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Optimal Mix of Policy Instruments and Green Technology Transitions *

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Abstract

Green innovation is a key element in fighting climate change. But there are several challenges that need to be addressed in managing a green technology transition, both in terms of interacting market failures (environmental externality, public good nature of innovation, strategic behaviour of incumbents protecting an emission-intensive technology) and as the structure of the technology market (whether the new technology is offered by a monopolistic incumbent or whether there is some competition induced by market entrants) will evolve throughout the transition. In this paper, we investigate the question what constitutes the optimal policy at different stages of the technology transition and for different market structures. We first analyse a policy mix that can implement a first-best outcome. We show that this mix will differ between different market settings and for different stages of the technology transition. Second, we investigate the choice between a push policy (subsidy for the new technology) and a pull strategy (tax on the old technology) and show that throughout the transition, the policy should be switched, often even more than once. Overall, our results indicate that managing a green technology transition requires a sequence of different policies attuned to the state of the transition and that this sequence differs substantially for different cases, for example, different levels of environmental damage or different cost advantages of the incumbent over entrants.

Keywords: Policy, Tax, Subsidy, Green Technology, Imperfect Competition, Technology Transition

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1 Introduction

Green technological change plays an important role in climate change policy and is seen as key to ensuring sustainable growth (OECD, 2012, 2013). However, achieving a green technology transition is often a complex problem, as different types of market failures occur simultaneously; the basic problem of an environmental externality can be amplified by problems of imperfect competition induced by the need to refund r&d investments as well as by strategic behaviour of incumbents invested in an emission-intensive industry who strive to reduce Arrow's replacement effect (Arrow, 1962). Furthermore, throughout the transition, the market structure often changes, with newcomers entering or leaving the market or incumbents switching from protecting their old "brown" technology to striving for a share of the market of the new "green" technology.

An interesting example is offered by the transition from fossil-fuelled to electrical vehicles (Wesseling et al., 2015): Albeit substantial innovation in electrical vehicles already occurred during the 1990s, mainly due to incumbents' efforts, there were little sales, and, later on, a stark drop in innovation from 2000-2006. However, when a newcomer (Tesla) entered the market, innovation and (somewhat later) sales started to increase and the newcomer became market leader (Pontes, 2020, Holland, 2020). However, the market structure is highly dynamic: incumbents are becoming competitive and contribute to a drop of EV prices. An example is the Renault Zoe in Europe (Taylor, 2020), which is provided by an incumbent and designed to compete for customers with traditional combustion-engine cars.

Given the above market failures and strategic incentives, it is likely that, in the absence of policies supporting green technological change, we cannot expect markets to deliver an efficient outcome. Indeed, many countries use a diverse set of instruments to support green technological change. In the above example of a transition to electrical mobility, countries have experimented with qualitatively different strategies to increase the speed of the transition, ranging from subsidies for the new technology, to investments in the infrastructure required for electrical mobility, to taxes on the old technology (either in form of taxes on fossil fuels or on vehicles using traditional combustion engines). The policies are thereby typically aimed at the product market, not at r&d, as technological development occurs at an international scale and many countries do not even have a domestic automobile industry.

In economic analysis, it is well-established what would be a first-best policy to counteract market failures arising from the environmental externality and the public good nature of technological knowledge, e.g., a Pigouvian tax on emissions combined with r&d policies (Poyago-Theotoky, 2007). Combinations of such instruments have been widely discussed in different contexts (see, e.g., Schneider and Goulder, 1997, Fischer and Newell, 2008 and Acemoglu et al., 2012). However, there is limited evidence as to what policy instruments should be used when policy makers can only partially influence market outcomes.

Furthermore, on top of the above market failures, a green technology transition often implies a change of the market structure as incumbents producing old technologies will face competition from new entrants that invest in the new technologies. Depending on the stage of the transition, incumbents may decide to strategically invest in the new technology to avoid competition, to follow the new entrant or to become a leader in this new technology market (see Bondarev et al., 2020). The above example of electrical mobility highlights this point.

To the best of our knowledge, there is no study that analyses how policy instruments should be chosen and set in different phases of the technology transition, that is, when the new technology enters the market (often more via attracting new customers than by enticing customers away from the old technology), when the new technology has achieved an intermediate market share (so that both technologies compete for the same customers), and when the old technology is (almost) phased out.

In this paper, we investigate this question. Based on the above example of electrical vehicles, we consider a setting where an incumbent and (possibly) several newcomers provide a green alternative to the brown technology offered by the incumbent and where the r&d decisions of these firms cannot be influenced by national policies. We first analyse how a complex set of policy measures should be designed for different market situations and at different stages of the technology transition. In a second step, we restrict our attention to simpler policy measures: A tax on the brown technology vs an undifferentiated subsidy for the green technology. We analyse which of these instruments should be chosen at which stage of the technology transition and how this depends on the market structure.

To do so, we build our model on the framework developed by Bondarev et al. (2020) but include environmental and technology policies. We assume that there are two types of technology on an imperfectly competitive market: an old technology that is polluting and a new technology that is clean. Two different types firms can offer the technologies: the old technology is developed solely by an incumbent, whereas the new technology can be offered both by the incumbent and newcomers. Depending on the market conditions, the market structure for the new technology can be a Cournot competition with both newcomers and incumbent, a Cournot competition between newcomers, or a monopoly with only the incumbent or a single newcomer offering the new technology. In contrast to Bondarev et al. (2020), who focus on the r&d stage, we consider a small open economy setting in which the r&d decisions are exogenous.

In this setting, we consider two policy instruments: an emissions tax on the old technology and subsidies (possibly differentiated between incumbent and newcomers) for the clean technology. We consider, first, the option to simultaneously use as many of these instruments as are necessary and, second, a more restricted policy setting. Our results in the first setting show that the tax/subsidy scheme is different depending on whether the new technology is supplied by the incumbent, new entrants or both. Furthermore, our results highlight that depending on environmental damage and the state of the new technology (i.e., the phase of the technology transition), a social planner might want to use only the old technology (albeit at reduced consumption levels), switch fully to the new one, or do this switch in multiple steps.

Regarding the second setting, where we consider a less complex (and thus arguably a more realistic) policy setting, our results indicate that during a technology transition, it will often be best to switch between taxing the old and subsidising the new technology. Similar to the results of the first setting, a policy would often consist of an initial stage, where a tax on the old technology limits damages but does not induce a change towards the new technology, a second stage, where a subsidy is used to bring the new technology into the market, a third stage, where a tax is used to keep the old technology out of the market, and (possibly) a final stage, where a subsidy is used to enhance the diffusion of the new technology.

The remainder of this paper is structured as follows. We provide a brief literature review in Section 2. The model is presented in Section 3. Section 4 focuses on the welfare optimisation including the optimal productions (Section 4.1) and the welfare comparison (Section 4.2). We analyse the equilibrium quantities of old and new technologies in Section 5. In Section 6, we study the first best policies including the optimal instruments to implement the first-best levels of production of the old and new technologies (Section 6.1) and the fiscal implications (Section 6.2). Section 7 studies the optimal choice of policies in a more restrictive setting, where a first-best outcome is not attainable. Section 8 concludes the paper.

2 Literature review

The literature on optimal policies for a green technology transition encompasses two strands of literature: innovation and environmental economics. On the one hand, r&d market failures due to the public good nature of innovation is well known in the innovation literature and several studies have analysed various policy instruments to address these market failures, namely patents by granting intellectual property rights, licensing, r&d subsidies and the encouragement of cooperative r&d (see Lahiri and Ono, 1999, Toshimitsu, 2003 Kitahara and Matsumura, 2006 and Poyago-Theotoky, 2007). For instance, Lahiri and Ono (1999) have discussed whether the regulator should tax or subsidise r&d efforts. They find that the firm with initial cost advantage (i.e.; the efficient firm) requires subsidies while the inefficient firm should be taxed. Kitahara and Matsumura (2006) have extended the previous paper to include uncertainty related to r&d investments. While it is difficult to find optimal tax rules that equate efficient and equilibrium r&d levels in this setting, they derive an optimal policy based on simple subsidies which depend on the realised cost differences.

In the same vein, Toshimitsu (2003) explores how policies of r&d subsidisation affect social welfare depending on the market structure. They find that it is welfare improving to provide r&d subsidies to the firms producing the high-quality of product whether the competition is Bertrand or Cournot. This is not the case when the regulator provides r&d subsidies to the firm producing a low-quality product, which improves social welfare only in the case of Bertrand competition. Other factors may also influence the behaviour of incumbent and entrant during the innovation transition. In the broadband telecoms industry, Bourreau et al. (2012) find that the access price has a non-monotonic effect on incentives to invest in the new generation network as a result of a replacement effect, low opportunity cost of investment effect and a retail-level migration effect. All these studies have focused on a specific market structure and do not include the environmental externality that is the key element in green technology transitions.

The second strand of literature studies environmental policies with or without an implementation of r&d policy. Most studies of environmental policy mainly focus on market-based instruments to regulate emissions due to their static efficiency and the application of Pigouvian rule that ensures that the optimal price of pollution fully reflects the marginal social damage. However, the use of a Pigouvian tax for environmental regulations has been criticised, especially in imperfectly competitive markets (see Buchanan, 1969, Lee, 1975 and Barnett, 1980). A comprehensive discussion on optimal tax rules under imperfect competition can be found in Requate (2006).

Most of the studies that combines both technology and environmental policies have used a specific market structure, which may limit the applicability of their results. In a monopolistic setting, Krass et al. (2013) study the role of three environmental policy instruments (taxes, fixed cost subsidies and consumer rebates) in the transition to innovative and "green" emissions-reducing technologies. They find that environmental taxes initially favour the transition to a greener technology, while a reverse transition may happen for a further tax increases. In addition, they find that the optimal policy can be a combination of the three policy instruments as they play complementary roles. Carraro et al. (2013) also show that one environmental policy instruments is usually not sufficient to achieve optimal outcomes, similar to the analysis in Schneider and Goulder (1997), Fischer and Newell (2008) and Acemoglu et al. (2012).

Carraro et al. (2013) contains papers that focus on different aspects of the issue within an oligopoly and duopoly market structure. For instance, Katsoulacos and Xepapadeas (1996a) analyse whether emission taxes are optimal in oligopolistic markets with a fixed or endogenous number of firms. They find that for a fixed number of firms, the environmental tax is sub-optimal (i.e.; less than marginal external damages) similar to the monopoly case (see Barnett, 1980), while it could be optimal to internalise the excess of the external marginal damages for an endogenous market structure, where the second-best emission tax could exceed marginal external damages. Katsoulacos and Xepapadeas (1996b) analyse how taxes and subsidies could induce environmental innovation in a duopoly under r&d spillovers. They show that the optimal environmental tax is lower than the marginal external damage and it may be optimal to tax environmental innovation when spillovers are sufficiently small. For the case where the environmental innovation already exists, Carraro and Soubeyran (1996) explore the role of environmental policy in providing incentives for its adoption. Their results show that while both environmental policy instruments generate less pollution, it is possible that the innovation subsidy is socially better than environmental taxes.

While all these studies have analysed optimal policies for the green transition, they do not focus on the interactions between the incumbent that has the incentive to protect the old technology and the new entrant that has incentive to invest in the new technology. This may result in different market configuration with different optimal policies.

As an alternative to an emissions tax, Denicolo (1999) studies pollution permits and compares the performance of two policies instruments in the green technology transition. He finds that the two instruments are fully equivalent if the regulator can easily adjust the levels of the instruments after the innovation stage. In case the regulator can pre-commit, taxes favour environmental innovation more than pollution permits. Furthermore, taxes provide more social welfare than permits, if the social damage is not too high. Whether the regulator should tax r&d efforts may also depend on the level of emissions tax and the level of environmental damages. Petrakis and Poyago-Theotoky (2002) find that it can be optimal to tax r&d efforts when environmental damages are large and the emissions tax is low. In this case, the regulator faces both r&d market failures and a pollution problem and she would implement a r&d tax to avoid over-production. Furthermore, they find that, in terms of social welfare, a policy that provides r&d subsidies is more likely to be better than a policy that supports r&d cooperation. However, r&d cooperation may be socially more desirable than non-cooperative r&d.

