Quota Markets and Technological Change

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Abstract

Quota or permit markets have become an essential tool for climate and energy policy. In addition to allocative efficiency their ability to promote technological change has been analyzed in many studies. We add to this literature by considering a case with several technologies that could be developed and where R&D firms are granted patents with a finite lifetime. We show that, in this setting, R&D incentives are not only too low, as is well known, but incentives are also distorted across technologies, which is a new result. Compared to the social optimum, the best technology is developed in too few cases, whereas a less promising technology might be developed even in cases where this is not socially optimal. Usually, correcting these incentives would require much information about the potentials of the different new technologies. However, we show that combining a quota market with a simple tax-subsidy scheme can mostly correct these distortions, even if the regulation authority has no information regarding new upcoming technologies. Thus such an amended quota market provides a simple but effective option to promote technological change.

Keywords: Quota Markets, Technological Lock-In, R&D, Promotion of Renewable Energy, Climate Change

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1 Introduction

Initiating and supporting technological change is one of the main objectives of environmental policy. In many cases, demanding targets (emission reductions or reduced resource consumption) can only be met at politically acceptable costs, if new technologies are developed and adopted. This holds in particular for climate policy and the promotion of renewable energy.

However, market failures, such as time-limited intellectual property rights, imperfect competition in the eco-industry, or technological spill-overs,[1] imply that technological change is unlikely to occur at a satisfactory speed or may even be forestalled completely by technological lock-in (see, e.g., Unruh (2000) or Krysiak (2011)). Thus policy measures have to be tailored to promote R&D activities and the diffusion of "green" technologies.

A particularly important example is given by renewable energy. Many countries have the stated objective to increaseg the share of renewables in energy production substantially within the next decades. However, only few technologies are currently competitive and existing infrastructure favors the use of non-renewable energy (Neuhoff, 2005).

To promote the development and adoption of renewable energy technologies, numerous policy instruments have been devised. Currently, the predominant measures are variants of feed-in tariffs and tradable quotas for renewable energy. Although these instruments are used for the same purpose, they differ strongly regarding their approach and implications. Feed-in tariffs promote renewables by reducing or eliminating competition. Usually, renewable energy technologies receive technology-specific subsidies that are calculated to make these technologies competitive and these subsidies are often guaranteed for a substantial part of the economic lifetime of the installations. Thus most or even all investment risk is socialized, which can lead to a rapid adoption of the subsidized technologies, as the example of Germany highlights (Menanteau et al., 2003).

However, feed-in tariffs have two major disadvantages. First, there is a substantial risk of inefficiency. As competition among technologies is reduced or eliminated, there is no guarantee that a given overall amount of renewable energy is supplied at least costs. Second, R&D efforts are unlikely to focus on the most promising technologies, as the economic viability of more costly or less efficient approaches is often ensured by the subsidies. This delays a selection of the best technologies, resulting in R&D efforts spent on technological options that have little chance ever to survive in a market without subsidies (Dinica, 2006). Due to these drawbacks, feed-in tariffs have proven to be a rather costly instruments in some countries, such as Germany (Menanteau et al., 2003). Designing better feed-in tariffs is thereby often hampered by imperfect information. As there is no

[1]See, for example, DeBrock (1985) Denicolò (1996) and Perino (2008) for the discussion about patent and property right; Elberfeld and Nti (2004) and David and Sinclair-Desgagné (2005) for the effects of imperfect competition, and Spence (1981) and Fischer et al. (2003) for technological spill-overs.

competition that selects technologies, a regulating authority will often need information about new technological developments that is private information of R&D firms and thus not easily observable.

In contrast, quota markets are based on competition. Usually, providers are required to show that a fixed share of the sold energy stems from renewable sources. If they cannot ensure this themselves, they buy tradable quotas from suppliers that exceed this share. It is usually expected that a competitive quota market will lead to an efficient allocation of production can be expected and that competition will sort out inefficient technologies rapidly. Furthermore, the quota system makes it easy for policy makers to ensure that quantity targets (such as the EU 20-20-20 target) are met.

But quota markets typically fail at inducing high levels of investment, as investors have to bear most of the investment risk. In contrast to feed-in tariffs, the incentive for investing in renewables varies strongly over time. Furthermore, in many cases one or two technologies will dominate the market due to initially low costs, which can cause a lock-in situation (Krysiak, 2011).

If feed-in tariffs fail for a lack of competition, whereas quota markets fail due to a too early selection among technologies and too little support for nascent technologies, it might be a good idea to search for intermediate solutions. In this paper, we will investigate some of these arguments in a theoretical model of technological change. We first analyze the implications of a quota market for R&D for the case where there are two competing new technologies as well as an incumbent technology. Adding to existing studies, which emphasize that total R&D efforts can be suboptimally low, we show that R&D efforts are distorted in a rather complex way. The best technological option might be developed in too few and a less promising technology in too many cases. We then show that a combination of quota and a subsidy system can correct most of these distortions without placing unreasonable information requirements on the regulating authority.

To this end, we use a highly stylized model that nevertheless captures several important aspects of technological change. First, the model accounts both for the necessity of granting patents (otherwise, R&D efforts would be too low) as well as for the inefficiency induced by the ensuing market power of R&D firms. Second, it captures the fact that the costs of using a technology can be site-specific, which is of particular importance for renewable energy. Finally, it allows for a lock-in effect, that is, a strong incumbent technology can prevent the development of new technological options.

Using this model, we first show that in the presence of market power in the R&D market (which is almost unavoidable, as R&D costs can often only be recovered via patents), a conventional quota market not only leads to too small overall R&D efforts but also to a distorted allocation of these efforts among technological options. The most promising technology will be developed in too few and less promising technologies in too many cases. To our knowledge, this is a new effect. Furthermore, this effect is not easily countered, as it demands technology-specific interventions; the common suggestion of general R&D subsidies would lead to a waste of efforts on inefficient technologies. But technology-specific interventions usually require detailed information, in particular, regarding the efficiency of to-be-developed technologies. In many cases, such information will not be completely available to regulating authorities.

