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Breakthrough inventions in solar PV and wind technologies: The role of scientific discoveries

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ABSTRACT

Breakthrough patents are highly influential patents with regard to further technology development. However, there is so far insufficient evidence about the driving forces for the creation of a breakthrough patent. We state that the probability of creating breakthrough patents is driven by the firms' closeness to science. In order to test this hypothesis, in a first step, we identify breakthrough patents based on forward citations. Subsequently, we estimate firm heterogeneity with regard to the probability to create breakthrough inventions based on a firm's closeness to science as well as on other potentially driving factors such as the tendency for international cooperation and the average number of people involved. Thereby we distinguish the solar PV industry (analytic knowledge-base) from the wind industry (synthetic knowledge-base). We find that closeness to science is more relevant in the wind industry to create breakthrough patents where technology development mostly relies on engineering knowledge. Furthermore, our results indicate that technological specialization is more advantageous for breakthrough creation in photovoltaics, while breakthrough patents in wind industry correlate with a broader knowledge-base.

1. Introduction

Following the COP21[1] agreement, today's industrialized countries committed to transform their economies to greenhouse gas neutrality by 2050 (Bundesregierung, 2016). The realization of this ambitious goal requires accelerated decarbonization of essentially all industrial sectors. This can be achieved by a considerable reduction in energy ‘consumption’ (e.g. by efficiency measures) and by the introduction and diffusion of innovative energy supply, power generation and mobility technologies. However, from today's perspective of the state-of-the-art of technology, there are still numerous technological gaps. That is, existing technologies fulfill a certain function in the energy and mobility system with an insufficient performance only: e.g. technologies are not efficient enough, not effective enough, not sustainable enough, etc. In order to bridge such technological gaps, technologies have to be invented and introduced that contribute considerably more to the overarching goal than existing technologies currently do. In this respect, so-called breakthrough inventions could shift the technological trajectory in a way that allows the achievement of the climate protection goals. Such a shift has become necessary because “the incremental improvement of existing systems will not be enough to achieve the scale of reduction in energy and materials consumption which will be needed in the industrial countries during the twenty-first century” (Freeman, 1992, p. 207). To understand the emergence of breakthrough inventions in wind and solar PV technologies, we study their foundations and differences in underlying knowledge-bases. In particular, we analyze the potentially diverging role of scientific discoveries for the development of breakthrough inventions in both technologies.

The understanding of the role of scientific knowledge for the emergence of breakthrough technologies will be valuable for innovation policymakers and firms concerned with such energy technologies alike. Therefore, we are looking for a method to assess the quality of a patent and specifically its characterization of a technological breakthrough with information included in a patent document (Squicciarini et al., 2013). Moreover, with regard to the significant economic role in terms of growth and transformation, it is relevant for managers and policymakers to understand how firms' science relatedness increases the chances to produce breakthrough inventions (Cohen and Caner, 2016).

The first step of our study is to review the application of the notion of a breakthrough invention in the existing body of literature. Despite a

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[1] United Nations Framework Convention on Climate Change, 21st Conference of the Parties.

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broad academic acceptance of the relevance of breakthrough inventions, the empirical evidence of their identification is scarce and the understanding why some firms are more effective in the generation of breakthrough inventions is rather limited. This is partly related to the fuzzy definition of the concept and a lack of empirical studies beyond case study approaches (Della Malva et al., 2015). Therefore, we discuss conceptual issues and conduct an empirical study to better understand breakthrough inventions in wind and solar PV technology. We study differences among these two technologies focusing on the type of knowledge they rely on. In addition, this study looks at the firm-technology level for characteristics to explain firm heterogeneity in breakthrough patents. Conceptually, we argue that the knowledge, a breakthrough invention is based on, is more deeply rooted in science compared to an incremental improvement of an existing technology. To test our hypotheses, we collect patent and firm level data from the OECD REGPAT database. It is furthermore important to differentiate between the ex-ante (market focus) and ex-post (technology evolution focus) characteristics of breakthrough inventions. In this paper, we focus on ex-ante technological novelty of inventions based on patent metrics.

