ as defined in (9) and (11) are zero. As $\Omega_\tau > 0$ and $\Omega_p \geq 0$, by (9) and (11) we must have $\Omega^s_\tau > 0$ and $\Omega^s_p \geq 0$.

Proof: s. The solution for s can be obtained by substituting (5) and (7) in to (13) and rearranging the resulting expression. □

A.1.3. Proof of Proposition 3

A first necessary condition for first-best is that $v\theta = z$ holds for all θ; see Eq. (12). From $z = s + k\theta$, this is equivalent to $s = 0$ and $v - k = 0$. Use the definition of v and k to write:

$$v - k - \delta = \frac{\Delta}{\beta}\left(\frac{\tau}{p}\right)^{\frac{\beta}{1-\beta}} - p\left(\frac{\tau}{p}\right)^{\frac{1}{1-\beta}}$$

$$= \left(\frac{\tau}{p}\right)^{\frac{\beta}{1-\beta}}\left[\frac{\Delta}{\beta} - \tau\right].$$

Observe that $v - k - \delta = 0$ holds when $\tau = 0$ and when $\tau = \Delta/\beta$. Differentiate $v - k - \delta$ with respect to τ:

$$\frac{\partial}{\partial\tau}(v - k - \delta) = \frac{1}{p}\frac{1}{1-\beta}\left(\frac{\tau}{p}\right)^{\frac{\beta}{1-\beta}-1}\left[\Delta - \tau\right].$$

The derivative is non-negative if $\tau \in [0, \Delta]$ and negative if $\tau > \Delta$. In other words, $v - k - \delta$ takes an inverted U-shape with a peak at $\tau = \Delta$ and reaching zero at $\tau = \{0, \Delta/\beta\}$. Proposition 2 rules out $\tau < \Delta$. Thus, $v - k = 0$ requires

$$\tau \geq \Delta/\beta, \tag{A.9}$$

which holds with equality only if $\delta = 0$.

A second necessary (but not sufficient) condition for first-best, is that the first-order conditions for τ (Eq. (A.1)) and p (Eq. (A.3)) hold with equality. In the first-best, $v-k = 0$. By (A.7) and (A.8) this implies that $\Omega_\tau = \Omega_p = 0$. In turn, by (A.9), the first (Pigouvian) term in (A.1) is non-positive, meaning that first-best requires $\Gamma_\tau \geq 0$, which holds with equality only if $Y''(E) \to -\infty$. At the same time, $\Omega_p = 0$ and (A.3) imply that $\Gamma_p \geq 0$. By (A.2) and (A.4), $\Gamma_\tau \geq 0$ and $\Gamma_p \geq 0$ can only be simultaneously true if $\Gamma_\tau = \Gamma_p = 0$. This requires $Y''(E) \to -\infty$ and

$$\Delta - \tau\frac{\phi}{p} = 0.$$

As $p \leq p_M = \phi/\beta$, a necessary condition for the latter is $\tau \leq \Delta/\beta$. This is consistent with (A.9) only if $\tau = \Delta/\beta$, implying $\delta = 0$ and $p = p_M$.

We are left to show that the solution $\tau = \Delta/\beta$, $p = p_M = \phi/\beta$ and $s = 0$ indeed implements the same allocation as the first-best in Proposition 1 (with $\delta = 0$). In Proposition 1, $\tau = \Delta$ and $p = \phi$. Hence, we require that the social value of innovation is the same, that is, $v(\Delta, \phi) = v(\Delta/\beta, p_M)$. We also require that the private value of the innovation is the same, that is, $s(\theta)$ from Proposition 1 equal to $z(\Delta/\beta, p_M, 0, \theta)$. One can use Eqs. (5) and (7) to straightforwardly confirm this is the case.

Last, note that an optimal tax on energy use E would set $Y'(E) = \xi + \Delta$ and eliminate the first term of (A.1). Therefore, if the policy maker can optimally set such an energy tax, we only require assumption $\delta = 0$; the other assumption $Y''(E) \Rightarrow -\infty$ can be dropped. □

A.1.4. Proof of Proposition 4

Proof is by contradiction. Suppose $s^{opt} \geq s^{naive}$. By Proposition 2, s^{opt} satisfies

$$s^{opt} = \left[\left(\frac{\tau}{p}\right)^{\frac{\beta}{1-\beta}}\left(\frac{\Delta}{\beta} - \tau\right) + \delta\right]\frac{\mathbb{E}[\theta f(z)]}{\mathbb{E}[f(z)]}. \tag{A.10}$$

Next, s^{naive} satisfies (13), with $\tau = \Delta$ and $p = \phi$, leading to $z = s$. It follows that $f(z)$ is constant, and we can write $\mathbb{E}[\theta f(z)]/\mathbb{E}[f(z)] = \mathbb{E}[\theta]$. This gives

$$s^{naive} = \left[\left(\frac{\Delta}{\phi}\right)^{\frac{\beta}{1-\beta}}\left(\frac{\Delta}{\beta} - \Delta\right) + \delta\right]\mathbb{E}[\theta]. \tag{A.11}$$

Observe that this coincides with the expected subsidy, s^{target}, from Proposition 1: $s^{naive} = \mathbb{E}[s^{target}]$.

Consider z under the optimal subsidy. As $\tau > \Delta$ and $p > \phi$ in this scenario (see Proposition 2), $z = s + k\theta$ is increasing in θ. Combined with the assumption that $f(c)$ is non-increasing in c, we have $Cov(\theta, f(z)) \leq 0$, implying:

$$\mathbb{E}[\theta f(z)] - \mathbb{E}[\theta]\mathbb{E}[f(z)] \leq 0 \quad \Rightarrow \quad \frac{\mathbb{E}[\theta f(z)]}{\mathbb{E}[f(z)]} \leq \mathbb{E}[\theta]$$

and with strict inequality if $f(z)$ is independent of z (uniform distribution $f(c)$). Therefore, from Eqs. (A.10) and (A.11), for $s^{opt} \geq s^{naive}$ to hold, we must have

$$\left(\frac{\tau}{p}\right)^{\frac{\beta}{1-\beta}}\left(\frac{\Delta}{\beta} - \tau\right) \geq \left(\frac{\Delta}{\phi}\right)^{\frac{\beta}{1-\beta}}\left(\frac{\Delta}{\beta} - \Delta\right).$$

By $\tau > \Delta$ this implies

$$\frac{\tau}{p} > \frac{\Delta}{\phi}.$$

Yet, by (A.4) and (A.8), this gives $\Gamma_p > 0$ and $\Omega_p > 0$, which implies the first-order condition (A.3) cannot hold; a contradiction. □

A.1.5. Proof of Proposition 5

Proof: $\bar{\Omega}_\tau = 0$. From (13), the optimal uniform subsidy implies $\mathbb{E}[(v\theta - z)f(z)] = 0$. From here it follows that the average innovation effect in Ω_τ is zero, and only the innovation screening effect remains: $\Omega_\tau = \Omega_\tau^s$.

Proof: $\tau = \Delta$ *and* $\Omega_\tau^s = 0$ *if* $p = \phi$. From (4), $z'_\tau = 0$ if $p = \phi$. From (9) it follows that $\Omega_\tau^s = 0$ and thus $\Omega_\tau = 0$. The optimal carbon price $\tau = \Delta$ follows from (A.1) and (A.2).