We then show that a quota market that is amended by a general tax on investments in new technologies and a subsidy for users of the best newly developed technology can improve R&D incentives; the best technology will be developed exactly when this is socially desirable and other technologies will only be developed if this is socially optimal. This regulation is not socially optimal, as there are still some distortions on the product market during the development phase and as the development of less promising technologies might be delayed compared to the social optimum. However, the regulation requires only observable information. The instruments can be designed solely with knowing the properties of already installed technology; no knowledge regarding the properties of the technologies that are to be developed is necessary.

Although our model is set up to depict investment in renewable energies, the driving assumptions of our approach easily transfer to more general settings. Thus our results have broader implications. Distorted R&D incentives are to be expected not only from quota markets for renewable energy but also from permit markets, if there is imperfect competition on the market for new technological developments. Nevertheless, our results also show that these problems can be solved and quota (or permit) markets offer the opportunity to achieve this even if the regulation authority lacks important information.

2 Review of the Literature

This paper is related to four strands of literature: first, the literature on the promotion of renewable energy. Second, the literature on technological lock-in. Third, the literature on environmental regulation, technology adaptation and investment in R&D and fourth, the literature on induced technological change. While the first and the second strands provide the motivation for our inquiry, the third and the fourth relate to our work with regard to the theoretical background.

The literature on the promotion of renewable energy has been growing since most industrialised countries started pursuing ambitious objectives for producing electricity from renewable energy source (RES). As Neuhoff (2005) notes, several barriers arise for the large-scale deployment of renewable energy technologies (due for example to market structures). To overcome these obstacles many countries implement very different regulatory promotion strategies for electricity from RES.[2] This strand of literature tries to answer the question which instruments and incentive schemes are more efficient in promoting RES. Menanteau et al. (2003) explores the efficiency of different incentives schemes on technological progress.

[2]For an overview on the implemented policies to promote RES, see for example Reiche and Bechberger (2004) and Haas et al. (2004).

This study takes into account uncertainties regarding cost curves and learning effect. The results show that feed-in tariffs are more efficient than a bidding system. Menanteau et al. (2003) also highlights the emergence of a quota-based green certificate trading system, which gives the opportunity for meeting a target in the most efficient way among several technologies.

Tamás et al. (2010) analyze feed-in tariffs and tradable green certificate for the UK. Butler and Neuhoff (2008) show that feed-in tariffs has been able to create more competition in Germany than any other policy strategy in the UK (at least among turbine producers and constructors), contrary to theoretical predictions. Mulder (2008) empirically investigates the success of different countries in stimulating investment for wind turbine. Popp et al. (2011) focus on patents and show in an empirical study that environmental regulation policy has a larger impact on investment than new knowledge. Reichenbach and Requate (2012) study the performance of feed-in tariffs for promoting the use of renewable energy sources in electricity production. Proposing a model which includes the existence of learning by doing and learning spill-overs, they suggest that two instruments are needed in order to reach the first-best policy.

Jaffe et al. (2003) give an overview on the existent contributions on the literature on technological lock-in. Arthur (1989) shows how an economy can gradually lock-in itself in an inferior equilibria. He proposes a dynamic setting with increasing returns to scale, which are due to externalities in technological adoption. Other papers link increasing such returns to learning processes (Arrow, 1962) or network externalities (Katz and Shapiro, 1986; Tse, 2002). Unruh (2000), Kline (2001) and Unruh (2002) address the relevance of technological lock-in in inferior technologies in an environmental context. Unruh (2000) narratively illustrates how industrial economies have become locked into fossil fuel-based technological systems. In his view, path-dependent processes driven by technological, organizational, social and institutional increasing returns to scale are the cause for the lock-in. Unruh (2002) and Neuhoff (2005) argue that exogenous forces are probably required in order to escape the actual carbon lock-in situation.

The literature on incentive effects of different environmental policy instruments on the development and adoption of advanced pollution abatement technology tries to answer the question which instruments create the better incentives to adopt a new more efficient technology and to invest in R&D. Answers usually focus on the effects on investments *level* caused by different instruments, that is, on the rate of investment. Important contributions are Malueg (1989), Milliman and Prince (1989), Jung et al. (1996) and Requate and Unold (2001, 2003). In these papers the new technology is given exogenously and it is already available. The authors several policy instruments (e.g., auctioned permits, emissions taxes and subsidies and issued marketable permits[3]) and generally find that market-based instruments provide the higher firm incentives to promote technological adoption compared to direct regulation. Milliman and Prince (1989) show that auctioned permits pro-

[3] Jung et al. (1996) also analyses performance standards.

vide the largest adoption incentives, followed by emissions taxes and subsidies and lastly by freely allocated permits and direct controls. Jung et al. (1996) confirm the results of Milliman and Prince (1989) for the case where firms are heterogeneous. The impact of imperfect competition on the supply of abatement technology are analyzed in David and Sinclair-Desgagné (2005).

More recent contributions by Biglaiser and Horowitz (1994), Denicolo (1999), Parry (1995) deal with simultaneous incentives for adoption and R&D of new technology, that is, firms incentives to adopt a new, cost-saving technology when the price of pollution (permit price or tax level) is endogenous.

Requate (2005) shows how decisions about the timing of environmental policy and and the capacity of commitment to a certain policy instruments can affect the adoption of a new technology and the engagement in R&D. The paper shows that, in terms of welfare, an ex-ante commitment to taxes contingent on R&D success performs better than other policy regimes. Döllen and Requate (2008) extend Requate and Unold (2003) by examining the polluting firm's incentives to invest in a new abatement technology when even better technology is expected to arrive in the future, albeit with uncertainty about its occurrence.

