Policy Research Working Paper 10506

Who Should Drive Green Technology Transitions in Developing Countries

State-Owned Enterprises versus Private Firms

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WORLD BANK GROUP
Development Economics
Development Research Group
June 2023

Policy Research Working Paper 10506

Abstract

Green technologies, such as renewable energy, often require adaptation to local conditions, such as high humidity, high altitudes or the specifics of a country's infrastructure, to achieve a maximal technical efficiency and a long lifetime of investments. This poses a problem for green technology transitions, as adaptations usually imply protected intellectual property rights and thus market imperfections that can lead to higher prices and thereby a lower uptake of the green technology. An alternative could be to use state-owned enterprises to adapt and promote green technologies, such as public utilities, which are more easily steered toward pursuing societal objectives. However, many empirical studies find state-owned enterprises to be less efficient. This theoretical contribution investigates the question whether a green technology transition that requires research and development is better driven by private firms or state-owned enterprises. The paper adapts a model to this setting, derives possible market outcomes from this model, investigates research and development and production decisions of private firms and a state-owned enterprise, and compares the welfare implications of the two options. The results show that there are cases where the cost inefficiency of the state-owned enterprise dominates (for example, if competition of directly importing firms reduces possible markups of private innovating firms), but also cases where a state-owned enterprise is the preferred choice (for example, if several private firms would adapt the technology, causing over-innovation). Most importantly, this is not solely a question of comparing costs, but rather of comparing market outcomes. For example, the use of a state-owned enterprise can avoid the often found problem of overinvestment in research and development by private firms and, in many cases, a state-owned enterprise will induce a wider diffusion of the green technology.

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Who Should Drive Green Technology Transitions in Developing Countries: State-Owned Enterprises versus Private Firms*

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Keywords: Green Technology, Innovation, Local Adaptation, Imperfect Competition, State-Owned Enterprises, Public Firms, Emissions, Policy, Emission Tax, Environmental Economics.

JEL Classification: D43, L10, L33, O30, Q55, Q58.

*The authors would like to thank Jon Strand and Carolyn Fischer for their valuable comments and suggestions. The views and interpretations are of authors and should not be attributed to the World Bank Group and the organizations they are affiliated with. We acknowledge World Bank's Research Support Grant (RSB) for the financial support.

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1 Introduction

Green technological change is among the most appealing solutions to many environmental problems, as it offers the chance to cure the problem rather than treating its symptoms. Via green technological change, harmful emissions, waste or resource use can be avoided, often without substantial reductions to consumption possibilities. The transition to renewable energy is a good example, where, due to research and development (R&D) efforts, the costs of these technologies dropped by many folds over a decade (Gambhir et al., 2014; IRENA, 2022). Similar examples can be found in the domain of mobility systems, the phase-out of highly toxic substances in the chemical industry, or agriculture.

Although the costs of technologies decrease, their deployment or adoption is not guaranteed for several reasons, for instance, due to the technology not fitting well to local conditions. A wind turbine that has been developed for on-shore use in Germany is not ideally suited for use in high altitudes (due to ice formation on rotors) or off-shore settings (due to corrosion). Similarly, a PV installation requires adaptations to climates with high humidity (otherwise, algae formation will severely reduce its lifetime). Such adaptations to local conditions can substantially enhance the efficiency or lifetime of the technologies in question and thus be instrumental to a rapid diffusion.

Adaptations to local contexts are frequently performed by domestic companies which are often already active in the industry in question, often using older emission-intensive technologies. Such firms might have the knowledge to adapt technologies to local conditions and the ability to ensure a rapid diffusion of green technologies (due to a pre-existing customer base). However, they might have limited interest in doing so, as it threatens the profitability of their older investments. Again, the transition to renewable energy serves as a good example, where domestic energy providers are often key actors in adapting wind power, storage technologies, or power-to-x technologies (e.g. synthetic gas or hydrogen production) to local conditions. But usually these energy providers are invested in fossil-fuel based power plants and hence might have an incentive to delay or prevent a transition to renewable energy.

Environmental policy thus has to find a way to set incentives for these actors to adapt green technologies to local conditions and to provide them at a price that ensures a rapid diffusion. This is not an easy task, as the externality from using the brown technology (e.g. CO_2-emissions) interacts with market power (which is required to refund R&D investments) and the risk that the green technology is imported directly (without adaptation), resulting in the diffusion of a green technology that has a lower lifetime or efficiency. Such a setting can result in numerous possible market outcomes, severe inefficiencies and might require the use of rather complex policy interventions to limit welfare losses (Bondarev et al., 2021; Dato and Krysiak, 2021).

However, there could be an alternative. In particular in the energy sector (but also in several other applications), there are state-owned enterprises (SOEs) that could be used to adapt technologies and drive the green technology transition. The literature suggests that SOEs are less efficient in production, usually having higher marginal costs (Megginson and Netter, 2001; Belloc, 2014). But they can be more easily controlled (thus having incentives that are more strongly aligned to societal objectives) and do not have to refund R&D investments, as losses can be passed on to tax-payers, which implies that they can price green technologies more aggressively, inducing a wider diffusion and less emissions.

This raises an interesting question: Should a country rely on private firms or state-owned enterprises to drive a green technology transition? In a setting without R&D, this question would be moot, as perfect competition would be possible, which would make it easy to align private and societal incentives. Similarly, in a setting with numerous policy interventions that correct all possible market failures efficiently, it is obvious that private firms would be preferable. However, in the above discussed setting of domestic technology adoption and under the assumption that only a limited policy intervention is possible to steer private firms, the question is both interesting and challenging, as it involves several interacting market failures that cannot be fully corrected.

Addressing the question, we first introduce a theoretical model that describes the situation and derive possible market outcomes for the cases of a private firm and a state-owned enterprise driving the technology transition. Whereas we allow for a single policy measure to influence the incentives of the private firm (an emission tax), we assume that the SOE has incentives that conform with societal objectives but is less efficient in production than the private firm. Using this setup, we analyze the R&D decisions in both cases and compare the social welfare achievable in the private firm and in the SOE case.

Our results indicate that, albeit the inefficiency of the SOE is important, the decisive point is that in the two policy options, different market structures for the green technology can emerge. A private firm will more often decide to not adapt the technology (leading to a transition towards a low-quality green technology) and might share the market for the green technology with other firms, inducing overinvestment in R&D. A state-owned enterprise will never share the market for the green technology (if another firm decides to adapt the technology, the SOE will leave the market to this firm to avoid overinvestment in R&D). Furthermore, the SOE will price the green technology more competitively, resulting in a more widespread use of the green technology. However, its cost disadvantage will counteract these points.

In addition, the preferability of the private firm or SOE policy depends (of course) on the inefficiency of the SOE, the quality of the green technology without adaptation, the scope of the local adaptation (how much can the quality be improved), and what we call a market expansion effect, that is, the ability of the green technology to serve customers that are not willing to buy into the brown technology.[1]

The paper is structured as follows. We first review some strands of literature that are connected to our work. Then, we set out and explain our model. In Section 4, we derive the possible situations on the output market. Section 5 contains the analysis of the adaptation decisions, given the market structures derived before, and 6 derives and discusses the conditions under which it is preferable to use an SOE to drive the technology transition compared to a private firm. Finally, we provide some policy insights as well as our conclusions.

2 Literature Review

Our analysis relates to different fields of literature, namely technological innovation, adaptation and diffusion, environmental economics as well as public firms and privatization. Within and across all those strands, considerable work has been devoted to analyzing instruments addressing inefficiencies that evolve with different kinds of market failures. Unregulated environmental externalities (like greenhouse gas emissions) are a prominent example. Much of the economic literature on environ-

[1] In the energy transition example, this market expansion would model the ability of decentralized renewables to serves communities that are not connected to a national grid and thus receive no electricity in the old, centralized energy system.

mental policies focuses on price-based instruments to regulate emissions as an application of the Pigouvian rule. However, the Pigouvian tax has been shown to yield inefficient outcomes if additional market failures like imperfect competition are taken into account (see Buchanan, 1969; Lee, 1975; Barnett, 1980; Katsoulacos and Xepapadeas, 1996a).[2]

In the innovation literature, it is a well-known result that the public good nature of innovation generally leads to underinvestment while complete absence of knowledge spillovers tends to induce costly overinvestment (Poyago-Theotoky, 2007). Different policy instruments like intellectual property rights, licensing, R&D subsidies or cooperative R&D encouragement have been examined as potential remedies (see Lahiri and Ono, 1999; Toshimitsu, 2003; Kitahara and Matsumura, 2006). As technological progress is often seen as an important part of the solution to environmental problems, much research has been undertaken on the intersection of both environmental and innovation policies. Numerous papers investigate either R&D incentives under different typical environmental instruments like taxes, tradable permit markets or standards (see Downing and White, 1986; Milliman and Prince, 1989; Jung et al., 1996; Requate and Unold, 2003; Requate, 2005), or study optimal green R&D subsidy schemes in combination with those instruments (see Katsoulacos and Xepapadeas, 1996b; Stranlund, 1997; Poyago-Thotoky et al., 2003; Poyago-Theotoky, 2007). One central conclusion from this literature is that a single policy instrument is typically insufficient to obtain first-best outcomes (see Carraro and Soubeyran, 1996; Fischer and Newell, 2008; Acemoglu et al., 2012; Krass et al., 2013).

Among the papers referred to above, it is common to assume that firms are profit-maximizing. Another strand of literature diverges from this common framework and analyzes, similar to our work, welfare-maximizing public firms, so-called state-owned enterprises (SOE). This focus is mainly motivated by the question of whether to privatize SOEs (or not). The majority of the extant empirical literature on the performance of SOEs finds that they are less efficient than private firms, at least with respect to short-term performance indicators like net income or value added, return on equity, sales or assets, or cost savings.[3] Belloc (2014) summarizes typical rationales for SOE inefficiencies into four channels: (1) Poor monitoring of managers and excessive bureaucracy; (2)

[2]For a comprehensive discussion on optimal tax rules under imperfect competition, see Requate (2006).

[3]See Vining and Boardman (1992) for a survey of 90 comparative studies; see Megginson and Netter (2001) for a literature review on performance changes of privatized companies.

lack of market discipline as the government can cover potential losses; (3) managerial corruption, illegal behavior and rent extraction by politicians; and (4) conflicting objectives and impacts of short-term political goals. Such inefficiencies might also affect the innovation behavior of public firms. Bortolotti et al. (2019) investigate the impact of state ownership on the innovativeness of firms, measured by the number, quality and value of patents produced within a sample of roughly 5,000 listed European firms in 1999-2016. They find less innovativeness under government control (fewer patents per dollar invested) and no difference in patent quality (measured by citations in other patent filings).

