MARKET MATURITY, PATENT RENEWALS AND THE PACE OF INNOVATION: THE CASE OF WIND POWER IN GERMANY

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MARKET MATURITY, PATENT RENEWALS AND THE PACE OF INNOVATION: THE CASE OF WIND POWER IN GERMANY

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Data on the patent renewals have been widely used to draw inferences on the value of patents. What is hypothesized here is that renewal fees create a recurring investment hurdle and therefore, that it is expensive for holders to keep a patent in force till its statutory life limit. Indeed, renewal fees have to be regularly paid; otherwise the patent lapses before its term. Hence, the value of maintaining patent protection over time is associated with the economic importance of the invention and firms' renewal strategies can be assimilated to a kind of revelation mechanism. A good understanding of patent value is therefore important to monitor innovation as a whole, but also to identify innovative firms or to signal invention quality to investors like venture capital firms.

This revelation mechanism has been dealt with extensively in the economic literature. In a seminal paper, Pakes and Schankerman (1986) have proposed an analysis of patent renewal decisions that provides some qualitative insights into the pace of innovation. However, two bias have not yet been addressed, or if so, in a very limited way. The first bias is linked to the intrinsic heterogeneity of patent value that has seldom been controlled in the literature. Economic analyses show that forward citations are an important component to discriminate among patents. The problem is that these citations are by nature dynamic, which necessitates a proper approach to assess their influence on patent renewals. The second bias is contextual and is linked to the degree of market maturity. In practice, the analysis of the decision to renew or not a patent is disconnected from the maturity of the market. Yet, market maturity can be expected to influence the magnitude and depreciation of returns from an innovation. Disregarding market maturity can thus bias the assessment of patents value and, as a result, the qualitative insights into the pace of innovation. Again, the concept is dynamic and necessitates integrating variables that change over time, in order to be able to analyse renewals.

This paper seeks to address these shortcomings and at exploring the link between market maturity and patent renewal decisions. With this aim in view, it builds on Barney (2000) and Bessen (2008) who are among the few who have addressed the introduction of patent metrics to control for observed sources of heterogeneity in patent quality. In addition to this approach of patent renewal decisions at the micro-level, we examine whether patent renewal decisions are affected by market maturity. With this purpose in mind, the analysis of renewals has to be restricted to patents within a same technology field. For the purposes of the empirical study, we decided to focus on the wind energy sector. The choice of this sector can be explained by the fact that wind power is a narrow technological field, easily identified by the F03D IPC class in patent databases. Furthermore, research and development activity in that sector has given rise to hundreds of patents pertaining to all elements of wind turbine design, manufacture, and operation. Many wind-power companies believe indeed that a strong IP position is important to protect their investments in R&D and to secure their market position.

We estimate a micro-level model of renewal decisions that control for both patent metrics and market maturity. The econometric model developed in our paper is flexible enough to enable to take into account updates in the value of individual patents in accordance to modifications of its institutional and technological environment. We use micro-level data from the Patstat database on the legal status of patents and some patent metrics related to European patents granted in class "F03D". Market maturity is measured on the basis of the dynamics of cumulated installed capacities for wind power in Germany. These installed capacities can be viewed as a proxy variable for the impact of "demand pull" policy instruments (mainly feed-in tariffs) that are alleged to have driven the development of wind power in Germany. The choice of Germany is explained by the fact that it is Europe's largest renewable energy market and that Germany's energy policy has provided reliable framework for investors[1].

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[1] As well as specific R&D funding opportunities, wind energy projects in Germany can count on numerous forms of financial support. There are many programs allocating R&D grants, interest-reduced loans and special partnership programs. Many of the programs are made available by the federal government but the federal states also offer special R&D programs.

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The remainder of the paper is organized as follows. In the next section, we put this paper in the context of the existing literature on the modelling of patent renewal decisions. In the subsequent section, we specify the econometric model. The fourth section describes the data and presents the results of our analysis. In the fifth and final section, we present our conclusions and recommendations for future research.

PATENT VALUE AND PATENT RENEWAL DECISIONS

An overview of the modelling of patent renewal decisions

A basic but key assumption in order to estimate patent value on the basis of patent renewal decisions is that, conditional on information available, patent owners are uniquely knowledgeable and well-qualified to make internal patent value assessments. They are also economically and financially motivated to make accurate judgments and sound investment decisions based thereon. The underlying principle is that, at the time maintenance fees are due, the patentee should have a good knowledge of the market value of a particular patented invention and can thus make an informed decision about whether or not to pay the renewal fees. Of course, we do not assume that all relevant decision-makers will behave rationally in all cases or at any time. For a variety of reasons, individual decision-makers may choose non-optimal investments in some, or even many cases. We only assume that, on average, decision-makers will pay maintenance fees only if they believe that a patent will produce expected future economic benefits that are sufficient to justify further investment in the invention at stake. This means that at each renewal date, in the case where the renewal fees are exceeding the patent value, a patent owner has to decide whether to discontinue or not the payment. This option to renew does exist because the payment of renewal fees is discretionary.