The *direction* of technology change and thus the choice of technology is addressed in the literature on price-induced technology change. Relevant contributions have been done for example by Magat (1978, 1979), Kaboski (2005) and Krysiak (2008, 2011). Magat (1978, 1979) show that different allocation of research and R&D funds between improvement in abatement technology and improvement in production technology lead back to the design of pollution control policies but not on the choice of the instrument.

Kaboski (2005) introduces factor price uncertainty and shows that this can affect the direction of technology change. Krysiak (2008) analyses a set up with cost uncertainty and shows that the type of implemented regulatory instrument matters for technology choice but not its design. Krysiak (2011) considers both vertical and horizontal technology progress and time-limited patent protection. This study confirms previous results showing that the choice between different environmental policy instruments has substantial impacts on the type of induced technological progress.

Finally, Goeschl and Perino (2007) consider a setting where technologies emit different pollutants and new technologies can never be perfect backstop. The shows that social optimal technology innovation occurs sequentially (rather than simultaneously) and that under certain condition the optimal portfolio of diversified technologies is finite.

Overall, the literature reveals a rather complex picture as to how policy measures influence and shape technological change. In particular, it cannot be expected that a simple policy measure will achieve both allocative efficiency and the implementation of socially optimal R&D incentives. Furthermore, the design of policy measure can have substantial and long-lasting effects on technological development.

3 The Model

Assume that green innovation is a two stage process: Firms in an R&D sector develop new technologies, which they sell to firms in a production sector.[4] The firms in the production sector buy the new technologies in order to meet a quota on green production. They are regulated with a tradable quota system; in aggregate, they have to produce a given amount of their output with the green technology.

For simplicity, we assume that innovation is a one-shot process. R&D firms decide whether to invest in developing a new technology or not. Developing requires some fixed investment costs. If a firm develops a technology, it is granted a time-limited patent so that it is the sole supplier of this technology for some time. After a patent expires, the technology becomes freely available.

Firms in the production sector can invest in a technology and produce renewable energy. Each firm has a location, which is suitable for the production of green energy using one specific technology, that is, there is no competition for locations between different technologies. The production is associated with site-specific costs and the number of available firms (and thus locations) is unlimited. However, firms with low site-specific costs will have more incentives to invest and produce, so that, for each technology, the site-specific costs of the next firm adopting this technology increase.

There is perfect competition in the production sector. Furthermore, investments last only a finite time, which we use to define a period; after each period, production equipment has to be renewed. Thus a period in our model corresponds to the economic lifetime of equipment used for the production of renewable energy (which will often be of the magnitude of 10-20 years).

The total of green production is given by the overall quota. For simplicity, we assume that conventional production is so much cheaper that this quota will never be exceeded. Furthermore, we assume that total production does not change over time (e.g., due to inelastic and time-invariant demand). Thus, we only need to model the market for the green product.

In our model, a technology is described by its efficiency, which denotes the amount of output that can be produced with one unit of the technology (i.e., by one firm at one location).

To keep the model tractable, we assume that there are three technologies with specific characteristics. There is an already existing technology, for which patents have expired and which cannot be improved further. This technology has the lowest efficiency. In addition, two new technologies can be developed. One technology with a high efficiency and one technology with an intermediate efficiency. This setup captures the two essential aspects of the problem considered in this paper: (i) a new technology has to succeed against an incumbent technology (whose development costs are already paid off), which might require specific policy measures;

[4] Lanjouw and Mody (1996) empirically show that there is a distinction between sectors which develop new technology and which adopt the newly developed technology.

(ii) the policy measures have to be designed in a way so that either both or only the more efficient one of the new technologies are developed. Covering a larger number of technologies would not add essential aspects to this setting but would complicate the analysis considerably.

This model is a simple but comparatively rich description of the innovation process for renewable energy. Production occurs at a large number of small units with site-specific costs. Producing firms can select from a set of available technologies and their decisions are determined by balancing costs (equipment costs and site-specific costs) with the technical efficiency (output per unit of equipment). Furthermore, the production sector includes much more firms than the R&D sector, so that there will be (approximately) perfect competition on the production side but imperfect competition on the R&D side. This imperfect competition in the R&D sector is a consequence of patent protection and thus a necessity (otherwise, there would be no incentive for investing in technology development) but can cause distortions both in the R&D process and the allocation of production to sites and technologies.

The general setup of our model is similar to that of Requate (2005), Döllen and Requate (2008), and Krysiak (2011). However, in contrast to these studies, we take into account the possibility of a development (and adoption) of two new technologies. This opens the option of analyzing distortions not only with regard to total R&D efforts but also with regard to the allocation of these efforts to new technologies. Krysiak (2011) pursues a somewhat similar approach. However, there is no incumbent green technology (which will be rather important in our setting) and the model does not admit a full solution, so that technological change for different instruments cannot be compared to the socially optimal outcome, as we will do.

Formally, let a_i denote the efficiency of technology $i \in \{1, 2, 3\}$. As described above, we assume $a_1 > a_2 > a_3$, where a_3 is the already existing incumbent technology and a_1, a_2 are new technological options that could be developed. If a technology is not developed, we set the corresponding $a_i = 0$, that is, the technology produces no output and will therefore not be used.

As innovation is assumed to be a one-shot process, we use a two period setup where the first period is the period where innovation takes place and the second period is an aggregate of all later periods. For a producing firm, the profit gained by using technology i at site j in period $t \in \{1, 2\}$ is given by

$$\pi_{i,j,t} = p_{q,t}\, a_{i,t} - p_{i,t} - x_{i,j}, \tag{1}$$

where $p_{i,t}$ denotes the price of one unit of equipment of technology i in period t, $x_{i,j}$ are the site-specific costs, and $p_{q,t}$ is the output price in period t (i.e., the price of quotas). Each firm can invest in only one unit[5] of technology i.

