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Faculty of Business and Economics

WWZ

April 2021

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WWZ Working Paper 2021/07

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A publication of the Center of Business and Economics (WWZ), University of Basel.

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Green Technology Transitions with an Endogenous Market Structure[⋆]

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Abstract

The transition to a green technology is central to environmental policy. During such a transition, technology and market structure often change simultaneously, as firms developing the new technology enter the market of incumbents supplying the old one. This leads to the questions how technological change and market changes interact and at which stage of the technology transition incumbents or newcomers are more likely to drive the technology transition. We advance a model that describes this co-evolution of technology and market. Our results show that this co-evolution induces substantial market failures. The transition might be blocked by an incumbent protecting the old technology and, even if it is not, emissions decline less rapidly than in the social optimum. Furthermore, incentives change during the transition: At the beginning, entrants can be crucial to start the transition, but, later on, the incumbent will usually become the driving force. When this switch occurs depends on the propensity of the new technology to attract new customers and on the possible speed of technological development. Our results have implications for environmental policy, as they indicate that supporting small newcomers might be desirable at the beginning but can be detrimental at later stages of a technology transition.

Keywords: Green Technology, Innovation, Imperfect Competition, Endogenous Market Structure, Technology Transition

[⋆]This research has been supported by the Swiss National Science Foundation under Grant 169764 and is part of the activity of the Swiss Competence Center for Energy Research CREST funded by Innosuisse.

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1. Introduction

A transition to greener technologies is often seen as a desirable way to cope with environmental pollution. Old, polluting technologies are to be replaced by new ones that emit less or use less resources. Obvious examples are the transition to a low-carbon energy system, where fossil fuels are replaced by renewable energy to combat climate change, the phase-out of CFC-based products in the 1980s and 90s to combat the problem of a degenerating ozone layer, and the current switch from diesel and gasoline cars to e-mobility, which is driven both by climate change concerns and problems with local air pollution.

These examples have two common aspects. First, there is a switch from prevailing production methods to not yet fully developed technologies that occurs over several stages of technology development. Second, this often implies a change of the market structure; incumbents with detailed knowledge of old technologies suddenly face competition from entrants engaged in r&d for the new technologies.

In this setting, two interesting questions arise: First, how do changes in market structure (e.g., the change from an oligopolistic or monopolistic situation to a more competitive market) and technological change interact? Imperfect competition is essential for generating the profits that are required to fund r&d activities, however, less competition could also result in less incentives to innovate.

Second, what are the roles of different players in a technology transition, and do they change over time? Incumbents who own an old technology have a strong incentive to protect their market against a novel green technology but newcomers might face higher r&d costs, as they sometimes have less technological experience. Furthermore, do these roles vary over time? Will an incumbent switch from preventing to supporting green technological change at some point of time or not? Might newcomers that have less means to influence market outcomes help or hinder technological change and emission reductions and does this change throughout the process of phasing out an old technology?

The importance of such questions is easily illustrated by the example of the automotive industry. Following Wesseling et al. (2015), three periods characterize the EV market dynamics under environmental regulation regarding incumbents. During the first period of the 1990s, incumbents have developed a significant number of EV patents but have not sold many EVs. The second period from 2000-2006 defines the period of inactivity as incumbents continued to develop only a low number of EV patents with fewer sales. During the third period from 2007, incumbents have invested again in EV r&d and have started to sell more EVs. Within the period of inactivity, Tesla Motors Inc. (Tesla) entered the market (in 2003). Since then, Tesla has invested much in r&d and driven technological development to a large extent. In 2019, Tesla had a share of 17% of the EV market (Pontes, 2020) and, in early 2020, the recent Tesla Model 3 became the best selling electric car (Holland, 2020). However, the EV market structure still changes dynamically, as incumbents in car manufacturing try to capture the market for EVs. In Europe for instance, Tesla is losing its leadership. The Renault Zoe was the highest-selling EV in Europe in July 2020, with 146 percent year-on-year growth (Taylor, 2020).

The illustration of the automotive industry shows that a small set of incumbent firms has not been able or willing to initiate the switch to a new technology (e-mobility), despite substantial own r&d efforts in this direction. A newcomer to this market has initiated a surprisingly rapid transition and the former incumbents have started to switch their product portfolio as a response. Some incumbents have even committed themselves to a full switch to electric vehicles in the near future. This suggests a strong interaction of technology and market dynamics. Furthermore, it indicates that players may reassess their role during the technology transition, switching from preventing to embracing green technological change.

Interestingly, other examples show different patterns of green technological change. For example, the CFC phase-out was driven to a substantial extent by incumbents, such as Dupont (Heyes, 2009). In contrast, the transition from coal or gas to renewables was first attempted by incumbents (e.g., Royal Dutch/Shell, BP and Total) but is now driven largely by new market entrants (Pinkse and Van den Buuse, 2012; Kelsey and Meckling, 2018).

In this paper, we present a model of a technology transition with an endogenous structure of the technology market that provides a framework for analyzing different patterns of green technology transitions. This model consists of an incumbent, who provides the old technology as a monopolist and can also develop the new technology, as well as of two types of entrants: Firms that develop the new technology and firms that copy and sell older versions of the new technology.

In this model, the different players interact on a technology market, where consumers choose between the old and the new technology and where the new technology has the potential to attract new customers, that is, to expand the market. This market has an endogenous structure in the sense that, depending on the decisions of the different players, the new technology can be provided only by the incumbent (resulting in a monopoly), by several firms that develop the new technology (resulting in an oligopoly, in which the income may or may not take part), or by firms that have not done any technology development and thus do not have to recover r&d costs (resulting in perfect competition).

Furthermore, the firms that develop the technology also interact in the r&d stage, where they strategically decide whether and how rapidly to develop the new technology, taking into account that their r&d efforts influence the structure of the technology market. This game is played repeatedly until either the old technology is phased out or development of the new technology ceases.

Using this structure, we show that there is a strong interaction between r&d decisions and the level of competition on the technology market that substantially alters the incentives of the different players and thus their roles during the technology transition. Furthermore, we show that the possibility of expanding the market by developing the new technology is crucial for the initial stages of the transition; if this market expansion is too small, the incumbent can successfully prevent the development of the new technology. If this expansion is very large, the incumbent will develop the new technology on his own from the very beginning. In intermediate cases, the new technology will be developed at the beginning either by newcomers, the incumbent, or both until the incumbent switches his role from preventing to embracing technological change. From this point on, he is likely to dominate the transition to the green technology.

We show that these different roles have important consequences for environmental pollution throughout the transition process. At the beginning of a transition, newcomers will be most effective to bring down pollution by driving out the old technology. An incumbent who innovates purely for strategic reasons might even induce an increase of emissions during the early stages of the technology transition. However, later on, an incumbent firm will bring down emissions more rapidly, as she controls both the old and the new technology and has lost interest in protecting the old one.

We analyze these outcome purely from a market perspective, that is, in the absence of any environmental policy. We contrast this with a socially optimal outcome to show that a policy intervention could be beneficial and to outline how such an intervention might be designed at different stages of the transition process. However, as our analysis is already fairly complex, we do not analyze environmental policy in detail.

The paper is set out in the following way. In the next section, we briefly review the related literature. In Section 3, we present our model. In Section 4, we analyze the model in subsequent steps: The socially optimal outcome, the technology market outcome, the r&d decisions, the dynamics of technological change, and the resulting environmental impact and implications for policy. Section 5 recaps and discusses our main insights.

2. Related Literature

In a literature review, Etro (2014) highlights that there is a lack of applications of endogenous market structures in studies of innovation. Notable exceptions are Peretto (2003), Etro (2004), Denicolò and Zanchettin (2010), and Chu et al. (2012), which, however, do not investigate (green) technology transitions. But there are numerous studies that address questions that come close to single aspects of the setting outlined above.

In the industrial organization literature, there are, of course, many contributions investigating endogenous market structures. In a dynamic context, this analysis usually focuses on monopolistic or oligopolistic situations. A typical example is Lambertini and Mantovani (2010), where the competition of multi-product duopolies is studied with both cost-minimizing and capacity-expanding investments being included. The paper takes the market structure as given and focuses on long-run equilibria, without studying the transition dynamics. It shows that quantity competition entails lower r&d incentives than price competition. Furthermore, cost-reducing innovations are more attractive initially than product-enhancing ones. Thus the form of competition and its intensity is crucial for the technological transition of an industry.

A second strand of literature focuses on the effects of a monopolistic market structure on intra-industry trade and general equilibrium effects in the spirit of Krugman (1980). However, most studies in this field do not allow for changes to the basic market structure, such as a transformation from monopolistic competition to an oligopoly, or vice versa, and are thus of limited use to investigate technology transitions.

Real business cycle models, as in Cook (2001) and Bilbiie et al. (2012) sometimes address the evolution of a market structure. In Cook (2001), a potential duopoly is studied, where one potential entrant is threatening the existing monopoly. The entrant decides when to enter the market and this defines the long-run equilibrium and associated business cycles (fluctuations). In Bilbiie et al. (2012), the number of entrants is endogenously defined and the general equilibrium effects of the resulting market structures are traced. However, the focus of these studies is on economy-wide fluctuations, not on a technology transition in a given industry itself. Changes in competitive pressure and the effect on innovations of firms are analyzed in Boone (2000). There, the role of intra-industry spillovers is the primary focus, and the effect of this structure on the total industry's r&d output is studied. However, the market structure is taken as given.

On a more general level, the study of endogenous market structures (endogenous entry and exit of firms) was pioneered in a dynamic setting by Hopenhayn (1992). This paper introduces a stochastic dynamic model of firms' entry and exit and studies the associated long-run stationary equilibrium allocation of firms' sizes and their profits. However, it does not analyze the question of transition dynamics. Kováč et al. (2010) develop a dynamic model in which the technological leader faces endogenous entry of followers. They show that the leader can adopt an accommodation strategy or a strategic predation. In the former case, the leader invests in r&d under a low r&d efficiency and/or a relatively large size of the market. In the latter case, pre-emptive r&d investment allows the leader to kick out all the other firms in order to benefit from the monopoly situation in the future, even though this may require incurring temporary losses. Wagener (2005) studies the endogenous determination of the number and type of steady-states of a dynamical system governing the market dynamics. He shows that a non-convexity in firms' cost structures may lead to a non-unique optimal investment behaviour and thus multiple steady-states. However, in contrast to Hopenhayn (1992), this study considers only a single firm and thus cannot capture an evolution of the market structure.