Proof: $\tau > \Delta$ *and* $\Omega_\tau^s > 0$ *if* $p \in (\phi, p_M]$. The remainder of the proof is by contradiction, where we first prove that $\tau > \Delta$, and next $\Omega_\tau > 0$.

Suppose $\tau \leq \Delta$. Then by (A.1), we require $\Gamma_\tau + \Omega_\tau \leq 0$. Use (7), and following the same steps as in the Proof to Proposition 2 (see (A.7)), we can write Ω_τ as

$$\Omega_\tau = k'_\tau\left[\left(\frac{\tau}{p}\right)^{\frac{\beta}{1-\beta}}\left(\frac{\Delta}{\beta} - \tau\right) + \delta\right]\int_{\underline{\theta}}^{\overline{\theta}}(\theta - \tilde{\theta})^2 f(z)g(\theta)d\theta, \tag{A.12}$$

where we know that by $p > \phi$, $k'_\tau > 0$. Hence, $\tau \leq \Delta$ would imply $\Omega_\tau > 0$, and we require $\Gamma_\tau < 0$. Yet by (A.2), $p > \phi$ and $\tau \leq \Delta$ imply $\Gamma_\tau > 0$; a contradiction.

Hence, we must have $\Delta > \tau$ and, by (A.1), $\Gamma_\tau + \Omega_\tau > 0$. Now suppose $\Omega_\tau \leq 0$. By (A.12), this requires $\Delta/\beta \leq \tau$. Next note that by (A.2) and $p \leq p_M$, we know

$$\Gamma_\tau \leq \left[\frac{\Delta}{\beta} - \tau\right]\frac{\beta}{(1-\beta)\tau}\left(\frac{\tau}{p}\right)^{\frac{\beta}{1-\beta}}\int_{\underline{\theta}}^{\overline{\theta}}\theta F(z)g(\theta)d\theta, \tag{A.13}$$

which implies $\Gamma_\tau \leq 0$ for $\Delta/\beta \leq \tau$ and $\Gamma_\tau + \Omega_\tau \leq 0$: a contradiction. From here it follows that $\Omega_\tau > 0$ and thus $\Omega_\tau^s > 0$. □

A.1.6. Proof of Proposition 6

Under a technology uptake subsidy, demand (2) reads

$$q = \theta\left(\frac{\tau}{(1-\sigma)p}\right)^{\frac{1}{1-\beta}}. \tag{A.14}$$

Similarly, for the maximum innovation cost z and value of innovation $v\theta$ (see Eqs. (5) and (7)) we now have

$$z = s + k\theta, \tag{A.15}$$

with k now given by $k = (p-\phi)\left(\frac{\tau}{(1-\sigma)p}\right)^{\frac{1}{1-\beta}}$. As before, we have $k'_\tau > 0$ whenever $\tau > 0$ and $p > \phi$, and $k'_p > 0$ if $\tau > 0$ and $p \in [\phi, p_M)$ with p_M still given by $p_M = \phi/\beta$. It then follows that $z'_\tau > 0$ if $\tau > 0$ and $p > \phi$, $z'_\tau = 0$ if $\tau = 0$ or $p = \phi$, $z'_p > 0$ if $\tau > 0$ and $p \in [\phi, p_M)$, and $z'_p = 0$ if $\tau = 0$ or $p = p_M$. In addition, we can establish that if $\tau > 0$ and $p > \phi$, $k'_\sigma > 0$ and thus $z'_\sigma > 0$, while $k'_\sigma = z'_\sigma = 0$ if $\tau = 0$ or $p = \phi$.

The social value of innovation is given by:

$$v(\tau, p, \sigma)\theta = \left[\frac{\Delta}{\beta}\left(\frac{\tau}{(1-\sigma)p}\right)^{\frac{\beta}{1-\beta}} - \phi\left(\frac{\tau}{(1-\sigma)p}\right)^{\frac{1}{1-\beta}} + \delta\right]\theta. \tag{A.16}$$

The first-order conditions (A.1) and (A.3) still hold for the optimal τ and p with the z and v adjusted for σ as in (A.14) and (A.16). Likewise, following the same steps as in the proof to Proposition 2 (see Appendix A.1.2), we again obtain (A.7) and (A.8) with the adjusted k, v and z.

In turn, the subsidy σ that maximizes welfare (6) satisfies:

$$\frac{\partial W}{\partial \sigma} = \underbrace{\int_{\underline{\theta}}^{\overline{\theta}} v'_\sigma \theta F(z) g(\theta) d\theta}_{\Gamma_\sigma} + \underbrace{\int_{\underline{\theta}}^{\overline{\theta}} [v\theta - z]\, z'_\sigma f(z) g(\theta) d\theta}_{\Omega_\sigma} \geq 0, \tag{A.17}$$

which holds with equality if the constraint $\sigma \leq \bar{\sigma}$ is not binding. We define σ^{opt} as the σ that ensures $\partial W/\partial \sigma = 0$. From here, it follows that $\sigma = \sigma^{opt}$ if $\sigma^{opt} \leq \bar{\sigma}$ (non-binding constraint) and $\sigma = \bar{\sigma} \leq \sigma^{opt}$ (binding constraint). Akin to (A.7) and (A.8) we can write

$$\Omega_\sigma = k'_\sigma [v - k] \int_{\underline{\theta}}^{\overline{\theta}} (\theta - \tilde{\theta})^2 f(z) g(\theta) d\theta, \tag{A.18}$$

with

$$v - k = \left(\frac{\tau}{(1-\sigma)p}\right)^{\frac{\beta}{1-\beta}} \left[\frac{\Delta}{\beta} - \frac{\tau}{1-\sigma}\right] + \delta.$$

The remainder of the proof then proceeds as follows. We first assume the optimal unconstrained σ can be implemented: $\sigma = \sigma^{opt} \leq \bar{\sigma}$. For this case we solve for the optimal τ under the assumption that $\sigma^{opt} < 1$. In turn, we solve for the optimal σ, p and innovation screening effects, where we show that indeed $\sigma^{opt} < 1$ must hold. Next, we consider the case where the optimal σ cannot be implemented: $\sigma = \bar{\sigma} < \sigma^{opt}$, and determine the remaining variables under this constraint.

Proof: $\tau = \Delta$ if $\sigma = \sigma^{opt}$. Suppose $\sigma^{opt} < 1$. From (A.7) and (A.18), we have $(1-\sigma)k'_\sigma = \tau k'_\tau$ and thereby $(1-\sigma)\Omega_\sigma = \tau\Omega_\tau$. In turn, by (A.16), $(1-\sigma)v'_\sigma = \tau v'_\tau$, and thus $(1-\sigma)\Gamma_\sigma = \tau\Gamma_\tau$. Then if $\sigma = \sigma^{opt}$, condition (A.17) holds with equality: $\Gamma_\sigma + \Omega_\sigma = 0$. In turn, this implies that for $\tau > 0$, $\Gamma_\tau + \Omega_\tau = 0$. By (A.1), we must then have $\tau = \Delta$ (Pigouvian pricing).