We link the measurement of breakthrough inventions with an explanation of their development based on different knowledge-bases. In particular, we distinguish between technologies that are science based and technologies that are more engineering based, thus studying the link between science and technology. We argue, that breakthroughs in science related technologies require firms to be close to the scientific knowledge frontier. This link is a gap in the literature so far. We test this novel approach with the solar and wind technology but presumably our findings hold for other similar technologies, too. The remainder of this paper is structured as follows: Section 2 defines the breakthrough concept and presents the industry background of solar PV and wind industry along with the relevance of science for new breakthrough discoveries. Section 3 presents the data and our research approach. Section 4 explains the results of the model estimation. The final section discusses the results and draws conclusions.

2. Theoretical background

2.1. Definition of the breakthrough concept

It is widely accepted that inventions result from cumulative knowledge recombination processes (Fleming and Sorenson, 2001; Schumpeter, 1939) but there is no single generally accepted definition of a breakthrough invention. Instead, different disciplines put special emphasis on particular aspects of this concept. This relates to the fact that breakthrough inventions are studied by different disciplines alike such as innovation economics, evolutionary economics and economic history. Moreover, the concept of a breakthrough invention resembles in some aspects other concepts such as radical or disruptive inventions: Zhou et al. (2005) use the term 'breakthrough innovation' as an umbrella term over radical (technology breakthrough) and disruptive (market breakthrough) innovation. Barnholt (1997) refers to breakthrough innovations as comprising exclusively 'revolutionary' scientific and technological breakthroughs. Tushman and Anderson (1986) define technological breakthroughs as inventions, which offer order-of-magnitude improvements in the price versus performance ratio over existing technologies. They classified such major technological shifts as either competence-enhancing or competence-destroying, depending if they strengthen or destroy established firms' existing competencies and knowledge. In the understanding of Wolff (1988) breakthrough innovations are unexpected, creative and predictably radically break with existing technological trajectories. Cohen and Caner (2016) as well as Kaplan and Vakili (2015) stress that breakthroughs advance the state of the technology, create new products and are mostly science-based. Fleming and Sorenson (2001) and Ahuja and Lampert (2001) identify breakthroughs as those inventions that serve as the basis for many subsequent technological inventions.

If we compare these definitions with the concept of a radical invention, the similarity becomes obvious. For instance, Chandy and Tellis (1998) define radical inventions as those that incorporate a substantially different technology compared to existing products and can fulfill consumer needs better than existing products. They distinctly define technological breakthroughs as those that fulfill the first but not necessarily the second condition. Utterback (1994) defines radical innovations or discontinuous change as "change that sweeps away much of a firm's existing investments in technical skills and knowledge, designs, production technique, plant and equipment." Another similar concept is disruptive invention (Christenson, 1997). Disruptive technologies are in their early stage inferior to established technologies measured by performance indicators that are most important to the typical customer. But once the new technology starts to replace the established product in the mainstream market, the disruption occurs.

Breakthrough patents

Whereas most patents represent incremental improvements along a technological trajectory (Dosi, 1988; Nelson and Sidney, 1982), breakthrough inventions are exceptional events that introduce new and potentially path breaking (shifting) technological concepts. Such inventions stimulate the formation of new markets, trigger follow-up inventions and fuel economic growth. Additionally, breakthrough inventions constitute the basis for new products and services (Fleming and Sorenson, 2001). Popp and Newell (2012) find that high quality (i.e. breakthrough) patents constitute a basis for a high number of succeeding innovations. With a focus in regional economics, Kerr (2010) investigates the speed at which clusters of technology-related inventions migrate spatially in the aftermath of breakthrough inventions. The empirical evidence shows significantly higher patenting growth in cities and technologies where breakthrough inventions have occurred. Popp and Newell (2012) analyze the return to R&D in some energy technology sectors and find, among other results, that high quality (i.e. breakthrough) patents may induce follow-up innovations in those sectors. From a macroscopic view, breakthrough inventions are crucial for the long term well-being of industries and even nations (Malerba, 2004). Breakthrough inventions often result from deep explorative R&D endeavors (O'Connor, 2008). However, some authors argue that breakthrough inventions can also emerge as the result of a long lasting exploitative research process that accumulates sufficient knowledge to solve a relevant and important problem (Schoenmakers and Duysters, 2010).