In addition to r&d investment, the investment behaviour of firms is also influenced by r&d spillovers. Haruna and Goel (2011) consider r&d investment that reduces the marginal cost of production with spillover effects in a three-stage game model. They show that the efficiency of the market size depends on the degree of spillovers. More precisely, large spillovers prevent new firms to enter the market, which can lead to an inefficient number of entrants.

An endogenous structure of markets is also frequently modelled in macroeconomic papers, such as Acemoglu et al. (2012), Jovanovic and Yatsenko (2012). The first paper compares innovation and standardization as engines of growth and derives an inverse-U relationship between growth and competition, as in Aghion et al. (2005). The second paper uses a vintage capital model to derive a non-monotonic relationship between growth and innovations efficiencies. In a more recent contribution, Acemoglu and Cao (2015) argue that the distribution of firm sizes is an important determinant of the type of innovative activities, with some equilibria resulting in the majority of r&d being done by incumbent large firms (in-house innovations) and in others by new entrants (smaller venture firms). Furthermore, Acemoglu et al. (2018) have recently extended the models on endogenous technological change to include endogenous exit and reallocation. They assume that the technology leadership may change due to a successful innovation or a relatively low productivity. In addition, firm's innovative capacity may change over time as large firms may have less incentives to innovate. The interactions between these two dynamics determine how the equilibrium will evolve over time.

A final strand of literature studies the transition to a "green" economy. In this context, the role of industrial policy has recently been shown to be important, see, for example, Rodrik (2014). It is argued that industrial policy should pursue proper institutional setup to promote green growth. Other papers show the importance of industrial policy coordination across industries and countries on the basis of empirical studies, such as O'Sullivan et al. (2013).

In this strand of literature, numerous papers address the effects of different policy measures for technological change. The direction of technology change (the choice of technology) is addressed in the literature on price-induced technology change, see, for example, Magat (1978, 1979), Katsoulacos and Xepapadeas (1996), Kaboski (2005), Goeschl and Perino (2007), Poyago-Theotoky (2007), and Krysiak (2008, 2011). Magat (1978, 1979) show that different designs of pollution control policies may induce different allocations of research and r&d funds between improvement in abatement technology and improvement in production technology. Katsoulacos and Xepapadeas (1996) show that an optimal emission tax can be lower than the marginal damage and that taxing environmental r&d may be optimal when r&d spillovers are sufficiently small. Poyago-Theotoky (2007) analyzes r&d decisions in the context of imperfect commitment of the regulator and environmental r&d spillovers. Kaboski (2005) shows that factor price uncertainty can affect the direction of technology change. Goeschl and Perino (2007) show that, in a setting where technologies emit different pollutants, socially optimal technology innovation occurs sequentially rather than simultaneously. Krysiak (2008) shows that different types of policy measures (permit trading, taxes, command-and-control) induce different directions of technology progress. Finally, Krysiak (2011) considers both vertical and horizontal technology progress and shows that some policy instruments are more prone than others to result in a technological lock-in.

All these contributions study the role of environmental policy in a technological transition in detail, but assume that the market structure is given and remains the same throughout the transition.

Overall, there are many contributions that either study evolving market structures, or the r&d incentives arising in a particular market structure, or a given technology transition, but, to the best of our knowledge, no model captures these aspects jointly.

3. The Model

To analyze the questions raised in the introduction, we need a model that describes the transition from an old to a new technology, covering both differing innovation incentives of incumbents and new entrants and changing levels of competition during the transition. We focus on slow, large-scale transitions, which typically require decades and thus several patent cycles, such as the likely passage from petrol-/diesel-based cars to electrical vehicles or the replacement of coal/gas/nuclear power by renewable energies.

We assume that there are two technologies (old brown and new green) that compete on a technology market that is (potentially) imperfectly competitive. A continuum of heterogeneous consumers decide whether and which technology to buy. This decision is based on the quality of a technology and its price.

For simplicity, we assume that the old technology is fully developed and sold by a single incumbent firm. Both assumptions could be dropped without major changes to our results. For instance, one could envisage that the old technology is a well-established oligopoly market with a limited number of players. In this case, the incumbents would still protect the old technology. Furthermore, we assume that each unit of the old technology that is used by consumers causes a constant damage d, so that total damage is linear in the amount of the old technology being used.

The new technology does not cause any damage but is not yet developed (it cannot be sold without some prior development) and can be developed either by the incumbent or by new entrants. Development can occur over several periods, where each period corresponds to one investment and patent cycle. After a patent runs out, the patented development becomes freely available knowledge. Thus firms copying former developments can enter the market after the first investment cycle, and firms that want to continue developing the new technology have to fend off this competition in order to gain a price above marginal costs that can repay r&d expenses.

All firms that have made an innovation, have copied a previous innovation or still produce the old technology (incumbent) can compete on the technology market. This can result either in perfect competition (if a copied version of the new technology is sold or if there is an infinite number of entrants that have made an innovation), Cournot competition (if the new technology is sold by a finite number of firms), or a monopoly (if only the incumbent serves the market). Thus we have an endogenous market structure on the technology market.

To capture the different innovation incentives and opportunities of incumbents and newcomers, we assume that these firms differ in several regards. First, these firms differ regarding their behavior on the technology market. The incumbent can offer both the old and the new technology and thus may have an incentive to protect sales of its old technology. However, the new technology can expand the market, so that the incumbent can have an incentive to sell both technologies simultaneously, even if there are no entrants.

Second, the firms differ regarding their innovation costs. Newcomers have to pay a fixed cost for starting r&d in this technology, as well as a variable cost that depends on the scope of the planned innovation. In contrast, the incumbent already owns r&d facilities from the past development of the old technology and thus pays only the variable r&d costs, which can be smaller or higher per unit of quality improvement than those of the newcomers.

In terms of timing, we assume that development occurs in periods, each of which corresponds to a product lifecycle (about 15-25 years). Each period is composed of two stages: (i) the r&d stage and (ii) the market stage. The r&d stage is at the beginning of each period when the incumbent and then potential newcomers decide whether to exert r&d efforts. In the market stage, final technology qualities become observable to everyone and all firms that have developed a technology compete on the market by setting production quantities. Beginning with the second period, firms that did not develop the technology further but simply copy last period's developments can also enter the market.

This game is repeated, with the highest quality available in period t becoming freely available in period $t + 1$. Given this limited life of patents and the long duration of each period in terms of years, we assume that all firms act myopically, that is, they do not take into account any consequences of their actions in period t on the profits achievable in subsequent periods. This is a simplification required to derive closed-form solutions. However, simple calculations show that given a duration of each period of $15 - 25$ years, a discount rate of $3 - 6\%$, and the fact that (due to the potential entry of copycats) profit margins decrease over time, intertemporal effects are very small. The myopic model is thus at least a good approximation.

In detail, we use the following assumptions.

3.1. Demand

There is a continuum of consumers that differ regarding the benefit that they gain from buying the technology. For a consumer of type x, the net benefit of buying the old technology in period t is given by

$$B(x) = K - x - P_t, \tag{1}$$

where K denotes the constant quality of the old technology and P_t its price in period t. In Eq. (1), we implicitly assume that the expenses for the technology are small enough to not alter the marginal utility of income and normalize this marginal utility to 1.

A consumer of the same type x gains the net benefit

$$b(x) = k_t - \alpha\, x - p_t, \tag{2}$$

from buying the new technology, where k_t is the quality of the new technology, p_t its price in period t, and $0 < \alpha < 1$ is a parameter that describes to what extent the new technology can expand overall demand.

We assume that $x \in \mathrm{R}_0^+$, that there is exactly one consumer of each type, and that each consumer buys at most one unit of the technology. A consumer of type x will buy the new technology if $b(x) > \max\{B(x), 0\}$, the old technology if $B(x) \geq \max\{b(x), 0\}$, and no technology if $\max\{b(x), B(x)\} < 0$.

If different qualities of the new technology are offered, consumers will choose the version that yields the highest net benefit, that is, the highest value of $k_t - p_t$. If this value is equal among different versions of the new technology, the consumer randomly chooses one of them (with equal probability for each version).

3.2. Incumbent

The incumbent can generate revenues from selling the old and the new technology. We assume that the incumbent has constant marginal costs of production c that are (without any substantial loss of generality) identical for the old and the new technology and constant over time. In the market stage, the incumbent sets quantities $Q_{I,t}, q_{I,t}$ for the old and new technology, respectively, that maximize total profit in period t:

$$\pi_{I,t} = (P_t - c)\, Q_{I,t} + (p_t - c)\, q_{I,t}. \tag{3}$$

In the r&d stage, the incumbent chooses whether and to what extent to develop the new technology. The incumbent can choose a development $\delta_{I,t}$ from a set of ideas $[0, \Delta]$, so that the new technology offered by the incumbent has a quality $k_{I,t} = k_{t-1} + \delta_{I,t}$, where k_{t-1} denotes the highest quality offered in the preceding period. We assume that $\Delta < K$, so that a phase-out of the old technology will always require multiple innovation steps. Depending on the choice of $\delta_{I,t}$, the development incurs r&d costs $\gamma\, \delta_{I,t}$.

3.3. Entrants

If a newcomer has successfully developed a version of the new technology in period t, she chooses a quantity $q_{N,t}$ of production that maximizes profit

$$\pi_{N,t} = (p_t - c)\, q_{N,t}, \tag{4}$$

where c are the newcomer's marginal costs of production, which are identical to that of the incumbent.