Costs of renewing a patent are multi-facets. They encompass internal costs to assess the usefulness of the patent, enforcement costs and those corresponding to the payment of renewal fees to the patent office. One important point to underline here is that renewal fees are generally a very small part of the total costs of a patent. Indeed, the cost of drafting and prosecuting a patent requires a much higher outlay to cover attorney fees and translation costs in foreign filings. Having that in mind, we do not make the assumption that renewal fees are the only cost of patent maintenance. In our model, the latent variable that drives the decision to renew or not the patent is the rent, net of all the non-observed costs of renewal (patent screening costs…).

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In practice, renewal fees depend on the age *a* of the patent and are revised in the course of time. Thereafter, $f_t^a \geq 0$ denotes the fee charged at age *a* for a patent with application date *t* to be renewed up to age *a*+1. Patent offices in Europe charge increasing fees each year (i.e. $f_t^{a+1} > f_t^a > 0 \; \forall a \in \{0,\cdots,A\}$ where A is the statutory life limit of patents). Most renewal costs like legal expenses are not directly observed nor easily measured, with the exception of renewal fees that are published by patent offices. As a result, a common practice consists in subtracting the unobserved renewal costs from the gross rent associated to the exclusivity right conferred by a patent on all industrial and commercial applications of the patented invention. The resulting net rent for a patent of age *a* applied for at time *t* is denoted by R_t^a. Gains that accrue from renewing a patent are obtained by adding the current flow of net benefits given by $R_t^a - f_t^a$ and the expected and discounted value $E_{t+a}\left[V_t^{a+1}\right]/1+r$ of the patent at age *a*+1 where *r* stands for the discount rate and E_{t+a} for the mathematical expectation conditional on all information available to the patent owner at date *t+a*. Renewing a patent is optimal if and only if the associated gains are positive. Thus, at any renewal date before the statutory life limit A, the private value of a patent is recursively defined by the following expression:

$$V_t^a = Max\begin{cases} R_t^a - f_t^a + \dfrac{E_{t+a}\left[V_t^{a+1}\right]}{1+r} & \text{if the patent is renewed} \\ \\ 0 & \text{if the patent is withdrawn} \end{cases} \quad \forall a < A \quad (1.a)$$

At the statutory life limit A, the expected future value of the patent falls to zero and the value of the patent is given by

$$V_t^A = Max\begin{cases} R_t^A - f_t^A & \text{if the patent is renewed} \\ \\ 0 & \text{if the patent is withdrawn} \end{cases} \quad (1.b)$$

The optimal age of withdrawal for a patent is the first age, conditional on information available at the current time, at which renewing the patent generates a net loss. Formally, it is the optimal stopping time associated with the dynamic programming problem (1):

$$a^* = Inf\left\{a \in \{0,\cdots,A\}\,;\; R_t^a - f_t^a + \frac{E_{t+a}\left[R_t^{a+1}\right]}{1+r} < 0\right\} \quad (2)$$

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Whether a^* is deterministic or random depends on assumptions about the dynamics of the rent and renewal fees. For the optimal age of withdrawal to be random, either the rent or the renewal fees must be affected by unexpected shocks; the observation of which constitutes new information. In that case, some authors call V_t^a the option value of patents in reference to the real option theory that analyses irreversible decisions when facing risk or uncertainty. Pakes (1986), Lanjouw (1998) or Baudry and Dumont (2006) for instance use this terminology. However, the stochastic nature of the dynamics of the rent complicates the determination of the optimal withdrawal date. As a result, the impact of observed patent characteristics on the decision rule is not captured, and the analysis is confined to the assessment of an average value of the patent right within a patent cohort. Our paper tries to solve this problem by extending the method to micro-level renewal data.

A simplified approach to patent renewal decisions

One of the reasons behind the complexity of decisions rules in real option models of patent renewals is that the rent may fall far below the renewal fee but, due to expected future positive shocks; this may be reversed in the short or medium term. Hence, comparing only the current values of the rent and of the renewal fee is generally not a relevant decision-rule. For such a decision-rule to be efficient, an additional assumption (called Assumption 1) on the dynamics of the rent and renewal fees is required.

Assumption 1: *The gap* $R_t^a - f_t^a$ *between the rent and the renewal fee decreases monotonically from an initial positive value to a possibly negative value with the aging.*

As such, Assumption 1 does not preclude the stochastic evolution of the rent. In the case where the rent is stochastic, the date at which the rent net of the renewal fees becomes negative is random. In other words, there is a "flexibility value" associated to the renewal mechanisms compared to a mechanism based on upfront fees.

A more restrictive form of Assumption 1 is generally used. It states that the rent itself monotonically decreases whereas, as observed for most patent offices, renewal fees are assumed to monotonically increase[2]. Whatever the form considered, Assumption 1 implies Proposition 1 and Corollary 1:

Proposition 1: *Under assumption 1, the rent will never exceed the renewal fee once it falls below it. As a result, maintaining the patent alive is optimal if and only if the rent exceeds the renewal fee.*

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[2] Schankerman and Pakes (1986) also use the same assumption but not in an option model context.

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Corollary 1: *Under assumption* 1*, if a patent applied for at date t is withdrawn at age a, then the rent has always exceeded the renewal fee from age* 0 *to age* $a - 1$.