Part of the literature also focuses on whether developing countries actively invest in green innovations and what are the alternative options to foster a worldwide diffusion of green technologies. Based on international patent data, many studies find that frontier green innovations are concentrated in high-income countries (Dechezleprêtre et al., 2011, Dutz and Sharma, 2012, and Napolitano et al., 2022). While Dechezleprêtre et al. (2011) and Dutz and Sharma (2012) explore historical patterns and difference across countries and regions, Napolitano et al. (2022) investigate the relationship between those patterns and income inequality. However, the three studies find the existence of limitations in the capacity and incentives for the developing countries to undertake frontier and relatively complex green innovation. This may also open opportunities to develop those green technologies in countries that have intermediate levels of per capita income (Napolitano et al., 2022).

As an alternative to frontier green innovations, many studies explore different ways of bringing green innovation to local and poor communities (Dutz and Sharma, 2012). Some studies focus on making the green technologies meet the needs of poor consumers with a dramatic reduction of prices. This strand of literature uses different name such as "bottom-of-the-pyramid (BoP)"(Prahalad, 2012), "inclusive innovation" (Foster and Heeks, 2013), "below-the-radar innovation" (Kaplinsky, 2011), "catch-up innovation" (Yuan et al., 2021) and "pro-poor innovation" (Tawney et al., 2015). The other strand of literature considers how to adapt innovation to local contexts to shape the technology diffusion. Different examples are discussed to support the importance of local innovation adaptation, for instance residential air conditioning or home food freezers (Ormrod, 1990). Dutz and Sharma (2012) highlight the adaptation of non-electric air conditioning technology from developed countries to the Chinese context by using the waste heat from buildings to power its machines, which is facilitated by customizable pre-fabricated construction modules and contributes to reducing up to 80% of electricity consumption. Even though the local adaptation of green innovation is widely discussed, to the best of our knowledge, there is no study that investigates this question in the context of a theoretical model.

In terms of theoretical contributions, a well-established strand of literature investigates models of mixed oligopolies, i.e., markets where SOEs compete with private firms. Those models are typically used to compare outcomes with the fully private case.[4] For instance, Delbono and Denicolo (1993) study a duopoly of two symmetric firms competing on an R&D market without knowledge spillovers. They show that introducing an SOE alleviates the overinvestment induced by a patent race in the private duopoly. The presence of the public firm is thus welfare enhancing. In a similar model, Poyago-Theotoky (1998) allows for knowledge spillovers which leads to the reversed result: the SOE invests more in the innovative activity compared to its private rival. This reduces free-riding costs compared to the private duopoly.[5] Bárcena-Ruiz and Garzón (2006) introduce environmental pollution and policy to a mixed oligopoly model and show that the privatization decision interacts with the environmental policy by increasing the optimal tax. In their model setting, the regulator chooses to not privatize the public firm in order to compensate the output reduction caused by an emission tax. Haruna and Goel (2019) examine a three-stage mixed duopoly model with symmetric firms where an environmental tax is set first, environmental R&D efforts are chosen second, followed by the production stage. Their results show that privatization of the SOE clearly leads to reduced R&D efforts and output, yet to an overall increase in emissions, thus higher environmental damages. Ouattara et al. (2019) extend this model by considering partial privatization. The authors confirm the overall conclusions of Haruna and Goel (2019) and add that, irrespective of spillover effects and the degree of privatization, the partially privatized firm will always invest more in R&D than the private firm.

Albeit being highly related especially to this last class of papers, our approach differs in several regards from the existing literature. First, we analyze a setting where the green technology is adapted not newly developed, which is of particular importance for many developing countries.

[4]See De Fraja and Delbono (1990) for a review on mixed duopoly models.

[5]There are many more theoretical papers on the impact of privatization on R&D investments that cannot all be reviewed here. To name a few relevant ones, see White (1996); Matsumura and Matsushima (2004); Ishibashi and Matsumura (2006); Matsumura et al. (2013); Kesavayuth and Zikos (2013).

Second, in contrast to much of the literature on mixed oligopolies, we do not assume symmetric cost structures in order to account for the empirically well-established point that SOEs are less efficient in production. Third, most papers with an environmental focus compare mixed to private oligopolies with additional policies (like an emission tax) present in both settings. Our approach views SOEs as a policy alternative to a private firm steered by an emission tax. Thus, we provide a policy comparison that is missing so far. Finally, our model has several features that are typically not or only partially present in the previous literature: Changing market structures (from monopoly to duopoly to perfect competition; market expansion effect), different kinds of actors (incumbent, entrant, direct importers), and the co-existence of a brown and green technology in the same market.

3 The Model

Our model builds on the framework developed by Bondarev et al. (2021) and modified by Dato and Krysiak (2021) with two major changes. First, we model R&D as a single-shot adaptation process of an existing technology instead of the initial development of a green technology (and repeated improvements later on). Second, we introduce a state-owned enterprise (SOE) into the framework that does not maximize profits but, in line with some of the studies reviewed above, maximizes social welfare.

We use a binary setting of technologies, that is, a single clean ("green") and a single dirty ("brown") technology. The brown technology is currently in use and has a fixed quality, that is, it cannot be developed further. The green technology is available at some quality (that is lower than that of the brown technology) on international markets. It can be adapted to local conditions, that is, its quality can be improved by domestic R&D.

The brown technology is provided by an incumbent, which can be a private firm (POE) or a state-owned enterprise. This actor can also adapt and provide the green technology. Alternatively, the green technology can be adapted and provided by a single domestic entrant or can be provided in its internationally available version by an unlimited number of directly importing firms. To induce a transition to the green technology, the brown technology (or the emissions stemming from its use) can be taxed.

This setting captures the essence of many R&D models: R&D efforts have to be refunded via sales of the technology, which is only possible in imperfectly competitive markets, that is, if the R&D results in protected IP. However, the improvements due to R&D may stand in competition with a freely-available, lower-quality version of the technology (which can limit the markup charged by the innovating firms). In addition, the model captures Arrow's replacement effect, that is, the incumbent has to decide between protecting sales of her brown technology and developing the market for the green technology. The domestic entrant is important in this regard, as the possible presence of this actor ensures that an incumbent might lose the market for the green technology if it does not innovate.

On the demand side, there is a continuum of customers that are heterogeneous with regard to their willingness to pay for the brown or green technology. Depending on the price, her individual willingness to pay, and the qualities of each technology, a customer buys a single unit of the brown technology, the adapted green technology, the non-adapted green technology, or no technology at all. Furthermore, customers can have a higher willingness to pay for the green technology, that is, the transition to the green technology can expand the market.

On this market, there is either a monopoly (always for the brown technology that is only offered by the incumbent and for the green technology, whenever it is adapted by a single actor), Cournot competition (if two actors adapt the green technology), or perfect competition (if the technology is directly imported without adaptation). Furthermore, the brown technology causes an external damage (proportional to the units sold) and can be subject to an emission tax.

In the adaptation decision, the incumbent moves first and a possible entrant afterwards. Each firm decides whether to make an adaptation of a fixed size (which is given and identical for all actors) at fixed costs or not to make an adaptation at all. A firm that does not make an adaptation cannot compete in the output market stage, as it cannot offer the green technology at an improved quality and the not-improved quality is offered at marginal costs by directly importing firms.

Finally, the incumbent can be a POE, which has the same marginal production costs as all other actors and maximizes its profit, or an SOE, which has higher marginal production costs but maximizes social welfare. As the SOE maximizes social welfare, it automatically internalizes the external damage, so that an emissions tax is only considered in the POE case.

This setting is designed to resemble the switch towards renewable electricity. The technology sold on the market is either electricity from emission-intensive power plants (that is, the brown technology) or renewable electricity. The brown electricity is available at all times (high quality), whereas the renewable electricity fluctuates. The impact of the fluctuations depends on the quality of the green technology and this quality can be increased by an adaptation to local conditions, e.g. by adapting wind power to high altitudes (avoiding ice formation on rotors, so that they can be used in a broader set of weather conditions). Another example would be the adaptation of PV or battery storage to local conditions, which can increase the technical efficiency and the reliability. The technologies are provided by energy providers to communities (who are the customers). Some communities might have limited access to the national grid (e.g. being subject to congestion-related blackouts due to old or insufficient grid lines) and thus have a higher willingness to pay for renewable electricity, as its provision does not depend on the grid (market expansion effect).

In the following, we describe the different parts of our model. For the reader's convenience, we provide a list with all variables in Appendix A.

3.1 Production Stage: Demand, Supply and Welfare

On the demand side, we use a setting of vertical product differentiation and consider a continuum of consumers (m) with heterogeneous utility $u_j(m)$ from using the brown technology ($j = b$) or the green technology ($j = g$). The net-utility of consumer m is given by:

$$u_j(m) = k_j - m_j - p_j \tag{1}$$

with p_j being the price of the respective technology. We assume that all consumers buy the technology that provides the higher net-utility but only if this net-utility is non-negative (otherwise, the consumer will not buy either technology).

The variable k_j denotes the quality of technology j. For the brown technology, we set the quality $k_b = 1$ as a normalization. For the green technology, we assume $k_g \leq 1$, so that the green technology cannot exceed the quality of the brown technology.

We use the parameter m_j to describe heterogeneous preferences among consumers as well as a market expansion effect. First, the maximal willingness to pay implied by Eq. (1) is $(k_j - m_j)$, that is, a consumer with a higher value of m_j gets less utility from using the technology and the price at which this consumer ceasing to buy the technology is lower. Second, we set $m_b = m$ (for the brown technology) and $m_s = \alpha\, m$ with $0 < \alpha < 1$ (for the green technology), that is, a consumer with $m > 0$ is willing to spend more for the green than for the brown technology. This implies that the market for the green technology has higher potential than the market for the brown technology,[6] which we call the "market expansion effect" of the green technology. Note that for $k_g < k_b$ and $p_g = p_b$, the market will be split, that is, some consumers will buy the green and some will buy the brown technology.

Given our above assumptions on qualities, we assume that m is distributed over $[0, 1/\alpha]$ and that this distribution is a uniform distribution.

On the supply side, there is an incumbent (i) and an entrant (n), which differ in several aspects. First, the incumbent can supply both the brown technology q_{bi} and the green technology q_{gi}, while the innovating entrant can supply only the green technology q_{gn}. Second, while all firms have the same marginal production costs c if there are private firms, the incumbent can also be an SOE with marginal production costs $c + c_s$ (where $c_s > 0$). Parameter c_s thus represents the production inefficiency of the SOE. The entrant and the direct importers are assumed to be private firms in any case.