In the r&d stage, the newcomer chooses an idea $\delta_{N,t} \in [0, \Delta]$ (i.e., from the same range of options that are accessible to the incumbent) that improves the quality of the new technology. Depending on how ambitious this idea is, the development induces r&d costs $\gamma_0 + \gamma_N\, \delta_{N,t}$.

The number of newcomers is endogenous: They try to enter the market (during the r&d stage) until there are so many successful innovations that trying to enter does not yield a non-negative profit anymore.

In addition to newcomers that develop the new technology further, there can be entrants that simply take the previous period's technology (which is freely available) and sell this technology. This is feasible in all periods after the first period in which the new technology has been developed (if it has been developed at all). For simplicity, we assume that these entrants can produce the old version of the new technology at the same marginal costs as the other newcomers (i.e., at marginal costs c). Given that firms that do not develop the technology further can enter the market without fixed costs and that there is an unlimited number of such firms, the price for the new technology will always equal the marginal costs c, whenever such firms enter the market.

3.4. Additional assumptions

To avoid tedious notation, we use some additional assumptions that have no strong impact on our qualitative results but that help to interpret them more easily. First, we normalize the quality of the old technology to $K = 1$. Thus, as soon as the new technology gains this quality, the old technology can be fully phased out.

Second, we set the marginal costs of producing the technologies equal to zero: $c = 0$. As pricing in our model is a markup on marginal costs, this simply anchors prices. Also, we set the starting quality of the new technology to zero: $k_0 = 0$. This implies that, without development, the new technology will not be used at all and that perfect competition is not feasible during the first period ($t = 1$), as all firms that are active in the market have to recover r&d costs.

Third, we assume that innovation is not costless, that is, that we have $\gamma > 0$ and $\gamma_0 + \gamma_N > 0$.

Finally, we assume that the achievable quality for the new technology is bounded above. For simplicity, we assume that this boundary equals $1 + \epsilon$ with $\epsilon > 0$ and (for notational simplicity) chosen in a way, so that $(1 + \epsilon)/\Delta$ is an integer. These assumptions imply that the new technology can fully replace the old technology and that at least $(1 + \epsilon)/\Delta$ steps of technological progress are required to achieve this.

4. Model analysis

We analyze the model introduced above in several steps. First, we characterize the socially optimal outcome to gain a benchmark. Second, we analyze the production stage of the game to derive possible technology market structures. Third, we investigate the r&d stage. Given all this information, we can then first characterize the r&d and market dynamics, showing how the market structure will evolve over time, and derive the environmental impact throughout the technology transition from this analysis. Finally, we compare the market outcomes to the socially optimal situation.

4.1. The socially optimal solution

In a first step, we characterize the socially optimal solution. As the model is deliberately designed to be simple apart from the strategic interaction of the incumbent and potential entrants (which does not influence the socially optimal solution), the social optimum is simple. At the production stage, a social planner would use the quantities[1]

$$Q_t(k_{t-1} + \delta_t) = \frac{\max\{1 - d - k_{t-1} - \delta_t,\ 0\}}{1 - \alpha}, \tag{5}$$

$$q_t(k_{t-1} + \delta_t) = \min\{\max\{\frac{k_{t-1} + \delta_t + \alpha\,(d\ - 1)}{\alpha\,(1 - \alpha)},\ 0\},\ \frac{k_{t-1} + \delta_t}{\alpha}\}. \tag{6}$$

Here, k_{t-1} denotes the quality of the new technology inherited from the previous period (with $k_0 = 0$) and δ_t is the quality enhancement achieved in the current period. Note that these quantities are in line with prices $P_t = d, p_t = 0$, which implies a full internalization of the external damage.

Welfare (before subtracting r&d costs) can be easily calculated by integrating the individual utilities over the continuum of consumers that actually buy a unit of technology, taking into account their choice of technology, and subtracting environmental damage:

$$W(k_t) := k_t\, q_t(k_t) + Q_t(k_t)\,(1 - d) - \frac{1}{2}\left(\alpha\, q_t(k_t)^2 + 2\,\alpha\, q_t(k_t)\, Q_t(k_t) + Q_t(k_t)^2\right). \tag{7}$$

The welfare gain due to increasing the quality of the new technology from k_{t-1} to $k_{t-1} + \delta_t$ (again before considering r&d costs) is given by:

$$\Delta W_t := W(k_{t-1} + \Delta) - W(k_{t-1}). \tag{8}$$

Taking into account the above quantities (Eqs. (5) and (6)), this welfare gain is either zero or a strictly convex function of δ_t. Consequently, if the social planner innovates in a given period, she will innovate as much as is feasible ($\delta_t = \Delta$, if $k_{t-1} < 1 + \epsilon$). Furthermore, the welfare gain is non-decreasing in k_{t-1} until $k_{t-1} = 1 - d$, which is the point where the new technology has driven the old one out of the market (given that the social planner fully internalizes the environmental damage). Thus, if innovation starts, the social planner will always innovate until this point is reached and possibly further until $k_t = 1 + \epsilon$.

[1]The maximum operators arise, as both Q_t and q_t are non-negative. The minimum operator results from the fact that, once $Q_t = 0$, an increase of the quality of the new technology has a smaller effect on q_t than for $Q_t > 0$, as there is no longer an opportunity to displace the old technology.

If innovation is optimal, the social planner would ask either the incumbent or a single new entrant to develop the technology, depending on who has the lower r&d costs. To simplify notation, let us define $\underline{\gamma}_t := \min\{\gamma\,\Delta, \gamma_0 + \gamma_N \ \min\ \Delta\}$, which denotes the minimal costs of achieving the highest possible technology advancement at time t. Finally, let ϱ denote the social discount rate and assume that the social planner uses a fixed time horizon $T > (1+\epsilon)/\Delta$ to assess the benefits of r&d.

Whether it is socially optimal to innovate depends on whether innovation costs are smaller or greater than current and future welfare improvements induced by the increasing quality of the new technology. Given the simplicity of our model, the new technology should be fully developed if

$$\sum_{t=1}^{\frac{1+\epsilon}{\Delta}} \frac{W(t\,\Delta) - \underline{\gamma}_t}{(1+\varrho)^{t-1}} + \sum_{t=\frac{1+\epsilon}{\Delta}+1}^{T} \frac{W(1+\epsilon)}{(1+\varrho)^{t-1}} > \sum_{t=1}^{T} \frac{W(0)}{(1+\varrho)^{t-1}}. \tag{9}$$

If this criterion does not hold, new technology should be developed until the old technology is fully replaced, if[2]

$$\sum_{t=1}^{\frac{1+d}{\Delta}} \frac{W(t\,\Delta) - \underline{\gamma}_t}{(1+\varrho)^{t-1}} + \sum_{t=\frac{1+d}{\Delta}+1}^{T} \frac{W(1+d)}{(1+\varrho)^{t-1}} > \sum_{t=1}^{T} \frac{W(0)}{(1+\varrho)^{t-1}}. \tag{10}$$

Note that, for sufficiently low r&d costs, the social planner will always decide to innovate fully. In particular, innovation will occur even if the technology cannot be sold during the first period(s), that is, if $\Delta - \alpha\,(1-d) < 0$ and thus $q_t(\Delta) = 0$.

This analysis shows that the setting considered is quite simple in a first-best situation with straight forward rules for pricing the technologies and for deciding whether to develop the new technology or not. Thus all complexities in the following analysis result solely from the strategic interaction of entrants and the incumbent.

4.2. Production stage and technology market structures

We now analyze the incumbent's and entrants' behaviour in the production stage of our model, that is, the stage where the already developed technology is produced and sold to consumers. We perform this analysis in three subsequent steps that resemble the phases of the technology transition: We describe the first period, where the new technology may enter the market, a number of intermediate periods, where the old and the new technology share the market, and a final period,

[2] To avoid notational complexity, we assume that $(1+d)/\Delta$ is an integer to state this condition.

where the old technology is phased out completely. For all phases, we take innovation and the number of entrants (n_t in period t) as given, as these will be decided in the r&d stage of the game.

For the first period, either only the old or both technologies will be sold. In this first stage, no old version of the new technology is available, as development has just commenced.

Proposition 1. *In period* 1*, where no freely available technological quality for the new technology is available (*$k_0 = 0$*), the following four market outcomes are possible, assuming that all entrants choose the same level of innovation and that* $\delta_{I,1}, \delta_{N,1} < 1$*:*

1. *If* $\delta_{I,1} > \alpha$ *and* $\delta_{I,1} \geq 2\,\delta_{N,1}$*, only the incumbent is active and sells both the old and the new technology, with*

$$q_{I,1} = \frac{\delta_{I,1} - \alpha}{2\,\alpha\,(1-\alpha)}, \tag{11}$$

$$Q_1 = \frac{1 - \delta_{I,1}}{2\,(1-\alpha)}. \tag{12}$$

2. *If* $\delta_{N,1} > \alpha/2$ *and* $\delta_{N,1} \geq \frac{2\,(n_1+1)\,(2-\alpha)\,\delta_{I,1} - 2\,\alpha}{2\,n_1\,(1-\alpha)}$*, the incumbent sells the old technology and the entrants sell the new technology, with*

$$q_{N,1} = \frac{2\,\delta_{N,1} - \alpha}{\alpha\,(2 + n_1\,(2-\alpha))}, \tag{13}$$

$$Q_1 = \frac{1 + n_1\,(1 - \delta_{N,1})}{2 + n_1\,(2-\alpha)}. \tag{14}$$

3. *If* $\frac{\delta_{I,1}}{2} < \delta_{N,1} < \frac{2\,(n_1+1)\,(2-\alpha)\,\delta_{I,1} - 2\,\alpha}{2\,n_1\,(1-\alpha)}$*, the new technology is sold both by incumbent and entrants and the incumbent sells the old technology with*

$$q_{N,1} = \frac{2\,\delta_{N,1} - \delta_{I,1}}{(n_1+2)\,\alpha}, \tag{15}$$

$$q_{I,1} = \frac{\delta_{I,1}\,(2\,(n_1+1) - n_1\,\alpha) - 2\,n_1\,\delta_{N,1}\,(1-\alpha)}{2\,(n_1+2)\,\alpha\,(1-\alpha)} - \frac{1}{2\,(1-\alpha)}, \tag{16}$$

$$Q_1 = \frac{1 - \delta_{I,1}}{2\,(1-\alpha)}. \tag{17}$$

4. *If* $\delta_{N,1} \leq \alpha/2$ *and* $\delta_{I,1} \leq \alpha$*, only the old technology is sold (by the incumbent), with*

$$Q_1 = \frac{1}{2}. \tag{18}$$

Proof. We first derive demand for both technologies from Eqs (1) and (2). If only the old technology is offered (no or no sufficient innovation), demand for the old technology equals $Y_1 = 1 - P_1$. If the old and the new technology are offered by the incumbent with the quality of the new technology being $\delta_{I,1}$, demand for the old technology is $Y_1 = \frac{1-(P_1-p_1)-\delta_{I,1}}{1-\alpha}$ and demand for the new technology equals $y_1 = \frac{\delta_{I,1}+\alpha\,(P_1-1)-p_1}{\alpha\,(1-\alpha)}$. In case the newcomers offer the new technology instead of the incumbent, the latter two equations still hold with $\delta_{I,1}$ being replaced by $\delta_{N,1}$. In case the incumbent and the newcomers share the market for the new technology, these equations still hold and, in equilibrium, the price of the version of the technology offered by a newcomer has to equal $p_{N,1} = p_1 + \delta_{N,1} - \delta_{I,1}$.