Figure 1 illustrates these key results in the case of renewal fees that start at 10€ and increase at a constant rate of 10% whereas the rent for the patents A, B and C respectively starts at 90€, 100€ and 40€ and decreases at a constant rate that amounts to 15%, 10% and 5% respectively. The associated optimal withdrawal age is 9 years for the patent A, 12 years for patent B and 10 years for patent C. If monetary flows are discounted at a 3% discount rate, patents A, B and C are respectively worth 304,81€, 458,61€ and 148,72€.

Figure 1 – A simple numerical example

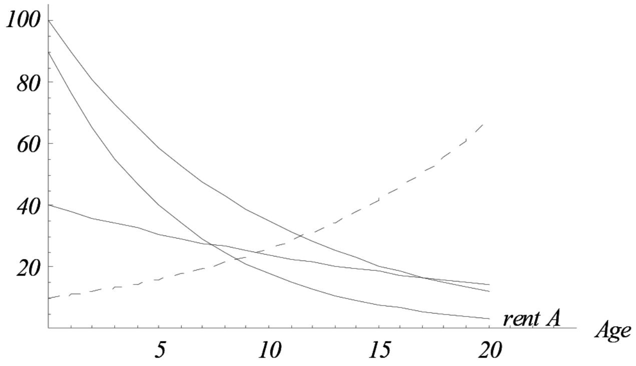

Figure 1 also highlights that patent value is tightly linked to patent duration but this relationship is not straightforward. In Figure 1, the height separating the decreasing profiles of the rent and the increasing profile of the renewal fees measures the net revenue that accrues from a patent at the corresponding age on the abscissa. The total value of a patent at the application date (age $a = 1$) is obtained by discounting and summing up the heights between the two profiles for all ages on the left of the crossing point between the two profiles. The first date on the right of the crossing point corresponds to the patent withdrawal date. Due to discounting, the total value of two patents cannot systematically be compared graphically. Nevertheless, simple cases that can be easily compared are considered on Figure 1. For instance, the patent B has a rent that exceeds the rent of patents A and C, and this rent also lasts longer than for patents A and C. This leads us to conclude that patent B has the highest total value. Patent A is withdrawn slightly before patent C but its rent is far higher than that of patent C at almost all

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dates before the withdrawing dates. Therefore, one can reasonably assert that the total value of patent A exceeds that of patent C. Thus, patent ranking from the earliest non-renewal date to the latest is A-C-B but the ranking from the lowest total value to the highest is C-A-B. Obviously, both rankings depart. A structural model of patent duration is thus required to derive estimates of patent value from observed characteristics affecting the date of patent withdrawal.

MODELLING THE IMPACT OF MARKET MATURITY AND PATENT QUALITY

Introducing determinants of renewal decisions

As stressed in the literature, there is a high heterogeneity in the value of patents with an average value of patents varying strongly across sectors/technologies (Schankerman, Pakes, 1986). The traditional solution adopted in seminal papers on patent valuation to account for this heterogeneity consists in assuming that patents differ in their initial rent at the filing date but that the rent decreases at a same constant decay rate for all patents. This solution is adopted for instance by Barney (2002) and Bessen (2008). The initial rent is treated as a random variable whose expected value is conditional on patent characteristics and context variables. Nevertheless, patent characteristics and context variables often vary with time and their dynamics cannot be consistently captured if they just affect the initial value of the rent. For their dynamics to be consistently captured, it is required that not only the initial value of the rent depends on these variables but its decay rate also. Forward citations and market maturity typically change over time and are supposed to affect the rate of decay of the rent. We thus suggest an adaptation of the initial model to tackle the dynamic nature of these variables.

Formally, the value R_{ti}^{a+1} of the rent (net of unobserved costs inherent to the renewal decision) at age a+1 for a patent i applied for at date t is written as the value of the net rent $R_{t\,i}^{a}$ at the previous age, affected by a decay or depreciation rate $\delta_{t\,i}^{a+1}$. Note that the index i is introduced to capture the fact that the value of the rent may be patent specific. Similarly, the rate of decay may depend on dynamic characteristics of patents. It may also be contingent to the application date t and to the age a of the patent. Proceeding recursively, we have

$$R_{t\,i}^{a} = R_{t\,i}^{0} \prod_{s=1}^{a} \left(1 - \delta_{t\,i}^{s}\right) \tag{3}$$

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Furthermore, heterogeneity of patents as regards the initial rent $R^0_{t\,i}$ follows on from observed and unobserved factors. Observed heterogeneity is captured by a vector $X_i = \left\{x_{1\,i}, \cdots, x_{k\,i}, \cdots, x_{K\,i}\right\}$ of values at date t for K objectively measurable characteristics of the patent or context variables. Unobserved heterogeneity, for its part, is taken into account by assuming that $R^0_{t\,i}$ has a random component drawn independently for each patent from a same probability distribution. Though not a necessary condition, it is convenient to assume that observed and unobserved heterogeneity affecting the initial rent interact multiplicatively and that observed heterogeneity is correctly captured by a Cobb-Douglas functional form of the elements of X_i. Accordingly, we have:

$$R^0_{t\,i} = \alpha_0 \left(\prod_{k=1}^{K} x_{k\,i}{}^{\alpha_k} \right) \varepsilon_i \tag{4}$$

where α_k (with $k \in \left\{0, \cdots, K\right\}$) are parameters to be estimated and ε_i is a i.i.d random term. The probability distribution of the initial rent directly follows on from the probability distribution of ε_i that captures unobserved heterogeneity.