All private firms maximize their profits π. If several of these firms compete in the market for the green technology, we assume Cournot competition. Profits at the production stage (P) for the incumbent and entrant are given by:

$$\pi_{P,i} = (p_b - (c + c_s) - t)q_b + (p_g - (c + c_s))q_{gi} \tag{2}$$

and

$$\pi_{P,n} = (p_g - c)q_{gn}, \tag{3}$$

where $c_s = 0$ if the incumbent is a private firm, and the tax $t = 0$ if the incumbent is an SOE. Note

[6] Even in the absence of the green technology, all consumers with $m > 1 - p_b$ would not buy the brown technology. If the green technology would have the same quality ($k_g = k_b = 1$), consumers up to $m > \frac{1-p_b}{\alpha}$ would buy the green technology, which is a higher limit, due to $\alpha < 1$.

that it is possible that a large number of directly importing firms supply the green technology with the aggregated quantity q_{gf}. In that case, its price will equal the marginal cost of production ($p_g = c$).

The SOE incumbent maximizes welfare W. Welfare at the production stage is defined as the sum of the consumer surplus, the surplus for both entrant and incumbent, and tax revenues (if there is a tax) net of the environmental damage $Dam(q_{bi})$ from using the brown technology. Welfare is given by

$$\begin{aligned} W_P(q_{bi}, q_{gi}, q_{gn}, q_{gf}) = &\int_{x_{g,b}}^{x_{g,0}} (k_0 + \delta_i - \alpha\, x)\, \mathrm{d}x + \int_0^{x_{g,b}} (1 - x)\mathrm{d}x \\ &- (c - \delta_n + \delta_i)q_{gn} - (c + c_s)(q_b + q_{gi}) - c\, q_{gf} - Dam(q_b), \end{aligned} \tag{4}$$

where:

$$x_{g,0} = \frac{(k_0 + \delta_i) - p_g}{\alpha},$$

$$x_{g,b} = \frac{1 + p_g - p_b - (k_0 + \delta_i)}{1 - \alpha},$$

and

$$Dam(q_b) = d\, q_b,$$

with d being the positive and constant marginal damage, k_0 and δ_v (where $v \in i, n$) denoting the quality of the generic green technology and the added quality due to local adaptation.

In the case of a private incumbent, the tax is chosen by a social planner who maximizes welfare, given the supply decisions made by the private firms. Note that, in many cases, the tax introduced here will not induce a first-best outcome. As the environmental externality interacts with market power, at least two policy interventions would be required to alleviate all market failures. Thus, by introducing only a single policy instrument, we deliberately choose a setting where policy intervention is constrained, which is likely to be the case in many applications.

Finally, we make some additional assumptions. First, we set marginal production costs equal to zero, i.e. $c = 0$ such that prices will effectively only consist of markups and the SOE inefficiency c_s wherever relevant. This simplifies our notation significantly without an impact on our qualitative results. Secondly, we assume that $d < 1$ due to our normalization of the brown technology's quality to 1. If the marginal damage would exceed this quality, the brown technology would never enter the market, which would not be an interesting case to explore.

To simplify our analysis, we assume that if the adapted green technology is priced in a way that renders a direct import (without adaptation) feasible (consumers are indifferent between both versions), the direct import will be used only. This rules out a number of cases of minor importance.

3.2 Adaptation Stage

At the adaptation stage (A), firms can increase the quality of the green technology through adaptation to local conditions, which increases the quality by $\delta_i = \Delta$ for the incumbent, where Δ is the maximum added quality to the green technology due to local adaptation. Similarly, the entrant can develop the quality choosing $\delta_n = \Delta$.[7] In contrast to the technology version freely available with quality k_0, the adaptation is private intellectual property of the developer which allows to offer the product with quality $k_0 + \Delta$.

Regarding adaptation costs, we assume a linear cost structure which simplifies the analysis later on significantly. Furthermore, both types of incumbent and the entrant face the same adaptation costs given by

$$\Gamma_v = \gamma\, \delta_v, \tag{5}$$

where γ is constant and strictly positive.

At the adaptation stage, the POEs maximize profit $\pi_{A,v}$ and the SOE maximizes the welfare W_A, respectively given by:

$$\pi_{A,v} = \pi_{P,v} - \Gamma_v, \tag{6}$$

$$W_A = W_P - \Gamma_n - \Gamma_i. \tag{7}$$

Similarly to Bondarev et al. (2021), we assume that, during the adaptation stage, the incumbent is a Stackelberg leader, choosing the adaptation level first and taking into account the effects of this choice on the entrant's decision.

[7] As shown by Bondarev et al. (2021), using a compact set of adaptation possibilities, that is, $\delta_v \in [0, \Delta]$, yields a corner solution in almost all cases due to the assumed linearity of R&D costs. To simplify the exposition, we thus constrain the decision set to corner solutions.

4 Production Stage Analysis

As a first step of our analysis, we focus on the production stage only so that the levels of adaptation investments are already decided and firms sell the technology in given qualities to consumers. We do this for the POE and the SOE cases. In the POE case, the market outcome is influenced by a tax on the emissions stemming from the use of the brown technology. This tax is set to optimize social welfare, given the choices of the incumbent, the possible entrant, and the consumers. Thus, the tax will be a second-best tax, as a single policy instrument is not sufficient to correct all market failures, with two exceptions: If the incumbent supplies only the brown technology and the green technology is either not supplied at all or under perfect competition, the tax is actually able to implement a first-best welfare outcome.

Several market structures can arise, as highlighted by our first proposition.

Proposition 1. *Given the qualities of the green technology ($k_0+\delta_i$, $k_0+\delta_n$, k_0), the following market outcomes are possible: The green technology might be provided by the incumbent or the entrant only, in a shared market, by the direct importers or not at all. The brown technology could be sold by the incumbent or not at all. This amounts to ten cases that are summarized in Table 1. Depending on whether the incumbent is an SOE or POE under emission taxation, the ten market cases exist under the different conditions stated in Table 2.*

Table 1: ***Set of potential market structures***

	brown technology available		brown technology phased out	
	$q_b > 0, q_{gi} = 0$	$q_b > 0, q_{gi} > 0$	$q_b = 0, q_{gi} > 0$	$q_b = q_{gi} = 0$
$q_{gn} = 0$, $q_{gf} = 0$	**Case** *ib* Brown technology only, Incumbent monopoly	**Case** *ib*-*ig* Incumbent monopoly	**Case** *ig* Incumbent monopoly	**Case** 0 No market
$q_{gn} > 0$, $q_{gf} = 0$	**Case** *ib*-*ng* Entrant supplies green technology, Incumbent supplies brown technology	**Case** *ib*-*ig*-*ng* Duopoly, Incumbent supplies brown technology	**Case** *ig*-*ng* Duopoly	**Case** *ng* Entrant monopoly
$q_{gn} = 0$, $q_{gf} > 0$	**Case** *fg*-*ib* Importers supply green technology, Incumbent supplies brown technology	-	-	**Case** *fg* Perfect competition

Table 2: ***Existence conditions for the different market structures***

Case	SOE
ib	$\delta_i + k_0 < c_s + \alpha\,(1 - c_s - d), \quad \delta_n + k_0 < \alpha\,(1 - c_s - d)$
ib-ig-ng	$\delta_n + c_s > \delta_i > \frac{(1-\alpha)(2\,c_s+\delta_n)+\alpha\,(1-d)-k_0}{2-\alpha}, \quad 1 - d - k_0 > \delta_i > c_s$
ib-ng	$\alpha\,(1 - c_s - d) < \delta_n + k_0 < 2\,(1 - c_s - d), \quad \delta_n > \frac{k_0-\alpha\,(1-c_s-d)}{1-\alpha}$
ib-ig	$\delta_i + k_0 > \alpha\,(1 - c_s - d) + c_s, \quad 1 - d - k_0 > \delta_i > c_s$
ig-ng	$\delta_n + c_s > \delta_i > \frac{1}{2}(2\,c_s + \delta_n - k_0), \quad \delta_i + k_0 > 1 - d, \quad \delta_i > c_s$
ig	$\delta_i > c_s - k_0, \quad \delta_i + k_0 > 1 - d$
ng	$\delta_n > k_0, \quad \delta_n + k_0 > 2(1 - c_s - d)$
fg-ib	$\delta_i < c_s, \quad \delta_n < \frac{k_0-\alpha\,(1-c_s-d)}{1-\alpha}, \quad 1 - c_s - d > k_0 > \alpha\,(1 - c_s - d)$
fg	$\delta_i < c_s, \quad \delta_n < k_0, \quad \frac{k_0}{\alpha} > 0, \quad k_0 > 1 - c_s - d$
0	$\delta_i + k_0 < c_s + \alpha\,(1 - c_s - d), \quad \delta_n + k_0 < \alpha\,(1 - c_s - d), \quad 1 - c_s - d < 0$
Case	**POE**
ib	$\delta_i + k_0 < \frac{2\,\alpha\,(1-d)}{1+\alpha}, \quad \delta_n + k_0 < \frac{2\,\alpha\,(1-d)}{1+\alpha}, \quad k_0 < \alpha(1 - d)$
ib-ig-ng	$2\delta_n + k_0 > \delta_i > \frac{(1-\alpha)\,\delta_n+3\,\alpha\,(1-d)-(2\alpha+1)k_0}{2+\alpha}, \quad 1 - d - k_0 > \delta_i > k_0 - \delta_n$
ib-ng	$\frac{4\,(1-d)}{3} > \delta_n + k_0 > \alpha\,(1 - d)$, if $\alpha < \frac{2}{3}$, then $\delta_n < \frac{2(k_0-\,\alpha\,(1-d))}{2-3\,\alpha}$. Otherwise, the inequality is reversed.
ib-ig	$\delta_i + k_0 > \frac{2\,\alpha\,(1-d)}{1+\alpha}, \quad 1 - d - k_0 > \delta_i > k_0$
ig-ng	$2\delta_n + k_0 > \delta_i > \frac{\delta_n-k_0}{2}, \quad \delta_i + k_0 > 1 - d, \quad \delta_i > k_0 - \delta_n$
ig	$\delta_i > k_0, \quad \delta_i + k_0 > 1 - d$
ng	$\delta_n > k_0, \quad \delta_n + k_0 > \frac{4\,(1-d)}{3}$
fg-ib	$\delta_i < k_0 - \delta_n, \quad 1 - d > k_0 > \alpha(1 - d)$, If $\alpha > \frac{2}{3}$, then $\delta_n < \frac{2(k_0-\alpha\,(1-d))}{2-3\,\alpha}$. Otherwise, the inequality is reversed.
fg	$\delta_i < k_0, \quad \delta_n < k_0, \quad \frac{k_0}{\alpha} > 0, \quad k_0 > 1 - d$
0	Does not exist, because it would require $d > 1$.