Calculating the equilibria of a Cournot game (or the monopoly outcome in cases without newcomers) directly leads to the equations above. The conditions for the different cases stem from the requirement that all prices and all quantities have to be non-negative. □

This proposition shows that, under our limit to possible innovations in the first period, the old technology will never be phased out immediately. Furthermore, it highlights that minimal innovations are required for the new technology to enter the market; either the entrants have to achieve an innovation $\delta_{N,1} > \alpha/2$, or the incumbent has to achieve $\delta_{I,1} > \alpha$. The asymmetry in these conditions stems from the fact that the incumbent has an incentive to protect the old technology. Selling the new technology is only profitable to him if the new technology creates sufficient additional demand, which is achieved either by a high initial quality (large Δ) or a strong market expansion effect (low α).

Finally, the proposition shows that, depending on innovations, it is possible that the incumbent and the entrants share the market for the new technology or that the new technology is only provided by the newcomers or only by the incumbent. As is to be expected, market sharing occurs if neither the incumbent nor the entrants exceed the other too strongly regarding the achieved quality improvement.

There are some notable additional insights to be gained. First, the range in which the market is shared increases with $\delta_{I,1}$ but decreases with α (and also with n_1). Thus, the more innovative the incumbent is, the broader is the range of innovations of the entrants that allows them to share the market with the incumbent. Furthermore, the smaller the market expansion effect is (i.e., the closer α gets to 1), the less situations arise in which the firms will share the market. The reason for this is that a smaller market expansion effect makes it more interesting for the incumbent to focus solely on the old technology.

Second, the barriers to entry increase with α. Thus, a successful phase-in of the new technology depends strongly on the possible market expansion. This is a well-known result from innovation studies, which show that people that adopt a new technology due to its novelty (and not with particular regard to its quality) are important for the first stages of market diffusion.

Finally, the number of entrants does not alter the barrier to entry but influences the shape of the market. A higher number of entrants increases competition between entrants but makes competition between the entrants and the incumbent less likely, as, for large values of n_1, the incumbent will prefer to focus on the old technology.

Thus already in the first period, a number of different outcomes are possible. We now move to the second stage of the transition, where the old and the new technology co-exist on the market. Note that this stage only exists if the new technology has been developed in the first period. Thus, there is an old version of the new technology, which will be sold if no strong improvements are made.

Proposition 2. *If the new technology has been developed and its freely available quality in period $t \geq 2$ is k_{t-1} and if $\delta_{I,t} + k_{t-1} < 1$ and $\delta_{N,t} + k_{t-1} < 1 + 1/n_t$, the old and the new technology are available, with the following cases:*

1. *If $\delta_{I,t} + k_{t-1} \geq \alpha$, the incumbent sells both the old technology and the new version of the new technology, with*

$$q_{I,t} = \frac{\max\{\delta_{I,t}, k_{t-1}\} + k_{t-1} - \alpha}{2\,\alpha\,(1-\alpha)}, \tag{19}$$

$$Q_t = \frac{1 - k_{t-1} - \max\{\delta_{I,t}, k_{t-1}\}}{2\,(1-\alpha)}. \tag{20}$$

2. *If $\delta_{N,t} + k_{t-1} > \alpha/2$ and $\delta_{I,t} \leq \frac{2\,n_t\,\delta_{N,t}\,(1-\alpha)+\alpha\,(2+n_t))-k_{t-1}\,(2+n_t\,\alpha)}{2+n_t\,(2-\alpha)}$, the old technology is sold by the incumbent and the new version of the new technology is sold by the entrants with*

$$q_{N,t} = \frac{2\,(k_{t-1} + \delta_{N,t}) + \alpha}{(2 + n_t\,(2-\alpha))\,\alpha}, \tag{21}$$

$$Q_t = \frac{(n_t + 1) - n_t\,(\delta_{N,t} + k_{t-1})}{2\,(n_t + 1) - n_t\,\alpha}. \tag{22}$$

3. *If $\delta_{N,t} + k_{t-1} > \alpha/2$ and $\frac{2\,n_t\,\delta_{N,t}\,(1-\alpha)+\alpha\,(2+n_t)-k_{t-1}\,(2+n_t\,\alpha)}{2+n_t\,(2-\alpha)} < \delta_{I,t} < \max\{\alpha, k_{t-1} + 2\delta_{N,t}\}$, the old technology is sold by the incumbent and the market for the new version of the new technology is shared by the entrants and the incumbent.*

In this case, we have

$$q_{N,t} = \frac{k_{t-1} + 2\,\delta_{N,t} - \delta_{I,t}}{(n_t + 2)\,\alpha}, \tag{23}$$

$$q_{I,t} = \frac{\delta_{I,t}\,(2\,(n_t + 1) - n_t\,\alpha) + k_{t-1}\,(2 + n_t\,\alpha) - 2\,n_t\,\delta_{N,t}\,(1 - \alpha)}{2\,(n_t + 2)\,\alpha\,(1 - \alpha)} - \frac{1}{2\,(1 - \alpha)}, \tag{24}$$

$$Q_t = \frac{1 - \delta_{I,t} - k_{t-1}}{2\,(1 - \alpha)}. \tag{25}$$

4. *If $\delta_{I,t} < k_{t-1} - n_t\,\delta_{N,t}$, and $\delta_{N,t} < \frac{2\,k_{t-1}-\alpha}{n_t\,(2-\alpha)}$, the incumbent will sell the old technology and the new technology is sold in its new (if either $\delta_{N,t} > 0$ or $\delta_{I,t} > 0$) or old (if $\delta_{N,t} = \delta_{I,t} = 0$) version, with*

$$q_{tot,t} = \frac{k_{t-1}}{\alpha} - \frac{1 - k_{t-1}}{2\,(1 - \alpha)}, \tag{26}$$

$$Q_t = \frac{1 - \ k_{t-1}}{2\,(1 - \alpha)}, \tag{27}$$

where $q_{tot,t}$ denotes the total supply of the new technology.

Proof. The proof proceeds as for Prop. 1, with some exceptions. First, the already existing quality of the new technology (k_{t-1}) alters demand, so that we get $Y_t = \frac{1-(P_t-p_t)-\delta_{I,t}-k_{t-1}}{1-\alpha}$ and $y_t = \frac{k_{t-1}+\delta_{I,t}+\alpha\,(P_t-1)-p_t}{\alpha\,(1-\alpha)}$. Second, the case where only the old technology is sold does not exist anymore. Third, as an additional constraint for the different cases, we get that the price quality combination offered for the new version of a technology has to meet the condition $\delta_{I,t} - p_t \geq 0$ (and similarly for the version offered by the newcomers), otherwise customers will choose the old version of the new technology (quality k_{t-1}), which is offered by possible entrants that have not made an improvement to the new technology, thus enter until the price for their version of the technology is reduced to marginal costs (which are normalized to zero). This additional constraint also leads to the max operator in Case 1, where the incumbent can be limited in setting the price for the new technology if the quality improvement is not substantial enough. □

Finally, there is the last stage of the transition, where the old technology is phased out. In this stage, market outcomes are slightly changed.

Proposition 3. *If the new technology has been developed and its freely available quality in period $t \geq 2$ is k_{t-1}, and if either $\delta_{I,t} + k_{t-1} \geq 1$ or $\delta_{N,t} + k_{t-1} \geq 1 + 1/n_t$, the old technology is phased out and only the new technology is sold, with the following cases:*

1. *If $\delta_{I,t} \geq k_{t-1} + 2\,\delta_{N,t}$, the incumbent sells the new version of the new technology, with*

$$q_{I,t} = \frac{\min\{\delta_{I,t} + k_{t-1}, 1 + \epsilon\}}{2\,\alpha}. \tag{28}$$

2. *If $\delta_{I,t} \leq \frac{n_t\,\delta_{N,t} - k_{t-1}}{n_t+1}$, the entrants sell the new version of the new technology, with*

$$q_{N,t} = \frac{\min\{\delta_{N,t} + k_{t-1}, 1 + \epsilon\}}{(n_t + 1)\,\alpha}. \tag{29}$$

3. *If $\max\{k_{t-1} - n_t\,\delta_{N,t}, \frac{n\,\delta_{N,t} - k_{t-1}}{n_t+1}\} < \delta_{I,t} < k_{t-1} + 2\,\delta_{N,t}$, incumbent and entrants both sell the new version of the new technology, with*

$$q_{N,t} = \frac{\{k_{t-1} + 2\,\min\{\delta_{N,t}, 1 + \epsilon - k_{t-1}\} - \min\{\delta_{I,t}, 1 + \epsilon - k_{t-1}\}}{(n_t + 2)\,\alpha}, \tag{30}$$

$$q_{I,t} = \frac{k_{t-1} + \min\{\delta_{I,t}, 1 + \epsilon - k_{t-1}\} + n_t\,(\min\{\delta_{I,t}, 1 + \epsilon - k_{t-1}\} - \min\{\delta_{N,t}, 1 + \epsilon - k_{t-1}\})}{(n_t + 2)\,\alpha}. \tag{31}$$

4. *If $\delta_{I,t} < k_{t-1} - n_t\,\delta_{N,t}$ and $\delta_{N,t} < \frac{2\,k_{t-1} - \alpha}{n_t\,(2-\alpha)}$, the new technology is sold in its new (if either $\delta_{N,t} > 0\ \delta_{I,t} > 0$) or old (if $\delta_{N,t} = \delta_{I,t} = 0$) version, with a total supply of*

$$q_{tot,t} = \frac{k_{t-1}}{\alpha}. \tag{32}$$

Proof. Similar to that of Prop. 2, but taking into account that there is no more demand for the old technology, as the quality of the new technology is at least as high as that of the old one. □

Propositions 2 and 3 show that once an old version of the technology becomes available, market outcomes are changed. We have similar outcomes as in Prop. 1, where a new version of the new technology is sold. In these cases, we have either Cournot competition or a monopolist (the incumbent) supplying the market.