The delineated concepts are rarely separated and often applied in an interchangeable manner. This creates uncertainty with regard to the representation of similar phenomena and also hinders further theory development. A clear concept definition is particularly relevant for the operationalization of the concept in an empirical study. For the classification of a patent into breakthrough (or non-breakthrough) we use a quantitative criterion, which is based on the number of citations a patent has received (forward citations) compared to, for instance, Dahlin and Behrens (2005) who study the degree to which inventions resemble or differ in terms of citation structures to identify breakthrough patents. For the quantitative citation based approach, different minimum threshold levels are common in the existing literature: Ahuja and Lampert (2001) and the OECD define breakthrough inventions as the top 1 % of cited patents (i.e. the most highly cited patents). Kerr (2010) relies on Ahuja and Lampert (2001) definition of breakthrough invention. Kerr (2010) identified the top 1 % of US patents by technology during the period 1975–1984 in terms of subsequent citations, which they refer to as breakthrough patents. Kelley et al. (2013) identify breakthrough patents as the ones having the highest number of forward citations in a given class. Instead of taking the top 1 %, Phene et al. (2006) apply a threshold level of the top 2 %. Conti et al. (2013) employ a dichotomous variable that takes a value of 1 if the patent is in the top 5 % of the sample of EPO patents invented in the same year (application date) and in the same technological category, and 0 otherwise. Chan et al. (2017) also operationalize the breakthrough property in a binary mode. The respective variable takes the value 1 if the number of forward citations is within the top 5 % of the distribution in its product class (during period 1985–2009) and takes the value 0 otherwise. Singh and Fleming (2010) define breakthrough inventions as patents being in the top 5 % in terms of frequency of citation in patents (among patents with the same application year and technology class).

The number of citations a patent receives is typically correlated with other quality measures such as its technological and economic value (Harhoff et al., 2003), its contribution to firm market value (Hall et al., 2005) and the inventor assessments of its economic value (Gambardella et al., 2008). Other approaches are common as well: Fontana et al. (2012) consider those inventions as breakthroughs that have won a prize in a competition that was organized by a leading journal for R&D practitioners. Cohen and Caner (2016) apply as a criterion the FDA classification of new drug approval. This system encompasses eight categories based on the chemical composition of a new drug. Category 1 refers to a new molecular entity (NME) which has not previously been marketed in the US. The respective breakthrough concept is defined as the annual count of category 1 new drug approvals that a firm receives.

Further elaborating on the citation based definition, we use a technology specific threshold for breakthrough patent classification which takes into account that having this special quality is harder in some technology fields than in others. In particular, a breakthrough patent is defined as a patent that exceeds the number of forward citations by at three standard deviations compared to the respective three digit IPC class.

2.2. Industry knowledge-base characterization of solar PV and wind

We focus our analysis on solar PV and wind energy technologies. Both technologies have been developed into a rather established design life cycle stage. However, Asheim and Gertler (2005) find that there are significant differences in innovation processes among firms in different industries related to the specificity of required and applied knowledge-bases. In their work, they distinguish three categories of knowledge-bases: analytical, synthetic and symbolic. The analytical knowledge-base is science based and focuses on the understanding and explanation of natural phenomena. In contrast, the synthetic knowledge-base is mostly related to engineering knowledge and encompasses the design of practical solutions to context specific human problems. Symbolic knowledge deals with the generation of cultural meaning.