Proof. From the net-utility function (Eq.1), we derive the demand for both technologies.[8] If only the brown technology is supplied in the market, demand is simply given by $y_b = 1 - p_b$. If the incumbent offers both brown and green technology monopolistically, the respective demand functions are $y_b = \frac{1-(p_b-p_g-(\delta_i+k_0))}{1-\alpha}$ and $y_g = \frac{(\delta_i+k_0)+\alpha(p_b-1)-p_g}{(1-\alpha)\,\alpha}$. Replacing δ_i with δ_n in the latter two equations yields the respective two demands in case the green technology is only offered by the entrant. These equations hold as well, if both incumbent and entrant offer the green technology in a shared market, where, in the equilibrium, the price of the green technology offered by the entrant is equal to $p_{g,n} = p_{g,i} + \delta_n - \delta_i$. The demands for the case that the green technology is supplied by the

[8] See Appendix B for more details on this proof.

large number of non-innovating direct importers is obtained by setting $\delta_v = 0$. Finally, we derive the demand if only the green technology is offered. If the incumbent is a monopolist, the demand is $y_g = \frac{(\delta_i + k_0) - p_g}{\alpha}$. The demand for all remaining cases can be computed analogously to the cases with the brown technology described above.

With the respective demand functions and Eqs. (2), (3), and (4), the usual calculations for the Cournot, monopoly and perfect competition cases yield the equilibrium quantities and prices for all cases summarized in the appendix (Table B1 and B2). Under the SOE regime, the incumbent maximizes welfare. Under the POE regime, the incumbent maximizes profits subject to a welfare maximizing second-best tax that is set by the regulator prior to the production decision (see appendix Table B2 for a list of all taxes).

Requiring all relevant quantities and prices in each case to be non-negative gives most of the market existence conditions listed in Table 2. In order to distinguish similar market outcomes with and without the brown technology, we include negativity constraints on the quantity or price of the brown technology for all phase out cases. Additionally, we formulate the conditions that determine whether direct importers can successfully enter the market. This is the case if $\delta_v - p_g \geq 0$, which completes the market existence conditions.

□

This proposition shows that numerous market outcomes are possible in the production stage, depending on the choices made by the different players during the adaptation stage. To investigate which of the market outcomes are relevant, we now turn to analyzing the adaptation decisions.

5 Adaptation Stage Analysis

Using the above insights into possible market outcomes, we now proceed to analyze the adaptation decisions of the SOE and the POE. In order to reduce the number of cases and conditions, we focus on those cases, where the brown technology is not fully phased out.

5.1 SOE Incumbent

We begin by analyzing the adaptation decisions made by a state-owned enterprise. The following proposition highlights the most important insights.

Proposition 2. *If the brown technology is still supplied by an SOE and the SOE faces potential competition for supplying the green technology by a private entrant as well as by firms that import the green technology without improving it, the following holds:*

1. *There is never a shared market, that is, only one type of actor (SOE, private entrant, importing firms) supply the green technology.*
2. *If $k_0 < \alpha\,(1 - c_s - d)$, only the brown technology is supplied.*
3. *If k_0 is very small, i.e. $k_0 < -\Delta + \alpha\,(1 - c_s - d + \frac{\sqrt{\frac{\gamma\,\Delta}{\alpha}}}{2-\alpha}\,(4\,(1-\alpha) + \alpha^2))$, the green technology is imported without adaptation.*
4. *If k_0 is greater but still small, i.e., $k_0 < \alpha\,(1 - d) + c_s\,(1-\alpha)\,(4 + \Delta - \alpha\,(2-\alpha)\,\sqrt{\frac{3-\alpha}{1-\alpha}})$, the technology is supplied in a fully adapted version by private entrants.*
5. *In all other cases, the green technology is supplied in a fully adapted version by the SOE.*
6. *The brown technology is still supplied if and only if*
   - *$d < (1 - c_s)$, whenever only the brown technology is supplied.*
   - *$d < (1 - c_s - k_0)$, whenever the green technology is imported without adaptation,*
   - *$d < (1 - c_s - \frac{k_0+\Delta}{2})$, whenever the green technology is provided in a fully adapted version by private entrants,*
   - *$d < (1 - k_0 - \Delta)$, whenever the green technology is provided in a fully adapted version by the SOE.*

Proof. We prove all assertions for the settings where the brown technology is still sold.[9] All welfare expressions for each market case are listed in Table C1 in Appendix C.

[9] For the cases, where the brown technology is phased out, the proof would proceed similarly with slightly altered expressions for the welfare levels.

We begin by proving Assertion 1 and compare $W_{ib-ng,soe}$ and $W_{ib-ig-ng,soe}$ for $d = 0$. This shows that, $W_{ib-ng,soe} \geq W_{ib-ig-ng,soe}$, whenever either $k_0 \leq B_1 - B_2$ or $k_0 \geq B_1 + B_2$, where $B_1 := \alpha - \Delta + (1-\alpha)(4-\alpha)\, c_s$ and $B_2 := (1-\alpha)(2-\alpha)\sqrt{\frac{(1-\alpha)\, c_s^2 + 2\,\alpha\gamma\,\Delta}{1-\alpha}}$. Comparing this to the conditions for the existence of a shared market in Prop. 1 shows that, for $k_0 = 0$, we always have $W_{ib-ng,soe} \geq W_{ib-ig-ng,soe}$, if a shared market is possible. Furthermore, the range of possible k_0 for which $W_{ib-ng,soe} < W_{ib-ig-ng,soe}$ declines at least as strong with d than the conditions for the existence of the shared market. Thus, for no $d > 0$, we can have a shared market with $W_{ib-ig-ng,soe} > W_{ib-ng,soe}$. Consequently, whenever a shared market would be possible, the SOE would refrain from innovating if it expects the entrant to innovate. This proves the Assertion 1.

Assertion 2 follows directly from Prop. 1. Regarding Assertion 3, we note that, for $k_0 < -\Delta + \alpha\left(1 - c_s - d + \frac{\sqrt{\frac{\gamma\,\Delta}{\alpha}}}{2-\alpha}\left(4\,(1-\alpha) + \alpha^2\right)\right)$, we always have $W_{0,soe} > W_{ib-ig,soe}$, that is, the SOE will not innovate, and the profit of a private entrant will be negative if the entrant innovates. Thus, there is no innovation, the green technology is imported and sold without adaptation.

Regarding Assertion 4, comparing $W_{ib-ig,soe}$ and $W_{ib-ng,soe}$ directly yields the condition of this assertion.

Assertion 5 follows from observing that if the conditions of Assertions 2 and 3 are not met, we always have $W_{ib-ig,soe} > W_{ib-ng,soe}$ and $W_{ib-ig,soe} > W_{fg-ib,soe}$, so that the SOE will innovate. Furthermore, Assertion 1 ensures that a private entrant will not innovate as well.

Finally, Assertion 6 follows from calculating the boundaries for which $q_{bi} > 0$ for the various cases. $\square$

Proposition 2 has several interesting implications. First, it shows that, in contrast to the case of a private incumbent presented in the next section, there will never be a shared market. There are two reasons for this. First, if the SOE offers the technology, it does so at marginal costs. As firms importing the international (unadapted) version of the technology do the same, both versions cannot co-exist (except for the case $\Delta = c_s$, where the SOE would not innovate, as this would be welfare decreasing). Second, the SOE will never share the market with a private entrant who does innovate, as this would imply that innovation is done twice. Either the inefficiency of the SOE is sufficiently small compared to the innovation costs, in which case the SOE will innovate and offer an amount of the green technology that leads to $p_s = c_s$ so that an entrant cannot recover his innovation costs. Or, the SOE decides to let a private entrant do the innovation, which happens whenever the SOE is rather inefficient, that is, c_s is large.

Second, Prop. 2 implies that there is a clear picture who will offer the green technology. If the internationally available quality is low, the market achievable with adaptation is too small to warrant the innovation costs and an unadapted version of the technology is offered. In case of a high international quality, the SOE will do the adaptation and will offer the green technology. In an intermediate case, the SOE will let a private entrant do the adaptation.

Note that an increasing inefficiency of the SOE (i.e., a higher value of c_s) will lead to a larger range in which a private entrant is active. A higher value of c_s reduces the boundary below which no adaptation takes place, as it increases the costs of providing the brown technology (which is done by the incumbent). Furthermore, it increases the boundary from which the SOE will supply the green technology, as the private entrant has a larger cost advantage so that the SOE will hold back from innovating in more cases.

Finally, note that a higher marginal damage leads to more cases with adaptation (as the brown technology is offered by the SOE at a smaller quantity and thus a higher price) and leads to more cases where the SOE is doing the innovation. The latter effect stems from the fact that a private entrant will offer a lower quantity of the green technology, if it does the adaptation. If the green technology is more desirable, as the brown one causes greater damage, the SOE will see more often a reason to do the innovation and thereby increase diffusion of the green technology.

5.2 POE Incumbent under a Second Best Tax

Second, we turn to the adaptation decisions in the POE case. The following proposition summarizes the main insights.

Proposition 3. *Let* $\underline{k_0} = \{k_0 : A_1 = 0\}$, $\underline{\underline{k_0}} = \{k_0 : A_2 = 0\}$, *and* $\underline{\underline{\underline{k_0}}} = \{k_0 : A_3 = 0\}$. *Assume that the brown technology is still sold on the market. Then, a POE incumbent and an entrant will pursue the following strategies:*

1. *The two firms will both adapt the green technology and share the market for this technology, if*

$max\{\frac{3\,\alpha}{1+2\alpha}(1-d), 3\sqrt{\alpha\,\gamma\,\Delta}-\Delta, \underline{\underline{k_o}}\} < k_0 < min\{1-d-\Delta, 2\Delta\}$.

2. *Only the entrant adapts and sells the green technology, if* $max\{\underline{k_0}, \frac{2-3\,\alpha}{2}\Delta+\alpha\,(1-\Delta)\} < k_0 < min\{\underline{\underline{k_o}}, \frac{4}{3}(1-d)-\Delta\}$.

3. *Only the POE incumbent adapts and sells the green technology, if* $max\{\underline{\underline{k_0}}, \frac{2\alpha}{1+\alpha}(1-d)\} < k_0 < min\{1-d-\Delta, \Delta, 3\sqrt{\alpha\,\gamma\,\Delta}-\Delta\}$.