In addition, there is a fourth case in both propositions, where improvements to the new technology become too small to support a non-competitive pricing. This case arises when the freely available old version of the new technology, which can be supplied in arbitrary quantity at marginal costs, offers a better quality/price combination to consumers than the new version of this technology sold at the Cournot (or monopolistic) price. The firms that developed the new version can only sell their technology, if they increase production beyond the Cournot level, so that the

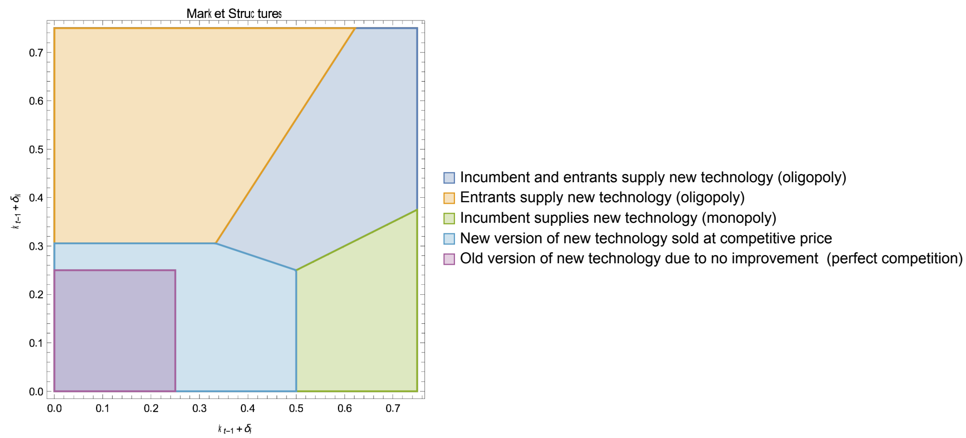

Figure 1: Technology market structures for different qualities offered by entrants ($k_t + \delta_N$) and the incumbent ($k_t + \delta_I$) calculated for $\Delta = 0.25$, $\alpha = 0.2$, $n = 3$, $\epsilon = 0$.

price of the new version drops sufficiently. The smaller the improvements are, the closer the price thus gets to the competitive level. Once there are no further improvements, the old version of the new technology is sold. Note that this is the eventual outcome, once the new technology cannot be improved anymore, and that this implies (as we assumed a limited lifetime of patents) that the market for the new technology will eventually become fully competitive.

Figure 1 shows different possible market structures as a function of the qualities of the new technology offered by entrants and the incumbent.

4.3. Innovation decisions

Based on the above market outcomes in the different phases of technological change, we can now analyze the innovation decisions. Our first result shows that all players will always choose a corner solution, that is, either full or no innovation, or, in case of the incumbent, a level of r&d efforts that prevents newcomers from making r&d efforts. To simplify our notation, we define $\zeta := \sqrt{\gamma_0 + \gamma_N \Delta}$ as a measure of the entrants' r&d costs.

Lemma 1. *In the r&d game, new entrants will always choose a corner solution (full or no innovation) and the incumbent either chooses a corner solution or a level of innovation that deters r&d by newcomers.*

Proof. The profits of the incumbent and the new entrants for the different outcomes of the production stage are given in Table 1 as a function of the quality changes δ_I, δ_N. Due to the temporal structure of the game, the new entrants move last and

Table 1: Profits achieved by incumbent and new entrants for the different cases in Prop. 1 and 2, where δ_I is the quality improvement made by the incumbent, δ_N that of the average newcomer, δ_{N_i} the quality improvement made by a particular newcomer i, δ_R the quality improvement made by all other newcomers, and n is the number of newcomers.

	Profit Incumbent	Profit Entrants
Case 1	$\frac{k_{t-1}^2+\alpha+2\,k_{t-1}\,(\delta_I-\alpha)+\delta_I\,(\delta_I-2\,\alpha-4\,\alpha\,\gamma\,(1-\alpha))}{4\,\alpha\,(1-\alpha)}$	–
Case 2	$\frac{(1+n\,(1-k_{t-1}-\delta_N))^2}{(2+n\,(2-\alpha))^2}$	$\frac{(\alpha-2\,k_{t-1}-2\,n\,\delta_{N_i}\,(1-\alpha)-\alpha\,\delta_{N_i}+(n-1)\,(2-\alpha)\,\delta_R)^2}{\alpha\,(2+n\,(2-\alpha))^2} - \gamma_N\,\delta_{N_i} - \gamma_0$
Case 3	$\frac{(1-k_{t-1}-\delta_I)^2}{4(1-\alpha)} + \frac{(k_{t-1}+(n+1)\,\delta_I-n\,\delta_N)^2}{(n+2)^2\alpha} - \gamma\,\delta_I$	$\frac{\left(n\,(\delta_{N_i}-\delta_N)+k_{t-1}+\delta_{N_i}+\delta_N-\delta_I\right)^2}{(2+n)^2\alpha} - \gamma_N\,\delta_{N_i} - \gamma_0$
Case 4	$\frac{1}{4}$, if $k_{t-1}=0$; $\frac{(1-k_{t-1})^2}{4\,(1-\alpha)}$, if $k_{t-1}>0$	–

their decision can thus be inspected without taking the effect on the incumbent's decision into account. The profit of the new entrants is a convex function of their r&d decision (the profit being a quadratic function of the quality change with the second derivative being strictly positive). Thus, a profit maximizing entrant will always choose a corner solution.

For the incumbent, we first consider only cases where the incumbent pursues the development of the new technology (Cases 1 and 3 of Prop. 1 and 2) and where the incumbent does not try to strategically deter newcomers from r&d. In Case 1, the incumbent's profit is a quadratic function of the quality change, again with a strictly positive second derivative, so that the incumbent will always choose a corner solution. In Case 3, the number of entrants is influenced by the incumbent's innovation with $n = \frac{k_{t-1}+2\,\Delta-\delta_I}{\zeta\,\sqrt{\alpha}} - 2$. This case again leads to a corner solution, as the profit is a quadratic function of δ_I and the candidate for the interior solution always corresponds to a profit minimum not a maximum. This analysis shows that the incumbent will either choose a corner solution or some level of r&d that deters market entry via r&d.

For the final step of technological change (Prop. 3), the analysis is almost identical and thus omitted here. □

This lemma simplifies the following analysis considerably. Note that it is mostly a consequence of the market structure analyzed in the preceding section. If innovation pays off, then it is best to innovate as much as is feasible. This holds directly for the potential newcomers, as the temporal structure of the r&d game implies that they cannot influence the incumbent's r&d decision. Thus, if they want to innovate it is best to innovate strongly, because the gain in revenues due to a higher quality of the technology is higher than the additional r&d costs; higher quality increases the overall market size (and thus sales) and the equilibrium price and thus has a nonlinear effect on profit, whereas r&d costs are linear in quality enhancement.

For the incumbent, a similar reasoning applies. In addition, two other effects arise: A better new technology means less revenue coming from the old technology, which reduces innovation incentives, and more innovation by the incumbent leads to less new entrants, thereby reducing the level of competition and thus increasing revenues from selling both the new and the old technology. Again, this leads to a situation where some innovation is always worse than either no or full innovation: It already reduces the revenue attainable with the old technology but does not keep competition at bay. The exception (as we will show below) is a case where full innovation is not profitable for the incumbent, but a small innovation might deter entrants from pursuing r&d. In this case, the incumbent might choose to do just enough r&d to deter market entry.

This reasoning holds for a cost structure that is linear in innovation. But it would still apply for mildly non-linear r&d costs, as long as the cost effects do not overcompensate the quadratic increase in revenue within the range of feasible innovations $[0, \Delta]$.

Based on Lemma 1, we can now analyze under which conditions entrants and the incumbent innovate. Given the complexity of the product market outcomes, this requires multiple steps. However, it is essential for analyzing the technology and market dynamics. Readers not interested in these intermediate results might consider to proceed to the next subsection, which contains all major insights of the paper.

Given that the incumbent moves first, we use the following strategy for deriving the possible equilibria: As the incumbent moves first, we start by investigating the entrants' r&d decision (Lemma 2). Using this information, we analyze the incumbent's r&d decision, first for the case where the entrants never innovate (Lemma 3), then for the case where at least one entrant always innovates (Lemma 4), and finally for the case where the entrants' decisions depends on the incumbent's r&d choice (Lemma 5). The proofs of all these Lemmata can be found in the appendix.