Under perfect competition and with free entry, technology i will be used at all

[5] As we have constant returns to scale, this is an innocuous assumption.

sites j with $x_{i,j} \leq \bar{x}_{i,t}$ where

$$\bar{x}_{i,t} = p_{q,t}\, a_{i,t} - p_{i,t}, \tag{2}$$

which is simply a zero-profit condition. Assuming that site-specific costs start at $x_{i,j} = 0$ and that, for all values of $x_{i,j}$, there is one site with these costs, output of technology i is given by

$$q_{i,t} = \int_0^{\bar{x}_{i,t}} a_{i,t}\, dx_{i,j} = a_{i,t}\, \left(p_{q,t}\, a_{i,t} - p_{i,t}\right). \tag{3}$$

Under these assumptions, the number of sold units of technology i equals $\bar{x}_{i,t}$.

Total green production equals the sum of the production with each technology, so that the market equilibrium is characterized by

$$\sum_{i=1}^{3} q_{i,t} = Q, \tag{4}$$

where Q denotes the quota. With (3), this implies a market clearing price of

$$p_{q,t} = \frac{Q + \sum_{i=1}^{3} a_{i,t}\, p_{i,t}}{\sum_{i=1}^{3} a_{i,t}^2}. \tag{5}$$

In the R&D sector, there are two firms with ideas for new technologies (technology 1 and 2). Each of them chooses whether to develop its idea. This development incurs fixed costs I. If a firm i develops its idea, it sets a price $p_{i,t}$ for its technology and gains the profit[6]

$$\pi_{i,t}^{RD} = (1+\gamma)\, \bar{x}_{i,t}\, p_{i,t} - I. \tag{6}$$

Thereby, γ measures the extent to which the R&D firm takes future periods into account. As the technology becomes freely available after a patent expires, other firms will copy this development and these entrants will drive the profit down to zero. Thus, we have

$$\gamma = \frac{1-(1+r)^{-T}}{r}, \tag{7}$$

with T denoting the lifetime of a patent measured in periods of our model and r is the firm's discount rate, which is assumed to be the same for both firms. So, if a patent lasts only one period (i.e., about 20 years), we have $\gamma = 0$, whereas, for an infinite lifetime of patents, we get $\gamma = 1/r$.

In the following sections, we will first characterize the socially optimal solution to gain a benchmark. Then we will show that a single quota market falls short of this benchmark for several reasons. Finally, we will discuss possible solutions and propose a quota market that is amended by a general tax on investments in new technologies and a subsidy for users of the best newly developed technology. We show that this yields an improvement over a conventional quota market while remaining an easily implementable policy.

[6]We have not included costs of producing the equipment (in contrast to developing it), as this would not add anything to the main results but would introduce an additional parameter.

4 The Social Optimum

In the above setting, a social planner would minimize the discounted costs of meeting the quota. As the technologies are only developed in the first period, we can again use an aggregate second period, which leads to the following costs (with $\delta = 1/\rho$ being the discount factor consistent with a social discount rate ρ):

$$C^{SP} = \sum_{i=1}^{3} \left(\int_0^{\bar{x}_{i,1}} x\, dx + I_i + \delta \int_0^{\bar{x}_{i,2}} x\, dx \right), \tag{8}$$

where $I_3 = 0$ (as this is the already developed incumbent technology) and $a_1 > 0$, $a_2 > 0$ only if these technologies are developed.

Minimizing these costs with regard to the $\bar{x}_{i,1}, \bar{x}_{i,2}$ under the constraints

$$Q = \sum_{i=1}^{3} \int_0^{\bar{x}_{i,1}} a_i\, dx, \tag{9}$$

$$Q = \sum_{i=1}^{3} \int_0^{\bar{x}_{i,2}} a_i\, dx, \tag{10}$$

yields the socially optimal production decisions

$$\bar{x}_{i,1} = \bar{x}_{i,2} = Q\, \frac{a_i}{\sum_{i=1}^{3} a_i^2}. \tag{11}$$

Since innovation occurs only in the first period, technology allocation remains constant over time.

Under these conditions, total costs as a function of the R&D decision are given by

$$C^{SP*} = n_I\, I + Q^2\, \frac{1+\delta}{2\, \sum_{i=1}^{3} a_i^2}, \tag{12}$$

where n_I is the number of developed technologies, $a_i = 0$ for the technologies that are not developed. This cost minimization problem has the following solution:

Proposition 1. *The social planner will develop technology* 1 *if and only if*

$$a_1 \geq \frac{a_3^2\, \sqrt{2\, I}}{\sqrt{(1+\delta)\, Q - 2\, I\, a_3^2}}. \tag{13}$$

The social planner will additionally develop technology 2 *if and only if*

$$a_2 \geq \frac{\left(a_1^2 + a_3^2\right)\, \sqrt{2\, I}}{\sqrt{(1+\delta)\, Q - 2\, I\, \left(a_1^2 + a_3^2\right)}}. \tag{14}$$

Proof. As both technologies incur the same development costs but $a_1 > a_2$, technology 1 will always be developed first. Comparing C^{SP*} from Eq. (12) for $a_1 = a_2 = 0$ and $I_1 = I_2 = 0$ (no development) with C^{SP*} for $a_2 = 0, I_1 = I, I_2 = 0$ (technology 1 developed) yields (13) as the only relevant solution (the other one being strictly negative).

Comparing C^{SP*} for $a_2 = 0, I_1 = I, I_2 = 0$ (technology 1 developed) with C^{SP*} for $I_1 = I_2 = I$ (both technologies vein developed) yields (14) as the only relevant solution (the other one again being strictly negative). As can be easily confirmed, the boundary set in Eq. (13) is strictly smaller than that in Eq. (14), so that technology 1 will indeed be developed whenever technology 2 is developed (we have $a_1 > a_2$). □

5 Conventional Quota Market and R&D Efforts

It is well known that in the presence of market power in R&D markets, simple measures of environmental policy will usually not be sufficient to induce a socially optimal amount of R&D (David and Sinclair-Desgagné, 2005). In this section, we show that such distortions arise not only for total R&D activities (which could often be corrected by a simple R&D subsidy) but also for the relation between R&D efforts for developing different technological options.