4. *None of the two firms adapts the green technology if* $k_0 < min\{\underline{k_0}, \underline{\underline{k_0}}, \frac{2\alpha}{1+\alpha}(1-d)-\Delta, \alpha(1-d)\}$.

with,

$A_1 := \Delta\left(8\,k_0-\alpha(4-3\,\alpha)^2\gamma-8\alpha(1-d)\right)+4\,(k_0-\alpha(1-d))^2+4\,\Delta^2$,

$A_2 := \frac{4\alpha(1-d)^2+(\Delta+k_0)(\alpha\,(3\Delta-8\,(1-d))+\Delta+3\,\alpha\,k_0+k_0)}{4\,(1-\alpha)\,\alpha}-(1-d)^2$,

$A_3 := \frac{1}{9(1-\alpha)\,\alpha}[\Delta(8\alpha\Delta+9\alpha(-(1-\alpha)\gamma-2(1-d))+\Delta)+9\alpha(1-d)^2+2k_0(\alpha(8\Delta-9(1-d))+\Delta)+(8\alpha+1)k_0^2]-\frac{(+3\Delta+3\,k_0-4\,(1-d))^2}{(4-3\,\alpha)^2}$.

Proof. The profits comparison between the two situations determine the conditions under which the entrant or POE incumbent adapts or does not adapt the green technology. Combining those conditions with the conditions that characterize the existence of each market configurations as described in Proposition 1, gives the assertions of this proposition. □

Proposition 3 highlights different configurations of how the POE incumbent and the entrant strategically adapt the green technology to the local context. One of the key drivers that motivates technology adaptation is the internationally available quality of the green technology. Two main mechanisms affect each firm's strategies in adjusting the green technology. The first mechanism is the opportunity for each firm to lead or share the green technology market. The initial level of the green technology k_0 has an upper limit when either the brown technology is still available on the market (Assertion 1-4), or one firm drives out the other firms by leading the green technology market (Assertions 2-3), or preventing the use of the imported green technology without adaptation (Assertions 1-3, i.e, Δ or 2Δ). The lower limit of the initial level of the green technology expresses whether the international quality is sufficiently high to motivate the firm to offer an adapted version of the green technology (Assertions 1-3).

As Prop. 3 shows, there is a minimum level of the initial quality that the green technology needs to have to motivate a local adaptation. This is expressed in the lower bound for the initial level of the green technology k_o (Assertions 1-3). Also, any firm can prevent the other firm from adapting the green technology, and this happens whenever k_0 is not sufficiently high to attract the other firm which is expressed in the upper limit of k_0 (Assertions 2-3). However, it may also happen that no firm has incentive to locally adapt the green technology because its international quality is not high enough. This is translated in the upper bound of k_0 in Assertion 4.

6 Policy Choice

After analyzing the choices that a private firm or a state-owned enterprise would make as an incumbent, we now turn to the question which kind of firm is the better choice for enacting a green technology transition. The preceding sections indicate that this is not only a choice of costs but a choice that can result in different market structures and thus different levels of diffusion of the green technology.

The following proposition highlights this point.

Proposition 4. *Assume that the brown technology is still sold. Then, comparing the welfare induced by having a private firm (POE) or a state-owned enterprise (SOE) as an incumbent yields the following insights:*

1. *If the incumbent does not supply the green technology in both options, using a POE is always as least as good as the SOE outcome.*
2. *If the POE option results in a shared market with an entrant, the welfare ranking of both options depends on the costs of innovation (γ) relative to the production inefficiency of the SOE (c_s):*

   (a) *If the SOE supplies the green technology, the POE option is advantageous, whenever*

$$k_0 + \Delta - \frac{\sqrt{2}}{3}\sqrt{4\,(k_0+\Delta)^2 - 9\,\alpha\,\gamma\,\Delta} < c_s < k_0 + \Delta + \frac{\sqrt{2}}{3}\sqrt{4\,(k_0+\Delta)^2 - 9\,\alpha\,\gamma\,\Delta} \quad (8)$$

(b) If the SOE lets the entrant supply the green technology, the POE option is advantageous, whenever

$$1-d-(k_0+\Delta)\frac{(3-\alpha)}{4-\alpha}-\frac{(2-\alpha)\sqrt{A_4}}{3\,\alpha\,(4-\alpha)} < c_s < 1-d-(k_0+\Delta)\frac{(3-\alpha)}{4-\alpha}+\frac{(2-\alpha)\sqrt{A_4}}{3\,\alpha\,(4-\alpha)}, \quad (9)$$

where

$$A_4 := \frac{9\,(4-\alpha)\,\alpha\,\left((1-d-k_0-\Delta)^2-2\,\Delta\,(1-\alpha)\,\gamma\right)+(1-\alpha)\,(\alpha+5)\,(k_0+\Delta)^2}{1-\alpha}. \quad (10)$$

3. *In all other cases, there is a threshold $\bar{c}$ for the production inefficiency of the SOE (c_s), so that for $c_s < \bar{c}$, welfare is higher in the SOE option and the opposite holds for $c_s > \bar{c}$. The thresholds that are relevant for the different cases are specified in Appendix D Table D1.*

Proof. The conclusions of and conditions for Assertions 2 and 3 follow directly from comparing the welfare levels achieved in the SOE and POE cases, which are reported in Appendix C. Assertion 1 follows from a similar comparison but also takes into account that we need to have $c_s < 1-k_0-d-\Delta$ for the brown technology to be sold, if the green technology is available in an adapted version (if this constraint is not met, no customer would buy the brown technology). This constraint rules out all cases in which welfare in the SOE case would be higher than in the POE case under the assumptions of Assertion 1. □

The different cases of the proposition confirm several intuitive aspects. If the incumbent has no market power regarding the green technology, either because the incumbent does not provide this technology or because there is competition by direct importers that enforces marginal cost pricing, the only relevant aspect of the decision problem is the cost inefficiency of the SOE. Thus, it is always better to have a private firm as an incumbent. The reason is simple: In this case, the tax on the brown technology is sufficient to induce an efficient level of use of the brown technology and, due to the lack of market power, a private incumbent cannot hamper the diffusion of the green technology.

If the private incumbent setting results in a shared market, there are more aspects to consider. The SOE has an inefficiency in production but the shared market in the private firm case has an inefficiency in the adaptation stage, as two firms do the adaptation and thus total adaptation costs are inefficiently high. On the other hand, the competition in the shared market reduces incentives for the private incumbent to limit access to the green technology. Comparing the cases thus involves comparing the inefficiency of the SOE to the adaptation costs (which are paid twice in the POE case) and taking into account the internationally available quality of the green technology as well as the market expansion effect, as these influence the extent to which the POE can use market power to limit the diffusion of the green technology (which results in higher emissions and less overall technology use corresponding to lower welfare).

Finally, in all other cases, we have two main effects. The SOE has higher production costs but prices the green technology efficiently, inducing an optimal diffusion of the green technology and thus optimal emission levels. A private incumbent is more efficient in production (lower marginal costs) but uses its market power to get a higher price for the green technology. This results in a suboptimal diffusion of the green technology. The tax on the brown technology cannot correct both emissions and the market power for the green technology, so welfare losses are incurred. This implies that the choice between the POE and the SOE case should rest on comparing these welfare losses with those generated by the production inefficiency of the SOE, which leads directly to the thresholds described in Appendix D Table D1.

Note that, albeit this main intuition appears to be quite simple, the different effects interact, leading to different thresholds for the different market cases. Thus, the overall decision problem is quite complex. It involves predicting the market cases that would arise for each choice (POE vs SOE) and assessing the welfare losses for each case.

7 Policy Implications

While designing policy instruments to incentivize green technology transitions, governments often face a critical policy question - whether they should provide incentives to private firms that are more efficient but set to maximize their own profits (private benefits) or engage state-owned enterprises, which are inefficient, but whose incentives are more in line with societal targets, such as reducing environmental damages or providing green technologies at prices that reflect marginal production costs.

The policy dilemma is more pertinent in developing countries where energy services are mainly provided by SOEs, but governments are looking for active participation of the private sector in green transitioning. Moreover, developing countries, which are struggling to provide basic services to their citizens, sometimes do not have adequate resources to spend on invention or development of new technologies with large risks of failure. Instead, they prefer to either adopt technologies that are commercially viable and available on international markets or to adapt these technologies only slightly in order to make them a better fit to local conditions.

This study provides some policy insights by developing a theoretical model to address the above policy dilemma. It finds that private firms are typically preferable as suppliers of green technologies if they do not simultaneously offer the older, brown technology, that is, if either new entrants adapt the technology or if the unadapted technology is sold in equilibrium. In this case, there are still some market failures (such as external damages from the use of the brown technology), but these distort the market for the green technology only slightly, so that simple policy measures (such as an emission tax) are sufficient.

If the private firm that is best suited to adapt the green technology to local conditions is an incumbent that owns/operates assets of the brown technology, the situation is more complex. This is a fairly common situation, as firms that are already active in the market, e.g. generating electricity with coal-fired power plants, are often well-placed to adapt green technologies and offer them to customers, such as electricity provided by renewables. In such situations, different market failures interact: Incumbents typically try to protect sales of their well-established brown technology which reduces incentives to take up the green technology, there is market power, and, due to high markups, there is the risk that too many firms adapt the green technology, leading to overinvestment in R&D.

These market failures cannot be completely corrected by a single policy intervention, so that, if highly complex policy interventions (e.g. an emission tax combined with several subsidies) are not feasible, they induce welfare losses. The policy question is then whether these remaining welfare losses outweigh the possible cost advantages of private firms, or not.

In cases where private firms have substantial efficiency advantages, for instance, due to long experience and gained expertise in the sector or due to institutional settings that are likely to render state-owned enterprises highly inefficient (e.g. due to a lack of effective public control), relying on private firms results in a more efficient green technology transition. Similarly, if the above market failures are not causing huge losses, because possible markups or strategic innovation behaviors (not adapting the green technology to protect the brown one) are sufficiently limited by competition or the quality of the internationally available (unadapted) version of the technology, it is still advisable to rely on private firms for the green technology transition.

However, there are also cases where using an SOE to drive the green technology transition results in higher welfare, even if the SOE produces inefficiently, that is, has substantially higher marginal costs than a private firm. SOEs, such as public electric utilities, have no incentive to protect sales of the brown technology. Thus, they will more often adapt a new technology to local conditions. Furthermore, they do not have to refund R&D expenditures via markups on the price of the green technology but can pass on transient losses to tax-payers. This results in a more rapid diffusion of the green technology, as it is offered at a lower price. Finally, using an SOE will avoid overinvestments in R&D; if a private entrant is willing to adapt the green technology to local conditions, the SOE will not contest this, so that the brown technology (e.g. electricity from coal-fired power plants) will be offered (for some times) by the SOE and a private entrant will supply the green technology (e.g. renewable electricity).

Our results indicate that the choice is not easy; apart from a few clear-cut cases (such as the ones mentioned above or the case where the SOE has no substantial cost disadvantage), it is important to pay close attention to the different market situations that would arise in either case. For example, in many cases, a high quality of the internationally available technology will favor using a private firm to drive the transition. Yet, if the green technology will be supplied solely by the private firm or the SOE (no entrants, no directly importing firms), the opposite holds.