Proof: σ and $p = p_M$ if $\sigma = \sigma^{opt}$. Assume still $\sigma^{opt} < 1$. Observe that by $(1-\sigma)v'_\sigma = -pv'_p$ and, accordingly $(1-\sigma)\Gamma_\sigma = -p\Gamma_p$. This implies that either Γ_σ and Γ_p have opposite signs, or $\Gamma_p = \Gamma_\sigma = 0$. Further, from (A.8) and (A.18), and the properties of k'_p and k'_σ, Ω_p and Ω_σ have the same sign for $p \in (\phi, p_M)$, while $\Omega_p = 0$ if $p = p_M$ and $\Omega_\sigma = 0$ if $p = \phi$. From here, it follows that $\partial W/\partial\sigma = \Gamma_\sigma + \Omega_\sigma = 0$ and $\partial W/\partial p = \Gamma_p + \Omega_p \geq 0$ can only be simultaneously true if either (i) $\Gamma_\sigma = \Gamma_p = 0$ and $\Omega_\sigma = \Omega_p = 0$, or (ii) $\Gamma_\sigma < 0$ and $\Gamma_p > 0$, while $\Omega_\sigma > 0$ and $\Omega_p \geq 0$. This is because $\Gamma_\sigma > 0$ and $\Omega_\sigma < 0$ imply $\Gamma_p < 0$ and $\Omega_p \leq 0$, which gives $\partial W/\partial p = \Gamma_p + \Omega_p < 0$. We show in turn that (i) provides a solution if $\delta = 0$, while (ii) offers a solution if $\delta > 0$:

First observe that $\Gamma_\sigma = \Gamma_p = 0$ if $v'_\sigma = v'_p = 0$. From (A.16), this requires $(1-\sigma)p = \phi$. In turn, both $\Omega_\sigma = \Omega_p = 0$ either if (a) $p = \phi$ and $p = p_M$, or (b) $v - k = 0$. The former cannot be true. One can show that the latter requires $\sigma = 1-\beta$ if $\delta = 0$, and $\sigma > 1-\beta$ if $\delta > 0$. From here, it follows that if $\delta = 0$ we obtain a solution with $\sigma = 1-\beta$ and $p = \phi/\beta = p_M$. If $\delta > 0$ however, $(1-\sigma)p = \phi$ would imply $p > \phi/\beta = p_M$ which is not feasible. The solution for $\delta > 0$ must thus satisfy (ii): $\Gamma_\sigma < 0$ and $\Gamma_p > 0$, while $\Omega_\sigma > 0$ and $\Omega_p \geq 0$. It then follows that $\partial W/\partial p = \Gamma_p + \Omega_p > 0$ and thus $p = p_M$. At $p = p_M$ and $\tau = \Delta$, we obtain

$$\Gamma_\sigma = \left[\frac{1}{\beta} - \frac{1}{1-\sigma}\right] \frac{\Delta}{1-\sigma} \frac{\beta}{1-\beta} \left(\frac{\tau}{(1-\sigma)p}\right)^{\frac{\beta}{1-\beta}} \int_{\underline{\theta}}^{\overline{\theta}} \theta F(z) g(\theta) d\theta.$$

Then $\Gamma_\sigma < 0$ requires $1-\sigma < \beta$, or $\sigma > 1-\beta$.

Proof: $\sigma^{opt} < 1$. As a final step, we establish that $\sigma^{opt} < 1$. Observe that for $\tau = \Delta$ and $p = p_M$, $\lim_{\sigma\to 1}[v-k] = -\infty$ and $\lim_{\sigma\to 1}[v-k] = \infty$. By (A.18), this gives $\lim_{\sigma\to 1}\Omega_\sigma = -\infty$. Similarly, $\lim_{\sigma\to 1}\Gamma_\sigma = -\infty$. Hence we must have $\sigma^{opt} < 1$.

Proof: $\tau > \Delta$ if $\sigma < \sigma^{opt}$. If instead $\sigma = \bar{\sigma} < \sigma^{opt}$, $\Gamma_\sigma + \Omega_\sigma > 0$, and thus $\Gamma_\tau + \Omega_\tau > 0$. It then follows from (A.1) that $\tau > \Delta$.

Note on first-best allocation. In the proof of Proposition 3, we establish that a necessary condition for first-best allocation is $v - k = 0$. For $\delta > 0$, we obtain $\Omega_\sigma > 0$ at $\sigma = \sigma^{opt}$. From (A.18), it then follows that $v - k > 0$, and the allocation is not first-best. Instead for $\delta = 0$, we have $\sigma = 1-\beta$, $\tau = \Delta$ and $p = p_M$ (see above). From (A.18) it follows that $v - k = 0$ which, in turn, implies the private value of innovation is equal to the social value. The allocation is then first best as in addition it ensures (i) the marginal private cost of energy is equal to social cost and (ii) the input price incurred by firms is equal to the marginal input cost (see also Proposition 1). The former follows from $\tau = \Delta$ and (ii) is due to $\sigma = 1-\beta$ and $p = \phi/\beta$ which imply $(1-\sigma)p = \phi$. Note that another way to establish optimal innovation decisions is by observing that the social value of innovation under uptake subsidies coincides with the first best in Proposition 1: $v(\Delta, p_M, 1-\beta) = v(\Delta, \phi, 0)$. The same is true for the private value of innovation z.

The remainder of the proof then follows the proof to Proposition 2 (see Appendix A.1.2):

Proof: $p > \phi$ if $\sigma < \sigma^{opt}$. Proof by contradiction. Assume $p = \phi$, then $z'_\tau = 0$ (and $k'_\tau = 0$) and by (A.7), $\Omega_\tau = 0$. $\Gamma_\tau + \Omega_\tau > 0$ then requires $\Gamma_\tau < 0$. With $p = \phi$, (A.2) becomes:

$$\Gamma_\tau = \left[\Delta - \frac{\tau}{1-\sigma}\right] \frac{1}{(1-\beta)\tau} \left(\frac{\tau}{(1-\sigma)\phi}\right)^{\frac{\beta}{1-\beta}} \int_{\underline{\theta}}^{\overline{\theta}} F(z)\theta g(\theta) d\theta.$$

$\Gamma_\tau > 0$ then requires $\tau < (1-\sigma)\Delta$, which is inconsistent with $\tau > \Delta$. Hence we must have $p > \phi$.

Proof: $\Omega_\tau > 0, \Omega_p \geq 0$ if $\sigma < \sigma^{opt}$. Proof by contradiction. We require $\Gamma_\tau + \Omega_\tau > 0$. Suppose $\Omega_\tau < 0$. Then $\Gamma_\tau > 0$. Yet this would imply $\Omega_p < 0$ and $\Gamma_p \leq 0$, which implies (A.3) is not satisfied. Similarly, if $\Omega_\tau = 0$, then $\Gamma_\tau > 0$. In turn, this implies $\Gamma_p < 0$ and either $\Omega_p = 0$ (if $v - k = 0$), or $p = \phi$ (if $k'_\tau = 0$. Here, $\Omega_p = 0$ would be inconsistent with (A.3), and we rule out $p = \phi$ above. Hence we must have $\Omega_\tau > 0$ with $v - k > 0$, and $\Omega_p \geq 0$.