Poyago-Theotoky (2007) show that when firms cooperate, their environmental innovation efforts are more important than when they do not cooperate, except for the case of relatively large environmental damages and efficient innovation where the opposite is true. They also find the same ranking in terms of social welfare.

Overall, all these contributions on green technology transition confine attention to finding adequate policy instruments in a specific market structure and avoid the interactions between the incumbent and the new entrant on the technology market. To the best of our knowledge, there is no specific study that explores in details the interrelations between market structure, r&d policy and environmental policy.

3 The model

In order to explore the optimal instruments for a transition from a polluting technology to a clean technology, we build our model on the framework developed by Bondarev et al. (2020). We assume that there are two types of technology on an imperfectly competitive market. One of the technologies is the old technology, which is polluting like petrol-/diesel-based cars or coal/fossil fuels power, and the other technology is a new, clean technology, like electrical vehicles or renewable energies.

On the supply side, we consider two different types of firms that can supply the technologies. The old technology is fully mature and sold only by a single incumbent. The new technology can be developed and sold by both the incumbent and the new entrants. Depending on the market conditions, the market structure can be a Cournot competition with both entrants and incumbent supplying the new technology, a Cournot competition among entrants, or a monopoly with only one firm providing the new technology. The incumbent and the entrants differ in two ways. First, only the incumbent can produce the old technology, while both type of firms can produce the new, clean one. Second, we assume that the incumbent has a cost advantage in the production of the new technology, benefiting from lower marginal production costs.

On the demand side, there is a continuum of heterogeneous consumers who decide on the technology to buy depending on both the quality of the technologies and their prices. As the new technology can still be developed, we assume that this development increases its quality, possibly up to a level, where it drives the old technology out of the market without any policy intervention. This point marks the end of the technology transition, whereas the beginning is the case where the new technology has so low quality that it cannot attract any consumer, even if it is offered at marginal costs. We take the quality of the new technology (often also referred to as the level of innovation) as the sole indicator of the progress of the technology transition; when we refer to early phases, this implies a low quality of the new technology, whereas later stages of the transition are synonymous with a quality of the new technology that almost equals that of the mature old technology.

3.1 Pollution Damage and Policy Instruments

We assume that the old technology is a polluting technology (for instance technology based on fossil fuel). Therefore, we introduce a damage function $Dam(q_l)$ that depends on the production of the old technology q_l. $Dam(q_l)$ is defined as:

$$Dam(q_l) = \frac{d}{2} q_l^a,$$

where d and a are positive and constant parameters. For simplicity, we assume a linear damage (i.e., $a = 1$) such that the marginal damage is given by $Dam' = d/2$.

The policy framework focuses on two types of instruments: A tax and subsidies. We consider that the pollution is a by-product of the production technology so that taxing the amount of a polluting technology production is equivalent to an environmental tax. Due to the pollutant content of the old technology, we assume that a tax τ is paid by the incumbent on each unit of old technology q_l. Note that we do not make any specific assumptions on τ. A positive value would mean that the incumbent pays an environmental tax following the polluter-pays principle. Depending on the market structure, τ can be negative, which means that the incumbent is subsided for producing the old technology. Furthermore, we consider a subsidy as a second instrument that can motivate firms to produce the green technology. Depending on the market structure, the subsidies on the new technology production provided by the regulator to the incumbent or to the new entrant can be different. We assume that s_i and s_n are the subsidy on each amount of new technology production for the incumbent (q_{si}) and the new entrants q_{sn}, respectively.

3.2 Demand

Following Bondarev et al. (2020), we assume that there is a continuum of consumers (i) with different utilities from buying the clean technology ($u_s(i)$) and the dirty technology($u_l(i)$) at each period t.[1] The utility for buying the old technology is given by:

$$u_l(i) = 1 - i - p_{l,t}, \tag{1}$$

where the quality of the old technology is constant and set to 1, and its price in period t is given by $p_{l,t}$.

The same type of consumer has the following utility from buying the new technology:

$$u_s(i) = k_t - \alpha\, i - p_{s,t}, \tag{2}$$

where k_t is the quality of the new technology at time t, its price in period t is given by $p_{s,t}$ and the new technology can expand overall demand, as we assume $0 < \alpha < 1$. We refer to this as a market expansion effect; the new technology cannot only win customers over from the old one but also attract people who would not buy the old technology. In our model, each consumer decides to buy the type of technologies that provides a strictly higher utility, as long as this utility is strictly positive (if the best choice leads to a negative utility, the consumer does not buy the technology at all).

[1] The dynamics of our model rely on how the accumulation of technology from previous periods affects the current level of innovation.

3.3 Supply

3.3.1 Incumbent

The incumbent offers a quantity $q_{l,t}$ of the old technology and $q_{si,t}$ of the new technology at each period t. We assume that the production of both technologies generates the same constant marginal cost c_i. The total profit of the incumbent with the economic instruments is given by:

$$\pi_{l,t} = (p_{l,t} - c_i)q_{l,t} + (p_{s,t} - c_i)q_{si,t} - \tau q_{l,t} + s_i q_{si,t}. \tag{3}$$

Without loss of generality, we set $c_i = 0$.

3.3.2 New entrants

A new entrant n has only access to the new technology market and offers a quantity $q_{sn,t}$ at a constant marginal cost $c \geq c_i$. With the implementation of the environmental taxes and the subsidy for the clean innovation, the profit of the entrant in period t is given by:

$$\pi_{n,t} = (p_{s,t} - c)q_{sn,t} + s_n q_{sn,t} \tag{4}$$

3.4 Set of market structures

The set of the market structures possibilities is composed of seven types of markets ranging from Case 0 to Case 6. In the Case 0, there is no new technology available in the market, therefore, the incumbent supplies only the old technology. From Case 1 to Case 3, the old technology is still supplied by the incumbent. Depending on the case, both types of firms (Case 1) or either incumbent (Case 3) or new entrant (Case 2) supply the new technology. Case 4 to Case 6 refer to the market structures in which the old technology is completely phased out. In this context, the new technology is supplied by both types of firms (Case 4) or by either the incumbent (Case 5) or new entrants(Case 6).

4 Welfare Optimisation

Using the model, we first focus on the welfare maximisation problem in order to analyse the optimal production of the old and new technologies. Then, we conduct a welfare comparison to explore the socially desirable market structure.

4.1 Optimal production of the old and new technologies

We first derive the following general demand functions for the old and the new technologies from equations (1) and (2) for a given and fixed number of n entrants:

$$p_{s,t} = k_{t-1} + \delta_{i,t} - \alpha\,[q_{l,t} + n\,q_{sn,t} + q_{si,t}] \tag{5}$$

and

$$p_{l,t} = 1 - q_{l,t} - \alpha\,[n\,q_{sn,t} + q_{si,t})] \tag{6}$$

We define welfare W as the sum of the consumer surplus and the producer surplus minus the damage from using the old technology. We first analyse case 1 as the "general" case in which new entrants and incumbent supply the new technology, while the old technology is still produced. From this case, we compute the FOCs of the welfare for the other cases with corresponding conditions.

The social planner solves the following welfare maximisation problem:

$$\begin{aligned}
\max_{q_l, q_{si}, q_{sn}} \; W_1(q_l, q_{si}, q_{sn}) = & \int_{x_{s,l}}^{x_{s,0}} (k_0 + \delta_i - \alpha x)\,\mathrm{d}x + \int_0^{x_{s,l}} (1-x)\,\mathrm{d}x - n\,(c - \delta_n + \delta_i) q_{sn} - Dam(q_l) \\
st \quad x_{s,0} = & \frac{k_0 - p_s - \alpha x + \delta_i}{\alpha} \\
x_{s,l} = & \frac{-1 + k_0 + p_l - p_s + \delta_i}{\alpha - 1} \\
& Eqs.(5) \; and \; (6)
\end{aligned} \tag{7}$$

As we have $c \geq c_i = 0$, the social planner will always prefer to have only the incumbent supplying the new technology, except for cases, where the incumbent only supplies the old technology. Furthermore, due to constant returns to scale, the social planner is indifferent with regard to the number of entrants. Thus, we set $n = 1$ for most of our analysis, apart from Section 7, where the social planner does not have sufficient instruments at hand to induce the socially best outcome.

The above program can be rewritten as:

$$\max_{q_l, q_{si}, q_{sn}} W_1 = \frac{(2 - d - q_{l,t}) q_{l,t} + [2(k_{t-1} + \delta_{i,t}) - \alpha(2q_{l,t} + q_{si,t} + q_{sn,t})](q_{si,t} + q_{sn,t}) - 2(c + \delta_{i,t} - \delta_{n,t}) q_{sn,t}}{2} \tag{8}$$

Solving the above program with the relevant conditions depending on the cases gives the following proposition.

Proposition 1. *When the environmental damage from using the old technology is considered,*

1- *The optimal quantities of the old technologies and the new technologies produced; and the optimal welfare are the following:*

(a) *If only the old technology is available, then,*

$q^*_{l,t,0} = 1 - d/2$; $q^*_{sn,t,0} = q^*_{si,t,0} = 0$ *and* $W^*_{0,t} = \frac{1}{8}(d-2)^2$

(b) *If both new technology and old technology is produced, then for* $j = 1:3$,

- $q^*_{l,t,j} = \frac{1}{1-\alpha}[-\delta_{i,t} + (1-d/2) - k_{t-1}]$, *where* $\delta_{i,t} = \delta_{n,t} - c$, *if only the entrant produces the new technology.*

- $q^*_{sn,t,j} = \frac{1}{\alpha(1-\alpha)}[\delta_{n,t} - c - \alpha(1-d/2) + k_{t-1}]$, *if only the entrant produces the new technology, and* $q^*_{sn,t,j} = 0$, *otherwise,*

- $q^*_{si,t,j} = 0$ *if only the entrant produces the new technology, and* $q^*_{si,t,j} = \frac{1}{\alpha(1-\alpha)}[\delta_{i,t} - \alpha(1-d/2) + k_{t-1}]$, *otherwise.*

- $W^*_{j,t} = \frac{4\delta_{i,t}[-2c+\alpha(d-2)+2k_{t-1}]+8\delta_{n,t}(c+\delta_{i,t})-4\delta^2_{n,t}+\alpha(d-2)(d+4k_{t-1}-2)-4c^2+4k^2_{t-1}}{8(1-\alpha)\alpha}$.