Our model captures several reasons why R&D incentives might be suboptimal from a societal perspective. First, due to time-limited patents, R&D firms cannot fully reap the future benefits of their development and thus have too little incentive to exert R&D efforts. Second, as long as they hold a patent, they will use the resulting market power to set suboptimally high prices for their technologies, implying a distortion on the product market (production is not allocated efficiently to the different technological options). Furthermore, as technological improvements are efficiency increases, there is a market shrinking effect; developing, for example, a PV cell with higher efficiency, reduces the amount of PV cells needed to reach the quota and thus the demand for PV cells. Again, this will distort R&D incentives, whenever firms have market power. Finally, R&D decisions are strategic decisions; whether a firm invests in developing a technology or not depends strongly on the R&D decision of its competitor.

We will show that these problems interact to form rather complex R&D incentives that can strongly deviate from socially optimal incentives. To derive the market outcome, we assume that R&D firms first simultaneously make the R&D decision and afterwards decide (again, simultaneously, if more than one firm has developed a technology) about the pricing of their technology. We analyze these decisions backwards.

Substituting Eqs. (2) and (5) in Eq. (6), observing that technology 3 is freely available (and thus $p_{3,t} = 0$), and simultaneously solving the profit maximization conditions of the firms (with regard to $p_{1,t}, p_{2,t}$), yields

$$p_{1,1} = Q\, \frac{a_1\, \left(2\, a_1^2 + a_2^2 + 2\, a_3^2\right)}{3\, a_1^2\, a_2^2 + 4\, a_3^2\, \left(a_1^2 + a_2^2\right) + 4\, a_3^2}, \tag{15}$$

$$p_{2,1} = Q\, \frac{a_2\, \left(a_1^2 + 2\, a_2^2 + 2\, a_3^2\right)}{3\, a_1^2\, a_2^2 + 4\, a_3^2\, \left(a_1^2 + a_2^2\right) + 4\, a_3^2}. \tag{16}$$

These relations hold, even if a technology is not developed (in which case, the a_i of this technology is zero). Furthermore, all technologies will be sold whenever they are developed; there are no corner solutions.

These prices cause a distortion in the production sector, the resulting production decisions can be characterized by

$$\bar{x}_{1,1} = Q\, \frac{a_1}{\sum_{i=1}^3 a_i^2}\, \frac{\left(a_2^2 + a_3^2\right)\, \left(2\, a_1^2 + a_2^2 + 2\, a_3^2\right)}{3\, a_1^2\, a_2^2 + 4\, a_3^2\, \left(a_1^2 + a_2^2\right) + 4\, a_3^2}, \tag{17}$$

$$\bar{x}_{2,1} = Q\, \frac{a_2}{\sum_{i=1}^3 a_i^2}\, \frac{\left(a_1^2 + a_3^2\right)\, \left(a_1^2 + 2\, a_2^2 + 2\, a_3^2\right)}{3\, a_1^2\, a_2^2 + 4\, a_3^2\, \left(a_1^2 + a_2^2\right) + 4\, a_3^2}, \tag{18}$$

$$\bar{x}_{3,1} = Q\, \frac{a_3}{\sum_{i=1}^3 a_i^2}\, \frac{\left(2\, a_1^2 + a_2^2 + 2\, a_3^2\right)\, \left(a_1^2 + 2\, a_2^2 + 2\, a_3^2\right)}{3\, a_1^2\, a_2^2 + 4\, a_3^2\, \left(a_1^2 + a_2^2\right) + 4\, a_3^2}. \tag{19}$$

Comparing this allocation of production to the technologies to the socially optimal solution (12) shows that this allocation is suboptimal. Thus granting R&D firms longer patents might increase innovation incentives but leads to a prolonged distortion in the production sector.

We now analyze the incentive for exerting R&D efforts. Given, Eqs. (15)–(18), we get the following profits for the two R&D firms, if they develop their technology:

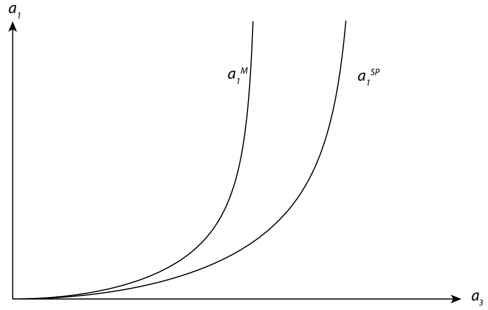
$$\pi_1^{RD} = (1+\gamma)\, \frac{Q^2\, a_1^2\, \left(2\, a_1^2 + a_2^2 + 2\, a_3^2\right)^2}{\left(3\, a_1^2\, a_2^2 + 4\, a_3^2\, \left(a_1^2 + a_2^2\right) + 4\, a_3^2\right)^2}\, \frac{a_2^2 + a_3^2}{a_1^2 + a_2^2 + a_3^2} - I, \tag{20}$$

$$\pi_2^{RD} = (1+\gamma)\, \frac{Q^2\, a_2^2\, \left(a_1^2 + 2\, a_2^2 + 2\, a_3^2\right)^2}{\left(3\, a_1^2\, a_2^2 + 4\, a_3^2\, \left(a_1^2 + a_2^2\right) + 4\, a_3^2\right)^2}\, \frac{a_1^2 + a_3^2}{a_1^2 + a_2^2 + a_3^2} - I. \tag{21}$$

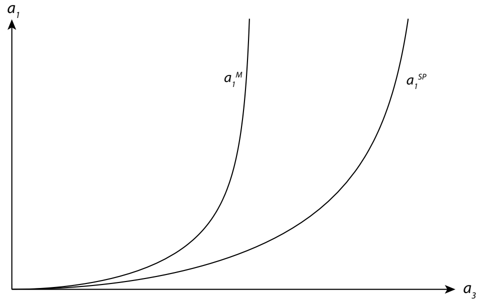
If firm i does not exert R&D efforts, its profit equals zero and the profit of the competing firm (if this one develops) is given by the above condition with $a_i = 0$.