Proof: Ω^s_τ and Ω^s_p. From (13), the optimal uniform subsidy again implies $\mathbb{E}[(v\theta - z)f(z)] = 0$. From (9) and (11) it follows that the average innovation effects in Ω_τ and Ω_p are zero, and only the innovation screening effects remain: $\Omega_\tau = \Omega^s_\tau$ and $\Omega_p = \Omega^s_p$. If $\sigma = \sigma^{opt}$ we then obtain $\Omega^s_p = 0$ (by $p = p_M$), $\Omega^s_\tau = 0$ if $\delta = 0$ and $\Omega^s_\tau > 0$ if $\delta > 0$. If $\sigma = \bar{\sigma} < \sigma^{opt}$, $\Omega^s_p \geq 0$ and $\Omega^s_\tau > 0$. □

A.1.7. Proof of Proposition 7

The policy maker makes a take-it-or-leave-it offer T, which innovators accept and sell if:

$$T \geq k\theta,$$

where we use the definition $k = (p - \phi)\big(\tau/p\big)^{\frac{1}{1-\beta}}$. It follows that innovators with $\theta \leq \theta^*$ sell for T and the government allows for competitive input supply, $p = \phi$. The cut-off type is

$$\theta^* = \frac{T}{k}, \tag{A.19}$$

and innovators with $\theta > \theta^*$ have $p > \phi$. In the following analysis we treat θ^*, rather than T, as the choice variable and show the arguments of $v(\tau, p)$ to make the distinction between innovations bought ($p = \phi$) and not bought ($p > \phi$) clear.[29] We continue to use z as the maximum innovation cost an innovator is willing to incur, where we note that for those innovators that do not sell their innovation, z is still given by (4), whereas for innovators that sell their innovation $z = z^*$ given by

$$z^* = s + T. \tag{A.20}$$

Proof: $\theta^* < \overline{\theta}$ and $p > \phi$ for innovators who relinquish property right. Observe that imposing $p = \phi$ on innovators who do not accept the offer implies all innovators accept the offer and thus $\theta^* = \overline{\theta}$. Yet implementing $\theta^* = \overline{\theta}$ by choosing a sufficiently high T is equivalent to setting $p = \phi$ for all $\theta \in [\underline{\theta}, \overline{\theta}]$. From Proposition 2, this is not optimal: we must have $\theta^* < \overline{\theta}$, with $p > \phi$ for innovators who do not sell their rights.

Proof: p, τ, Ω_τ if $\theta^* = \underline{\theta}$. If in the optimum $\theta^* = \underline{\theta}$ holds, then no innovator sells its patent, and the proof to Proposition 2 (Appendix A.1.2) applies.

Proof: p, τ, Ω_τ if $\theta^* \in \left(\underline{\theta}, \overline{\theta}\right)$. If in the optimum, $\theta^* \in \left(\underline{\theta}, \overline{\theta}\right)$ we can write the first-order conditions (8) and (10) as:

$$\frac{\partial W}{\partial \tau} = \frac{\Delta - \tau}{-Y''(E)} + \underbrace{\int_{\underline{\theta}}^{\theta^*} v'_\tau(\tau, 0)\theta F(z^*)g(\theta)d\theta}_{\Gamma_{\tau,p=\phi}} + \underbrace{\int_{\theta^*}^{\overline{\theta}} v'_\tau(\tau, p)\theta F(z)g(\theta)d\theta}_{\Gamma_{\tau,p>\phi}} + \underbrace{\int_{\theta^*}^{\overline{\theta}} [v(\tau, p)\theta - z] z'_\tau f(z)g(\theta)d\theta}_{\Omega_\tau} = 0, \tag{A.21}$$

and

$$\frac{\partial W}{\partial p} = \underbrace{\int_{\theta^*}^{\overline{\theta}} v'_p(\tau, p)\theta F(z)g(\theta)d(\theta)}_{\Gamma_{p,p>\phi}} + \underbrace{\int_{\theta^*}^{\overline{\theta}} [v(\tau, p)\theta - z] z'_p f(z)g(\theta)d\theta}_{\Omega_p} = 0. \tag{A.22}$$

The expression above defines the Λ separately for $\theta \leq \theta^*$ innovations (with $p = \phi$), and $\theta > \theta^*$ innovations (with $p > \phi$). As $p = \phi$ implies the innovation decision is independent of θ for $\theta \leq \theta^*$ innovations, the innovation effect Ω includes only by $\theta > \theta^*$ innovations. The Γ_τ, Γ_p, Ω_τ and Ω_p can then be expressed akin to (A.2), (A.4), (A.7) and (A.8), respectively. Similarly, (13) now reads

$$\frac{\partial W}{\partial s} = \int_{\theta^*}^{\overline{\theta}} [v(\tau, p)\theta - z(\tau, p, s, \theta)] f(z)g(\theta)d\theta = 0. \tag{A.23}$$

The remainder of the proof closely follows the proof to Proposition 2:

Proof: $\tau > \Delta$. Proof by contradiction. Assume $\tau \leq \Delta$. Then $v'_\tau(\tau, 0) \geq 0$ and $v'_\tau(\tau, p) > 0$ and $\Gamma_{\tau,p=\phi} \geq 0$ and $\Gamma_{\tau,p>\phi} > 0$. In addition, $v'_p(\tau, p) < 0$ and thus $\Gamma_{p,p>\phi} < 0$. Eqs. (A.21) and (A.22) then require that $\Omega_\tau < 0$ and $\Omega_p > 0$ which cannot be simultaneously true.

Proof: $\Omega_\tau > 0$, $\Omega_p \geq 0$. Proof by contradiction. By $\tau > \Delta$ and (A.21), $\Gamma_{\tau,p=\phi} + \Gamma_{\tau,p>\phi} + \Omega_\tau > 0$. Suppose $\Omega_\tau < 0$. Then $\Gamma_{\tau,p=\phi} + \Gamma_{\tau,p>\phi} > 0$. Yet this would imply $\Omega_p < 0$ and $\Gamma_{p,p>\phi} < 0$, which implies (A.22) is not satisfied. Similarly, if $\Omega_\tau = 0$, then (A.21) requires $\Gamma_{\tau,p=\phi} + \Gamma_{\tau,p>\phi} > 0$. In turn, this implies $\Omega_p = 0$ and $\Gamma_{p,p>\phi} < 0$ which is inconsistent with (A.22). Hence, $\Omega_\tau > 0$ from which follows $\Omega_p > 0$ if $p < p_M$ and $\Omega_p = 0$ if $p = p_M$.

[29] We prove below that the policy maker indeed finds it optimal to set $p > \phi$ for the innovators that did not accept the offer T.