Heterogeneity of patents as regards the rate of decay of the rent follows on from patent characteristics (like forward citations) and context variables (like market maturity) that change over time. Let $Z_i^{t+a} = \left\{z_{1\,i}^{t+a}, \cdots, z_{m\,i}^{t+a}, \cdots, z_{M\,i}^{t+a}\right\}$ denote the vector of values taken by the M dynamic variables $z_{m\,i}^{t+a}$ ($m \in \left\{1, \cdots, M\right\}$) affecting at age a the depreciation $\delta^a_{t\,i}$ of the rent for patent i applied for at date t. In order to be consistent with the fact that this depreciation rate ranges between 0 and 1, a logistic specification is more specifically convenient:

$$\delta^a_{t\,i} = \frac{1}{1 + \exp\left(\beta_0 + \sum_{m=1}^{M} \beta_m \, z_{m\,i}^{t+a}\right)} \tag{5}$$

where β_m (with $m \in \left\{0, \cdots, M\right\}$) are parameters to be estimated. A positive value of β_m means that an increase of the dynamic variable $z_{m\,i}^{t+a}$ weakens the rate of depreciation of the rent, and thus positively impacts the value of the patent.

Potential dynamic determinants of the renewal decisions

Market maturity

The maturity of a market is intuitively defined as the share of the market potential that has already been exploited. In the early stage of diffusion of a

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new technology, when maturity is low, innovators that are granted patents can expect that the growing market will generate revenues for a long time. Conversely, in the late stage of diffusion, when maturity is high, it is likely that new patented inventions will hardly be successful in generating high revenues because most of the potential of the market has been exploited. Therefore, market maturity is expected to be a key determinant of patent renewal decisions and of patent value.

The difficulty of measuring the degree of maturity for testing its influence on patent renewal decisions is that a market potential is not necessarily known in advance. To circumvent this difficulty, it is convenient to rely on a common representation of the diffusion of a new technology on its market. The empirical analysis of the diffusion of a new technology has its origins in the pioneering work of Griliches (1957) and Mansfield (1961). Originally, it was intended to formally reproduce the S-shaped time path of the rate of diffusion typically observed for many technologies. This analysis is usually said to be holistic as it provides an aggregated representation of individual decisions that are not explicitly analyzed but are assumed to interact through the transmission of information and feedbacks. The term epidemiological is sometimes used in place of the term holistic in reference to the dissemination of infectious diseases which also follows a S-shaped curve. A popular version of the S-shaped curve is the model of technology diffusion inspired by Bass (1969). It states that the cumulated number of adopters of a given technology at date *t* is

$$k_{t+1} = k_t + \underbrace{\theta_1 \left(\kappa - k_t\right)}_{\Delta k_t^1} + \underbrace{\theta_2 \left(k_t / \kappa\right) \left(\kappa - k_t\right)}_{\Delta k_t^2} \tag{6}$$

The market potential is κ. A fraction θ_1 of the unexploited potential $\kappa - k_t$ is added at each date. It corresponds to adopters who choose a technology regardless its current development. The number of these independent new adopters is Δk_t^1. Additional adopters may opt in and their number Δk_t^2 is a fraction $\theta_2\left(k_t/\kappa\right)$ of the unexploited potential that increases with the current diffusion of the technology at stake. These additional adopters are therefore referred to as imitators and are influenced by early adopters.

Figure 2.a shows the resulting S-shaped diffusion in the case where $\kappa = 100$, $\theta_1 = 0.0025$ and $\theta_1 = 0.3$ whereas Figure 2.b displays the associated growth rate of the cumulated number of adopters. This growth rate decreases as the new technology diffuses and goes to zero when the market potential is reached. Therefore, a natural candidate to measure market maturity is

$$m_{t+1} = \exp\left(-\left(k_{t+1} - k_t\right)/k_t\right) \tag{7}$$

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This expression ranges in the interval [0,1] and increases with k_t. It goes to one when the market potential is reached and, last but not least, it can be computed without any knowledge of the actual potential k.