Depending on the parameters, the R&D game has two different possible outcomes: There can be a unique equilibrium (in which none, one or both technologies are developed) or there can be two equilibria in each of which only one technology is developed. To keep differences to the social planner's results as small as possible, we assume that in the latter case it is always technology 1 (i.e., the more efficient technology) that is developed. Furthermore, we assume that $\gamma \leq \delta$, that is, the R&D firms place at most the same importance to future periods as the social planner.[7]

[7]This holds whenever the firms' discount rate is not strictly smaller than the social discount rate.



(a) $\delta = \gamma$



(b) $\delta > \gamma$

Figure 1: The lowest level of efficiency of technology 1 for which this technology will be developed as a function of the efficiency a_3 of the incumbent technology in the market solution (a_1^M) and in the social optimum (a_1^{SP}) for $\delta = \gamma$ and $\delta > \gamma$.

Under these assumptions, we get the following results regarding the more efficient technology.

Proposition 2. *Compared to the social planner's solution, the more efficient technology* 1 *is developed in too few cases in the market outcome (whenever* $a_3 > 0$*). The gap between the socially optimal and the market solution widens with an increasing efficiency of the incumbent technology* 3 *and with the difference between* γ *and* δ*, that is, the gap is wider for a shorter life-time of patents.*

Proof. From Eq. (20), it follows that the incentive to develop technology 1 decreases in the efficiency of the competing new technology 2. As the social planner always develops technology 1 first, we can thus set $a_2 = 0$. In this case, Eq. (20) implies that the firm develops technology 1 if and only if

$$a_1 \geq \frac{2\, a_3^2 \sqrt{I}}{\sqrt{(1+\gamma)\, Q - 4\, I\, a_3^2}}. \tag{22}$$

Comparing this to Eq. (13) in Prop. 1 directly yields the above results. □

Figure 1 depicts this result. The left graph illustrates the level of a_1 above which the social planner and the R&D firm would develop technology 1 for $\delta = \gamma$ and the right one for $\delta > \gamma$. The figure illustrates that, both from the perspective of a social planner (a_1^{SP}) and the firm's perspective (a_1^M), technology 1 has to be the more promising the more efficient the incumbent technology is to warrant R&D efforts. But the firm's decision depends more elastically on a_3 than the social planner's one, so that the gap between the market and the socially optimal solution widens with an increasing a_3.

So, with imperfect competition in the R&D sector, the more efficient technology is not always developed when this is socially desirable. This is a well-known effect (see, e.g., Requate (2005)). What our proposition adds are (i) the effects of time-limited patents and (ii) competition among new technologies, which will be addressed below.

Regarding (i), Figure 1 indicates that reducing the lifetime of a patent leads to a larger difference between the market and the social planner's solution. Observe, however, that even if patents are granted for the indefinite future, technology development is not socially optimal. Thus the problem cannot be solved via patent law.

Regarding (ii), the following proposition shows that R&D incentives are not simply too small but in addition their allocation to technologies is distorted.

Proposition 3. *Let*

$$\bar{a}_2 := \frac{\sqrt{\left(a_1^2 + a_3^2\right)\,\left(\sqrt{2\,(1+\gamma)}\,a_1^2 + 2\,\left(\sqrt{2\,(1+\gamma)} - \sqrt{4\,(1+\delta)}\right)a_3^2\right)}}{\sqrt{\left(\sqrt{9\,(1+\delta)} - \sqrt{8\,(1+\gamma)}\right)a_1^2 - 2\,\left(\sqrt{2\,(1+\gamma)} - \sqrt{4\,(1+\delta)}\right)a_3^2}}. \tag{23}$$

If $a_2 > \bar{a}_2$, technology 2 is developed in too many cases in the market solution compared to the social planner's solution.

If $a_2 < \bar{a}_2$, technology 2 is developed in too few cases in the market solution compared to the social planner's solution.

Proof. The difference of the profit that the firm developing this technology 2 makes and the social net benefit of developing this technology for the case where technology 1 is developed equals

$$Q^2\,a_2^2\,\frac{\frac{2\,(1+\gamma)\,\left(a_1^2+a_3^2\right)^2\,\left(a_1^2+2\,a_2^2+2\,a_3^2\right)^2}{\left(3\,a_1^2\,a_2^2+4\,a_3^2\,\left(a_1^2+a_2^2\right)+4\,a_3^2\right)^2} - (1+\delta)}{2\,\left(a_1^2+a_3^2\right)\,\left(a_1^2+a_2^2+a_3^2\right)}. \tag{24}$$

For $a_2 = \bar{a}_2$, as defined in Eq. (23), this expression is zero (which is the only positive value of a_2 for which this holds). For all larger values of a_2, the firm's incentives for developing technology 2 are larger than the social net benefit. For all smaller values of a_2, they are smaller. Thus for $a_2 > \bar{a}_2$, there are parameter combinations for which technology 2 is developed although this is socially suboptimal and there are no parameter combinations for which this technology is not developed if it would be socially desirable to do so. For $a_2 < \bar{a}_2$, the opposite holds. □

The situation is depicted in Figure 2. As we assume $a_1 < a_2$, only the area below the $45°$-line (dashed) is relevant. As this figure shows, there are regions where technology 2 is developed despite such a development being socially undesirable (A) and regions where the opposite holds (B). Region C represents the parameter combination where a_2 is developed and this is also socially optimal.