Proof: $\overline{\Omega}_\tau = \overline{\Omega}_p = 0$, $\Omega^s_\tau > 0$, *and* $\Omega^s_p \geq 0$. By (A.23), $\overline{\Omega}_\tau$ and $\overline{\Omega}_p$ are zero (see (9) and (11) for definitions). As $\Omega_\tau > 0$ and $\Omega_p \geq 0$, by (9) and (11) we must have $\Omega^s_\tau > 0$ and $\Omega^s_p \geq 0$. □

A.1.8. Endogenous spillovers: further derivations

Derivation of Eq. (17). With endogenous spillovers, welfare can be written as

$$W = Y(E) - (\xi + \Delta)E + \int_{\underline{\theta}}^{\overline{\theta}} \int_0^z \left(\left[\frac{\Delta}{\beta} \left(\frac{\tau}{p} \right)^{\frac{\beta}{1-\beta}} - \phi \left(\frac{\tau}{p} \right)^{\frac{1}{1-\beta}} \right] \theta - (c - \kappa \Theta) \right) f(c) dc g(\theta) d\theta,$$

where z now satisfies (16). Observe that Θ is common across c and θ. This allows us to write

$$W = Y(E) - (\xi + \Delta)E + \int_{\underline{\theta}}^{\overline{\theta}} \int_0^z \left(\left[\frac{\Delta}{\beta} \left(\frac{\tau}{p} \right)^{\frac{\beta}{1-\beta}} - \phi \left(\frac{\tau}{p} \right)^{\frac{1}{1-\beta}} \right] \theta - c \right) f(c) dc g(\theta) d\theta + \kappa \Theta \int_{\underline{\theta}}^{\overline{\theta}} F(z) g(\theta) d\theta.$$

In turn, observe that

$$\kappa \Theta \int_{\underline{\theta}}^{\overline{\theta}} F(z) g(\theta) d\theta = \int_{\underline{\theta}}^{\overline{\theta}} \int_0^z \left[\kappa \int_{\underline{\theta}}^{\overline{\theta}} F(z) g(\theta) d\theta \right] \theta f(c) dc g(\theta) d\theta,$$

where we use $\Theta = \int_{\underline{\theta}}^{\overline{\theta}} \int_0^z \theta f(c) dc g(\theta) d\theta$. From here, we obtain welfare

$$W = Y(E) - (\xi + \Delta)E + \int_{\underline{\theta}}^{\overline{\theta}} \int_0^z \left(\underbrace{\left[\frac{\Delta}{\beta} \left(\frac{\tau}{p} \right)^{\frac{\beta}{1-\beta}} - \phi \left(\frac{\tau}{p} \right)^{\frac{1}{1-\beta}} + \kappa \int_{\underline{\theta}}^{\overline{\theta}} F(z) g(\theta) d\theta \right]}_{\equiv v(\tau,p,s)} \theta - c \right) f(c) dc g(\theta) d\theta,$$

which is equivalent to (6) and (7) with δ given by (17).

First-order conditions for optimal policies. Below we derive the first-order conditions that characterize optimal policy. Akin to Eq. (8), we write

$$\frac{\partial W}{\partial \tau} = \frac{\Delta - \tau}{-Y''(E)} + \int_{\underline{\theta}}^{\overline{\theta}} v'_\tau \theta F(z) g(\theta) d\theta + \int_{\underline{\theta}}^{\overline{\theta}} [v\theta - z]\, z'_\tau f(z) g(\theta) d\theta = 0.$$

Now define $\check{v} = v - \delta$ as the social value per unit of innovation excluding the spillover. Then $v'_\tau = \check{v}'_\tau + \delta'_\tau$. In turn, from $\delta = \kappa \int_{\underline{\theta}}^{\overline{\theta}} F(z) g(\theta) d\theta$ we have $\delta'_\tau = \kappa \int_{\underline{\theta}}^{\overline{\theta}} f(z) z'_\tau g(\theta) d\theta$. This allows us to write

$$\frac{\partial W}{\partial \tau} = \frac{\Delta - \tau}{-Y''(E)} + \int_{\underline{\theta}}^{\overline{\theta}} \check{v}'_\tau \theta F(z) g(\theta) d\theta + \left[\int_{\underline{\theta}}^{\overline{\theta}} f(z) z'_\tau g(\theta) d\theta \right] \left[\kappa \int_{\underline{\theta}}^{\overline{\theta}} \theta F(z) g(\theta) d\theta \right] + \int_{\underline{\theta}}^{\overline{\theta}} [v\theta - z]\, z'_\tau f(z) g(\theta) d\theta = 0,$$

and in turn

$$\frac{\partial W}{\partial \tau} = \frac{\Delta - \tau}{-Y''(E)} + \underbrace{\int_{\underline{\theta}}^{\overline{\theta}} \check{v}'_\tau \theta F(z) g(\theta) d\theta}_{\text{diffusion effect } (\Gamma_\tau)} + \underbrace{\int_{\underline{\theta}}^{\overline{\theta}} [v\theta - z + \kappa\Theta]\, z'_\tau f(z) g(\theta) d\theta}_{\text{innovation effect } (\Omega_\tau)} = 0, \tag{A.24}$$

where we exploit $\Theta = \int_{\underline{\theta}}^{\overline{\theta}} \theta F(z) g(\theta) d\theta$. Note that the diffusion effect (Γ_τ) is equivalent to the Γ_τ in Eq. (A.2), which was obtained under exogenous spillovers. The innovation effect (Γ_τ) now contains an additional term $\kappa\Theta$ compared to the case of exogenous spillovers.

Following similar steps as above, we obtain

$$\frac{\partial W}{\partial p} = \underbrace{\int_{\underline{\theta}}^{\overline{\theta}} \check{v}'_p \theta F(z) g(\theta) d\theta}_{\text{diffusion effect } (\Gamma_p)} + \underbrace{\int_{\underline{\theta}}^{\overline{\theta}} [v\theta - z + \kappa\Theta]\, z'_p f(z) g(\theta) d\theta}_{\text{innovation effect } (\Omega_p)} \geq 0, \tag{A.25}$$

and holding with strict equality if $p < p_M$. Here again the diffusion effect is equivalent to Γ_p in Eq. (A.4). Finally, (18) characterizes the optimal subsidy, which we can equivalently write as

$$\frac{\partial W}{\partial s} = \int_{\underline{\theta}}^{\overline{\theta}} [v\theta - z + \kappa\Theta]\, z'_s f(z) g(\theta) d\theta = 0. \tag{A.26}$$

A.1.9. Proof to Proposition 8

Decompose the innovation effects Ω_τ and Ω_p in to average innovation effects and innovation screening effects:

$$\Omega_\tau = \underbrace{\mathbb{E}\left[\left(v\theta - z + \kappa\Theta \right) f(z) \right] \mathbb{E}\left[z'_\tau \right]}_{\overline{\Omega}_\tau} + \underbrace{\mathrm{Cov}\left(\left(v\theta - z + \kappa\Theta \right) f(z), z'_\tau \right)}_{\Omega^s_\tau},$$

and

$$\Omega_p = \underbrace{\mathbb{E}\left[\left(\upsilon\theta - z + \kappa\Theta\right)f(z)\right]\mathbb{E}\left[z'_p\right]}_{\overline{\Omega}_p} + \underbrace{\mathrm{Cov}\left(\left(\upsilon\theta - z + \kappa\Theta\right)f(z), z'_p\right)}_{\Omega_p^s}.$$

Next, we establish that under optimal across-the-board subsidies, the average innovation effect is zero. To do so, observe that from $z = s + (p - \phi)\theta_i (\tau/p)^{\frac{1}{1-\beta}} - \kappa\Theta$, we have $z'_s = 1 + \kappa\Theta'_s$ with $\Theta'_s > 0$. Then (A.26) can be written as

$$\frac{\partial W}{\partial s} = \left[1 + \kappa\Theta'_s\right]\int_{\underline{\theta}}^{\overline{\theta}} \left(\upsilon\theta - z + \kappa\Theta\right)f(z)g(\theta)d\theta. \tag{A.27}$$

If the policymaker sets an optimal across-the-board subsidy, we must have $\partial W/\partial s = 0$ which, by Eq. (A.27), implies $\mathbb{E}\left[\left(\upsilon\theta - z + \kappa\Theta\right)f(z)\right] = 0$. From here, it directly follows that $\overline{\Omega}_\tau = \overline{\Omega}_p = 0$.