(c) *If the old technology is phased out, then for* $j = 4:6$,

- $q^*_{l,t,j} = 0$;

- $q^*_{sn,t,j} = \frac{1}{\alpha}[\delta_{n,t} - c + k_{t-1}]$, *if only the entrant produces the new technology, and* $q^*_{sn,t,j} = 0$, *otherwise;*

- $q^*_{si,t,j} = 0$ *if only the entrant produces the new technology, and* $q^*_{si,t,j} = \frac{1}{\alpha}[\delta_{i,t} + k_{t-1}]$, *otherwise;*

- $W^*_{j,t} = \frac{(k_0+\delta_i)^2}{2\alpha}$, *where* $\delta_{i,t} = \delta_{n,t} - c$, *if only the entrant produces the new technology.*

2- *The optimal welfare is decreasing in the level of damage and increasing in the level of innovation.*

Proof. The optimal quantities of the old technology and the new technology (i.e., the first part of Prop.1) is obtained by solving the program in Eq .(8) with relevant conditions $q_{l,t} = 0$, $q_{sn,t} = 0$, or $q_{si,t} = 0$ depending on the market structure. These optimal quantities are used to compute the optimal social welfare. More details are provided in Appendix A in which Table 3 summarises the results. As we assume that the cost of producing the new technology by the new entrant is higher than that of the incumbent, whenever the two firms supply the new technology, the social planner will optimally prefer the incumbent to produce the new technology. This translates into the following optimal condition $\delta_{i,t} = \delta_{n,t} - c$. The second part of the Prop.1 comes from a negative derivative of the optimal welfare with respect to the level of damage and a positive derivative with respect to the level of innovation. Thus, the higher is the damage, the lower is the optimal welfare, whereas a higher innovation induces a higher optimal welfare. Note that this is only true under the conditions that define the existence of each cases. □

Three levels of interpretation can be provided for Prop.1. First, the level of damage and the level of innovation have positive and negative effects on the optimal production of the new technology and that of the old technology, respectively. Thus, the phase-out of the old technology is motived by its high environmental damage and/or a high innovation. Second, the different market structure simplifies to three groups leading to the same welfare for all market structures within the same group. Whenever a group of market structure is socially desirable, the social planner would then be indifferent regarding which one to choose within that group. Finally, from the second part of Prop.1, the environmental damage and the innovation compensates each other in term of welfare. Therefore, whether one group of market structures is more socially desirable than the other depends on if the level of damage or the level of innovation is high enough.

4.2 Welfare comparison

The different cases following the market structure give different social welfare, which depends on the level of damage, the level of innovation of both the incumbent and the new entrant and other cost and demand parameters. Moreover, under the condition $\delta_n = \delta_i + c$, the welfares from Case 1 to Case 3 are equivalent and the welfares from Case 4 to Case 6 also equivalent. Therefore, the welfare comparison will be analysed across three groups of cases: (i) Only old technology (Case 0), (ii) Old and new technologies (Cases 1-3) and (iii) Only new technology (Cases 4-6).

We use the group (iii) as a reference market structure. We are interested in under which conditions on the damage and level of innovation, the social planner should favour a transition from groups (i)-(ii) to that reference market structure. We also analyse the transition from group (ii) to group (ii) as an intermediary to the full transition to group (iii). We claim the following proposition.

Proposition 2. *In term of welfare comparison,*

1- *The social planner would prefer to switch from producing only the old technology to producing only the new technology whenever the following condition holds:* $\alpha d(d-4) < 4[(\delta_{i,t} + k_{t-1})^2 - \alpha]$. *This translates into the following range on damages and level of innovation:*

   (a) *If* $(\delta_{i,t} + k_{t-1})^2 < \alpha$, *then* $1 - \frac{1}{\sqrt{\alpha}}(\delta_{i,t} + k_{t-1}) < \frac{d}{2} < 1 + \frac{1}{\sqrt{\alpha}}(\delta_{i,t} + k_{t-1})$

   (b) *If* $(\delta_{i,t} + k_{t-1})^2 > \alpha$, *then* $\delta_{i,t} > (\frac{d}{2} - 1)\sqrt{\alpha} - k_{t-1}$.

2- *The transition from the production of both old and new technologies to the production of only the new technology is characterised by the following:*

   (a) *The social planner would prefer to produce both technologies whenever the innovation is not sufficient.*

   (b) *When the innovation is sufficient (i.e.,* $\delta_{i,t} > 1 - d/2 - k_{t-1}$*), the social planner would switch to the sole use of the new technology.*

3- *For an intermediary situation, the social planner may decide first to switch from producing only the old technology to producing both technologies. This situation is characterised by the following:*

   (a) *When the innovation is not sufficient with* $\delta_{i,t} < -\alpha(d/2 - 1) - k_{t-1}$, *the social planner will accept small environmental damages and rely only on the old technology.*

(b) *For sufficient innovation, i.e.,* $1 - (\delta_{i,t} + k_{t-1})/\alpha < d/2 < 1 - \delta_{i,t} - k_{t-1} < 1$, *it is welfare improving to switch to the production of both technologies.*

Proof. For Part 1 of proposition 2, we compare the optimal social welfare that we obtained in the Section 4.1 for the case 0 (i.e., $W^*_{0,t}$) and cases 4-6 (i.e., $W^*_{j,t}$, with $j = 4, 5, 6$). This gives the first inequality. Depending on how large is the accumulated level of innovation (i.e., $\delta_{i,t} + k_{t-1}$) to cover the market share α, the range of the marginal damage $d/2$ is different. This gives the range of the damages and the level of innovation. In Part 2 of the proposition, the decision of the social planner to switch from producing both new and old technologies to producing only the new technology depends on the welfare difference. We then compare the optimal social welfare $W^*_{j,t}$ with $j = 1, 2, 3$ in the group of cases (ii) to the optimal social welfare $W^*_{j,t}$ with $j = 4, 5, 6$ in the group of cases (iii). We find that the minimum of the welfare from group (ii) is equivalent to the welfare of the group (iii). The social planner would then prefer to produce both technologies whenever the damage is low or the innovation is not sufficient. The reverse happens when the innovation is sufficient or the damage is sufficiently high (i.e., $d/2 > 1 - \delta_{i,t} - k_{t-1}$). The proof of part 3- of the proposition is similar to the previous one. We compare the optimal welfares in Case 0 and group (ii). We find that the social planner would be indifferent when $d/2 = 1 - (\delta_{i,t} + k_{t-1})/\alpha$. □

Part 1 of Proposition 2 shows that, for a small accumulated level of innovation, the social planner would prefer to produce only the old technology for small damages. In contrary, when the market has accumulated enough innovation compared to the market share, the transition to only the new technology is welfare improving even for small damages. Furthermore, this arbitrage needs to match with the conditions that define the cases of only new technology production. Here, we focus on the case 5 as the most relevant case for the social planner due to the cost advantage of the incumbent. This condition dictates that $d/2 > 1 - (k_{t-1} + \delta_i)$. Given that $1 - \frac{1}{\sqrt{\alpha}}(\delta_i + k_{t-1}) < 1 - (k_{t-1} + \delta_i) < 1 + \frac{1}{\sqrt{\alpha}}(\delta_i + k_{t-1})$, the social planner would prefer the situation with only the production of the new technology (namely with only the incumbent), which can be implemented under the following condition: $1-(k_{t-1}+\delta_{i,t}) < \frac{d}{2} < 1+\frac{1}{\sqrt{\alpha}}(\delta_{i,t}+k_{t-1})$. The above condition highlights different configurations regarding whether case 0 is already rolled out by the market existence condition or should be rolled out by the social planner. More precisely, for $d/2 \in [1-(k_{t-1}+\delta_{i,t}), 1]$, case 0 can still be implemented but the social planner would need to force the implementation of cases with only the new technology that give a higher welfare. The first part of the proposition then highlights three main drivers of the green technology transition: accumulated innovation, market share for the new technology and the level of damages.

Part 2 of Proposition 2 shows that with small damages, the social planner would prefer to keep some amount of the old technologies in the market. The level of innovation would be sufficient to compensate the small damages. If the damages are large, the social cost of producing the old technology is so high such that it becomes welfare improving to rely only on the new technology. Note that the high damage translates into the impossibility of the economy to compensate the marginal damage ($i.e., d/2$) with the remaining capacity for the innovation accumulation of the new technology ($1-\delta_{i,t}-k_{t-1}$). The second part of the proposition reflects two main drivers: the level of innovation and the level of damages. Note that the market share does not play an important role in this case as the economy already has the two technologies.

As an intermediary situation, the social planner may decide a gradual transition to the production of only the new technology. In this case, the economy will first switch from producing only the old technology to producing both technologies before a full switch to only producing the new technology. This temporary transition will basically depend on the level of the damage.

Overall, the analysis so far indicates that, at the start of a transition (low quality of the green technology), high environmental damages are the main driver of the transition. Later on, when the green technology is more mature, environmental damages do not play the

Table 1: *Equilibrium Price and Quantity*

Cases	Quantities			Prices	
	q_l	q_{si}	q_{sn}	p_l	p_s
Case 0	$\frac{1-\tau}{2}$	0	0	$\frac{1+\tau}{2}$	0
Case 1	$\frac{1}{2(1-\alpha)}[(1-\tau) -(\delta_{i,t}+s_i)-k_{t-1}]$	$\frac{1}{6\alpha(1-\alpha)}[(4-\alpha)(\delta_{i,t}+s_i) -2(1-\alpha)(\delta_{n,t}+s_n) -3\alpha(1-\tau)+2(1-\alpha)c +(\alpha+2)k_{t-1}]$	$\frac{1}{3\alpha}[2(s_n+\delta_{n,t}) -(s_i+\delta_{i,t}) -2c+k_{t-1}]$	$\frac{1}{6}(2c+\delta_{i,t} -2\delta_{n,t}-k_{t-1}+3 +s_i-2s_n+3\tau)$	$\frac{1}{3}(c+2\delta_{i,t} -\delta_{n,t}+k_{t-1} -s_i-s_n)$
Case 2	$\frac{1}{4-\alpha}[-(s_n+\delta_{n,t}) +2(1-\tau)+c-k_{t-1}]$	0	$\frac{1}{\alpha(4-\alpha)}[2(s_n+\delta_{n,t}) -\alpha(1-\tau) -2(c-k_{t-1})]$	$\frac{1}{4-\alpha}[c-\delta_{n,t} -k_{t-1}-s_n +(2-\alpha)\tau+2]$	$\frac{1}{4-\alpha}[-\alpha+(2-\alpha)c+2\delta_{n,t} +2k_{t-1}+\alpha\tau-(2-\alpha)s_n]$
Case 3	$\frac{1}{2(1-\alpha)}[-(\delta_{i,t}+s_i) +(1-\tau)-k_{t-1}]$	$\frac{1}{2\alpha(1-\alpha)}[(\delta_{i,t}+s_i) -\alpha(1-\tau)+k_{t-1}]$	0	$\frac{1}{2}(\delta_{i,t}+k_{t-1}-s_i)$	$\frac{\tau+1}{2}$
Case 4	0	$\frac{1}{3\alpha}[2(s_i+\delta_{i,t})-(s_n+\delta_{n,t}) +c+k_{t-1}]$	$\frac{1}{3\alpha}[2(s_n+\delta_{n,t}) -(s_i+\delta_{i,t}) -2c+k_{t-1}]$	0	$\frac{1}{3}(c+2\delta_{i,t}-\delta_{n,t} +k_{t-1}-s_i-s_n)$
Case 5	0	$\frac{\delta_{i,t}+s_{i,t}+k_{t-1}}{2\alpha}$	0	0	$\frac{1}{2}(\delta_{i,t} +k_{t-1}-s_i)$
Case 6	0	0	$\frac{s_n+\delta_{n,t}-c+k_{t-1}}{2\alpha}$	0	$\frac{1}{2}(c+\delta_{n,t} +k_{t-1}-s_n)$

only important role anymore, rather the economic benefits (e.g., the market expansion) also become a main driver of the transition. Furthermore, there is not a single best outcome in terms of market structure throughout the transition, rather the answer to the question which market structure is socially desirable depends strongly on the situation (size of the market expansion effect, marginal damages) and the stage of the technology transition (accumulated level of innovation/quality of the new technology).

5 Equilibrium of the old and new technologies production

To analyse the optimal policy instruments, we start by analysing the equilibrium of the production of the old and new technologies. By applying the corresponding conditions for the quantities, we get the specific demand functions for each market structure. We then solve the corresponding profit-maximisation problem of a Cournot or monopoly game by providing equilibrium quantities and prices using Eqs (3), (4), (5) and (6). The results are summarised in Table 1.

In Case 0, a higher tax on the old technology will increase the price of the old technology which will decrease the amount of old technology production from the incumbent. This is also the case in Case 1 where both firms receive subsidy. A higher subsidy on the new technology will reduce the equilibrium price of the new technology, will motivate more demand for the new technology and thus, firms that receive the subsidy will produce more. However, due to the interactions between the two firms, a higher subsidy to one firm will reduce the quantity of the new technology supplied by the other firm. Also, the tax on the old technology increases the amount of the new technology supplied by the incumbent, whereas the subsidy on the new technology reduces the supply of the old technology.