In the analytical knowledge-base, knowledge is more often codified than in the other two types. Still, tacit knowledge plays its role in the analytical knowledge-base, too. The process of knowledge creation and inventive activities usually requires the involvement of both types of knowledge (Johnson et al., 2002). The focus on codification relates to knowledge generation, which is based on the application of scientific principles and methods. Additionally, R&D processes are more formalized, e.g. in formal R&D units and R&D results are documented in scientific publications and patents. Such activities require specialized experts such as scientific staff that have extensive university training. Typically, knowledge application leads to new products and processes as well as often inventions, which have a stronger breakthrough character. In contrast, application of synthetic knowledge is often based on the need to solve specific problems emerging from collaboration with suppliers and clients. Products thereof are often produced in small series and research is of minor importance and has a stronger applied character focusing on product and process development. Actual knowledge creation is less deductive based on scientific principles but more inductive based on testing, experimentation and simulation (Lorenz and Lundvall, 2006). As a consequence, this results in rather incremental inventions, i.e. incremental improvements of existing products and processes. To differentiate the two types of knowledge-bases (Asheim et al., 2011) suggest i.a. making use of patent citations where knowledge-bases citing many other patents are dominantly synthetic while knowledge-bases citing many scientific publications are dominantly of the analytical type.

2.2.1. Characterization of the wind industry

Based on the before delineated criteria, the wind industry can be designated as a predominantly synthetic knowledge-based industry. The wind industry originally developed on the basis of *bricolage* processes (Garud and Karnøe, 2003). A diverse network of collaborating actors recombined low-tech knowledge-bases and small-scale craft capabilities. Current technology development focuses strongly on blade design. Here we find both, product and process innovations (ZSW, 2017). Nowadays, the production of wind turbines is characterized by standardized industrial processes that draw upon skilled manual labor (together with tools for welding, milling and drilling). Key components are for instance transmission systems. Due to complexity and large size, wind power plants are usually manufactured at small-scale base on labor-intensive manufacturing processes (Hoppmann et al., 2013). That is, the complex product architecture goes together with (compared to solar PV) low production quantities. The focus of the innovation process shifted over time from the system architecture and core components to different sub-systems and components of the product, rather than from product to process innovations (Huenteler et al., 2016a). So called DUI-based (Doing, Using and Interacting) innovation processes in the wind power industry depend on novel recombination of experience based knowledge and competencies (Huenteler et al., 2016a; Martin and Moodysson, 2013). That is, new knowledge does not predominantly emerge from science but from on-the-job training, as well as from interaction between various firms and from solution oriented producer-user interaction (Huenteler et al., 2016a; Jensen et al., 2007). In this more incremental way of learning by doing, tacit knowledge embedded in craft and practical skills is of high significance (Binz and Truffer, 2017).

Yet, for the future, we expect a shift towards a stronger analytical knowledge-base. As the wind industry has matured, significant cost reductions by innovations could already be realized. Further reductions can for instance be achieved through facilitation of system integration. However, a number of further technological developments, reaching from infrastructure innovation and energy system operating to innovative business models, have to be realized first, requiring a shift towards a stronger science orientation (IRENA, 2017). Besides engineering tasks, there is a need to tackle problems of fundamental research. While in the past progress was often incremental, more fundamental research could trigger more technological breakthroughs. This could further decrease levelized costs of electricity (LCOE) for instance by aerodynamics modelling as a key discipline of rotor design. Further research priorities are (among others) smart rotor designs, matching site conditions as well as materials and structures. Market requirements are still very country specific. For instance, there are significant differences with regard to turbine performance, hub height and blade length. In Denmark and Germany there are typically larger and more powerful wind turbines than in the US (ZSW, 2017). Nowadays, innovative turbine designs are still predominantly developed in the few countries that were involved in early industry formation and market deployment (in particular Denmark, Germany and the US). Regions and countries can still benefit from first mover advantages in later industry life cycle phases (Huenteler et al., 2016a).

2.2.2. Characterization of the solar PV industry

In contrast to the wind industry, the solar PV industry has been more strongly based on analytical (scientific) knowledge from its very beginning. Progress relates to improvements in material science and in general to the development of new scientific knowledge, so called STI-mode (Science, Technology and Innovation) of innovation. An ever better understanding of the influence of basic material properties on solar PV device processing is essential to make further progress in PV technologies. This kind of knowledge is critical for increasing efficiently and reducing production costs of PV cells.