Next, define $\tilde{z} \equiv z(\tau, p, s, \Theta, \tilde{\theta})$ such that $\upsilon\tilde{\theta} - \tilde{z} + \kappa\Theta = 0$. Then subtracting both $\tilde{z}'_\tau \mathbb{E}[(\upsilon\theta - z)f(z) + \kappa\Theta]$ and $\mathbb{E}[(\upsilon\tilde{\theta} - \tilde{z})(z'_\tau - \tilde{z}'_\tau)f(z)]$ from Ω_τ as defined in (A.24), gives

$$\Omega_\tau = k'_\tau(\upsilon - k)\int_{\underline{\theta}}^{\overline{\theta}} (\theta - \tilde{\theta})^2 f(z)g(\theta)d\theta. \tag{A.28}$$

Similarly, we can show that

$$\Omega_p = k'_p(\upsilon - k)\int_{\underline{\theta}}^{\overline{\theta}} (\theta - \tilde{\theta})^2 f(z)g(\theta)d\theta. \tag{A.29}$$

Observe that (A.28) and (A.29) are equivalent to (A.7) and (A.8). Hence, the remainder of the proof is equivalent to the proof of Proposition 2. □

Appendix B. Calibration: details

This section details our calibration approach. All calibrations are done such that the key parameters match observed development for a benchmark case when carbon prices are Pigouvian $\tau = \Delta$ and abatement input prices are monopolistic, $p = p_M$. The numerical optimization was carried out using the MATLAB Optimization Toolbox.

Social cost of carbon Δ. The marginal damage form CO_2 emissions set equal to $\Delta = \$100/tCO_2$.

Production function $Y(E)$ and energy cost ξ. We assume that demand of energy is linear and that the inverse demand curve takes the form:

$$\xi + \tau = b - cE,$$

where the left-hand side is the total energy price (including energy and emission prices). We calibrate b and c such that E is equal to the average 2010–2019 EU industrial emissions of 515MtCO_2 (EEA, 2023), with $\xi = \$28/t\ CO_2$ based on an average 2010–2019 coal price of \$82/t and emission factor of 2.86 tCO_2/t (BP, 2022; EIA, 2021), and $\tau = \$13/tCO_2$ equal to the average EU ETS price for 2010–2019. The energy demand function implies a non-constant price elasticity of energy use. To ensure that for observed carbon prices elasticities fall within the values reported in the meta-analysis by Labandeira et al. (2017), we require that the (absolute) price elasticity of energy use is equal to −0.21 at $E = E_0$ and $\tau = 0$.

Distribution of patent quality $G(\theta)$. We nonparametrically calibrate $G(\theta)$ to the 5-year citation distribution of patents registered in 2017 for climate change mitigation technologies in the production or processing of goods from the EPO Patstat data, as shown in Fig. 1. We use the Y02P class in the Cooperative Patent Classification (CPC) system where we exclude the 219 out of 86,238 patents with more than 200 citations as outliers (0.25% of all patents).

Spillovers, δ, input production cost ϕ and innovation cost distribution $F(c)$. We jointly parameterize the remaining parameters such that we match the following three empirical regularities:

(i) Social returns to R&D Bloom et al. (2013), Zacchia (2020) and Myers and Lanahan (2022) estimate that knowledge spillovers imply social returns to R&D are 2 to 4 times the private returns. This would give a ratio π/δ between 1 and 3. While there is evidence that knowledge spillovers are larger for green technologies (Popp and Newell, 2012; Dechezleprêtre et al., 2017; Barbieri et al., 2020), we adopt a conservative approach and calibrate δ such that $\pi/\delta = 1$ at Pigouvian carbon prices ($\tau = \Delta$), monopoly input prices ($p = p_M$) and remaining calibrated parameters.

(ii) Mean private value per citation We parameterize ϕ such that the mean private value per citation, $\mathbb{E}[\pi/\theta]$ is consistent with empirical estimates. Our primary sources are Hall et al. (2005) and Kogan et al. (2017). Hall et al. (2005) find a very skewed distribution of citations, with an additional citation associated with a 3 percent increase in market value, consistent with the "million dollar" worth of a citation reported by Harhoff et al. (1999) (Hall et al., 2005, p. 29). Kogan et al. (2017) find that additional citation around the median number of citations is associated with \$15,000–\$500,000 (1982USD). Based on this we parameterize ϕ such that $\mathbb{E}[\pi/\theta] = \$1,000,000$. Depending on the value of β the value varies between $\$457,000$–$\$1,270,000$.