Lemma 2. *If the incumbent innovates, at least one newcomer innovates and enters the market, if and only if*

$$k_{t-1} + \Delta \geq 3\, \zeta \sqrt{\alpha}, \tag{33}$$

$$k_{t-1} + \Delta \leq 1 - 2\, \zeta\, \sqrt{\alpha}\, \frac{(1-\alpha)}{\alpha}. \tag{34}$$

If the incumbent does not innovate, at least one newcomer innovates and enters the market, if and only if

$$k_{t-1} + \Delta \geq \frac{1}{2}\left(\zeta \sqrt{\alpha}\,(4-\alpha) + \alpha\right). \tag{35}$$

Lemma 3. *Assume that Condition* (35) *and at least one of the Conditions* (33)–(34) *is not met, so that the entrants never innovate. In this case, the incumbent innovates if and only if*

$$\gamma < \begin{cases} \frac{(\Delta-\alpha)^2}{4\,(1-\alpha)\,\alpha\,\Delta}, & k_{t-1} = 0, \\ \frac{k_{t-1}^2\,(1-\alpha)+2\,\Delta\,(k_{t-1}-\alpha)+\Delta^2}{4\,(1-\alpha)\,\alpha\,\Delta}, & k_{t-1} > 0, \end{cases} \tag{36}$$

$$\Delta + k_{t-1} \geq \alpha. \tag{37}$$

If the incumbent innovates, the quality improvement will be as large as possible, that is, $\delta_I = \Delta$.

Lemma 4. *Assume that Condition* (35) *and all of the Conditions* (33)–(34) *are met, so that at least one entrant always innovates. In this case, the incumbent innovates if and only if*

$$\gamma < \frac{\frac{(k_{t-1}+\Delta-1)^2}{4\,(1-\alpha)} + \zeta^2 - \frac{(k_{t-1}+\Delta-1-\zeta\,\sqrt{\alpha})^2}{(2-\alpha)^2}}{\Delta}. \tag{38}$$

If the incumbent innovates, the quality improvement will be as large as possible, that is, $\delta_I = \Delta$.

Lemma 5. *Assume that Condition* (35) *is met but that at least one of the Conditions* (33)–(34) *is not met. Then, the following holds:*

1. *If*

$$\gamma < \frac{\frac{(k_{t-1}+\Delta)^2+\alpha\,(1-2\,(k_{t-1}+\Delta))}{\alpha\,(1-\alpha)} - \frac{4\,(k_{t-1}+\Delta-1-\zeta\,\sqrt{\alpha})^2}{(2-\alpha)^2}}{4\,\Delta}, \tag{39}$$

   the incumbent will innovate with $\delta_I = \Delta$.

2. *If Eq.* (39) *does not hold but*

$$\gamma < \frac{\alpha + k_{t-1}^2 - 2\,\tilde{\delta}\,\alpha + \tilde{\delta}^2 + 2\,k_{t-1}\,(\tilde{\delta}-\alpha)}{4\,\alpha\,(1-\alpha)\,\tilde{\delta}} - \frac{k_{t-1} + \Delta - 1 - \zeta\,\sqrt{\alpha}}{\tilde{\delta}\,(2-\alpha)^2} \tag{40}$$

   with

$$\tilde{\delta} = \begin{cases} \alpha & \text{if } \alpha \geq \max\{k_{t-1}, k_{t-1} + 2\,\Delta - 3\,\zeta\,\sqrt{\alpha}\}, \\ k_{t-1} & \text{if } \alpha < k_{t-1} < \Delta < \frac{3}{2}\,\zeta\,\sqrt{\alpha}, \\ k_{t-1} + 2\,\Delta - 3\,\zeta\,\sqrt{\alpha} & \text{if } \alpha < k_{t-1} < 3\,\zeta\,\sqrt{\alpha} - \Delta < \Delta \\ k_{t-1} + 2\,\Delta - 3\,\zeta\,\sqrt{\alpha} & \text{if } \alpha + 3\,\zeta\,\sqrt{\alpha} - 2\,\Delta < k_{t-1} < \min\{\alpha, 3\,\zeta\,\sqrt{\alpha} - \Delta\}, \end{cases} \tag{41}$$

then the incumbent innovates with $\delta_I = \tilde{\delta} < \Delta$, which is the value of δ_I that just enables Case 1 of Prop. 1 and 2.

Together, these Lemmata provide a full picture of the r&d process, which provides the basis for our main results on technology and market dynamics.

4.4. Dynamics of technological change and evolving market structures

Using the above information, we can now assess the innovation dynamics. We first provide a broad characterization of innovation incentives.

Proposition 4. *In the first period, there are three main settings that differ regarding the main driver of innovation:*

1. *If $\Delta < \frac{\alpha}{2}$, there will be no innovation.*
2. *If $\frac{\alpha}{2} \leq \Delta < \alpha$, innovation is driven either directly by new entrants or by the incumbent in response to a threat of market entry. Thus, in this case, innovation only occurs if the entrants' r&d costs are sufficiently small (i.e., Cond.* (34) *holds).*
3. *If $\Delta \geq \alpha$, innovation can either be driven by the incumbent (irrespective of the behaviour of potential entrants) or jointly by the incumbent and entrants. Thus innovation can happen if the innovation costs of either the incumbent or the entrants are sufficiently small (i.e., Cond.* (36) *or Cond.* (34) *holds).*

Proof. By Lemma 3, the incumbent will only innovate if either $\Delta \geq \alpha$ or if there is a credible threat of innovation by newcomers. The latter case only arises if either Cond. (35) or Cond. (33)–(34) hold. By Lemma 4 and 5 Assertions 2 and 3 follow from this.

Furthermore, if $\Delta < \frac{\alpha}{2}$, Cond. (35) cannot be met in the first period (where $k_{t-1} = 0$, so that the entrants will never innovate if the incumbent does not innovate, and the incumbent will not innovate, as $\Delta < \alpha$. This proves Assertion 1. □

The three cases outlined in Proposition 4 correspond to starkly different sets of incentives for developing the new technology. If $\Delta \geq \alpha$, it is beneficial for the incumbent to have the new technology; the gains from selling the new technology can immediately outweigh lost revenue for the old technology. This case occurs if the market expansion effect is substantial (α being small) and the new technology can be developed rapidly (Δ being large). In this case, r&d costs are the only bottleneck for the development of the new technology. If these costs can be recovered (either Cond. (36) or Cond. (34) holds), innovation will start.

In the other case ($\Delta < \alpha$), the emergence of the new technology is initially seen as a threat by the incumbent, as the losses (less revenue from selling the old technology) exceed the highest possible gains from selling the new technology. Thus, without the threat of entry, the incumbent will not develop the new technology. This implies that the new technology will either be developed by the entrants or by the incumbent, but now as a strategic means to prevent or at least limit market entry.

Finally, if we even have $\Delta < \frac{\alpha}{2}$, the quality of the new technology that can be achieved in a first stage is so small, compared to the potential market expansion, that the incumbent can successfully prevent a sale of the new technology by expanding the quantity offered of the old technology. Anticipating this, no newcomer will try to develop the new technology, as r&d expenses cannot be recovered. This even holds if the entrants' r&d costs are very small, as the profit achievable by selling the new technology is zero.

Note that the conditions separating the different cases of Prop. 4 are independent of r&d costs. Thus, even if innovation costs are close to zero, the incumbent will prevent the development of the new technology, whenever $\Delta < \frac{\alpha}{2}$. This stands in marked contrast to the social optimum, where we have shown that for low innovation costs, the new technology should always be developed.

The next proposition shows, that the first period is indeed crucial: If innovation is not started then, it will never occur. If it is started, the old technology will always be phased out.

Proposition 5. *The old technology will be completely replaced by the new technology if and only if there is innovation in the first period.*

Proof. If there is no innovation in the first period, the next (and all subsequent) period will be exactly identical, so that there will never be innovation.

If there is innovation in the first period, all conditions for innovation in subsequent periods get more relaxed, due to $k_{t-1} > 0$, except for Cond. (34). However, whenever Cond. (33) is met (as it becomes more relaxed with increasing k_{t-1} it is always met if it was met in a previous period) and Cond. (34) is not met, Cond. (35) will be met. This implies that if there was innovation by incumbent or newcomers at some point of time, this innovation will always be continued by the incumbent or by entrants later on. □

This proposition shows that innovation will always be continued up to the full development of the new technology if it has been started in the first period. The intuition is quite simple: Once innovation has started, the position of the incumbent is weakened, as at least an old version of the new technology will always be available. Thus, the incumbent has less incentive to prevent innovation than in the first period. This incentive to forestall innovation decreases faster than the incentive to innovate (which is also reduced, as the existence of the old version of the new technology reduces the profit achievable in the market), innovation will never stall, once it has begun.

So far, we have only investigated the questions whether and to what extent the new technology will be developed. As we have shown, the answers to these question depend strongly on the market situation and the resulting incentives. The next results outline how technological development and the structure of the technology market interact over time.

Proposition 6. *Assume that* $\gamma_0 + \gamma_N > 0$*,* $\gamma > 0$ *and* $\alpha < 1$*. Then, the following points hold:*

1. *Market sharing: A shared market occurs in the first period or never. If it occurs in the first period, it will end before the new technology is fully developed.*
2. *Monopoly: If the incumbent provides the new technology alone at some point of time, newcomers will never (re-) enter the market at some later point of time as long as innovation continues.*

Proof. The first assertion follows from Cond. (33), (34), and (38), which (together) are most easily met for k_{t-1}. In addition, they will never be jointly met for $k_{t-1} = 1 + \epsilon - \Delta$, which corresponds to the final period of innovation.

The second assertion follows from this and from Cond. (39) and (36) becoming more relaxed with an increasing k_{t-1}. As shown for the first assertion, if the entrants do not innovate in the first period, they will never innovate later on, if the incumbent also innovates. Thus newcomers might continue (for some time) to innovate, if the incumbent innovates but will never newly start to do so. As Cond. (39) and (36) become more relaxed with an increasing k_{t-1}, the incumbent will never stop innovating, once she has innovated without an entrant being present in the market. Together, these points imply that if newcomers have left the market, they will never enter again. □

This proposition shows that a shared market is an outcome that can only start to exist at the beginning of a technology transition and will certainly cease to exist at some time. Furthermore, if the incumbent takes over the development of the new technology, this is irreversible. Newcomers will never enter again at a later stage of technology development until the new technology has reached full maturity. At this stage, the market will become perfectly competitive, as there are no more patents.