In Case 2, a higher environmental tax will reduce the production of the old technology as well, which will favour the production of the new technology from the new entrant. The tax will also increase the equilibrium price of the new and the old technology. Furthermore, the subsidy on the new technology has the same effects on the quantity of new and old technology in term of the sign but are different in term of the size. The subsidy decreases the equilibrium prices of the new and old technologies.

In Case 3, the environmental tax and subsidies have opposite effects on corresponding quantities of the technology production whereas the environmental tax increases the price of the old technology and the subsidy reduces the price of the new technology as in Case 1. The results of Case 4 are similar to those of the Case 1, excepts for the amount of new technology supplied by the incumbent. More specifically, the effect of the subsidy is reduced as the incumbent does no longer benefit from the supply reduction of the old technology. A similar pattern is observed from Case 5 compared to Case 3. Finally, in Case 6 and compared to Case 2, the new entrant benefits from a lower effect of the subsidy on the quantity produced and a higher effect on the price. This is because the indirect effect of the subsidy on the price of the new technology through the reduction of the old technology production does no longer exist in this case.

The above results can be summarised in the following proposition:

Proposition 3. *When both environmental tax on the old technology and different subsidies for the incumbent and the new entrant on the new technologies are implemented, at the equilibrium:*

1- The environmental tax reduces the equilibrium quantity of the old technology

2- The subsidy for the new technology increases the equilibrium quantity of the new technology produced by the firm that receives the subsidy.

3- The subsidy for the new technology reduces the amount of the old technology while

(a) The environmental tax increases only the equilibrium quantity of the new technology produced by the incumbent with no effect on the quantity of the new entrant, if both firms share the new technology market;

(b) The environmental tax increases the equilibrium quantity of the new technology produced by both the incumbent and the new entrant, if the new technology market is not shared between the two firms.

6 First best policies

6.1 Optimal instruments

In this section, we focus on the optimal instruments to implement the first-best production levels of the new and the old technology. We derive the value of the tax on the old technology (τ) and the subsidies provided to support the production of the new technology (s_i and s_n) that ensure that the productions in the equilibrium situation (Section 5) are equal to the ones of the welfare maximisation problem (Section 4). Furthermore, we compute the existence conditions for each case. These conditions are non-negativity constraints on quantities and

Table 2: *Optimal instruments*

Cases	Optimal instruments			Existence Conditions
	τ^*	s_i^*	s_n^*	
Case 0	$d-1$	0	0	$d/2 < 1-(\delta_{i,t}+k_{t-1})/\alpha$
Case 1	$d-1$	$\delta_{i,t}+k_{t-1}$	$\delta_{i,t}-\delta_{n,t}+c$	For $0 < d < 2(1-k_{t-1}) \leq 2$ such that $\delta_{i,t} > 0$, $\alpha(1-\frac{d}{2})-k_{t-1} < \delta_{i,t} < (1-\frac{d}{2})-k_{t-1}$
Case 2	$\frac{1}{1-\alpha}[-c+d(1-\alpha/2)$ $+(-1+k_{t-1}+\delta_{n,t})]$	0	$\frac{1}{1-\alpha}[-c+\alpha(-1+d/2)$ $+k_{t-1}+\delta_{n,t}]$	For $0 < d < 2(1-\frac{k_{t-1}}{\alpha}) < 2$, such that $\delta_{i,t} > 0$, $\delta_{i.t} < \alpha(1-\frac{d}{2})-k_{t-1}$ and $c-k_{t-1}+\alpha(1-\frac{d}{2}) < \delta_{n,t} < c-k_{t-1}+(1-\frac{d}{2})$
Case 3	$d-1$	$\delta_{i,t}+k_{t-1}$	$\delta_{i,t}-\delta_{n,t}+c$	For $0 < d < 2(1-k_{t-1}) \leq 2$ such that $\delta_{i,t} > 0$, $\alpha(1-\frac{d}{2})-k_{t-1} < \delta_{i,t} < (1-\frac{d}{2})-k_{t-1}$
Case 4	0	$2(\delta_{n,t}-c)+k_{t-1}-\delta_i$	0	$\delta_{i,t}-2(\delta_{n,t}-c) > k_{t-1}+(1-\frac{d}{2})$
Case 5	0	$k_{t-1}+\delta_{i,t}$	0	$\delta_{i,t}+k_{t-1} > 1-\frac{d}{2}$
Case 6	0	0	$c+k_{t-1}+\delta_{n,t}$	If $d < 2$, $\delta_{n,t}-c+k_{t-1} > 1-\frac{d}{2}$ If $d > 2$, $\delta_{n,t}-c+k_{t-1} > 0$

prices (i.e.; $q_{l,t} \geq 0$, $q_{si,t} \geq 0$, $q_{sn,t} \geq 0$, $p_l \geq 0$ and $p_s \geq 0$). In addition, whenever this is relevant, we also consider the condition to avoid copycats for the new technology developed by the incumbent or the new entrant following the condition $\delta_{i,t}+c-p_s \geq 0$ and $\delta_{n,t}-p_s \geq 0$. The results are summarised in Table 2.

The results show that, first, the tax and subsidy scheme is sufficient to internalise the damage from using the old technology (i.e.; price is equal to marginal damage) and to set the price of the new technology to be equal to the lower marginal production cost of the new technology. Second, a high damage would require a high tax in order to implement the first best solution in equilibrium. Third, given that the existence condition of each market structure is different as well as the optimal instruments for some cases, the type of instruments (tax or subsidy) is also different.

More precisely, in Case 0 and for low damage (or insufficient innovation), i.e., $d/2 < 1/2 < 1-(\delta_{i,t}+k_{t-1})/\alpha$, the social planner would need to provide a subsidy for the production of the old technology. On the contrary, a tax would be required when the damage is high (or the innovation is sufficient) and is in the range of $1/2 < d/2 < 1-(\delta_{i,t}+k_{t-1})/\alpha$. Case 1 is not optimal, if the damage is sufficiently high (or the innovation is sufficiently accumulated). In Case 1, the social planner should tax the old technology if $1 < d < 2(1-k_{t-1})$, otherwise (i.e., $d < 1$) she should provide subsidy on the old technology to the incumbent. For the new technology, she should provide a subsidy to the incumbent and no subsidy to the new entrant.

Case 2 is a bit different from the previous cases as the incumbent does no longer compensate the loss of profit by replacing the production of the old technology with that of the new technology. Whenever the new entrant has motivation to produce the new technology, this reduces the optimal production of the old technology from the incumbent. Consequently, a higher innovation by the new entrant will reduce the level of production of the old technology and will then increase the optimal tax on the old technology. In addition, the level of damage positively effects the optimal subsidy as this increases the optimal production of the new technology. The social planner decision is as follows: A tax on the old technology should be implemented if $\delta_{n,t} > 1 + c - k_{t-1} - (1 - \frac{\alpha}{2})d$, otherwise a subsidy should be provided to the incumbent. For the new technology, the social planner should always provide subsidy to the new entrant.

The tax and subsidy scheme in Case 3 is the same as the one in Case 1, as at the optimum, it is preferable for the social planner to let only the incumbent produce the new technology due to its cost advantage. In Case 4, for low levels of damage (i.e., $d < 2$), providing a positive subsidy to the incumbent is not feasible, whereas a negative subsidy to the incumbent is feasible, if $\delta_{i,t} - 2\delta_{n,t} > -2c + k_{t-1}$. For high levels of damage (i.e., $d > 2$), the social planner should provide a positive subsidy to the incumbent when $-2c + k_{t-1} + (1 - \frac{d}{2}) < \delta_{i,t} - 2\delta_{n,t} < -2c + k_{t-1}$, or a negative subsidy to the incumbent when $\delta_{i,t} - 2\delta_{n,t} > -2c + k_{t-1} + (1 - \frac{d}{2})$.

Case 5 is similar to Case 1 in term of the new technology as here, the old technology is phased out. The implementation of the optimal production of the new technology would require a positive subsidy to the incumbent. Therefore, the only condition that is relevant is the condition under which the case 5 exists. For Case 6, given the existence condition, it is never feasible to implement a negative subsidy to the new entrant. The social planner will always provide a positive subsidy to the new entrant.

Overall, the analysis first shows that the optimal tax has often the same value (internalising the damage in monopoly of the old technology), whereas the level of subsidy reflects the accumulated level of innovation and thus the stage of the transition. The exception is when only the new entrant supplies the new technology such that the incumbent is losing part of the market that she cannot compensate with the new technology market. In this case, the optimal tax depends not only on damages but also on the stage of the technology transition. Second, in terms of environmental tax, the analysis shows that low damages require a subsidy (i.e., negative environmental tax). An environmental tax is needed for high damages. The exception is when the entrant only supplies the new technology. In this case, for low damages, a subsidy is required only if the level of innovation of the entrant is low. Third, in terms of innovation subsidy, the analysis shows that a subsidy should be provided to the firm that supplies the new technology. The exception is when the two firms share the new technology market, and the old technology is phased out. In this case, a negative subsidy is required for the incumbent when the incumbent's innovation is high.

The above analysis can be summarised in the following propositions.

Proposition 4. *The optimal instruments that are required to implement the first best solution satisfy the followings:*

1- As long as the incumbent supplies only the old technology or the new technology,

(a) the optimal level of tax on the old technology is $\tau^* = d - 1$

(b) and the optimal level of subsidy is $s_i^* = k_{t-1} + \delta_{i,t}$

2- When the new entrant only supplies the new technology,

(a) the optimal level of tax on the old technology is given by $\tau^* = \frac{-c+d(1-\alpha/2)+(-1+k_{t-1}+\delta_{n,t})}{1-\alpha}$

(b) and the optimal level of subsidy is given by

$s_n^* = \frac{-c+\alpha(-1+d/2)+k_{t-1}+\delta_{n,t}}{1-\alpha}$

Proposition 5. *Given the conditions that characterise the existence of each of the market structure, the full set of decisions for the social planner is described as follows:*

1- When the old technology is available and the incumbent supplies the new technology, low damages require a subsidy whereas a tax is needed for high damages.

2- When the old technology is available and only the entrant supplies the new technology, a tax is needed for high damages. For low damages, a subsidy is required only if the level of innovation of the entrant is sufficiently low, i.e., $\delta_{n,t} < c - d(1-\alpha/2) + (1-k_{t-1})$. *Otherwise, a tax would be required.*

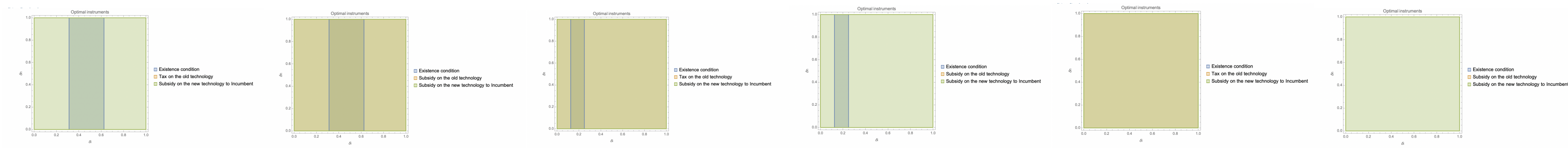
3- When the new technology is available (and except for the case in which the two firms share the market of the new technology and the old technology is phased out), a subsidy should be provided to the firm supplying this technology.

4- When the two firms share the market of the new technology and the old technology is phased out,

(a) for low damages, a subsidy to the incumbent is not feasible, whereas a negative subsidy to the incumbent is feasible when $\delta_{i,t} - 2\delta_{n,t} > -2c + k_{t-1}$.