However, one important result of our analysis is clear: It is not straight forward to say that a private firm is the better choice, even if an SOE is known to be inefficient. If the continuation of existing market failures is likely and SOEs are not expected to go through deregulation to have a competitive market environment, supporting the SOEs for green transition could be the better option than waiting for the perfect market environment desired by private firms. Albeit this is debatable, as it provides perverse incentives by preserving inefficiency of SOEs, considering the predominant presence of SOEs in the developing world and the urgency of green transition to address global climate change, using SOEs for green transition might be a useful option in many cases.

8 Conclusions

In this paper, we have asked whether countries that do not fully develop new technologies but rather adapt internationally available technologies to local conditions should use private firms or state-owned enterprises to drive a green technology transition. Private firms are often more efficient in production, but they may use the market power that stems from the R&D results (for adapting the technology) to protect old brown (emission-intensive) technologies or to gain high markups for providing green technologies. State-owned enterprises can be steered more easily towards societal objectives, but they might be less efficient in production, causing a higher-priced green technology.

This question of who should drive a green technology transition is pertinent in the transition to renewable energies for many countries, as renewable energy technologies are typically developed by only a few countries, and as many countries have energy providers that are state-owned enterprises or have the option to (re-)nationalize private energy providers.

As we have shown, this question is a rather complex one. The answer depends not only on obvious aspects, such as the potential inefficiency of state-owned enterprises, but also on the different market structures that arise in the private-firm and the state-owned enterprise option. The private firm option is typically preferable if the green technology is not provided by the same firm that offers the brown technology. In this case, a simple policy, such as taxing emissions from the brown technology, is able to correct at least the environmental externality, so that the efficiency advantage of private firms usually dominates the decision. In other cases, additional aspects have to be taken into account. An SOE will price the green technology more aggressively (at marginal costs), often inducing a higher diffusion of this technology. Furthermore, an SOE will always avoid overinvestment in R&D, which can happen if private firms compete in adjusting the new technology. Finally, an SOE has no incentive to protect sales of the brown technology, which a private incumbent might have and which might lead to a lack of innovation efforts. These aspects have to be compared to the effects of potentially higher marginal production costs of an SOE, which reduces diffusion of the new technology as well as total technology use and thus welfare. We have provided clear insights into when and why a private firm or an SOE might be better suited to drive a green technology transition.

To the best of our knowledge, this is the first attempt to compare the state-owned enterprises to environmental policy in terms of their ability to achieve societal objectives with an R&D decision for improving green technologies. The model that we use is highly stylized in order to gain analytical results. However, it captures some effects that are likely to be relevant in important applications, such as Arrow's replacement effect, a possible market expansion by shifting to decentralized renewables (or other green technologies), and the possible competition between firms that adapt a new technology to local conditions (and thus have to recapture R&D costs via price markups) and firms that directly import the technology without quality-increasing adaptations.

Perhaps the most important insight of our analysis is that there are indeed cases where using an inefficient state-owned enterprise is better than relying on private firms. Our analysis shows that such cases either arise from the combination of market power induced by protected IP rights and an insufficient number of policy instruments to correct all market failures or from the well-known effect that competition might induce too much R&D spending (several firms pursuing the same ideas). Both cases are likely to be relevant in applications where market power is indeed important (as in the energy markets of many countries) or where high gains can be expected from adapting technologies (which induces too many firms to exert R&D efforts).

However, it should be clear that our analysis is only a theoretical contribution. Whether and where the effects that we have found in our analysis are actually relevant remains to be confirmed by empirical work.

Of course, the fact that using a state-owned enterprise could be the better solution results from our assumption that there is no possibility for implementing a first-best policy that corrects environmental externalities, market power, and (possibly) incentives for overinvesting in R&D. In theory, this appears to be a strong assumption. However, our results show how strongly the different market failures interact, implying that the choice of a first-best policy would be very demanding and the policy mix would change over time if the green technology is developed further. Given that most countries still strive to implement even a "simple" correction of many major environmental externalities, it appears likely that we cannot expect first-best policies consisting of several interdependent market interventions anytime soon to become the norm. Until this changes, using state-owned enterprises might be a promising alternative.

References

Acemoglu, D., P. Aghion, L. Bursztyn, and D. Hemous (2012). The environment and directed technical change. *The American Economic Review 102*(1), 131–166.

Bárcena-Ruiz, J. C. and M. B. Garzón (2006). Mixed oligopoly and environmental policy. *Spanish Economic Review 8*(2), 139–160.

Barnett, A. H. (1980). The pigouvian tax rule under monopoly. *The American Economic Review 70*(5), 1037–1041.

Belloc, F. (2014). Innovation in state-owned enterprises: Reconsidering the conventional wisdom. *Journal of Economic Issues 48*(3), 821–848.

Bondarev, A., P. Dato, and F. C. Krysiak (2021). Green technology transitions with an endogenous market structure. *WWZ Working Paper*.

Bortolotti, B., V. Fotak, and B. Wolfe (2019). Innovation at state-owned enterprises. *BAFFI CAREFIN Centre Research Paper* (2018-72).

Buchanan, J. M. (1969). External diseconomies, corrective taxes, and market structure. *The American Economic Review 59*(1), 174–177.

Carraro, C. and A. Soubeyran (1996). Environmental policy and the choice of production technology. In *Environmental policy and market structure*, pp. 151–180. Springer.

Dato, P. and F. C. Krysiak (2021). Optimal mix of policy instruments and green technology transitions. *WWZ Working Paper*.

De Fraja, G. and F. Delbono (1990). Game theoretic models of mixed oligopoly. *Journal of Economic Surveys 4*(1), 1–17.

Dechezleprêtre, A., M. Glachant, I. Haščič, N. Johnstone, and Y. Ménière (2011). Invention and transfer of climate change–mitigation technologies: a global analysis. *Review of environmental economics and policy*.

Delbono, F. and V. Denicolo (1993). Regulating innovative activity: the role of a public firm. *International Journal of Industrial Organization 11*(1), 35–48.

Downing, P. B. and L. J. White (1986). Innovation in pollution control. *Journal of environmental economics and management 13*(1), 18–29.

Dutz, M. A. and S. Sharma (2012). Green growth, technology and innovation. *World Bank Policy Research Working Paper* (5932).

Fischer, C. and R. G. Newell (2008). Environmental and technology policies for climate mitigation. *Journal of environmental economics and management 55*(2), 142–162.

Foster, C. and R. Heeks (2013). Conceptualising inclusive innovation: Modifying systems of innovation frameworks to understand diffusion of new technology to low-income consumers. *The European Journal of Development Research 25*, 333–355.

Gambhir, A., R. Gross, and R. Green (2014). The impact of policy on technology innovation and cost reduction: a case study on crystalline silicon solar pv modules. *Imperial College WP*.

Haruna, S. and R. K. Goel (2019). Optimal pollution control in a mixed oligopoly with research spillovers. *Australian Economic Papers 58*(1), 21–40.

IRENA (2022). *Renewable Power Generation Costs in 2021.* International Renewable Energy Agency (IRENA).

Ishibashi, I. and T. Matsumura (2006). R&d competition between public and private sectors. *European Economic Review 50*(6), 1347–1366.

Jung, C., K. Krutilla, and R. Boyd (1996). Incentives for advanced pollution abatement technology at the industry level: An evaluation of policy alternatives. *Journal of environmental economics and management 30*(1), 95–111.

Kaplinsky, R. (2011). Schumacher meets schumpeter: Appropriate technology below the radar. *Research Policy 40*(2), 193–203.

Katsoulacos, Y. and A. Xepapadeas (1996a). Emission taxes and market structure. In *Environmental policy and market structure*, pp. 3–22. Springer.

Katsoulacos, Y. and A. Xepapadeas (1996b). Environmental innovation, spillovers and optimal policy rules. In *Environmental policy and market structure*, pp. 143–150. Springer.

Kesavayuth, D. and V. Zikos (2013). R&d versus output subsidies in mixed markets. *Economics Letters 118*(2), 293–296.

Kitahara, M. and T. Matsumura (2006). Realized cost-based subsidies for strategic r&d investments with ex ante and ex post asymmetries. *The Japanese Economic Review 57*(3), 438–448.

Krass, D., T. Nedorezov, and A. Ovchinnikov (2013). Environmental taxes and the choice of green technology. *Production and operations management 22*(5), 1035–1055.

Lahiri, S. and Y. Ono (1999). R&d subsidies under asymmetric duopoly: a note. *The Japanese economic review 50*(1), 104–111.

Lee, D. R. (1975). Efficiency of pollution taxation and market structure. *Journal of Environmental Economics and Management 2*(1), 69–72.

Matsumura, T. and N. Matsushima (2004). Endogenous cost differentials between public and private enterprises: a mixed duopoly approach. *Economica 71*(284), 671–688.

Matsumura, T., N. Matsushima, and S. Cato (2013). Competitiveness and r&d competition revisited. *Economic modelling 31*, 541–547.

Megginson, W. L. and J. M. Netter (2001). From state to market: A survey of empirical studies on privatization. *Journal of economic literature 39*(2), 321–389.

Milliman, S. R. and R. Prince (1989). Firm incentives to promote technological change in pollution control. *Journal of Environmental Economics and Management 17*(3), 247–265.

Napolitano, L., A. Sbardella, D. Consoli, N. Barbieri, and F. Perruchas (2022). Green innovation and income inequality: A complex system analysis. *Structural Change and Economic Dynamics 63*, 224–240.

Ormrod, R. K. (1990). Local context and innovation diffusion in a well-connected world. *Economic Geography 66*(2), 109–122.

Ouattara, K. S. et al. (2019). Pollution abatement and partial privatization. *Economics Bulletin 39*(3), 1887–1897.

Poyago-Theotoky, J. (1998). R&d competition in a mixed duopoly under uncertainty and easy imitation. *Journal of Comparative Economics 26*(3), 415–428.

Poyago-Theotoky, J. A. (2007). The organization of r&d and environmental policy. *Journal of Economic Behavior & Organization 62*(1), 63–75.

Poyago-Thotoky, J. et al. (2003). Optimal environmental taxation, r&d subsidization and the role of market conduct. *Finnish Economic Papers 16*(1), 15–26.

Prahalad, C. K. (2012). Bottom of the pyramid as a source of breakthrough innovations. *Journal of product innovation management 29*(1), 6–12.

Requate, T. (2005). Dynamic incentives by environmental policy instruments—a survey. *Ecological Economics 54*(2–3), 175–195.

Requate, T. (2006). Environmental policy under imperfect competition. *The international yearbook of environmental and resource economics 2007*, 120–207.