The main cause of these results is that the innovation incentives for the incumbent increase over time: Her old technology becomes less and less valuable as the new technology progresses, and thus there is less and less reason not to innovate in order to protect the old technology. Furthermore, as the incumbent becomes less inclined to protect his old technology, a shared market becomes less likely. Such a market can exist, if the incumbent limits her own sales of the new technology to protect the old technology and thereby creates room for newcomers to co-exist on the market. This becomes less attractive to the incumbent over time, as the old technology becomes less important for her total profit.

As the following corollary shows, the above proposition implies that, in the final period in which there is innovation (i.e., the period t for which we have $k_{t-1} \geq 1 + \epsilon - \Delta$), the incumbent will serve the market alone, whenever newcomers are not much more efficient in r&d.

Corollary 1. *Let T be the first period for which $k_T \geq 1 - \Delta$ (if such a period exists). Then, whenever $\gamma\,\Delta < (\gamma_0 + \gamma_N\,\Delta)\,\frac{16-12\,\alpha+\alpha^2}{4\,\Delta\,(2-\alpha)^2}$ or if $(\gamma_0 + \gamma_N\,\Delta) > \frac{2-\alpha}{\sqrt{\alpha}\,(4-\alpha)}$, the incumbent alone will do the final step of innovation.*

Proof. This follows directly from Lemmata 2–5 by setting $k_{t-1} \geq 1 - \Delta$. □

This result is highly intuitive: The incumbent knows that if this step is done, the old technology will be phased out. As the incumbent is not able to prevent this (as the new technology is already far developed), it is better for the incumbent to do this final step than to hand the market completely to another firm.

With these results, we have characterized the transition process as far as is possible without using specific parameter assumptions. Our analysis shows that there are four main types of technology transitions, whenever the condition of Corollary 1 holds:

1. The incumbent does the innovation alone, from beginning to end.
2. The newcomers start the innovation and the incumbent takes over later.
3. Newcomers and the incumbent start the innovation jointly and the incumbent takes over after some time.
4. Newcomers and the incumbent start the innovation jointly, then the newcomers drive the transition for some time until the incumbent takes over eventually.

Thus, even in our fairly simple model, rather complex and diverse technology transitions are possible. Most importantly, they differ substantially regarding the evolution of the market structure. If the market expansion is very small, the technology transition will never be started. For intermediate levels of the market expansion, the transition will be started either by entrants or by entrants and the incumbent simultaneously. In both cases, the incumbent will eventually take over at some later point of time, as long as the condition of Corollary 1 holds. In this case, it is possible that the market for the new technology changes from a shared market to a

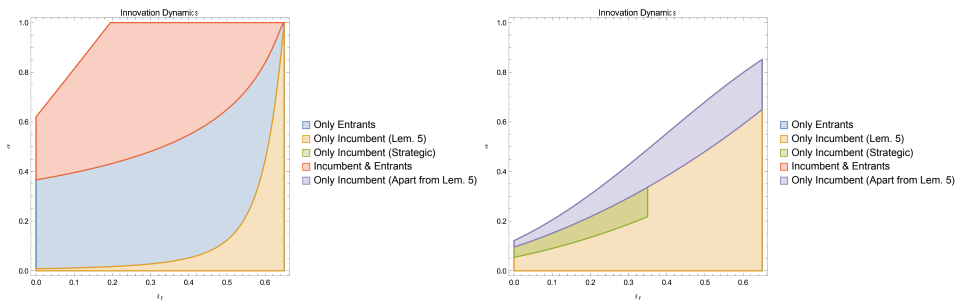

Figure 2: The transition process from the first period ($k_0 = 0$) to the final period ($k_T = 1 - \Delta$) calculated for $\Delta = 0.35$, $\zeta = 0.18$, $\gamma = 0.18^2$, $\epsilon = 0$ and differing values of α (left figure) and for $\Delta = 0.35$, $\zeta = 1$, $\gamma = 0.5$, $\epsilon = 0$ (right figure). The development will occur for the respective value of α along a horizontal line from left to right (increasing k_t). White areas are areas where no development will occur.

market served only by newcomers to a market served only by the incumbent. Finally, if the new technology expands the market strongly, the incumbent has strong incentives to pursue the new technology and will (except for cases where the r&d is much more expensive for the incumbent than for newcomers) follow through with the complete development of the new technology on its own.

The left and right part of Figure 2 depict different possible cases. In the left part, Cases 1,2 and 4 discussed above are possible, depending on the value of α. This figure is calculated for low r&d costs, which make it possible for entrants to start the innovation, and for r&d costs that are identical for entrants and the incumbent. In contrast, the right part of Figure 2 is calculated for high r&d costs for the entrants, so that the incumbent will drive the transition from the very beginning. As this figure shows, the market structure will remain unchanged (no entrant enters until the technology is fully developed), but the reason why the incumbent innovates can change over time, with the incentive to prevent entry becoming more important over the development process. This part of the figure also shows that strategic innovation, that is, innovation that is only made up to the point where it deters entry, is possible in the early stages of the technology transition.

As different market structures imply different levels of competition, this evolution of market structures has interesting effects for emissions during the technology transition, which we analyze in the following.

4.5. Emissions and policy implications

As most technology transitions take several decades, it is important to investigate not only whether such a transition is induced but also to have a close look at how rapidly emissions are reduced during the transition. This reduction has two components: How rapidly the new technology is developed and how widely it is used. Whereas the first point has an almost clear answer in our setting (except for the second case of Lemma 5, development either does not occur at all or as rapidly as possible), the second point is of substantial complexity. The extent to which the new technology replaces the old one depends on the relative prices of these technologies, which, in turn, depend on the level of competition on the market for the new technology and thus on the market structure.

In order to focus the analysis, it is important to note that Proposition 5 implies that if there is innovation in the first period, emissions will always go down to zero in the long run, as the old technology will be phased out eventually in this case. However, the dynamics of emissions can vary both qualitatively and quantitatively before this blissful state is attained.

The following Corollary to Proposition 4 shows that the incentives for innovation matter substantially for the dynamics of the environmental impact.

Corollary 2. *If the innovation process is started by the entrants or if we have $\Delta > \alpha$, emissions will decrease monotonically over time. In contrast, if innovation occurs as a result of strategic behavior, as outlined in Lemma 5, emissions can first increase before they eventually decline.*

Proof. The first part of the Corollary results directly from Prop. 1 and 2: Comparing usage of the old technology in Cases 1-3 to that in Case 4 of Prop. 1 (which equals the initial level of emissions), shows that for $\Delta \geq \alpha$, always full innovation (if it occurs) and a number of entrants that equals $n_t = \frac{k_{t-1}+2\,\Delta-\delta_I}{\zeta\,\sqrt{\alpha}} - 2$ for Case 3 of Prop. 1 and 2, or $n_t = \frac{\frac{2\,k_{t-1}+2\,\Delta-\alpha}{\zeta\,\sqrt{\alpha}}-2}{2-\alpha}$ for Case 2 of Prop. 1 and 2, the usage of the old technology is always reduced by innovation.[3]

This does not hold if we compare Case 1 of Prop. 1 with initial emissions (Case 4 of Prop. 1), for $\Delta < \alpha$. In this case, it is possible to find admissible parameter values so that emissions after an innovation are higher than before. □

Given that the new technology has zero emissions, this corollary is a somewhat surprising result. The reason why emissions could increase is that, in case the incumbent is driven to innovate in order to prevent market entry (i.e., the conditions of Lemma 5 hold), the incumbent has an incentive to strongly limit the sales of the new technology. The new technology will be used to serve the expanded market (i.e., customers who did not buy the old technology) and to keep customers from

[3]The number of market entrants is derived by setting the profit of the entrants (see Table 1) equal to zero for the respective case.

switching to the new technology, the incumbent will even reduce the price of the old technology. This actually increases sales of the old technology, which increases emissions.

This corollary thus shows that, even if we get the new technology, it is important to understand the incentives for developing the new technology. If these incentives result from strategic behavior, the switch to the new technology could be accompanied by temporarily increasing emissions, which will never happen in case of non-strategic innovation.

In addition to this qualitative difference in emission dynamics, the use of the old technology can decline more or less rapidly over time, depending on the market structure that is induced by the innovation. The following proposition yields an important insight to this point.

Proposition 7. *Assume that $k_t < 1 - \Delta$ and that*

$$\zeta < \frac{(1 - k_t - \Delta)\ \sqrt{\alpha}}{2\,(1 - \alpha)}. \tag{42}$$

Then, environmental damage is strictly smaller if the technology is supplied only by new entrants than in any other market equilibrium. In contrast, if $k_t < 1 - \Delta$ and

$$\zeta > \frac{(1 - k_t - \Delta)\ \sqrt{\alpha}}{2\,(1 - \alpha)}, \tag{43}$$

environmental damage is strictly smaller if the new technology is provided by the incumbent alone or by the incumbent and entrants simultaneously than in any other market equilibrium.

Proof. This follows directly from comparing emissions in Case 2 of Prop. 2 with those of Cases 1 and 3 for the number of entrants spelled out in the proof of Cor. 2. □

This result implies that the question who develops the new technology is important for the environmental impact during the transition phase. Note that the r.h.s. of Cond. (42) declines with technological progress. Thus, if the entrants' innovation costs are not too high, there will be less environmental damage whenever the entrants start to develop the new technology, but this can change later in the innovation process, where having the incumbent developing the new technology can lead to a stronger reduction of environmental damage.

This outcome is due to a trade-off between two effects. First, there is a competition effect. If only newcomers develop the new technology, there will be more competition in the market for the new technology (as substantially more newcomers enter, if the incumbent is not present in this market). This leads to a lower price of the new technology, which reduces usage of the old technology and thus environmental damage. Second, there is a dynamic effect: The incumbent will protect its old technology less, if he gets (at least some of) the profits from selling the new technology. Thus, in any market equilibrium in which the incumbent sells the new technology, emissions react more strongly to the quality of the new technology.