(b) for high level of damage, a positive subsidy to the incumbent is required when $-2c + k_{t-1} + (1 - \frac{d}{2}) < \delta_{i,t} - 2\delta_{n,t} < -2c + k_{t-1}$, *or a negative subsidy to the incumbent when* $\delta_{i,t} - 2\delta_{n,t} > -2c + k_{t-1} + (1 - \frac{d}{2})$.

For illustration purposes, we provide graphs in Fig 1-6 for different levels of damage to show the different decisions regarding the optimal instruments. The first three figures concern the cases when the old technology is still produced whereas the remaining three cases focus on the phase-out of the old technology.



(b) $t > 0$ *and* $s_i > 0$ **(c)** $t < 0$ *and* $s_i > 0$

(c) *d=0.75*

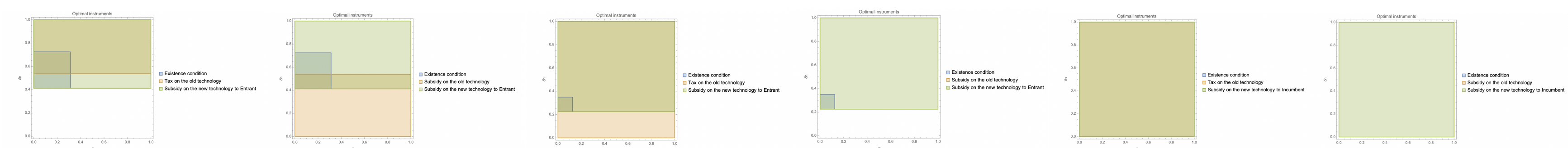
(e) $t > 0$ *and* $s_i > 0$ **(f)** $t < 0$ *and* $s_i > 0$

(f) *d=1.5*

(h) $t > 0$ *and* $s_i > 0$ **(i)** $t < 0$ *and* $s_i > 0$

(i) *d=10*

Figure 1: *Illustration of case 1 for different scenarios with respect to the values of the damage.*



(b) $t > 0$ *and* $s_n > 0$ **(c)** $t < 0$ *and* $s_n > 0$

(c) *d=0.75*

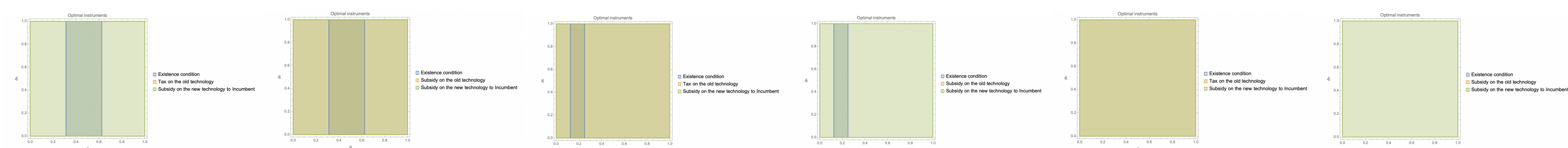
(e) $t > 0$ *and* $s_n > 0$ **(f)** $t < 0$ *and* $s_n > 0$

(f) *d=1.5*

(h) $t > 0$ *and* $s_n > 0$ **(i)** $t < 0$ *and* $s_n > 0$

(i) *d=10*

Figure 2: *Illustration of case 2 for different scenarios with respect to the values of the damage.*



(b) $t > 0$ *and* $s_i > 0$ **(c)** $t < 0$ *and* $s_i > 0$

(c) *d=0.75*

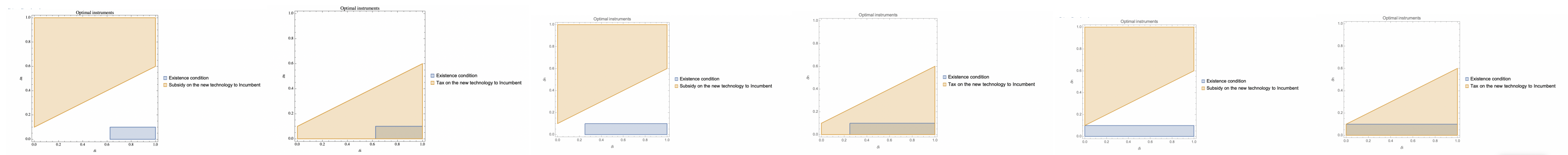
(e) $t > 0$ *and* $s_i > 0$ **(f)** $t < 0$ *and* $s_i > 0$

(f) *d=1.5*

(h) $t > 0$ *and* $s_i > 0$ **(i)** $t < 0$ *and* $s_i > 0$

(i) *d=10*

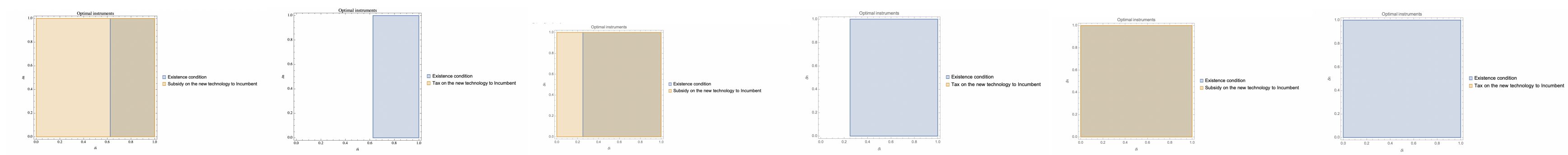
Figure 3: *Illustration of case 3 for different scenarios with respect to the values of the damage.*



(b) $s_i > 0$ **(c)** $s_i < 0$ **(e)** $s_i > 0$ **(f)** $s_i < 0$ **(h)** $s_i > 0$ **(i)** $s_i < 0$

(c) *d=0.75* **(f)** *d=1.5* **(i)** *d=10*

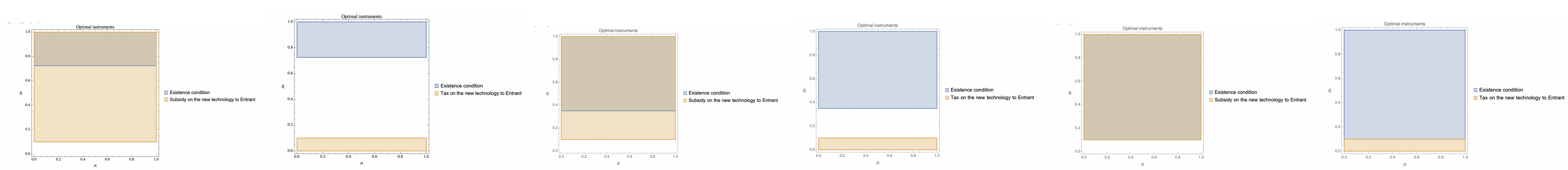
Figure 4: *Illustration of case 4 for different scenarios with respect to the values of the damage.*



(b) $s_i > 0$ **(c)** $s_i < 0$ **(e)** $s_i > 0$ **(f)** $s_i < 0$ **(h)** $s_i > 0$ **(i)** $s_i < 0$

(c) *d=0.75* **(f)** *d=1.5* **(i)** *d=10*

Figure 5: *Illustration of case 5 for different scenarios with respect to the values of the damage.*



(b) $s_n > 0$ **(c)** $s_n < 0$ **(e)** $s_n > 0$ **(f)** $s_n < 0$ **(h)** $s_n > 0$ **(i)** $s_n < 0$

(c) *d=0.75* **(f)** *d=1.5* **(i)** *d=10*

Figure 6: *Illustration of case 6 for different scenarios with respect to the values of the damage.*

For the cases where the old technology is still sold, we distinguish between cases 1 and 3 (one firm produces the new technology); and case 2 (the two firms share the new technology market). Figure 1 and 2 show that the number of situations in which these cases are feasible gets smaller with an increasing damage. Moreover, if the damage is low, only a subsidy can implement the first-best outcome. In contrast, for a moderate damage (as long as the cases are still feasible), a tax is required.

As in the previous case, Figure 2 shows that as long as the damage is high, case 2 is less attractive and may not even be possible for a very high damage. The difference is that, depending on the level of innovation, the optimal policy can be a tax or a subsidy on the old technology when the damage is low. More precisely, in later stage of the transition process, where the entrant can offer a comparatively high quality of the green technology, the social planner would prefer to tax the old technology. On the contrary, when the level of innovation is low (early stages of the transition), it is preferable to use a subsidy.

Figures 5 and 6 illustrate the first cases when the old technology is phased out. The two cases display the same patterns: A subsidy is required to implement the first-best outcome, irrespective of the level of damage. In Case 4, where the new technology market is shared between the two firms, this is different. Figure 4 shows that it is never optimal to provide a subsidy on the new technology, if the damage is low or moderate. However, the social planner will use a subsidy for high damages.

6.2 Fiscal implications

While the social planner would decide whether environmental tax or/and subsidy is suitable to implement the first best, this decision also has fiscal implications. In this subsection, we investigate the fiscal implications in term of the budget Ω_i required to implement the policy mix, which equals the total tax revenue T_i net of the total expenses for subsidies for the new technology S_i. We discuss under which conditions this budget is positive or negative.

When only tax or subsidy is implemented, this is obvious. However, the question becomes interesting whenever the two instruments are implemented together.

Proposition 6. *In term of budget,*

1- *When only the old technology is available, the budget is negative for small damages and positive for high damages.*

2- *When both old and new technologies are available in the market, the budget is negative for small damages, while it can be negative or positive for high damages.*

3- *When the old technology is phased out, the budget is negative, except when both firms supply the new technology.*

4- *When both firms supply the new technology and the old technology is phased out,*

   (a) *for sufficiently low level of damage, the budget is positive*

   (b) *for a sufficiently high level of damage, the budget can be negative or positive.*

Proof. For part 1 of Proposition 6, only the tax is implemented as only the old technology is available. Therefore, the budget gives: $\Omega_0 = T_0 = -(1-d)(2-d)/2$. We can easily check that for $d < 1$, $\Omega_0 < 0$, that is the regulator provides subsidy to produce the old technology. When $1 < d < 2$, $\Omega_0 > 0$ and the regulator collects a tax from the production of the old technology.

In part 2- of the proposition, (i) both technologies are produced by the incumbent (forced by the social planner in Case 1) or the incumbent supplies the old technology and the new entrant supplies the new technology. For the first case (i), the total tax and total subsidy are given by $T_j = \tau_j^* q_{l,t,j}^* = (d-1)\left(2(1-\delta_{i,t}-k_{t-1})-d\right)/[2(1-\alpha)]$ and $S_j = s_{i,j}^* q_{si,t,j}^* = (\delta_{i,t}+k_{t-1})\left(2(\delta_{n,t}-c+k_{t-1}-\alpha)+\alpha d\right)/[2\alpha(1-\alpha)]$, with $j = 1, 3$. The budget gives $\Omega_j = T_j - S_j = (\delta_{i,t}+k_{t-1})(-4\alpha-2c+3\alpha d+2\delta_{n,t}+2k_{t-1})+\alpha(d-2)(d-1)/[2(\alpha-1)\alpha]$, with $j = 1, 3$. The total tax is positive if $1 < d < 2(1-k_{t-1})$ and negative when $d < 1$. Moreover, the total subsidy is always positive. We can then deduce that the budget is negative for $d < 1$. The budget can be positive or negative depending on the extend to which the total tax compensates the total subsidy. We can then find a range of the damage within the interval of $1 < d < 2(1 - k_{t-1})$ for positive or negative budget.

Similarly, in the second case (ii), the budget is given by

$\Omega_2 = \frac{\alpha(d(2-\alpha)-2(1-k_{t-1}-\delta_{n,t}+c))(2(1-k_{t-1}-\delta_{n,t}+c)-d)-(\alpha d-2(\alpha-k_{t-1}-\delta_{n,t}+c))^2}{4\alpha(1-\alpha)^2}$. As in the previous case, we can find a range of the damage within the interval $d > \frac{2}{2-\alpha} - k_{t-1} - \delta_{n,t} + c$ such that the budget is positive or negative. However, when $d < \frac{2}{2-\alpha} - k_{t-1} - \delta_{n,t} + c$, the budget is negative.