Figure 2.a – S-Shaped diffusion curve for the Bass model

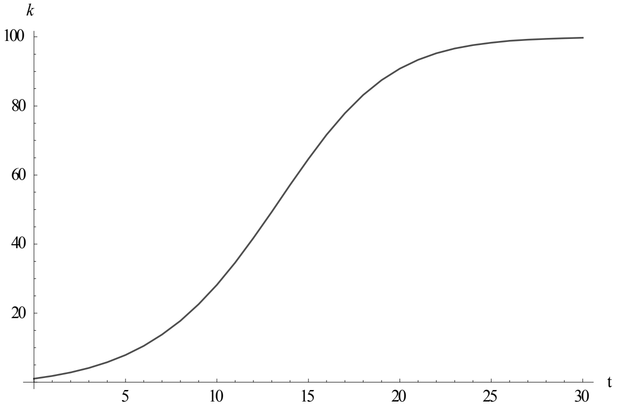
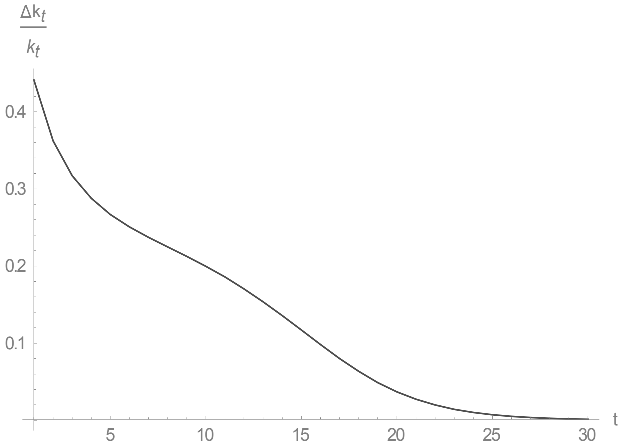


Figure 2.b – Growth rate of market size in the Bass model



Patent quality

Patent quality is often quoted as a shortcut to refer to all the characteristics of a patent that are susceptible to strengthen the ability of the patent holder to raise revenues from the patent. The concept of patent quality can often take a myriad of viewpoints. However, the empirical literature

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has tried to develop “metric standards” for patent quality, i.e. observed and objectively measurable characteristics of patents that are systematically reported by patent offices.

While it is notoriously difficult to determine the quality of an individual patent (and hence of a patent portfolio), some metrics are now being used as a yard stick to capture the technological importance of an invention, its economic value, and the possible impact on subsequent technological developments. Forward citations, i.e. the number of citations a patent receive in subsequent patent applications, have emerge as a key patent metric for this purpose. Forward citations mirror the technological importance for subsequent developments. Trajtenberg (1990) has shown a close association between citation-based patent indices and independent measures of the social value of innovations. Interestingly, the link appears to be nonlinear (increasing) with the number of citations, implying that the informational content of forward citations rises at the margin. Harhoff *et al.* (2003) for their part have studied the ability to explain the value of patents stated in surveys by patent holders by the number of citations a patent receives and their work concludes that these values are positively related to forward citations. In a similar vein, Hall *et al.* (2005) have explored the usefulness of patent citations as a measure of the “importance” of a firms’ patents, as indicated by the stock market valuation of the firm’s intangible stock of knowledge. They estimate Tobin’s q equations by using ratios of R&D to assets’ stocks, of patents to R&D, and of citations to patents as regressors. They find that each ratio significantly affects a firm’s market value, with an extra citation per patent boosting market value by 3%. Further findings indicate that “unpredictable” citations have a stronger effect than the predictable portion, and that self-citations are more valuable than external citations. Some authors have stressed the importance of distinguishing self-citations from non-self-citations. Self-citations are citations received from patents hold by the same patent holder. They may be more valuable than external cites, more specifically in technological fields where new products combine many patents that acts as complements.

THE CASE OF EPO WIND POWER PATENTS IN GERMANY

Data collection

Data on patent citations and patent renewals have been extracted from the Patstat database of the European Patent Office (EPO). In order to

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make sure that patents collected refer to inventions in relation with wind power, two criteria have been crossed in the query. First, only patents from the F03D technology field of the International Patent Classification (IPC) have been extracted[3]. This technology field is devoted to invention on "wind turbines" and is identified as the reference technology field for inventions related to wind power. Second, only patents with at least one applicant name reported in the list of wind turbine manufacturers provided by *The Wind Power* website have been extracted[4]. The *Wind Power* is a professional worldwide database about wind turbines and wind farms. It contains data related to wind farms, turbines, manufacturers, developers, operators and owners that cover several decades. The first patent in our dataset dates back to 1987. In order to be able to analyse renewal decisions at least up to age four, the last date of application has been set to 2010. Last but not least, our study deals only with granted patents. Indeed, patents applied for but not granted are supposed, by definition, not to fulfil the patentability criteria.

Forward citations are easily collected in the *Patstat* database. Patent renewals deserve more attention. There are derived from information gathered in the *legal status* optional table of the database. Information on the legal status is systematically provided for patents applied for at the EPO but not for patents applied for at national patent offices (except for the USPTO). Therefore our study focuses on patents applied for at the EPO. It is expected that these patents are of higher value than patents applied for at national offices because EPO patents are intended to protect the patented invention in several targeted countries at once with a single application. We have more specifically made a focus on EPO patents targeting Germany because this country is one of the first to have set up policies to promote renewable energy sources (with an emphasis on wind power) and is by far the largest national market in Europe for wind turbine manufacturers. Last but not least, it is particularly interesting to link the issue of market maturity to the specific case of wind turbines in Germany as this country is considered as the archetypal consolidating market. Indeed, the picture emerging from the figures from the *Windpower Intelligence database*[5] is that, contrary to some other renewable green-tech sectors, the sector has entered into a phase of consolidation with much of the recent wind farm