During the “solar boom” phase (about 2007–2012) many start-ups have been founded and brought new technologies to the market (ZSW,

Table 1
Cited patent and citation counts.

Technology	Cited patents	Citations	Patents (3 digit)	Citations (3-digit)
Solar PV	2287	6780	55,672	86,867
Wind	1116	3830	19,284	29,430

2017). Meanwhile, China has become the major player in the industry while most other countries rather pursue niche strategies. The solar PV market experienced massive price decreases within a relative short period in time triggered by considerable increases in production capacities and scale effects. Additionally, public subsidies substantially added to this development in the solar PV market and even lead to an unhealthy growth (ZSW, 2017). Main drivers of technological progress are Japan, the US, Germany and particularly China, which sources knowledge from development centers in Europe but also conducts own research.

Solar PV continuously improves in its degree of efficiency but is getting closer to physical boundaries. The technological trajectory has branched out into different materials. Consequently, material research is a driver of technology development and materials determine the boundaries of efficiency improvements. It is expected that silicon technologies will continue to dominate the market. Due to continuously falling prices barriers to enter the market for other technologies have been formed. Also tandem cells are developed to overcome efficiency boundaries of silicon cells. As solar PV modules have developed into commodities premium producers can only survive in niche markets, for instance building wall applications or agrophotovoltaics (ZSW, 2017).

Meanwhile, the mainstream market for PV modules has developed into a mass manufactured commodity market. This development generally applies to technologies, which have relatively simple product architecture and can be produced in large-scale processes. It made the formerly leading firms in the US, Germany and Japan lose their market dominance over a relatively short period of time (Binz and Truffer, 2017).

Innovation processes in STI-based industries are based on knowledge which draws upon scientific principles that can be codified, for instance in patents, analytical knowledge-bases such as material sciences, while economic valuation is nowadays organized in standardized, global mass markets (Dewald and Fromhold-Eisebith, 2015). Successful firms usually have formal R&D units, close ties to universities and other research organizations and repeated radical technology breakthroughs (Binz and Truffer, 2017; Huenteler et al., 2016b). Knowledge spill-overs have been most prominent from the semiconductor and glass industry and we also observe reverse spill-overs.

2.3. Firm heterogeneity and NPL covering new scientific knowledge

With regard to breakthrough inventions, we are looking for an explanation why some firms are more likely to develop such inventions than others, mainly focusing on the science closeness of the firm. Within the literature, some studies relate to possible factors driving the creation of breakthrough inventions. For instance, Srivastava and Gnyawali (2011) conclude that the quality and diversity of the technological resources of a firm are positively correlated with breakthrough inventions. Schilling and Green (2011) analyze how different features of the research process (search depth, search scope and atypical connections) influence the probability of breakthrough idea generation. Cohen and Caner (2016) find that breakthrough inventions occur with a higher probability in pharmaceutical firms that conduct extensive exploitative research. By analyzing panel data of US biopharmaceutical firms, they find that emphasis on exploitative invention has a stronger positive effect on breakthrough inventions than does a firm's emphasis on exploratory invention. Furthermore, heterogeneous knowledge available in firms' R&D alliance network increases the number of breakthrough inventions along a U-shaped curve. Castaldi et al. (2015) investigate how variety affects the innovation output of a region. By analyzing patent data for US states in the period 1977–99 and associated citation data, they find that related variety will enhance innovation as related technologies are more easily combinable into a new technology. Interestingly, unrelated variety fosters technological breakthrough since such innovations are often based on recombinations of previously unrelated technologies that represent fully new functionalities. Arts and Veugelers (2013) study the US patent record in biotechnology from 1976 to 2001. The analysis shows that breakthroughs in biotechnology rely on both, non-technical and technical prior art, particularly if it is more recent and from many different technology fields. Yet, breakthroughs are less likely to have a dissimilar set of technical prior art citations as they are more likely to use prior art previously cited by many other inventions. Breakthroughs are more novel in the sense that they are more likely to recombine technological components for the first time.