For Parts 3- and 4- of the proposition, the old technology is completely phased out. Consequently, there is no tax on the old technology collected by the regulator. The total budget in the three cases is given by the same following expressions: $\Omega_j = -s^*_{i,j} q^*_{si,t,j} = -(\delta_{i,t} + k_{t-1})^2/\alpha$, with $j = 4, 5, 6$. Although, the budget is the same in absolute value, for all the three cases, the sign can be different depending on the existence condition of the case that can trigger whether it is a negative or positive subsidy. Namely, when both firms supply the new technology, for sufficiently low level of damage (i.e., $d < 2$), only a negative subsidy to the incumbent is feasible (when $\delta_{i,t} - 2\delta_{n,t} > -2c + k_{t-1}$). In this case, the budget is positive as the regulator would implicitly tax the incumbent for producing a new technology. For a sufficiently high level of damage (i.e., $d > 2$), the subsidy can feasibly be negative or positive. Thus, the budget is negative when $-2c + k_{t-1} + (1 - \frac{d}{2}) < \delta_{i,t} - 2\delta_{n,t} < -2c + k_{t-1}$ and positive when $\delta_{i,t} - 2\delta_{n,t} > -2c + k_{t-1} + (1 - \frac{d}{2})$. In both the other cases, the existence condition dictates a positive subsidy to the incumbent or new entrant for producing the new technology. Therefore, the budget is always negative.

$\square$

7 Less Complex Policies

So far, we have analysed policies that can potentially use an environmental tax and two different subsidies to implement the socially optimal market outcome. In many applications, actual policies will be less sophisticated, for example due to legal considerations (using different subsidies for incumbents and entrants is legally challenging), implementation problems (coordinating different instruments can be difficult, in particular, if they are handled by different public authorities), and the still wide-spread view in politics that a single instrument should suffice to address an environmental problem.

In this section, we thus explore which instruments to use, if there is a limited choice of instruments, and whether the choice should be altered along the transition towards a green technology, that is, along a pathway of an increasing quality of the green technology.

We constrain the policy setting to two instruments: A tax on emissions originating from the use of the old technology and a subsidy for the new technology that is not differentiated between the incumbent and possible newcomers. As we deviate from implementing the socially optimal market outcome analysed in the preceding sections, where differentiated subsidies have been used to ensure that the effects of imperfect competition are countered for the new technology, we now consider a number of market entrants n that can deviate from 1 (the number is set by the firms' innovation choices happening outside the country and thus n is a parameter in our model). This is instructive, as it highlights how the level of competition alters the incentives for choosing different policy instruments.

However, to avoid tedious case distinctions, from now on we use the assumption that entrants and the incumbent offer the same level of innovation (i.e., $\delta_{i,t} = \delta_{n,t}$) and that no copycats can enter the market, as innovation is sufficient to keep them out. Due to these assumptions, the distinction between past quality (i.e., k_{t-1}) and current innovation (i.e., δ_i, δ_n) becomes unimportant, so that we simply use k to indicate the currently relevant quality of the new technology.

Note that in the policy setting that we now analyse, the social planner is no longer able to ensure that the new technology is only provided by the most cost-efficient supplier, as the subsidy cannot be differentiated between suppliers anymore. Thus the difference in marginal production costs (i.e., c) becomes much more relevant for policy design.

To analyse the different policies, we pursue the following strategy: We differentiate between 14 possible cases: Nine cases with a uniform subsidy for the new technology (the new technology being offered either by entrants and the incumbent, only by entrants or only by the incumbent and each of these cases with or without the old technology still being sold, in addition three cases where the subsidy is set to keep the old technology out of the market or to keep either the incumbent or entrants of the market) and five cases using only a tax on sales of the old technology (the new technology being offered either by entrants and the incumbent, only by entrants or only by the incumbent, not at all, and a tax that keeps the old technology just out of the market).

For the ten cases, where the instrument is optimised, we derive the optimal value from the following problem: The social planner maximises welfare given as:

$$\max_P \int_{x_{s,l}(P)}^{x_{s,0}(P)} (k - \alpha x)\,\mathrm{d}x + \int_0^{x_{s,l}(P)} (1 - x)\,\mathrm{d}x - (c)q_{sn}(P) - Dam(q_l(P)), \tag{9}$$

where P denotes either a tax on the old technology or a uniform subsidy for the new technology and where the quantities $q_l(P), q_{si}(P), q_{sn}(P)$, and thus the boundaries $x_{s,l}(P), x_{s,0}(P)$ are altered by the policy.

For the most complex case, where entrants and the incumbent offer the new technology and the old technology is still sold, these quantities follow from the following description of Cournot competition. The incumbent maximises his profit according to Eq. (3) with either τ or s_i being zero. Similarly, each entrant maximises his profit (Eq. (4)) with s_n being either zero (in case a tax is used) or equal to s_i (for a uniform subsidy). Each of them takes Eq. (5) with $k_{t-1} + \delta_i = k$ into account, and the incumbent also considers Eq. (6). This problem yields the market outcome in terms of $q_l(P), q_{si}(P), q_{sn}(P), p_{s,t}(P), p_{l,t}(P)$ as a function of the policy instrument $P = \{\tau, s_i\}$. The $x_{s,l}(P), x_{s,0}(P)$ follow, as before, from

$$x_{s,0}(P) = \frac{k - p_s - \alpha x}{\alpha}, \tag{10}$$

$$x_{s,l}(P) = \frac{k + p_l - p_s - 1}{\alpha - 1}. \tag{11}$$

For the cases where an instrument is used to keep a firm or a technology out of the market, the required value of the tax or subsidy is derived from setting the respective production quantity equal to zero.

For each case, we also derive the conditions under which this case exists (all quantities $q_l(P)$, $q_{si}(P)$, $q_{sn}(P)$ being strictly positive, if the case in questions requires this, for the optimal level of the policy instrument). Then we compute and compare welfare levels for each of the feasible cases and select the policy that yields the highest welfare.

Albeit these computations can be easily done analytically, the plethora of cases and resulting conditions does not provide a useful picture. Thus, we present the results graphically based on numerical solutions of the above problem. Given that the relevant parameter space of the model is compact, this analysis covers all interesting settings. For α and k, the relevant parameter space is $[0, 1]$ by definition (for α, this represents our model assumptions, for k, values of $k \geq 1$ imply (by our model of demand) that the old technology is phased out even without any policy intervention). For the damage parameter d, the relevant parameter space is $[1, 2]$, as for $d < 1$, the market supply of the old technology is inefficiently low, even taking into account environmental damages, and for $d > 2$, the old technology will always be phased out immediately by the social planner. For n, the interesting range is from $n = 1$ (the least competitive case) to a value, where the market outcome for the new technology is close to the one resulting from perfect competition, which is the case from $n = 50$ onwards. Finally, for c, we use two values $c = 0$, which represents a case of cost symmetry, and $c = 1/4$, which represents a case with a cost advantage of the incumbent that is relevant for market outcomes but does not yet preclude entry of newcomers.

Figures 7 and 8 show the results of our computations. They indicate that a tax is of interest in three different situations: During the first stages of innovation (when the quality of the new technology k is too low for entering the market) to reduce the use of the old technology, in some intermediate cases (high damages and many entrants without a cost disadvantage), and to phase out the old technology early on. In contrast, a subsidy is of interest in intermediate stages of the transition (in case of a large market expansion effect, i.e., a small value of α, also at the beginning) and at the very end of the transition, when a tax on the old technology is no longer required to reduce its use or to keep it out of the market.

An important insight here is that taxes are more attractive in case of high damages and high numbers of entrants. The intuition is apparent: A tax is ideally suited to deter customers from the old technology (without causing additional effects) but cannot correct imperfect competition for the new technology. In contrast, a uniform subsidy for the new technology has effects on the pricing of the new technology, but only indirect effects on the pricing of the old technology. Thus, in cases where a high number of entrants ensure competition for the new technology, a tax is more attractive and, of course, the same holds in case the damages are so large that reducing sales of the old technology becomes of utmost importance.

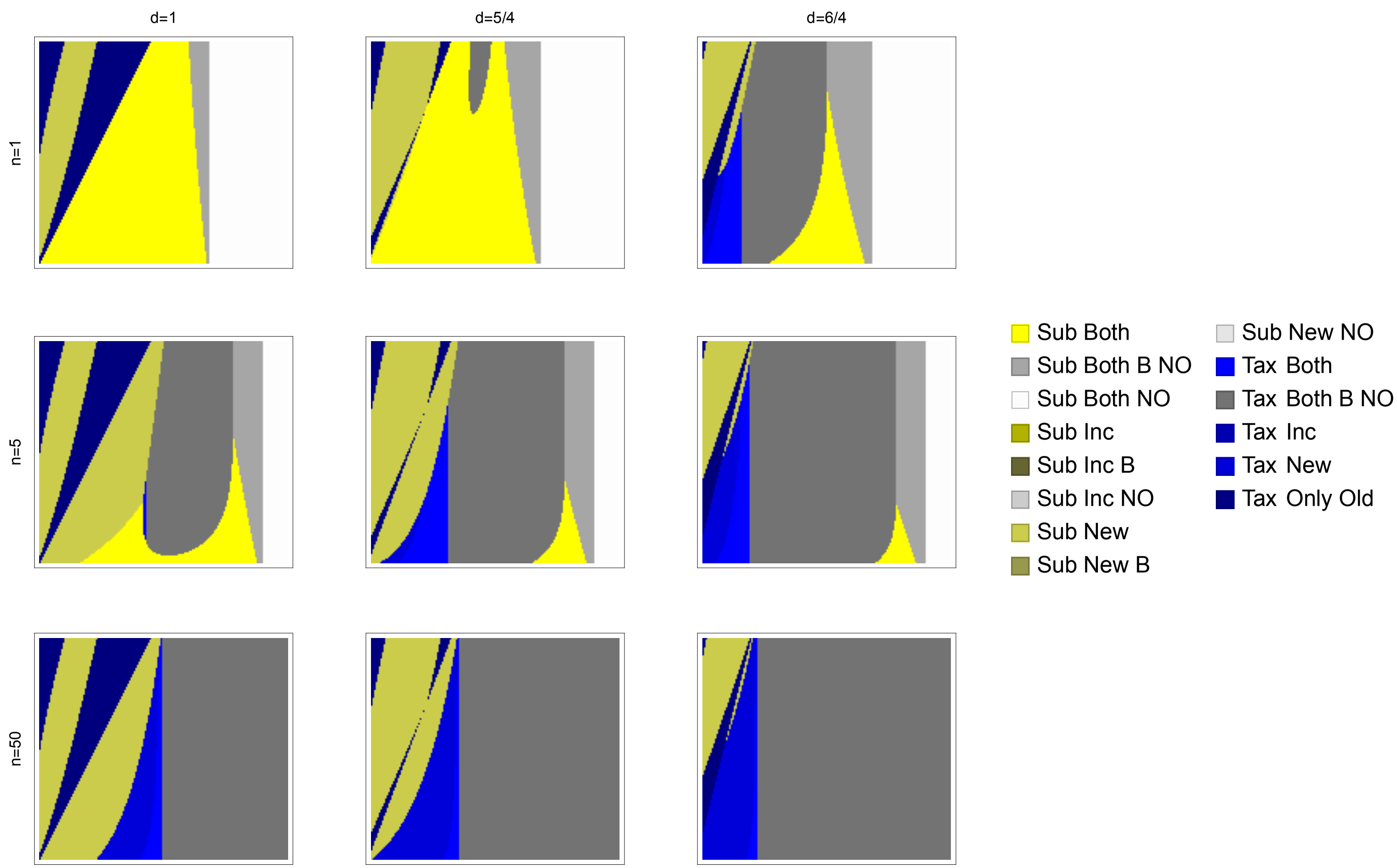


Figure 7: *Optimal choice between a tax on emissions and a subsidy for the new technology for* $c = 0$ *and different values of* n *and* d*. Each graph presents a plot over* $k \in [0, 1]$ *(horizontal axis) and* $\alpha \in [0,1,0,9]$ *(vertical axis). The colours represent the different policies (blue colours: tax is optimal, yellow/brown: subsidy is optimal, grey/white: old technology phased out) as indicated in the plot legends, where "Sub" refers to the subsidy, "Tax" to the tax, "Both" to incumbents and entrants offering the new technology, "Inc" to incumbent only offering the new technology, "New" to newcomers only offering the new technology, "NO" to no old technology available anymore, and "B" to a boundary case, where the instrument is configured to either keep out the old technology (in case of the tax) or either entrants or incumbent (in case of subsidies).*