As the first effect is independent of the state of development of the new technology, whereas the second effect depends on cumulated development, the second effect becomes stronger during the development process. Thus, it can be the case that it is better to have entrants doing the first stages of green technology development and the incumbent taking over later on.

Our analysis so far shows how the evolving market structure influences emissions and under which conditions we can expect a technology transition. The final step of our analysis is to compare these market outcomes to the benchmark of the socially optimal solution derived at the beginning of this section. The following proposition derives two important insights from this .

Proposition 8. *Compared to the socially optimal solution, the technology transition starts in too few cases: Whenever the transition takes place in the market outcome, it is socially optimal to have a transition to the new technology, but there are parameter values for which such a transition is socially desirable but not induced by market incentives.*

If $d > \max\{\frac{1}{2}, \frac{1-\Delta}{2-\alpha}\}$*, emissions during the transition are higher than socially optimal emissions. The difference declines over time.*

Proof. To prove the first point, note that a single newcomer can achieve the highest profit from providing the new technology (without considering r&d costs). Thus, we compare the profit of such a newcomer (see Table 1 for Case 2 with $n = 1$ and $\delta_{N_i} = \Delta$) to the ΔW_t of Eq. (7). Even for $d = 0$ (no damages from using the old technology), the welfare gain of the social planner is strictly greater than private profits for all $k_{t-1} \in [0, 1 + \epsilon]$, as long as $\Delta > \alpha/2$, which is (according to Prop. 4) a necessary condition for innovation to start at all in the market outcome. As the incumbent gains less profit from providing the new technology and the social planner calculates with the minimal r&d costs, this implies that the social planner would do the innovation more often, even if she considered only single-period benefits (as the firms do).

The second point follows from comparing Cond. (5) to the minimal usage of the old technology among all market outcomes. □

This proposition shows that the market dynamics cause two main failures. First, they do not induce a green technology transition in all cases where such a transition would be socially beneficial. This is caused by two effects: The incumbent, who wants to protect his old technology and is thus biased against the development of the new technology, and the effect of a limited lifetime of patents, where a firm that develops a technology has to refund the r&d costs within the lifetime of a patent.

Second, even if a transition occurs, there can still be too high emissions during the phase where both technologies co-exist. The reason is simply that the external damage is not internalized. If the marginal damage is high enough, usage of the old technology should be smaller even than the reduced amount supplied by the monopolist.

The first point implies that we might need an intervention to start the technology transition. By Prop. 5, such an intervention will be required only for some time, as market incentives to continue a started transition are higher than the incentives to start the transition in the first place.

Relating the second point to Propositions 6 and 7 shows that such an intervention should, in many cases, consist of r&d support for newcomers during the early stages of the technology transition, as this will increase both the number of cases under which such a transition occurs and reduce emissions. Counteracting this effect are r&d costs, which are typically higher if newcomers do the development, as several firms have redundant r&d efforts. But later on, such support should be scrapped, as it will often be socially beneficial that the incumbent takes over (reducing both total r&d costs and (possibly) emissions), which will happen in any case, as long as the condition of Cor. 1 is met.

5. Conclusion

In this paper, we have analyzed the transition towards a green technology in a theoretical model that captures the interactions between technological development and changes to the market structure via entry and exit of firms. We have shown that these interactions have substantial importance; in many cases the market structure will change substantially over time and this has strong implications both for r&d incentives and for environmental pollution throughout the transition process.

Our model and results are novel in that they provide, at least to our knowledge, the first analysis of a green technology transition in which the structure of the market on which the new technology is sold is fully endogenous. In our case, the market can (and often will) vary from a fairly competitive market to a oligopolistic market to a monopoly. Furthermore, our analysis captures aspects in analyzing green technological change that have not been investigated in conjunction so far, like the ability of a new technology to expand a market, the incentives of incumbents to protect an old technology, and the influence of time-limited patents on pricing and thus on r&d decisions. Finally, our model provides a novel perspective on the different roles played by incumbents and small newcomers throughout the technology transition; it captures the change to these roles over the step-by-step development of a new green technology.

Our results suggest that these points can have substantial importance for a green technology transition. The market expansion effect and the incentive to protect an old technology have been shown to be of high relevance both for incumbents and newcomers: For incumbents, the prospect of a strong market expansion can overcome the desire to protect an old technology. For newcomers, the market expansion is the main chance to refund early r&d efforts. If this expansion effect is small, that is, if even in the early stages of development, the new technology will mostly replace the old one (not generate new customers), the incumbent will use his market power to prevent the entry of the new technology. For an intermediate market expansion effect, the incumbent would still like to achieve this but will fail, as the new market is substantial enough to refund r&d costs; such a situation could either lead to newcomers entering the market or to an incumbent doing r&d for purely strategic reasons (keeping out competition). Finally, if the market expansion effect is large, the incumbent will actively develop the new technology.

The limited lifetime of patents is also important for the transition. At the beginning, this reduces innovation incentives, as r&d costs have to be recovered within a few years, which is difficult for a novel technology that does not yet have a quality that is able to compete with an established technology. Later on, the threat of copycats providing an old version of the new technology become important as an incentive to keep innovating and to price the new technology reasonably, which leads to lower emissions during the transition process.

Finally, the roles of the different actors can change considerably during the transition process. At the beginning, the incumbent will try to block the development of the new technology in many cases and newcomers are then essential to start the transition. Furthermore, newcomers will often push the new technology more aggressively at the beginning, thereby reducing emissions more strongly compared to the case where the incumbent provides the new technology (here, emissions could even increase temporarily). Later on, the incumbent will switch her position: Instead of protecting its technology, she will begin to actively engage in developing the new technology. At this point, market entrants can start to become detrimental to the transition process. They engage in redundant r&d efforts (which is costly) and will lead to a slower replacement of the old technology at the end of the transition process and thus to higher emissions.

We have deliberately refrained from going into details as to how policy might alter this process. However, our analysis indicates two important points. First, there is a clear case for interfering with the market-driven innovation process, as the green technology transition will occur in too few cases, if left to the market, and the level of emissions throughout the transition will usually be too high if marginal damages are high (only converging to optimal emission levels at the very end of the process). Second, our analysis suggests that policy measures should support newcomers at the beginning of this process, as they are instrumental to get the transition started, but should focus on an incumbent later on, as this firm will become the cheapest option to finalize the development of the green technology and will be instrumental to bring down emissions more rapidly.

Of course, our analysis is highly abstract and neglects many features found in real-world technology transitions, such as r&d spillovers or protection of intellectual property apart from patents. However, it can still help to explain features found in reality. A prime example is the transition to e-mobility. Here incumbents have (for more than a decade) done just enough innovation to cover the market of early adopters, thereby essentially reducing the market expansion effect, so that newcomers had little chance to enter the market. Eventually, a newcomer initiated the transition against incumbents trying to protect their old technologies and the incumbents are currently starting to switch to an active engagement with e-mobility, even at the expense of sales of their conventional cars. Another example is the phase-out of CFCs, which was driven by incumbents; a case that is also possible in our model.

These dynamics match the patterns identified with our model at least roughly and the model provides both an argument as to why these patterns might have emerged and a prediction what is likely to happen in the future (incumbents driving the newcomer out eventually but thereby destroying their old technology basis).

But while our model provides interesting insights, many points are left open. First, we have analyzed only the case of myopic players, as this has proven to be highly complex already. An interesting approach could be to limit the transition process to two or three stages and to analyze these stages in an intertemporal optimization model. Most likely, this will yield higher incentives for protecting the old technology and thus a smaller likelihood of a successful technology transition. Furthermore, it could lead to an outcome where the transition is stopped after some time, which (surprisingly) never happens in our myopic player framework.

Second, it would be interesting to analyze the effect of environmental policy and r&d policies on the technology transition. Whereas analyzing a first-best policy (where externalities are fully internalized, market power is successfully countered, and innovation is mainly funded by subsidies) is likely to yield few new insights, it could be interesting to examine second-best policies in our framework, for example, whether an r&d subsidy or an emissions tax is more suitable at which stage of the innovation process.

Appendix A. Analysis of r&d decisions

Appendix A.1. Proof of Lemma 2

By Table 1 on p. 20, an entrant's profit is strictly decreasing in the number of entrants n. Thus, setting the profit equal to zero for $n = 1$ for the Cases 2 and 3 of Prop. 1 and 2 gives necessary and sufficient conditions for innovation. In Case 2, the resulting condition Eq. (35) already implies the conditions that are required for the existence of the technology market equilibrium. In Case 3, additional conditions arise from Prop. 1 and 2, which results in Eqs. (33)–(34). □

Appendix A.2. Proof of Lemma 3

This lemma follows directly from comparing the incumbent's profit in Cases 1 and 4 of Prop. 1 and 2 and from considering the additional conditions of these cases in Prop. 1 and 2. □

Appendix A.3. Proof of Lemma 4

This follows directly from comparing the incumbent's profit in Cases 2 and 3 of Prop. 1 and 2. The additional conditions of these cases are already implied by Conditions (35) and (33)–(34), which are met by assumption. □

Appendix A.4. Proof of Lemma 5

Cond. (39) follows directly from comparing the incumbent's profit for the Cases 1 and 2 of Prop. 1 or 2. These cases are the relevant ones, as under the assumptions of Lemma 5, the entrants will innovate if and only if the incumbent does not innovate strongly enough. Under Cond. (39), it is best for the incumbent to innovate fully.

If Cond. (39) does not hold, it might still be profitable for the incumbent to innovate just as much as is necessary to prevent newcomers from innovating. This level has to meet the conditions of Case 1 in Prop. 1 or 2 and has to make entry in Case 3 not profitable for the first entrant. Depending on the model parameters, the active constraint differs, which leads to the values of $\tilde{\delta}$ specified in Cond. (41).[4] Comparing the incumbents profit between Cases 1 and 2 for this choice of δ_I yields Cond. (40). □

[4] The last two values arise from constraining the first entrant's profit, the first two ones from the conditions of Case 1 in Prop. 1 or 2.

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