Requate, T. and W. Unold (2003). Environmental policy incentives to adopt advanced abatement technology: Will the true ranking please stand up? *European Economic Review 47*(1), 125–146.

Stranlund, J. K. (1997). Public technological aid to support compliance to environmental standards. *Journal of Environmental Economics and Management 34*(3), 228–239.

Tawney, L., M. Miller, and M. Bazilian (2015). Innovation for sustainable energy from a pro-poor perspective. *Climate Policy 15*(1), 146–162.

Toshimitsu, T. (2003). Optimal r&d policy and endogenous quality choice. *International Journal of Industrial Organization 21*(8), 1159–1178.

Vining, A. R. and A. E. Boardman (1992). Ownership versus competition: Efficiency in public enterprise. *Public choice 73*(2), 205–239.

White, M. D. (1996). Mixed oligopoly, privatization and subsidization. *Economics letters 53*(2), 189–195.

Yuan, M., W. Chen, and J. Qin (2021). Bank-based financing and catch-up innovation: A three-way interaction approach. *Economics Letters 209*, 110089.

Appendix

A Variables and Parameters

Table A1: ***Variables and parameters***

Subscript j refers to	Technology
Subscript $j = b$ refers to	Brown technology
Subscript $j = g$ refers to	Green technology
Subscript i refers to	Incumbent
Subscript n refers to	Entrant
Subscript f refers to	Direct Importers
Subscript v refers to	Firm doing the local adaptation
Subscript $v = i$ refers to	Firm doing the local adaptation is an incumbent i
Subscript $v = n$ refers to	Firm doing the local adaptation is an entrant n
Subscript P refers to	Production stage
Subscript A refers to	Adaptation stage
m	Consumer index
m_j	Consumer of the technology j
m_b	Consumer of the brown technology b
m_g	Consumer of the green technology g
$m_{b,0}$	Consumer that is indifferent between buying and not buying technology b
$m_{g,0}$	Consumer that is indifferent between buying and not buying technology g given that b is not supplied.
$m_{b,g}$	Consumer that is indifferent between buying technology b and g given that both are supplied.
$u_j(m)$	Utility of the consumer m from using the technology j
p_j	Price of the technology j
p_b	Price of the brown technology b
p_g	Price of the green technology g
$p_{g,i}$	Price of the green technology g offered by the incumbent i
$p_{g,n}$	Price of the green technology g offered by the entrant n
k_j	Quality of the technology j
k_b	Quality of the brown technology b
k_g	Quality of the green technology g
k_0	Initial quality of the generic green technology g
α	Market expansion effect
q_{bi}	Supply of the brown technology b by the incumbent i
q_{gi}	Supply of the green technology g by the incumbent i
q_{gn}	Supply of the green technology g by the entrant n
q_{gf}	Supply of the green technology g by importing firms f
y_b	Demand of the brown technology b by consumers
y_g	Demand of the green technology g by consumers
c_s	Production inefficiency of the SOE
c	Marginal production costs for private firms, either incumbent i or entrant n
t	Unit tax on the brown technology b

Table A2: ***Variables and parameters (cont.)***

Dam	Environmental damage from using the brown technology b
d	Marginal environmental damage
δ_v	Added quality to the green technology g due to local adaptation from firm v
δ_i	Added quality to the green technology g due to local adaptation from incumbent i
δ_n	Added quality to the green technology g due to local adaptation from entrant n
Δ	Maximum added quality to the green technology g due to local adaptation
Γ_v	Adaptation costs by firm v
Γ_i	Adaptation costs by incumbent i
Γ_n	Adaptation costs by entrant n
γ	Marginal cost of adaptation
$\pi_{P,i}$	Profit of the incumbent i at the production stage P
$\pi_{P,n}$	Profit of the entrant n at the production stage P
$\pi_{P,v}$	Profit of firm v at the production stage P
$\pi_{A,v}$	Profit of firm v at the adaptation stage A
W	Welfare
W_P	Welfare at the production stage P
W_A	Welfare at the adaptation stage A
$W_{ib,soe}$	Welfare if only the brown technology b is supplied by the SOE incumbent
$W_{ib-ig-ng,soe}$	Welfare if both SOE incumbent i and entrant n supply the green technology g and the SOE incumbent supplies the brown technology b
$W_{ib-ng,soe}$	Welfare if entrant n supplies the green technology g and the SOE incumbent supplies the brown technology b
$W_{ib-ig,soe}$	Welfare if the SOE incumbent supplies the green technology g and the brown technology b
$W_{ig-ng,soe}$	Welfare if both SOE incumbent and entrant n supply the green technology g and the brown technology b is phased out
$W_{ig,soe}$	Welfare if only the SOE incumbent supplies the green technology g and the brown technology b is phased out
$W_{ng,soe}$	Welfare if only the entrant n supplies the green technology g and the brown technology b is phased out
$W_{fg-ib,soe}$	Welfare if the directly importing firms f supply the green technology g and the SOE incumbent supplies the brown technology b
$W_{fg,soe}$	Welfare if the directly importing firms f supply the green technology g and the brown technology b is phased out
$W_{0,soe}$	Welfare if there is no market for the the green technology g and the brown technology b is phased out

B Production Stage: Prices, Quantities and Taxes

In this appendix, we provide more details on the derivation of the equilibrium quantities, prices and taxes. For illustrative purposes, we present the main calculation steps for the shared market (Case ib-ig-ng) with a POE incumbent, which typically produces the most complex results.

First, note that Eq. (1) essentially consists of two linear functions describing the net-utility that a given consumer obtains from purchasing one or the other technology. Obviously, consumers will choose whatever yields the higher net-benefit. If these two functions intersect in the relevant domain, the continuum of heterogeneous consumers is divided into green-technology-buyers and brown-technology-buyers. Otherwise, only one type of technology is demanded.

Table B1: ***Production stage: equilibrium prices and optimizing tax levels***

SOE	p_b	p_g	t
Case ib	$c_s + d$	-	-
Case ib-ig-ng	$c_s + d$	c_s	-
Case ib-ng	$c_s + d$	$\frac{\delta_n + k_0 - \alpha(1-c_s-d)}{2-\alpha}$	-
Case ib-ig	$c_s + d$	c_s	-
Case ig-ng	-	c_s	-
Case ig	-	c_s	-
Case ng	-	$\frac{\delta_n + k_0}{2}$	-
Case fg-ib	$c_s + d$	0	-
Case fg	-	0	-
POE	p_b	p_g	t
Case ib	d	-	$2\,d - 1$
Case ib-ig-ng	$\frac{1}{3}(3\,d + 2\,\delta_i - \delta_n + k_0)$	$\frac{1}{3}(2\delta_i - \delta_n + k_0)$	$2\,d + \delta_i + k_0 - 1$
Case ib-ng	$\frac{k_0 - \alpha\,(1+2\,d) + 4\,d + \delta_n}{4-3\,\alpha}$	$\frac{2(\delta_n + k_0 - \alpha(1-d))}{4-3\,\alpha}$	$\frac{\alpha + 2(\alpha-4)\,d - 4\delta_n - 4\,k_0 + 4}{3\,\alpha - 4}$
Case ib-ig	$\frac{1}{2}(2\,d + \delta_i + k_0)$	$\frac{\delta_i + k_0}{2}$	$2\,d + \delta_i + k_0 - 1$
Case ig-ng	$\frac{1}{3}(2\,\delta_i - \delta_n + k_0)$	-	
Case ig	-	$\frac{\delta_i + k_0}{2}$	-
Case ng	-	$\frac{\delta_n + k_0}{2}$	-
Case fg-ib	d	0	-
Case fg	-	0	-

Demand for each technology is given by the mass of consumers choosing the respective technology type. If only one technology type is demanded, the demand function is simply derived by setting the according net-utility function equal to zero and solving for m, i.e. the last incremental consumer that still receives a non-negative net-utility from consuming. This gives

$$
\begin{aligned}
& m_{b,0} := y_b = \; 1 - p_b \quad \text{(brown technology only)} \\
& \text{or} \\
& m_{g,0} := y_g = \; \frac{(\delta_v + k_0) - p_g}{\alpha} \quad \text{(green technology only)}.
\end{aligned} \tag{B1}
$$

If both technologies are demanded, we calculate the point where both net-utility functions intersect ($m_{b,g}$). Demand for the brown technology is then equal to the mass of consumers on the interval $[0; m_{g,b}]$ while demand for the green technology is determined with the interval $]m_{b,g}; m_{g,0}]$:

$$
\begin{aligned}
& m_{b,g} := y_b = \frac{1 - (p_b - p_g - (\delta_v + k_0))}{1 - \alpha} \quad \text{(brown technology)} \\
& \text{and} \\
& m_{g,0} - m_{b,g} := y_g = \frac{(\delta_v + k_0) + \alpha(p_b - 1) - p_g}{(1 - \alpha)\, \alpha} \quad \text{(green technology only)}.
\end{aligned} \tag{B2}
$$

Solving the case-specific market clearing conditions (Case ib-ig-ng: $y_g = q_{gi} + q_{gn}$ and $y_b = q_{bi}$) simultaneously for prices p_b and p_g gives the respective inverse demand functions. For Case ib-ig-ng, that is

$$
\begin{aligned}
& p_b(q_{bi}, q_{gi}, q_{gn}) = 1 - q_b - \alpha\, (q_{gi} + q_{gn}) \\
& \text{and} \\
& p_g(q_{bi}, q_{gi}, q_{gn}) = (k_0 + \delta_i) - \alpha\, (q_b + q_{gi} + q_{gn}).
\end{aligned} \tag{B3}
$$

We derive equilibrium quantities and prices with Cournot, monopoly and perfect competition calculus, using the inverse demand functions for each market outcome as well as profits (Eqs. (2), (3)) and welfare (Eq. (4)). If the incumbent is a POE, it maximizes profits facing a tax t on emissions. If the incumbent is an SOE, it maximizes welfare instead of profits. For our exemplary Case ib-ig-ng (POE setting), the Cournot first order conditions read

$$
\begin{aligned}
\frac{\partial \pi_{P,i}}{\partial q_b} &= 1 - 2\, q_b - t - \alpha\, (2\, q_{gi} + q_{gn}) = 0, \\
\frac{\partial \pi_{P,i}}{\partial q_{gi}} &= (k_0 + \delta_i) - \alpha\, (2\, (q_{gi} + q_b) + q_{gn}) = 0, \\
\frac{\partial \pi_{P,n}}{\partial q_{gn}} &= (k_0 + \delta_n) - \alpha\, (q_{gi} + q_b + 2\, q_{gn}) = 0.
\end{aligned} \tag{B4}
$$

and can be solved for

$$
\begin{aligned}
q_b^* &= \frac{1-(\delta_i+k_0)-t}{2\,(1-\alpha)}, \\
q_{gi}^* &= \frac{4\,\delta_i-2\,\delta_n+(\alpha+2)\,k_0-\alpha\,(\delta_i-2\,\delta_n-3\,t+3)}{6\,(1-\alpha)\,\alpha}, \\
q_{gn}^* &= \frac{k_0-\delta_i+2\,\delta_n}{3\,\alpha}.
\end{aligned} \tag{B5}
$$

This step provides the equilibrium quantities in the SOE incumbent setting. For the POE incumbent, we obtain all expressions depending on the tax rate t. Given the choices of the market actors, this tax rate is set by the regulator to maximize welfare. Hence, we plug the equilibrium quantities into welfare function (Eq. 4)), optimize with respect to the tax and solve the first order condition for t, which in POE Case ib-ig-ng is:

$$t^* = 2\,d+\delta_i+k_0-1 \tag{B6}$$

All resulting equilibrium taxes and prices are summarized in Table B1, equilibrium quantities are summarized in Table B2.