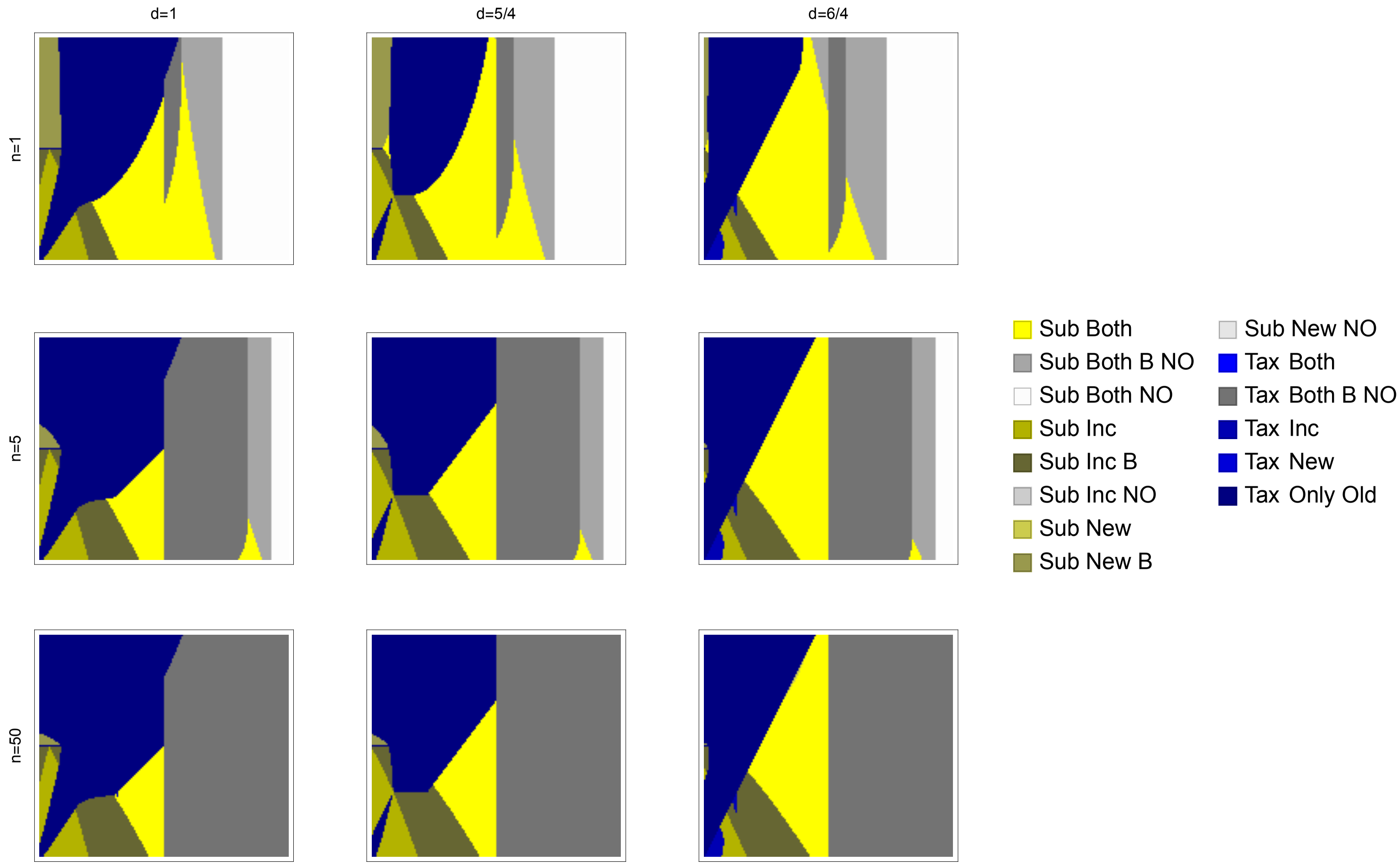


Figure 8: *Optimal choice between a tax on emissions and a subsidy for the new technology for $c = 1/4$ and different values of n and d. Each graph presents a plot over $k \in [0, 1]$ (horizontal axis) and $\alpha \in [0, 1, 0, 9]$ (vertical axis). The colours represent the different policies (blue colours: tax is optimal, yellow/brown: subsidy is optimal, grey/white: old technology phased out) as indicated in the plot legends, where "Sub" refers to the subsidy, "Tax" to the tax, "Both" to incumbents and entrants offering the new technology, "Inc" to incumbent only offering the new technology, "New" to newcomers only offering the new technology, "NO" to no old technology available anymore, and "B" to a boundary case, where the instrument is configured to either keep out the old technology (in case of the tax) or either entrants or incumbent (in case of subsidies).*

Third, a cost advantage of the incumbent renders a subsidy-based policy more attractive, as the cost difference reduces competition on the market for the new technology, even in case of a high number of entrants. However, the cost advantage also implies that a uniform subsidy is also working less well: There are many more cases, where the new technology cannot enter the market (and thus the social planner uses a tax to reduce consumption of the old technology), as the incumbent has more strategic leverage to keep out entrants. Furthermore, in case of many entrants, a tax will be used to keep out the old technology till the end of the transition, as it is too costly to rely on entrants to produce enough of the new technology to replace the old one.

Finally, and most importantly, the analysis shows that a social planner should switch between policy instruments during the transition. A tax is useful as long as the new technology has not yet entered the market (the tax reduces damages), but, in many cases, a subsidy is the instrument of choice once the new technology starts to be sold. In a later intermediate stage, (where the new technology has gained a substantial share of the market), a tax might be better suited and it is typically used to start the full phase-out of the old technology. But in many settings, a subsidy is again the instrument of choice at the end of the transition.

The reasons are, first, that, at the start of the technology transition, a tax is often not able to ensure the market entry of the new technology. Given the low quality of the new technology, only a subsidy that reduces its price substantially below the price of the old technology can support market entry. Thus, a tax would reduce damages at the price of severely reduced consumption, whereas a subsidy might reduce emissions less, but can sustain a high level of consumption.

After the new technology has gained some level of quality, a tax can become attractive in case there is sufficient competition on the market for the new technology and damages are high, for the reasons discussed above. First, this can hold for medium levels of quality of the new technology, where this technology is bought mostly by customers that would not buy the old technology.[2] Second, a tax is usually preferable to keep the old technology out of the market, as long as the new technology has not yet a quality, where it automatically replaces the old technology in most uses.

Finally, once the new technology has gained a high quality, a subsidy becomes again the instrument of choice, as it does not only keep out the old technology but also increases the diffusion of the new one. Indeed, in a few cases, the enhanced diffusion facilitated by the subsidy becomes so attractive that a social planner will even allow the old technology to re-enter the market at low levels (see, e.g., the case $c = 0, n = 5$ in the above figures).

In addition, our analysis shows that the socially best transition (taking into account the policy constraints covered in this section) will progress through a variation of market structures, where, in many cases, the first entry of the new technology will be due to the incumbent, but newcomers are instrumental to achieve a wider diffusion of the new technology. In almost all cases, the transition will end with a market that is shared by the incumbent and newcomers.

The reason is that, at the beginning of the process, the incumbent can easily deter newcomers due to the low quality of the new technology and, due to the subsidy, it can be optimal for the incumbent to offer the new technology to customers that do not buy the old one (market expansion). Later on, it becomes harder for the incumbent to deter newcomers, as the quality of the new technology has made it an attractive choice from many customers.

Overall, the analysis of restricted policies amplifies the arguments of the preceding section: First, what type of policies should be used depends on the market structure, that is, who (an incumbent or entrants) is supplying the new green technology. Even in a setting with three instruments (tax and two subsidies), we find cases where conventional policy measures (Pigouvian tax) are not optimal. This holds in almost all cases with more restricted policy options.

[2] This is the reason, why this case occurs mostly for low levels of α, where this market expansion effect is strong.

Second (and more importantly policy), instruments should be adjusted throughout the transition; in particular, a policymaker using restricted policy instruments should switch between policies that push new technologies into the market, like subsidies for the green technology, and policies that manage the decline of the old technology, like a tax on emission-intensive technologies. Depending on market conditions, multiple switches might be required.

8 Conclusion

A transition to greener, that is, less emission-intensive, technologies is widely considered to be the best and often the only option to solve environmental problems, such as climate change. However, such transitions are difficult to initiate and manage. Often, several market failures interact, such as the public good nature of innovation, strategic behaviour of incumbents offering old, emission-intensive technologies, and an environmental externality. Therefore, a set of policy measures is required to manage a green technology transition in a socially optimal way.

Furthermore, throughout such a transition, the structure of the technology market will often change. While, at the beginning, the new technology might be offered only by a single firm, entrants often increase competition later on. Also, incumbents are likely to switch from protecting their old "brown" technology to competing for a share of the green technology market at some point during the transition (Bondarev et al., 2020). Both points have ramifications for the design of policy measures, as they shifts the balance between different types of market failures that need to be addressed by a policy mix.

In this paper, we have studied the design of a transition policy for the case of a small country that can influence which technologies are used but has no influence on the r&d decisions of international firms. This resembles the setting typically found in the automobile industry and the energy industry, both of which are of central importance in climate policy.

While we base our analysis on an existing model of a technology transition (Bondarev et al., 2020), we use a novel and original focus in our model analysis: We inquire how policies should be adapted to different market situations and how they should be altered during a technology transition.

Our results indicate that this question is important. Even in a rather complex policy setting, where policy-makers have three different instruments at hand, these instruments have to be used in different ways for different market structures (i.e., whether new technology is offered on a monopolistic market by the incumbent or in Cournot competition between newcomers and (potentially) the incumbent). Furthermore, the socially best setting changes throughout the transition, as the new technology matures.

This effect is strongly enhanced in the setting, where a policymaker can use only a single instrument and thus has to decide whether to tax the old or subsidise the new technology. Here, it is usually optimal to switch at least once between these instruments during the transition, and often at least two switches are optimal. Furthermore, whether and when to switch depends strongly on the market details, in particular, on the number of entrants, a possible cost advantage of the incumbent, and the strength of the market expansion effect.

To the best of our knowledge, this is the first analysis of a second-best policy design that takes different market failures as well as different stages of the technology transition into account. Our results suggest that this type of analysis might have some value, as optimal policy choices depend strongly on the relative importance of the different market failures and this changes drastically during the process of the technology transition.

Our model is highly abstract, but it should be able to capture several aspects that are of importance in real-world technology transitions. Among these are the existence of incumbents that could provide a green technology, but that choose strategically to keep this technology in a market niche to avoid Arrow's replacement effect. Second, entrants that have no stake in the market of the old technology can also provide the new one but might be hindered both by strategic behaviour of the incumbent and a cost disadvantage. Arguably, both aspects have some importance in the transition to electrical vehicles and similar structures can be found in the transition to renewables in electricity generation. Finally, our model accounts for the choice between "push" policies that aim to even the path for new technologies and "pull" or "decline" policies that strive to initiate the transition by phasing out the emission-intensive technology. This choice is among the often (and often hotly) debated policy choices in energy and climate policy. It is obvious that a combination of these policies would be optimal, however, many countries focus on one of the instruments. Here, our results strongly suggest that countries should at least be open to switching among policies over time.