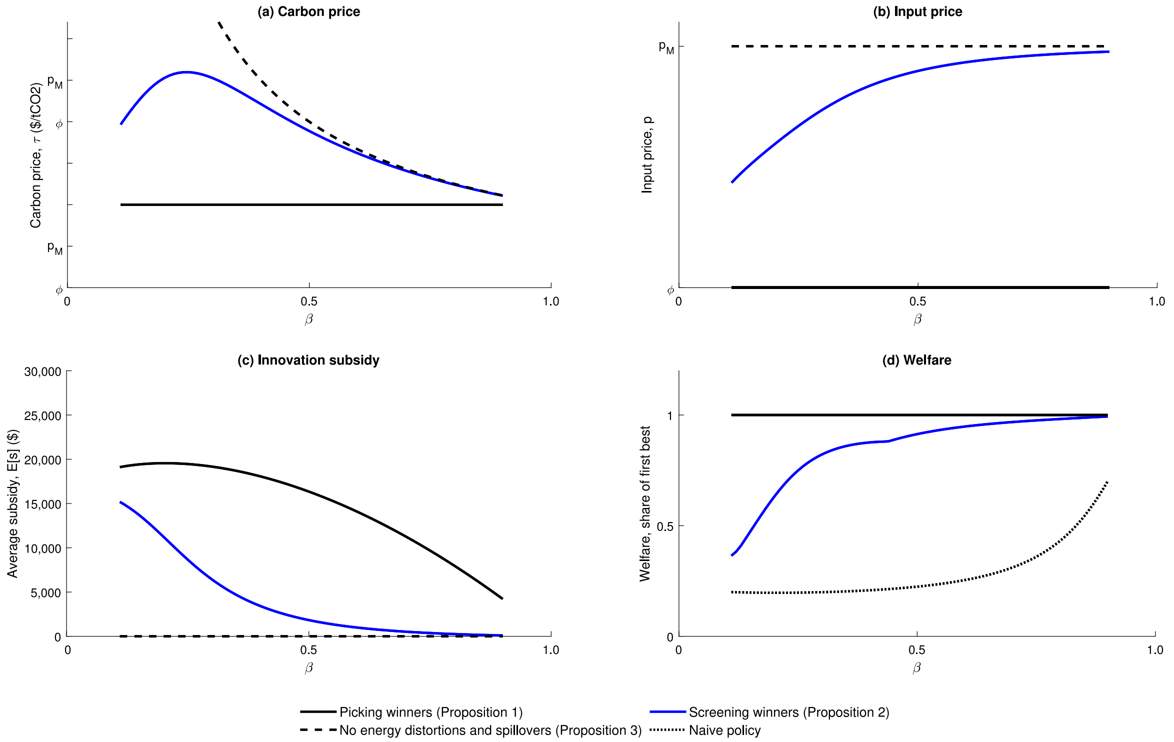

Fig. C.1. Optimal policies in the numerical calibration with $\delta = 0$.
Notes: The figure displays optimal policies in three settings. When the policy maker is able to pick winners by using targeted subsidies (Proposition 1), when the policy maker cannot pick winners and uses across-the-board subsidies (Proposition 2), and a policy that leads to first-best under in the absence of energy demand distortions and innovation spillovers (Proposition 3). Panel (a) is the carbon price τ in $/tCO$_2$, (b) is the abatement input price relative to the monopoly price $p_M = \phi/\beta$ and unit cost ϕ, panel (c) is the average innovation subsidy in $, $\mathbb{E}[s]$, and (d) is the welfare, as defined in eq. Eq. (6), compared to the first-best level. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

(iii) Emission reduction in response to carbon pricing In our model, carbon prices reduce emission through three channels: energy reductions, diffusion of existing abatement technologies and innovation in additional technologies. The importance of the latter channel is strongly influenced by the cost distribution of innovation $F(c)$. We calibrate the model such that achieved emission reductions are consistent with Colmer et al. (2022), who finds that the second trading period of EU ETS reduced emissions by 8%–12% with an average price of around \$15/tCO$_2$. Scaled to our benchmark Pigouvian price, we require τ = \$100/tCO$_2$ to reduce emissions on average by 66.7%. We adopt a uniform distribution for $F(c)$ over $[0, \bar{c}]$ and parameterize $\bar{c}$ such that the total emissions reduction from energy use and technology adoption are consistent with this result. According to our calibration, this includes reduced emissions from energy use (44.6%) and technology development (22.2%). Parameter $\bar{c}$ is re-calibrated for all β such that this reduction holds for all β.

Appendix C. Additional figures

Fig. C.1 displays the optimal policy mix without innovation spillovers ($\delta = 0$). As discussed in Section 6.2, this figure more explicitly shows that energy market distortions due to Pigouvian pricing substantially limit the optimal price premium for innovation screening. Additionally, Fig. C.1 highlights that even in the absence of innovation spillovers, the premium is large. In other words, the fact that innovators do not appropriate the full surplus of their innovations already rationalizes a substantial carbon price premium. Note that in this case, the carbon price never exceeds the benchmark presented in Proposition 3: without innovation spillovers there is no reason to raise the carbon price above Δ/β.

References

Abrams, D.S., Akcigit, U., Grennan, J., 2013. Patent Value and Citations: Creative Destruction or Strategic Disruption? National Bureau of Economic Research Working Paper No. 19647.
Acemoglu, D., Aghion, P., Bursztyn, L., Hemous, D., 2012. The environment and directed technical change. Amer. Econ. Rev. 102 (1), 131–166.
Acemoglu, D., Akcigit, U., Alp, H., Bloom, N., Kerr, W., 2018. Innovation, reallocation, and growth. Amer. Econ. Rev. 108 (11), 3450–3491.
Acemoglu, D., Akcigit, U., Hanley, D., Kerr, W., 2016. Transition to clean technology. J. Polit. Econ. 124 (1), 52–104.
Aghion, P., Dechezleprêtre, A., Hemous, D., Martin, R., Van Reenen, J., 2016. Carbon taxes, path dependency, and directed technical change: Evidence from the auto industry. J. Polit. Econ. 124 (1), 1–51.