The surprising insight is that the less efficient technology might be developed too often, whereas Proposition 2 shows that the more efficient technology is always

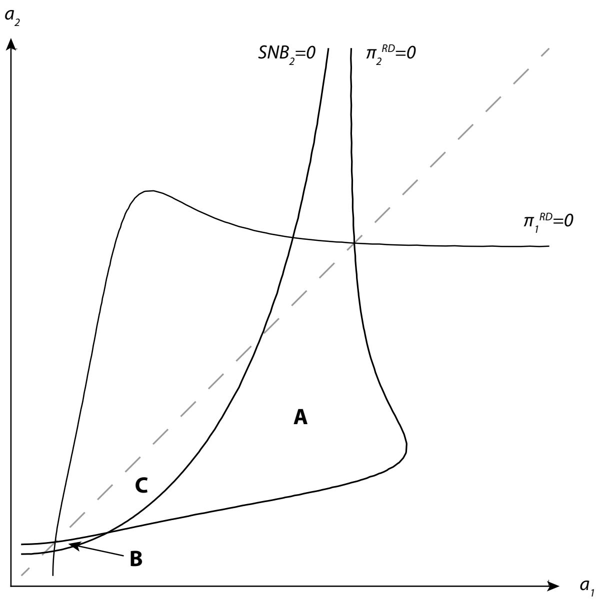


Figure 2: Market vs. social planner's incentives to develop technology 2

developed in too few cases. The reason is that as shown by Eqs. (15)–(19), the R&D firms use their market power to set too high prices leading to too small use of their technologies in production. Thus technology 1 is used less than would be socially optimal, leaving room for technology 2 to be profitably developed in too many parameter constellations.

Together, Propositions 2 and 3 imply that the market failures caused by market power of R&D firms and time-limited patents do not only lead to suboptimally small R&D efforts but also distort the allocation of these efforts to technologies. It is not only the "speed" but also the direction of technological progress that is suboptimal.

In contrast to too small aggregate efforts, this distortion cannot be corrected by simple policy measures, as the development of one technology needs to be encouraged whereas the development of the other technology might need to be discouraged. General R&D subsidies will not have such differentiated effects. But differentiated policy measures, such as differentiated subsidies or technology-specific feed-in tariffs, might be difficult to implement. Most importantly, a regulation authority will often not have the information that is necessary to implement such policies (e.g., the technologies' potentials might be private information of the R&D firms). Thus policies will often be either ineffective in promoting technological change or be effective but at unreasonably high costs.

In the following section, we will analyze an amended quota system that implements reasonable (albeit not socially optimal) R&D incentives with very low information requirements.

6 Improved Quota Regulation

The main difficulty in establishing socially reasonable R&D incentives is that it is hard for a regulation authority to assess potentials of new technologies. Usually, R&D firms will have much better information regarding the potential of different technologies and use this advantage to increase their profits.

In order to capture such a setting, we assume that the regulation authority does not know the potential of the new technologies. Thus it cannot assess which technology should be developed and which amount of subsidies are necessary to promote the development of a technology. Note that we still assume that there is perfect information on the firm-level; an R&D firm knows both its own technology and that of its competitor. This is clearly a strong simplification. However, it captures the idea that firms that are active in R&D will have much better information on all technological options than a regulation authority.

In this setting, we consider the following additions to the quota market introduced above. First, the regulation authority announces that firms utilizing the best newly developed technology receive a subsidy for each unit produced with this technology. This will increase the market share of the best technology and thereby increase the incentive to develop this technology. However, even this differentiation will often not be sufficient to ensure that a less efficient technology is not developed when such a development is socially undesirable. Thus, as a second additional measures, the use of all technologies is taxed. This reduces the price R&D firms can charge and thereby development incentives.

Finally, we set the lifetime of a patent to one period (i.e., to one investment cycle, which will usually equal 15-25 years). This is not necessary but will reduce overall costs, as the development of the best technology can be ensured when this is socially desirable even without longer lasting patents and as patent protection distorts prices and thus leads to higher costs in production.

The following proposition characterizes this approach.

Proposition 4. *Assume that, in the first period, users of the best newly developed technology receive a subsidy σ for each produced unit and all technologies are taxed with a value-added tax τ (charged on the basis of the expenses for this technology). Let*

$$\sigma = \frac{Q}{a_3^2}, \tag{25}$$

$$\tau = \frac{1-\delta}{1+\delta}. \tag{26}$$

Then the best technology is developed if and only if this is socially desirable. Furthermore, if the best technology has at most twice the efficiency of the incumbent *technology, then the second new technology is developed only if this is socially desirable.*

Proof. Without loss of generality (and in conformity to our preceding analysis), let us assume that the best new technology is technology 1. Thus, in the first period, the producing firms have a profit of

$$\pi_{i,j,1} = \left(p_{q,1} + \sigma_{i,1}\right) a_{i,1} - p_{i,1}\,(1+\tau) - x_{i,j}, \tag{27}$$

with $\sigma_{1,1} = \sigma$ (as in Eq. (25)) and $\sigma_{2,1} = \sigma_{3,1} = 0$.

Using the same steps as in the calculations of the preceding section (but with $\gamma = 0$, as patents are granted only for one period), the profit of the firm developing technology 1 equals

$$\pi_1^{RD} = \frac{Q^2\,a_1^2\,(1+\delta)}{2\,a_3^2\,(a_1^2+a_2^2)} - I, \tag{28}$$

for the case where technology 2 is not developed. This equals exactly the social net benefit of developing technology 1 when technology 2 is not developed. For the case where technology 2 is developed, we get a net profit of

$$\frac{Q^2 a_1^2\left(a_2^2+a_3^2\right)\left(\left(\frac{a_2^2}{a_3^2}+4\right)a_1^2+3a_2^2+4a_3^2\right)^2(\delta+1)}{2\left(a_1^2+a_2^2+a_3^2\right)\left(4a_3^4+4\left(a_1^2+a_2^2\right)a_3^2+3a_1^2a_2^2\right)^2} - I, \tag{29}$$

which is strictly greater than the net social benefit of developing technology 1, when technology 2 is also developed. this implies that technology 1 is always developed, when this is socially desirable. As Proposition 1 shows that technology 1 is always developed first, the amended quota market leads to the development of the more efficient technology exactly when this development is socially optimal.