Of course, our paper has numerous limitations. Among them are the choice of a specific demand structure, where the new technology enters first via a market expansion (not via a replacement of the old technology for high-value customers). Depending on the application, this might be a problematic setting. However, it is unlikely that the qualitative insights gained here depend on this choice. Second, we consider a setting where the r&d decisions are exogenous and not influenced by the policy measures. Clearly, this is the case for most countries in the current energy transition, where technology development occurs on an international scale and many countries do not even have a domestic industry offering cars or energy conversion technologies. However, due to this choice our analysis does not apply to cases like the US, UK, China or Germany, where policies clearly shape r&d decisions. Finally, we consider a setting where the old technology is offered by a monopolistic incumbent. This deviates from most real-world settings. However, this simplification has little consequence for our main results. All that is important is that the market for the old technology is not perfectly competitive, that is, that the incumbent can set a price for the old technology that exceeds marginal costs (otherwise, the incumbent would have little incentive to protect sales of the old technology). The monopolistic setting is clearly an extreme case, but using Cournot competition would very likely result in similar outcomes but at the expense of a much less tractable analysis.

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Appendix

A Social Optimum

A.1 Case 1: New entrants and incumbent supply new technology

Solving the program in Eq. (8) and assuming that the total production of the new technology is given by $Q_{s,t} = q_{si,t} + q_{sn,t}$, yields:

$$q^*_{l,t,1} = \frac{1}{1-\alpha}[-\delta_{i,t} + (1 - d/2) - k_{t-1}], \tag{12}$$

$$Q^*_{s,t,1} = \frac{1}{\alpha(1-\alpha)}[\delta_{n,t} - \alpha(1 - d/2) - c + k_{t-1}] \tag{13}$$

and

$$\delta_{i,t} = \delta_{n,t} - c \tag{14}$$

As we assume that the cost of producing the new technology by the new entrant is higher than that of the incumbent, whenever the two firms supply the new technology, the social planner will optimally prefer the incumbent to produce the new technology. This translates into $q^*_{sn} = 0$ and $Q^*_s = q^*_{si}$. thus, the optimal welfare is given by:

$$W^*_{1,t} = \frac{4\delta_{i,t}[-2c + \alpha(d-2) + 2k_{t-1}] + 8\delta_{n,t}(c + \delta_{i,t}) - 4\delta^2_{n,t} + \alpha(d-2)(d + 4k_{t-1} - 2) - 4c^2 + 4k^2_{t-1}}{8(1-\alpha)\alpha} \tag{15}$$

From the derivative of the welfare with respect to d:

$$W^*_{1d} = \frac{d + 2(\delta_i + k_0 - 1)}{4(1-\alpha)},$$

we can easily show that the optimal level of the welfare is a decreasing function of the level of damage whenever the marginal damage is sufficiently low (i.e, $d/2 < 1 - \delta_{i,t} - k_{t-1}$). Note that this condition needs to match with the condition that defines the existence of Case 1.

A.2 Case 0: Only old technology

In case the incumbent in a monopoly supplying only the old technology, the welfare maximisation problem is similar to the one in Case 1 except that we solve for the FOC with respect to $q_{l,t}$ given the condition that $q_{sn,t} = q_{si,t} = 0$. The optimal level of the old technology production and the optimal welfare are given by:

$$q^*_{l,t,0} = 1 - d/2 \tag{16}$$

and

$$W^*_{0,t} = \frac{1}{8}(d-2)^2 \tag{17}$$

Taking the derivative of the optimal welfare with respect to d gives:

$$W_{0,d} = \frac{d-2}{4}$$

Thus, the higher is the damage, the lower is the optimal welfare if the marginal damage is low (i.e., $d < 2$). This condition is the also part of the conditions that define the existence of case 0, namely for positive $q^*_{l,t,0}$.

A.3 Case 2: New technology only sold by new entrants

From the welfare optimisation in Case 1, we solve for the FOCs with respect to $q_{l,t}$ and $q_{sn,t}$ given the condition that $q_{si,t} = 0$. This gives the following optimal amount of the old and new technologies:

$$q^*_{l,t,2} = \frac{1}{1-\alpha}[-\delta_{n,t} - d/2 + c + 1 - k_{t-1}] \tag{18}$$

and

$$q^*_{sn,t,2} = \frac{1}{\alpha(1-\alpha)}[\delta_{n,t} - \alpha(1-d/2) - c + k_{t-1}] \tag{19}$$

From the optimal levels of production, the optimal value for the welfare is given by:

$$W_{2,t} = \frac{\delta^2_{n,t} + [-2c + \alpha(d-2) + 2k_{t-1}]\delta_{n,t} + (c - k_{t-1} + 1)\alpha d + \alpha(d/2)^2 + \alpha + (c - k_{t-1})(2\alpha + c - k_{t-1})}{2\alpha(1-\alpha)} \tag{20}$$

Taking the derivative of the welfare with respect to d gives:

$$W_{2,d} = -\frac{-2c + d + 2(\delta_{n,t} + k_{t-1} - 1)}{4(\alpha - 1)}$$

As in the previous cases, we can easily show that the optimal level of the welfare is a decreasing function of the level of damage whenever the marginal damage is sufficiently low with $d/2 < 1 - k_{t-1} - \delta_{n,t} + c$. This condition should match with the one that defines the existence of Case 2 and similar to the one in Case 1 with $\delta_{i,t} = \delta_{n,t} - c$.

A.4 Case 3: New technology only sold by incumbent

The welfare maximisation in Case 3 is similar to that in Case 1 by solving for the FOCs with respect to $q_{l,t}$ and $q_{si,t}$ given the condition that $q_{sn,t} = 0$, the optimal levels of production are given by:

$$q^*_{l,t,3} = \frac{1}{1-\alpha}[-\delta_{i,t} - d/2 + 1 - k_{t-1}] \tag{21}$$

and

$$q^*_{si,t,3} = \frac{1}{\alpha(1-\alpha)}[\delta_{i,t} - \alpha(1-d/2) + k_{t-1}] \tag{22}$$

The optimal value for the welfare is given by:

$$W^*_{3,t} = \frac{\delta^2_{i,t} + (-2\alpha + \alpha d + 2k_{t-1})\delta_{i,t} + \alpha(d/2)^2 - (1 - k_{t-1})\alpha d + \alpha + k_{t-1}(k_{t-1} - 2\alpha)}{2\alpha(1-\alpha)} \tag{23}$$

Taking the derivative of the welfare with respect to d gives:

$$W_{3,d} = \frac{d + 2(\delta_{i,t} + k_{t-1} - 1)}{4(1-\alpha)}$$

This is the same as the one on the Case 1 with the same conclusion.

A.5 Case 4: New entrants and incumbent supply new technology and old technology is phased out

In Case 4, the optimal levels of the new technology production are obtained by solving the FOCs of the welfare maximisation problem in Case 1 with respect to $q_{sn,t}$ and $q_{si,t}$ given the condition that $q_{l,t} = 0$. The total optimal level of the new technology production is given by:

$$Q^*_{s,t,4} = \frac{1}{\alpha}[\delta_{n,t} - c + +k_{t-1}] \tag{24}$$

As in the case 1, the social planner will prefer the incumbent to supply the new technology such that $q^*_{sn,t,4} = 0$, $q^*_{si,t,4} = Q^*_{s,t,4}$ and Eq.14 holds. The optimal social welfare is given by:

$$W^*_{4,t} = \frac{-\delta^2_{n,t} + 2(c + \delta_{i,t})\delta_{n,t} - 2(c - k_{t-1})\delta_{i,t} - c^2 + k^2_{t-1}}{2\alpha} \tag{25}$$

Under Eq.14, the optimal level of production becomes $(\delta_{i,t} + k_{t-1})/\alpha$ and the optimal welfare becomes $(\delta_{i,t} + k_{t-1})^2/(2\alpha)$. It is cn easily seen that innovation by the incumbent is welfare improving.

A.6 Case 5: Only incumbent supplies new technology and old technology is phased out

As in the previous cases, we solve for the FOC of $W_{1,t}$ with respect to $q_{si,t}$ given the condition that $q_{l,t} = q_{sn,t} = 0$. Under Eq. (14), the optimal production of the new technology and the associated optimal welfare are the same as in Case 4: $q^*_{si,t,5,} = q^*_{si,t,4,}$ and $W^*_{5,t} = W^*_{4,t}$.

A.7 Case 6: Only new entrant supplies new technology and old technology is phased out

The problem in Case 6 is similar to the previous case in which we solve for the FOC of $W_{1,t}$ with respect to $q_{sn,t}$ given the condition that $q_{l,t} = q_{si,t} = 0$. The optimal production of the new technology by the new entrant and the optimal social welfare are similar to the ones in the Case 5, $W^*_{6,t} = W^*_{5,t}$ with $\delta_{i,t} = \delta_{n,t} - c$.

Table A summarises the optimal quantities of the old technology and the new technology and the optimal social welfare.

Table 3: *Optimal quantities of the old technology and the new technology and the optimal social welfare.*

Cases	q_l
Case 0	$1 - d/2$
Case 1	$\frac{1}{1-\alpha}[-\delta_i + (1 - d/2) - k_0]$
Case 2	$\frac{1}{1-\alpha}[-\delta_n - d/2 + c + 1 - k_0]$
Case 3	$\frac{1}{1-\alpha}[-\delta_i - d/2 + 1 - k_0]$
Case 4	-
Case 5	-
Case 6	-

Cases	q_{si}
Case 0	-
Case 1	$\frac{1}{\alpha(1-\alpha)}[\delta_n - \alpha(1 - d/2) - c + k_0]$
Case 2	-
Case 3	$\frac{1}{\alpha(1-\alpha)}[\delta_i - \alpha(1 - d/2) + k_0]$
Case 4	$\frac{1}{\alpha}[\delta_n - c + +k_0]$
Case 5	$\frac{1}{\alpha}[\delta_i + k_0]$
Case 6	-

Cases	q_{sn}
Case 0	-
Case 1	0
Case 2	$\frac{1}{\alpha(1-\alpha)}[\delta_n - \alpha(1 - d/2) - c + k_0]$
Case 3	-
Case 4	0
Case 5	-
Case 6	$\frac{1}{\alpha}[\delta_n + k_0 - c]$

Cases	W
Case 0	$\frac{1}{8}(d - 2)^2$
Case 1	$-\frac{4\delta_i[-2c+\alpha(d-2)+2k_0]+8\delta_n(c+\delta_i)-4\delta_n^2+\alpha(d-2)(d+4k_0-2)-4c^2+4k_0^2}{8(\alpha-1)\alpha}$
Case 2	$\frac{\delta_n^2+[-2c+\alpha(d-2)+2k_0]\delta_n+(c-k_0+1)\alpha d+\alpha(d/2)^2+\alpha+(c-k_0)(2\alpha+c-k_0)}{2\alpha(1-\alpha)}$
Case 3	$\frac{\delta_i^2+(-2\alpha+\alpha d+2k_0)\delta_i+\alpha(d/2)^2-(1-k_0)\alpha d+\alpha+k_0(k_0-2\alpha)}{2\alpha(1-\alpha)}$
Case 4	$\frac{-\delta_n^2+2(c+\delta_i)\delta_n-2(c-k_0)\delta_i-c^2+k_0^2}{2\alpha}$
Case 5	$\frac{(k_0+\delta_i)^2}{2\alpha}$
Case 6	$\frac{(k_0-c+\delta_n)^2}{2\alpha}$