Table B2: *Production stage: equilibrium quantities*

SOE	q_b	q_{gi}	q_{gn}	q_{gf}
Case ib	$1-c_s-d$	-	-	-
Case ib-ig-ng	$\frac{1-d-(\delta_i+k_0)}{1-\alpha}$	$\frac{2(1-\alpha)c_s+\alpha\,(d-\delta_i+\delta_n+1)+2\delta_i-\delta_n+k_0}{(1-\alpha)\,\alpha}$	$\frac{c_s-\delta_i+\delta_n}{\alpha}$	-
Case ib-ng	$\frac{2-2\,c_s-2\,d-\delta_n-k_0}{2-\alpha}$	-	$\frac{\delta_n+k_0-\alpha\,(1-c_s-d)}{(2-\alpha)\,\alpha}$	-
Case ib-ig	$\frac{1-d-(\delta_i+k_0)}{1-\alpha}$	$\frac{\delta_i+k_0-c_s-\alpha\,(1-c_s-d)}{(1-\alpha)\,\alpha}$	-	-
Case ig-ng	-	$\frac{k_0-2\,c_s+2\,\delta_i-\delta_n}{\alpha}$	$\frac{c_s-\delta_i+\delta_n}{\alpha}$	-
Case ig	-	$\frac{(\delta_i+k_0)-c_s}{\alpha}$	-	-
Case ng	-	-	$\frac{\delta_n+k_0}{2\,\alpha}$	-
Case fg-ib	$\frac{1-c_s-d-k_0}{1-\alpha}$	-	-	$\frac{k_0-\alpha\,(1-c_s-d)}{(1-\alpha)\,\alpha}$
Case fg	-	-	-	k_0/α

POE	q_b	q_{gi}	q_{gn}	q_{gf}
Case ib	$1-d$	-	-	-
Case ib-ig-ng	$\frac{1-d-(\delta_i+k_0)}{1-\alpha}$	$\frac{\alpha\,(3\,d+\delta_i+\delta_n+2\,k_0-3)+2\delta_i-\delta_n+k_0}{3\,(1-\alpha)\,\alpha}$	$\frac{k_0-\delta_i+2\,\delta_n}{3\,\alpha}$	-
Case ib-ng	$\frac{4-4\,d-3\,\delta_n-3\,k_0}{4-3\,\alpha}$	-	$\frac{2(\alpha\,(d-1)+\delta_n+k_0)}{\alpha\,(4-3\,\alpha)}$	-
Case ib-ig	$\frac{1-d-(\delta_i+k_0)}{1-\alpha}$	$\frac{\alpha\,(2\,d+\delta_i+k_0-2)+\delta_i+k_0}{2(1-\alpha)\,\alpha}$	-	-
Case ig-ng	-	$\frac{2\,\delta_i-\delta_n+k_0}{3\,\alpha}$	$\frac{k_0-\delta_i+2\,\delta_n}{3\,\alpha}$	-
Case ig	-	$\frac{\delta_i+k_0}{2\,\alpha}$	-	-
Case ng	-	-	$\frac{\delta_n+k_0}{2\,\alpha}$	-
Case fg-ib	$\frac{1-d-k_0}{1-\alpha}$	-	-	$\frac{k_0-\alpha\,(1-d)}{(1-\alpha)\,\alpha}$
Case fg	-	-	-	k_0/α

C Adaptation Stage: Welfare

Substituting the equilibrium prices and quantities of the production stage (see Table B1 and B2) into the expression for welfare Eq. (7), with $\delta_v = 0$ or $\delta_v = \Delta$ depending on the respective case, yields the characterizations of welfare summarized in Table C1.

Table C1: *Welfare achieved for all possible market cases*

Case	SOE
ib	$W_{ib,soe} = \frac{1}{2}(1 - c_s - d)^2$
ib-ig-ng	$W_{ib-ig-ng,soe} = \frac{12\,(1-\alpha)\,c_s^2 - 8\,(1-\alpha)\,c_s\,(\Delta+k_0) - 8\,\alpha\,\Delta\,(2\,(1-\alpha)\,\gamma+1-d)}{8\,(1-\alpha)\,\alpha} + \frac{4\,\alpha\,(1-d)^2 - 8\,k_0(\alpha(1-d)-\Delta) + 4\,\Delta^2 + 4\,k_0^2}{8\,(1-\alpha)\,\alpha}$
ib-ng	$W_{ib-ng,soe} = \frac{4\,(4-\alpha)\,\alpha(c_s+d-1)^2 + 8\,(3-\alpha)\,k_0(\alpha\,(c_s+d-1)+\Delta) + 4\,(3-\alpha)\,k_0^2}{8\,(2-\alpha)^2\,\alpha} + \frac{4\,(3-\alpha)\,\Delta^2 + 8\,\alpha\,\Delta\,\left((3-\alpha)\,(c_s+d-1) - (2-\alpha)^2\,\gamma\right)}{8\,(2-\alpha)^2\,\alpha}$
ib-ig	$W_{ib-ig,soe} = \frac{4\left((1-\alpha)\,c_s^2 - 2\,(1-\alpha)\,c_s\,(\Delta+k_0) - 2\,\alpha\,\Delta\,((1-\alpha)\,\gamma-d+1) + \alpha\,(1-d)^2 - 2\,k_0\,(\alpha\,(1-d)-\Delta) + \Delta^2 + k_0^2\right)}{8\,(1-\alpha)\,\alpha}$
ig-ng	$W_{ig-ng,soe} = \frac{4\,(((1-\alpha)\,c_s + \alpha\,(1-d) - \Delta - k_0)((1-\alpha)\,(-c_s) - \alpha\,(1-d-2\Delta) - \Delta + (2\alpha-1)\,k_0))}{8\,(1-\alpha)^2\,\alpha} + \frac{8\,c_s\,(2\,(1-\alpha)\,c_s + \alpha\,(1-d) - \Delta - k_0)}{8\,(1-\alpha)\,\alpha} - 2\,\gamma\,\Delta$
ig	$W_{ig,soe} = \frac{(\Delta+k_0-c_s)^2}{2\,\alpha} - \gamma\,\Delta$
ng	$W_{ng,soe} = \frac{3\,(\Delta+k_0)^2 - 8\,\alpha\,\gamma\Delta}{8\,\alpha}$
fg-ib	$W_{fg-ib,soe} = \frac{4\left(\alpha\,(1-c_s-d)\,(1-c_s-d-2k_0) + k_0^2\right)}{8\,(1-\alpha)\,\alpha}$
fg	$W_{fg,soe} = \frac{k_0^2}{2\,\alpha}$
0	$W_{0,soe} = 0$
Case	**POE**
ib	$W_{ib,poe} = \frac{1}{2}(1 - d)^2$
ib-ig-ng	$W_{ib-ig-ng,poe} = \frac{(\alpha+8)\,\Delta^2 - 18\,\alpha\,\Delta(2\,(1-\alpha)\,\gamma-d+1) + 9\,\alpha\,(1-d)^2 + 2\,k_0\,(\alpha\,(\Delta-9(1-d)) + 8\,\Delta) + (\alpha+8)\,k_0^2}{18\,(1-\alpha)\,\alpha}$
ib-ng	$W_{ib-ng,poe} = \frac{2\,\alpha\,\Delta\,(3\,\alpha\,\gamma - 4\,\gamma - 3\,(1-d)) + 4\,\alpha\,(1-d)^2 - 6\,k_0\,(\alpha\,(1-d)+\Delta) + 3\,\Delta^2 + 3\,k_0^2}{2\,\alpha\,(4-3\,\alpha)}$
ib-ig	$W_{ib-ig,poe} = \frac{(\alpha+3)\,\Delta^2 - 8\,\alpha\,\Delta\,((1-\alpha)\,\gamma+1-d) + 4\,\alpha\,(1-d)^2 - 8\,\alpha(1-d)\,k_0 + (\alpha+3)\,k_0^2 + 2\,(\alpha+3)\,\Delta\,k_0}{8\,(1-\alpha)\,\alpha}$
ig-ng	$W_{ig-ng,poe} = \frac{2\left(\Delta\,(2\,\Delta - 9\,\alpha\gamma) + 2\,k_0^2 + 4\,\Delta\,k_0\right)}{9\,\alpha}$
ig	$W_{ig,poe} = \frac{3\,(\Delta+k_0)^2 - 8\,\alpha\,\gamma\,\Delta}{8\,\alpha}$
ng	$W_{ng,poe} = \frac{3\,(\Delta+k_0)^2 - 8\,\alpha\,\gamma\,\Delta}{8\,\alpha}$
fg-ib	$W_{fg-ib,poe} = \frac{\alpha\,(1-d)\,(1-d-2\,k_0) + k_0^2}{2\,(1-\alpha)\,\alpha}$
fg	$W_{fg,poe} = \frac{k_0^2}{2\,\alpha}$
0	-

D Policy Choice

In the following table, we state the inefficiency threshold levels under which the POE is preferred over the SOE.

Table D1: ***Threshold $\bar{c}$ for c_s under which a POE is preferable to an SOE, depending on who supplies the green technology (GT).***

		POE	
		Entrant supplies GT	POE supplies GT
SOE	Entrant supplies GT	-	$\frac{\left(8-10\,\alpha+2\,\alpha^2\right)(1-d)+\left(8\,\alpha-2\,\alpha^2-6\right)(k_0+\Delta)-(2-\alpha)\sqrt{A_5}}{2\,(1-\alpha)\,(4-\alpha)}$
	SOE supplies GT	$\frac{\left(4-7\,\alpha+3\,\alpha^2\right)(k_0+\Delta)}{(4-3\,\alpha)\,(1-\alpha)}-\sqrt{A_6}$	$\frac{1}{2}\,(2-\sqrt{3})\,(k_0+\Delta)$