The analysis of non-patent references recently gained attention while different suggestions have been made with regard to their interpretation. For instance, Narin et al. (1987) regard such references as an indication for a direct influence of science on technology. Whereas, Meyer (2000) concludes that non-patent references should not be seen as a direct and unidirectional link from science to technology. Tijssen (2001) shows that non-patent literature serves as an indicator for the interaction between science and technology instead of a direct link between a scientific source and an invention. In a comprehensive study Callaert et al. (2006) found that non-patent literature can have nine distinct sources: scientific journals, conference proceedings, reference books/databases, industry related documents, books, patent related documents, research/technical reports, newspapers and unclear/other. For instance, an examination of 10.000 USPTO patents showed that 55 % of all non-patent literature citations were to scientific journals. The number is even higher at the EPO where 64 % of all non-patent literature citations are academic journals. Gilsing et al. (2011) find that the main transfer channel of scientific knowledge for industry is academic publications. Firms with scientific capabilities can be expected to generate more “unexpected” outcomes, leading to a higher probability of breakthrough inventions (Sobrero and Roberts, 2001).

In this paper, non-patent literature citations are employed as an indicator for the scientific knowledge relatedness of the development of a patented technology. The reasoning for this indicator is that most non-patent literature citations are academic papers and that academic papers are the main communication channel between the scientific and technological domain (It should be noted that some of the other non-patent literature citations could also be of scientific origin). Also, radical innovations incorporate more scientific knowledge than incremental innovations (Jelicic and Castaldi, 2016). Therefore, by focusing on the science closeness of a firm we explain (parts of) the variation in the generation of breakthrough patents and thereby also help managers and policy makers to develop targeted strategies to increase the number of realized breakthroughs. Based on the previous discussion of technology knowledge-base characterization and citations referring to non-patent literature as a proxy for science closeness we formulate two diverging hypotheses: Broadly speaking, the first one states that science closeness is more important in the solar PV industry while contrariwise the second one states that this holds rather true for the wind industry.

Hypothesis 1a. Since technology development in the solar PV industry is (compared to the wind industry) more strongly reliant on scientific knowledge (analytic knowledge-base) those firms that are closest to scientific knowledge sources have a higher probability to produce breakthrough inventions.

Hypothesis 1b. Since the wind industry uses relatively little scientific knowledge for its technology development (so far), it is rather those firms that make use of scientific knowledge that have a higher probability in generating breakthrough inventions in the industry.