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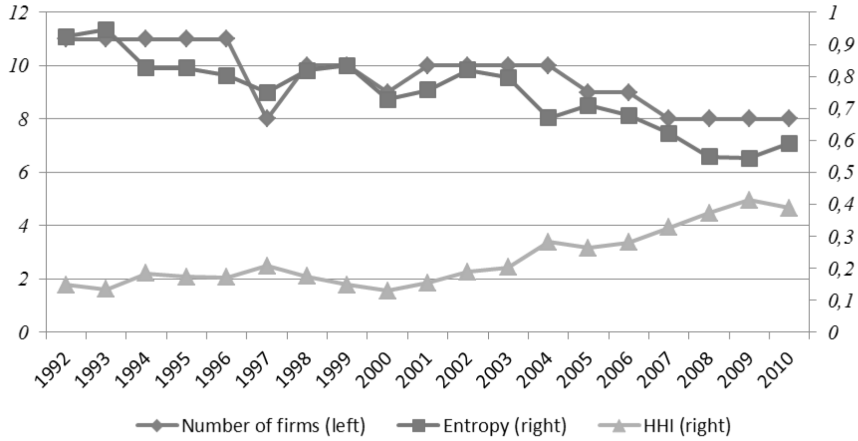
[3] For a comprehensive description of the IPC, consult the website of the World International Patent Office (WIPO) at http://www.wipo.int/classifications/en/ (consulted on March 12, 2016).

[4] Accessible at http://www.thewindpower.net/ (consulted on March 12, 2016).

[5] Available at http://www.windpowermonthly.com/intelligence (consulted on March 12, 2016).

development occurring outside the older established markets. Technology has converged on a relatively narrow range of designs, and it has left the shelter of state support and is starting to make its way in a less-regulated global market. Figure 3 illustrates this trend. It displays the number of manufacturers having sold wind turbines in Germany at the different dates[6] and two indexes of market concentration computed on the basis of rated power (namely the entropy index and the Hirschman Herfindahl Index). All along the period studied in this paper, the trends both for the number of suppliers and for the entropy decreases whereas the trend for the HHI increases. Therefore, concentration in the wind power sector in Germany cannot be disputed.

Figure 3 – Dynamics of market concentration for the German wind power market (number of firms on the left vertical axe, Entropy and HHI on right vertical axe)



Once an EPO patent has been granted, the patent holder has to pay national renewal fees to the patent offices of targeted countries. The *Patstat* database reports both the application date and the grant date so that we know from which date the analysis of the renewal decision for each patent has to start. The current and past renewal fees required by the German Patent Office are provided by the EPO official journal.

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[6] Data from DEWI http://www.dewi.de/dewi_res/index.php (consulted on March 12, 2016).

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Table 1 – Summary statistics on patents collected

Age	Average renewal fees (constant 2000 Euros)	Proportion of patents renewed	Cumulated proportion of patents renewed	Cumulated citations received for patents renewed	Cumulated citations received for patents withdrawn
1	0	1	1	0.27027	0.263158
2	0	1	1	1.24324	0.921053
3	58.68	1	1	3.00901	1.81579
4	58.68	0.9846	0.9846	5.04878	3.50617
5	80.53	0.9937	0.9784	7.92835	4.87952
6	117.96	0.9726	0.9516	10.5	6.85714
7	160.56	0.9810	0.9335	14.2154	8.53125
8	214.08	0.9778	0.9128	17.7738	9.58416
9	262.43	0.9902	0.9039	21.3971	11.6214
10	315.95	0.9944	0.8988	26.4045	12.7885
11	422.99	0.9744	0.8758	26.125	13.5463
12	557.04	0.9760	0.8547	33.1475	14.8108
13	685.42	1	0.8547	33.1667	16.045
14	819.48	0.9821	0.8395	45.5636	19.375
15	953.02	0.9667	0.8115	68.7931	20.5752
16	1108.40	1	0.8115	92.9524	21.9469
17	1269.01	0.9091	0.7377	134.3	23.4123
18	1429.50	0.9000	0.6640	68.0	31.6174
19	1584.90	0.8571	0.5691	72.8333	33.4138
20	1745.50	0.7500	0.4268	73.3333	35.0427

Table 1 provides details on the frequencies of withdrawals for the patents studied. It also displays the average renewal fees to be paid at the different ages of a patent (in constant 2000 Euros), the average number of cumulated citations received at a given date for respectively patents that are renewed at this age and patents that are withdrawn at this age. These last two columns suggest that there is a positive link between cumulated citations received and the probability to renew a patent. Data on installed capacities for wind power in Germany come from *The Wind Power* website. The corresponding maturity index (7) has been computed for each date from 1987 to 2010. It is expected that in the early stage of development of a new technology, only few patents are applied for by specialized firms exploring this new technological *niche* while patent counts increase sharply when the patent race becomes