Ahlvik, L., Liski, M., 2022. Global externalities, local policies, and firm selection. J. Eur. Econom. Assoc. 20 (3), 1231–1275.
Akcigit, U., Hanley, D., Stantcheva, S., 2022. Optimal taxation and R&D policies. Econometrica 90 (2), 645–684.
Barbieri, N., Marzucchi, A., Rizzo, U., 2020. Knowledge sources and impacts on subsequent inventions: Do green technologies differ from non-green ones? Res. Policy 49 (2), 103901.
van den Bijgaart, I., 2017. The unilateral implementation of a sustainable growth path with directed technical change. Eur. Econ. Rev. 91, 305–327.
Bistline, J., Mehrotra, N., Wolfram, C., 2023. Economic Implications of the Climate Provisions of the Inflation Reduction Act. National Bureau of Economic Research Working Paper No. 31267.
Bloom, N., Schankerman, M., Van Reenen, J., 2013. Identifying technology spillovers and product market rivalry. Econometrica 81 (4), 1347–1393.
BP, 2022. BP statistical review of world energy 2022.
Calel, R., 2020. Adopt or innovate: Understanding technological responses to cap-and-trade. Am. Econ. J. Econ. Policy 12 (3), 170–201.
Calel, R., Dechezleprêtre, A., 2016. Environmental policy and directed technological change: evidence from the European carbon market. Rev. Econ. Stat. 98 (1), 173–191.
Colmer, J., Martin, R., Muûls, M., Wagner, U.J., 2022. Does Pricing Carbon Mitigate Climate Change? Firm-Level Evidence from the European Union Emissions Trading Scheme. CEPR Discussion Paper No. DP16982.
Datta, A., Somanathan, E., 2016. Climate policy and innovation in the absence of commitment. J. Assoc. Environ. Resour. Econ. 3 (4), 917–955.
Dechezleprêtre, A., Martin, R., Mohnen, M., 2017. Knowledge Spillovers from Clean and Dirty Technologies. Tech. Rep., GRI Working Paper No. 135.
Drupp, M.A., Nesje, F., Schmidt, R.C., 2022. Pricing Carbon. CESifo Working Paper No. 9608.
EEA, 2023. EU Emissions Trading System (ETS) data viewer. https://www.eea.europa.eu/data-and-maps/dashboards/emissions-trading-viewer-1.
EIA, 2021. Carbon dioxide emissions from the consumption of energy 2020: Coal emissions by quarter. https://www.eia.gov/coal/production/quarterly/co2_article/co2.html.
European Commission, 2023. Innovation fund: What is the innovation fund. https://climate.ec.europa.eu/eu-action/funding-climate-action/innovation-fund/what-innovation-fund_en. (Accessed 25 May 2023).
Fischer, C., 2008. Emissions pricing, spillovers, and public investment in environmentally friendly technologies. Energy Econ. 30 (2), 487–502.
Fischer, C., Hübler, M., Schenker, O., 2021. More birds than stones–A framework for second-best energy and climate policy adjustments. J. Public Econ. 203, 104515.
Fischer, C., Newell, R.G., 2008. Environmental and technology policies for climate mitigation. J. Environ. Econ. Manag. 55 (2), 142–162.
Fischer, C., Preonas, L., Newell, R.G., 2017. Environmental and technology policy options in the electricity sector: are we deploying too many? J. Assoc. Environ. Resour. Econ. 4 (4), 959–984.
Galasso, A., Mitchell, M., Virag, G., 2016. Market outcomes and dynamic patent buyouts. Int. J. Ind. Organ. 48, 207–243.
Gerlagh, R., Kverndokk, S., Rosendahl, K.E., 2009. Optimal timing of climate change policy: Interaction between carbon taxes and innovation externalities. Environ. Resour. Econ. 43 (3), 369–390.
Gerlagh, R., Kverndokk, S., Rosendahl, K.E., 2014. The optimal time path of clean energy R&D policy when patents have finite lifetime. J. Environ. Econ. Manag. 67 (1), 2–19.
Gilbert, R., Shapiro, C., 1990. Optimal patent length and breadth. Rand J. Econ. 106–112.
Greaker, M., Heggedal, T.-R., Rosendahl, K.E., 2018. Environmental policy and the direction of technical change. Scand. J. Econ. 120 (4), 1100–1138.
Greaker, M., Pade, L.-L., 2009. Optimal carbon dioxide abatement and technological change: should emission taxes start high in order to spur R&D? Clim. Change 96 (3), 335–355.
Grubb, M., Drummond, P., Poncia, A., McDowall, W., Popp, D., Samadi, S., Penasco, C., Gillingham, K.T., Smulders, S., Glachant, M., et al., 2021. Induced innovation in energy technologies and systems: a review of evidence and potential implications for CO2 mitigation. Environ. Res. Lett. 16 (4), 043007.
Hall, B.H., Jaffe, A., Trajtenberg, M., 2005. Market value and patent citations. Rand J. Econ. 16–38.
Harhoff, D., Narin, F., Scherer, F.M., Vopel, K., 1999. Citation frequency and the value of patented inventions. Rev. Econ. Stat. 81 (3), 511–515.
Harstad, B., 2020. Technology and time inconsistency. J. Polit. Econ. 128 (7), 2653–2689.
Hart, R., 2008. The timing of taxes on CO2 emissions when technological change is endogenous. J. Environ. Econ. Manag. 55 (2), 194–212.
Hart, R., 2019. To everything there is a season: Carbon pricing, research subsidies, and the transition to fossil-free energy. J. Assoc. Environ. Resour. Econ. 6 (2), 349–389.
Hémous, D., 2016. The dynamic impact of unilateral environmental policies. J. Int. Econ. 103, 80–95.
Hopenhayn, H., Llobet, G., Mitchell, M., 2006. Rewarding sequential innovators: Prizes, patents, and buyouts. J. Polit. Econ. 114 (6), 1041–1068.
Jaffe, A.B., Newell, R.G., Stavins, R.N., 2005. A tale of two market failures: Technology and environmental policy. Ecol. Econom. 54 (2–3), 164–174.
Kogan, L., Papanikolaou, D., Seru, A., Stoffman, N., 2017. Technological innovation, resource allocation, and growth. Q. J. Econ. 132 (2), 665–712.
Kremer, M., 1998. Patent buyouts: A mechanism for encouraging innovation. Q. J. Econ. 113 (4), 1137–1167.
Kremer, M., 2000. Creating markets for new vaccines. Part II: Design issues. Innov. Policy Econ. 1, 73–118.
Kremer, M., Levin, J., Snyder, C.M., 2022. Designing advance market commitments for new vaccines. Manage. Sci. 68 (7), 4786—4814.
Labandeira, X., Labeaga, J.M., López-Otero, X., 2017. A meta-analysis on the price elasticity of energy demand. Energy Policy 102, 549–568.
Lach, S., Neeman, Z., Schankerman, M., 2021. Government financing of R&D: A mechanism design approach. Am. Econ. J. Microecon. 13 (3), 238–272.
Laffont, J.-J., Tirole, J., 1994. Environmental policy, compliance and innovation. Eur. Econ. Rev. 38 (3–4), 555–562.
Laffont, J.-J., Tirole, J., 1996. Pollution permits and environmental innovation. J. Public Econ. 62 (1–2), 127–140.
Montero, J.-P., 2002a. Market structure and environmental innovation. J. Appl. Econ. 5 (2), 293–325.
Montero, J.-P., 2002b. Permits, standards, and technology innovation. J. Environ. Econ. Manag. 44 (1), 23–44.
Montero, J.-P., 2011. A note on environmental policy and innovation when governments cannot commit. Energy Econ. 33, S13–S19.
Myers, K.R., Lanahan, L., 2022. Estimating spillovers from publicly funded R&D: Evidence from the US department of energy. Amer. Econ. Rev. 112 (7), 2393–2423.
OECD, 2021. OECD R&D tax incentives database, 2021 edition.
Popp, D., 2006. R&D subsidies and climate policy: is there a "free lunch"? Clim. Change 77 (3), 311–341.
Popp, D., 2019. Environmental policy and innovation: a decade of research. Int. Rev. Environ. Resour. Econ. 13 (3–4), 265–337.
Popp, D., Newell, R., 2012. Where does energy R&D come from? Examining crowding out from energy R&D. Energy Econ. 34 (4), 980–991.
Popp, D., Newell, R.G., Jaffe, A.B., 2010. Energy, the environment, and technological change. In: Handbook of the Economics of Innovation, vol. 2, Elsevier, pp. 873–937.
Popp, D., Santen, N., Fisher-Vanden, K., Webster, M., 2013. Technology variation vs. R&D uncertainty: What matters most for energy patent success? Resour. Energy Econ. 35 (4), 505–533.
Requate, T., 2005. Dynamic incentives by environmental policy instruments—a survey. Ecol. Econom. 54 (2–3), 175–195.
Sarnoff, J.D., 2020. Negative-emission technologies and patent rights after COVID-19. Clim. Law 10 (3–4), 225–265.
Scherer, F.M., Harhoff, D., 2000. Technology policy for a world of skew-distributed outcomes. Res. Policy 29 (4–5), 559–566.
Scotchmer, S., 1999. On the optimality of the patent renewal system. Rand J. Econ. 181–196.
Silverberg, G., Verspagen, B., 2007. The size distribution of innovations revisited: an application of extreme value statistics to citation and value measures of patent significance. J. Econometrics 139 (2), 318–339.
Trajtenberg, M., 1990. A penny for your quotes: patent citations and the value of innovations. Rand J. Econ. 172–187.
Weyl, E.G., Tirole, J., 2012. Market power screens willingness-to-pay. Q. J. Econ. 127 (4), 1971–2003.
World Bank, 2022. Carbon pricing dashboard. https://carbonpricingdashboard.worldbank.org/. (Accessed 1 June 2022).
Zacchia, P., 2020. Knowledge spillovers through networks of scientists. Rev. Econom. Stud. 87 (4), 1989–2018.