Finally, the firm developing technology 2 gets the following profit

$$\frac{a_2^2\left(a_1^2+a_3^2\right)(1+\delta)\left(\left(2-\frac{a_1^2}{a_3^2}\right)a_2^2\,Q+2a_3^2\,Q\right)^2}{2\left(a_1^2+a_2^2+a_3^2\right)\left(4a_3^4+4\left(a_1^2+a_2^2\right)a_3^2+3a_1^2a_2^2\right)^2} - I. \tag{30}$$

By Eq. (12), the social net benefit of developing technology 2 in addition to technology 1 is

$$\frac{Q^2\,a_2^2\,(1+\delta)}{2\left(a_1^2+a_3^2\right)\left(a_1^2+a_2^2+a_3^2\right)} - I. \tag{31}$$

Under the assumptions $a_2 < a_1 < 2\,a_3$ and $a_1 > a_3$, the social net benefit is greater, so that technology 2 is only developed, if it is socially desirable. □

This amended quota market leads to the development of the best new technology, whenever this is socially desirable, and restricts development of less promising technologies to cases where this is socially optimal. However, this approach does not ensure that less promising technologies will always be developed, when this would be socially optimal. Thus the solution is not perfect.

However, the approach outlined in Prop. 4 uses only easily available information. All that the social planner needs to know is the efficiency of the incumbent technology, which is clearly observable information. It is not necessary to have any information regarding which new technology will yield which efficiency, the mechanism will ensure that the most promising technology is developed first and the second technology only when this is desirable.

Furthermore, if the second technology is not developed in the first period, the process can be repeated. Setting the same tax and a subsidy

$$\sigma = \frac{Q^3\,(1+\delta)}{2\,I\,\left(a_1^2+a_3^2\right)^2} - \frac{Q}{a_1^2+a_3^2} + \frac{2\,I}{Q\,(1+\delta)}, \tag{32}$$

in a subsequent period will ensure that technology 2 is developed then exactly in those cases where this is socially optimal. Again, all necessary information is observable, as technology 1 has already been used for one period, so that its efficiency is known.

Overall, this process will thus ensure a socially optimal development of the technologies. After development is finished, the equilibrium in the product market will also be efficient, as the distortions arising from market power exist only during the first periods where the technologies are developed. So, the main costs of this approach are the market distortion and potentially a delayed development of the less efficient technology.

This approach combines elements of a subsidy- and a quota-based approach. In contrast to the quota analyzed in Section 5, it implements better R&D incentives. In contrast to a subsidy-based approach (such as feed-in tariffs), the market mechanism eliminates the need to have detailed information regarding yet to be developed technologies.

In practice, where more than two new technologies will compete, it might be reasonable to cluster these technologies. Technologies that are close to the benchmark set by the best new technology, could receive a subsidy during the first phase, a similar cluster of less promising new technologies would be encouraged during the second period.

7 Conclusions

In this paper, we have shown that a quota (or a permit) market does not always lead to socially optimal technological change, if there is imperfect competition in the R&D sector. That R&D efforts may be too small in such a setting is a well-known result. What our study adds is to show that the allocation of R&D efforts to different new technologies is distorted. The most promising technology is developed in too few cases, whereas a less promising technology might be developed too often.

This raises the question how to correct the R&D incentives. In contrast to the situation with a single new technology, a general R&D subsidy will not suffice, as R&D incentives are too small for one and too large for another technology. Also, altering the lifetime of a patent will not help, as the effect remains, even if patents are granted without time limit. What is needed is a technology-specific solution. While devising such a solution is simple in principle (technology-specific subsidies will easily do the job), finding a solution that does not require too much information is hard.

We show that an amended quota market, where a subsidy is paid to users of the best new technology and all investments are taxed, might present a convenient albeit not perfect solution. The subsidy increase innovation incentives for the best technology, whereas the tax reduces these incentives for the less promising technology. Without having any information regarding the properties of the new technologies, the regulation authority can set these instruments so that R&D incentives for the best technology become optimal while the development of the second-best technology is confined to cases where this is socially desirable. A repeated application of this procedure could ensure socially optimal technical change.

Although our model is stylized and sets up for the particular example of renewable energy, our main arguments do not rest on highly specific points. The essential driver of our result is the imperfect competition between different technologies on the R&D market. The availability of different technologies implies that an R&D firm cannot reap all benefits of its development, even if it holds a patent (some profit remaining for firms in the production sector), implying that R&D incentives are too small on average. The imperfect competition induced by patents leads to too high prices for newly developed technologies, which open room for the market entry of competing technologies even in cases where this is socially undesirable. Thus R&D incentives are too small and distorted among technologies.

These drivers are likely to be present in many applications. In almost all cases of major technological change, there will be different technological options that can be pursued. Thus we will usually have several new technologies competing for market shares. Patents lead to imperfect competition but, in many cases, they are essential to provide any substantial R&D incentives at all. Thus our results should be relevant in a broad range of applications.

Of course, there are several caveats in our analysis. Most importantly, we have assumed asymmetric information between R&D firms and the regulation authority but neither uncertainty nor asymmetric information on the firm level. This is a simple but a rather drastic way of capturing the idea that R&D firms will usually be better informed about technological options (developed by themselves or their competitors) than a regulation authority. Allowing for imperfect information on the firm level would result in a setting where the first-best solution becomes unattainable. But even in such a case, the distortions derived in this paper would very likely exist and the idea of combining a quota market (where firms and not the regulating authorities decide which technologies are most promising) and a tax-subsidy-scheme (which corrects for the most important consequences of imperfect competition) appears to be an attractive solution.

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