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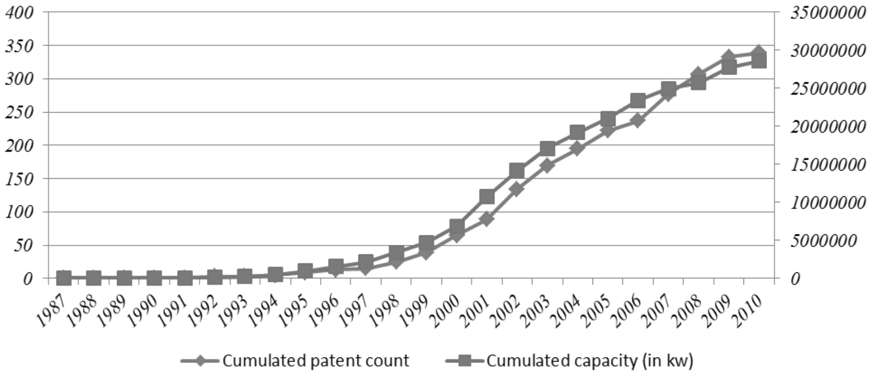
fiercer as the market grows. The growth of patent counts is expecting to slow down in the late stage of development when the market is mature. Figure 4 highlights the existence of such a tight link between market maturity and what could be called technological maturity. Indeed a striking feature of Figure 4 is that both the dynamics of installed capacity and the dynamics of patent counts exhibit a S-shaped time path and that the two time paths overlap. This high correlation implies that it would be counterproductive to introduce patent counts to capture competition between innovations and to explain the depreciation rate of patent rents. Thus, the effects estimated for market maturity can be interpreted either as the effect of a larger market or as the effect of a maturing technology.

Figure 4 – The S-shaped curve in terms of EPO patent counts (left vertical axe) and installed capacities (right vertical axe) for wind power in Germany



Estimation method

Given that the dynamics of the rent as defined by (5) fulfils Assumption 1, Corollary 1 implies that any patent applied for at date *t* which is still alive at age *a* satisfies the following set of properties:

$$R^{s}_{ti} \geq f^{s}_{ti} \quad \forall s \in \{0, \cdots, a-1\} \tag{8}$$

Moreover, Assumption 1 implies that $R^{a-1}_{ti} \geq f^{a-1}_{ti}$ is a sufficient condition for all inequalities in (8) to be satisfied. Therefore, the information revealed by observing that a patent applied for at date *t* is still alive at age *a* may be synthesised by this last condition. Combining this result with (3) and (4), we finally obtain that a patent *i* applied for at date *t* is renewed up to (at least) age *a* if and only if

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$$\varepsilon_i \geq Q_{t\,i}^{a-1} \quad \text{with} \quad Q_{t\,i}^{a-1} = \frac{f_t^{a-1}}{\alpha_0 \left(\prod_{k=1}^{K} x_{k\,i}^{\alpha_k} \right) \prod_{s=1}^{a-1} \left(1 - \delta_{t\,i}^{s} \right)} \tag{9}$$

Where the $\delta_{t\,i}^{s}$ are defined in (5). Once expressed in logarithms, (9) is similar to the key condition that Schankerman and Pakes (1986) or Schankerman (1998) use to obtain their econometric model. Nevertheless, the estimation method proposed by these authors requires a partition of the patent dataset in such a way that the threshold value $Q_{t\,i}^{a-1}$ is identical for all patents within a same subset. Moreover, the size of each subset of patents has to be sufficiently large to obtain reliable measures of the proportion of patents withdrawn at each age. This means that this econometric method works for patent cohorts (Schankerman and Pakes 1986) or patents belonging to large technological classes (Schankerman 1998) as long as none of the characteristics that distinguish patents within a subset is used as an explanatory variable.

For these reasons, we suggest an alternative econometric approach that also relies on condition (9) but that is adapted to the use of micro-level patent characteristics. For this purpose, it is worth noting that Assumption 1 implies that the value of the threshold $Q_{t\,i}^{a-1}$ decreases with age *a*. Furthermore, a patent *i* applied for at date *t* is optimally withdrawn at age *a* if and only if condition (9) prevails at age *a* – 1 but not at age *a*. This yields the probability $\Pr_{t\,i}^{a}$ of an optimal withdrawal at age *a* conditionally on a renewal up to age *a*:

$$\Pr_{t\,i}^{a} = \frac{\Phi\left(Q_{t\,i}^{a}\right) - \Phi\left(Q_{t\,i}^{a-1}\right)}{1 - \Phi\left(Q_{t\,i}^{a-1}\right)} \tag{10}$$

where Φ denotes the cumulative density function of ε_i. In the terminology of duration models, $\Pr_{t\,i}^{a}$ is nothing else than the hazard rate characterising the econometric model of patent duration. The corresponding survival function is $1 - \Phi\left(Q_{t\,i}^{a-1}\right)$. Let Ω_a denote the subset of patents renewed up to at least age *a* whatever their application date and let $\mathbf{I}_i^a$ be a variable that takes value 1 if patent $i \in \Omega_a$ is renewed at age *a* and value 0 otherwise. The log-likelihood of withdrawal *versus* renewal at age *a* for a patent *i*, conditional on the fact that we know that $i \in \Omega_a$, is given by:

$$L_i^a = \mathbf{I}_i^a \ln \Pr_{t\,i}^{a} + \left(1 - \mathbf{I}_i^a\right) \ln \left(1 - \Pr_{t\,i}^{a}\right) \tag{11}$$

Summing over all ages and all patents, we obtain the following log-likelihood

$$L_{tot} = \sum_{a=1}^{A} \sum_{i \in \Omega_a} L_i^a \tag{12}$$

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Note that a same patent appears several times in (12) but at different ages. Estimates of parameters α_k ($k \in \{0,\cdots,K\}$) of the initial rent, of parameters β_m ($m \in \{0,\cdots,M\}$) of the rate of decay of the rent and of parameters of the probability distribution of ε are obtained by maximising (12) with respect to all these parameters. The advantage of estimating the discrete time duration model developed above rather than an *ad hoc* patent duration model relies on its structural specification that directly provides estimates of all parameters required to assess the patent value.

Estimation results

Maximisation of the likelihood function (12) for the optimal withdrawal at a given age conditional on renewal up to that age has been implemented to the dataset described in the previous subsection. Table 2 reports the estimated coefficients and below, each estimated value, and in brackets, the t-statistic indicating whether the estimated value is significantly different from zero or not. The upper part of table 2 reports estimation results for the initial value of the rent whereas the lower part displays estimation results for the rate of decay. Three different models have been estimated to highlight the effect of forward citations as an indicator of patent quality on the one hand, and the effect of market maturity, on the other hand.

Table 2 – Estimation results

	Sample size: 333		
	Model 1	Model 2	Model 3
	Natural logarithm of the initial rent		
Constant	84.8029 (0.7742)	84.4995* (2.2557)	96.8477* (3.3905)
Standard Deviation	31.6306 (0.7410)	34.4276* (3.3446)	20.7318* (2.9581)
Market maturity		7.5890* (3.4108)	-36.115 (-1.2524)
	Depreciation rate of the rent		
Constant	-3.6399 (-0.6747)	4.2221 (0.7948)	-2.6958 (-0.5758)
Market maturity		-8.9372* (-2.1765)	-0.5259 (-0.1344)
Self-forwards citations	-0.8223 (-0.7138)		-0.5177* (-3.1220)
Non self-forwards citations	0.1186 (0.6228)		0.0744 (1.2298)
Log-likelihood	-211.0290	-213.09	-208.19

*: statistically different from zero at a 5% risk of error.

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Model 1 attempts to explain renewal decisions on the basis of forward citations only, but self-citations and non-self-citations are treated separately. None of the estimated coefficients is significant, even the constant component of the expected value and the standard deviation of the initial rent. This result casts doubts on the ability to explain firms' strategies with regards to patent renewals and, thus, to accurately assess the value their patents, without introducing additional exogenous variables. By contrast, Model 2 focuses on the role of maturity and highlights that it may found to be a key determinant of patent renewal decisions. Indeed, not only the constant component of the expected initial rent and the standard deviation of the initial rent are significant, but also the coefficient associated with the effect of market maturity on the expected initial rent. The higher is market maturity at the application date, the higher is the initial rent. Moreover, market maturity also has a significant and negative impact on the depreciation rate. It means that a higher maturity at a given age of the patent accelerates the depreciation of the rent at that age. Going back to Figure 2 that illustrates the typical S-shaped diffusion of a new technology, we observe that market maturity is, by construction, higher during the late stage of the diffusion (on the right) than during the early stage (on the left). This means that patents applied for and granted during the late stage have a higher rent in the short term but depreciate faster than patents applied for and granted during the early stage. Said in another way, the time path of the rent for patents applied for during the early stage are close to the profile C in Figure 1 whereas it is closer to the profile A during the late stage. The total effect on the value of patents is ambiguous and crucially depends on the discount rate. Nonetheless, it clearly appears that patents granted during the early stage of diffusion are long lasting patents whereas patents granted during the late stage are rather short-life patents. Model 3 finally examines the consequences of introducing both forward citations and market maturity to explain patent renewal decisions. A striking consequence is that market maturity no longer seems to impact renewal decisions, but self-forward citations are now found to have a significant impact on depreciation. Actually, it seems that the effect of self-citations substitutes to that of market maturity. This may be consistent with the fact that on the late stage of diffusion of a new technology, incumbent firms have been granted many patents on the corresponding technology fields and, therefore, that the number of self-citations drastically increases. Accordingly, it is still true that patents granted during the late stage of diffusion will last shorter than patents granted during the early stage of diffusion.

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CONCLUSION

The model developed in this paper extends the usual approach to patent renewal decisions by allowing for the introduction of dynamic determinants of these decisions. Formally, the extension consists in allowing observed heterogeneity across patents and throughout time in terms of depreciation. Such an extension is required to consistently tackle the influence of key patent metrics, like forward citations, that have been found to be linked to patent value in the empirical literature. It is also crucial if one is intended to control for the influence of market maturity on the time path of the rent.

An application to patent renewals for patents granted by the EPO in Germany on wind turbines confirms that the time path of the rent is highly dependent on market maturity. However, following what is done in the literature, our approach postulates that the rent associated to a patent necessarily decreases. This excludes the possibility of a late emergence of an innovation once the economic and technological conditions exist. The possibility of an increasing rent implies an analysis of renewal decisions based on option real theory. Although this approach does exist (Pakes, 1986; Baudry, Dumont, 2006), it is not really adapted to tackle observed heterogeneity across patents. Further research should investigate the implications for measuring the pace of innovation and comparing innovation across sectors.

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