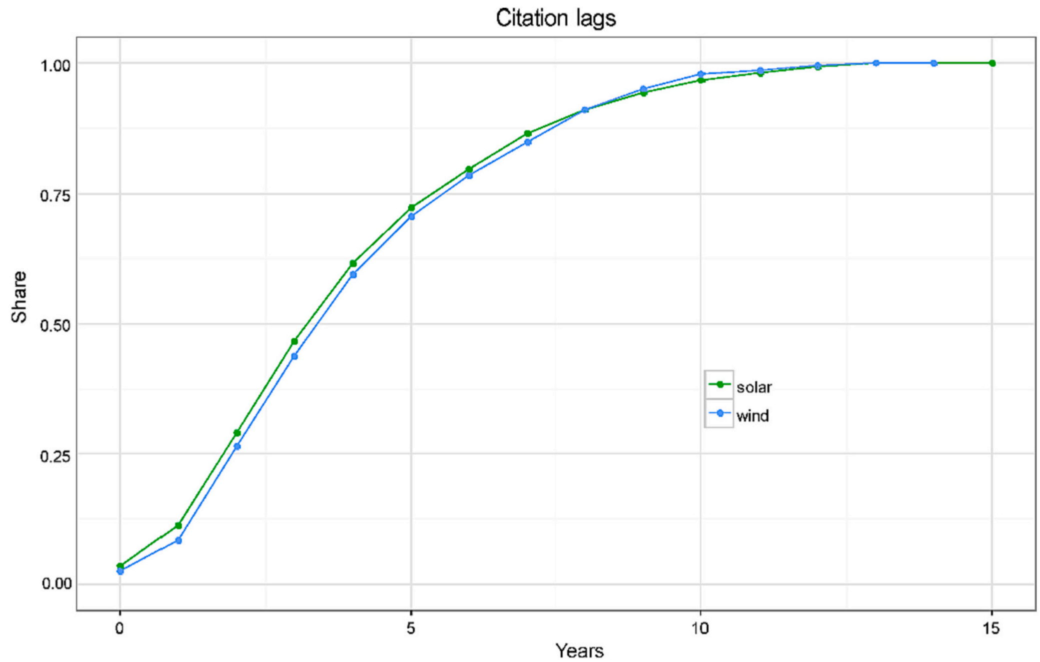

Fig. 1. Accumulated citation lags.

3. Data and methodology

3.1. Data

We start by collecting patent applications from the OECD REGPAT database in solar PV and wind technologies. Respective IPC classes were taken from the IPC Green Inventory, which was developed by the IPC Committee of Experts and includes relevant IPC classes for environment-related patents.[2] We take into account approved national and international patents that have a priority year between 2000 and 2010 and citations with a citation lag of up to five years (truncated counts). The time period is chosen to specifically consider the period of emergence of both renewable energy technologies (see Li et al., 2020). Next, we retrieved from the patent applications their 3-digit IPC class and collected all cited patens that are classified by one of these 3-digit IPC classes. This finally resulted in the number of patents and citations shown in Table 1.

3.2. Identification of breakthrough patents

As delineated in Section 2, we identify breakthrough patents by means of forward citations (Ahuja and Lampert, 2001; Della Malva et al., 2015; Singh and Fleming, 2010). This approach relates to the assumption that the number of forward citations a patent receives is linked to its technological importance (Carpenter et al., 1981) and even its economic value (Hall et al., 2005).

The distribution of forward citation counts is typically skewed. That is, there is a large share of patents that receive no (or very few) citations and a small number of patents that receive a very large number of forward citations. Due to the correlation, this goes together with the impact and value of patents which is also very skewed (Harhoff et al., 2003). Therefore, it is a credible assumption that patents, which receive the highest numbers of forward citation counts, are the most important technological inventions in their respective field.

For an empirical study we have to specify what exactly “the highest numbers of forward citation counts” means. For instance, Schoenmakers and Duysters (2010) simply regard those patents as breakthroughs, which received >20 forward citations, regardless of technology and time specific effects that may influence the number of citations. Others take a certain percentage as a threshold. For instance, the top 1 % or 5 % in terms of citations received compared to patents filed in the same year and/or in the same 3-digit technology class (Ahuja and Lampert, 2001; Della Malva et al., 2015; Singh and Fleming, 2010). Generally, truncated citation counts are used but some authors prefer truncated and untruncated counts (Arts and Veugelers, 2013). To identify breakthrough patents, we calculate the truncated count of forward citations as the number of citations received within 5 years after priority filing. This covers a large part of the citations, as can be seen from the cumulative citation delays for wind and solar PV technology over all years (included in the database) shown in Fig. 1. The figure shows that for both technologies after five years about 75 % of all citations have been made and that it takes another 10 years until a share of 100 % has been reached.

As we applied truncated counts for a period of five years, Tables 2 and 3 show the number of citations for each technology and their

Table 2
Citations distribution across years (solar PV).

Year	Freq	Share	share_sum
0	327	0.04823009	0.04823009
1	731	0.10781711	0.15604720
2	1667	0.24587021	0.40191740
3	1654	0.24395280	0.64587021
4	1410	0.20796460	0.85383481
5	991	0.14616519	1.00000000

Table 3
Citations distribution across years (wind).

Year	Freq	Share	share_sum
0	140	0.03655352	0.03655352
1	322	0.08407311	0.12062663
2	973	0.25404700	0.37467363
3	940	0.24543081	0.62010444
4	853	0.22271540	0.84281984
5	602	0.15718016	1.00000000

[2] See Annex for a list of the used classes. IPC Green Inventory is accessible via: https://www.wipo.int/classifications/ipc/en/green_inventory/.

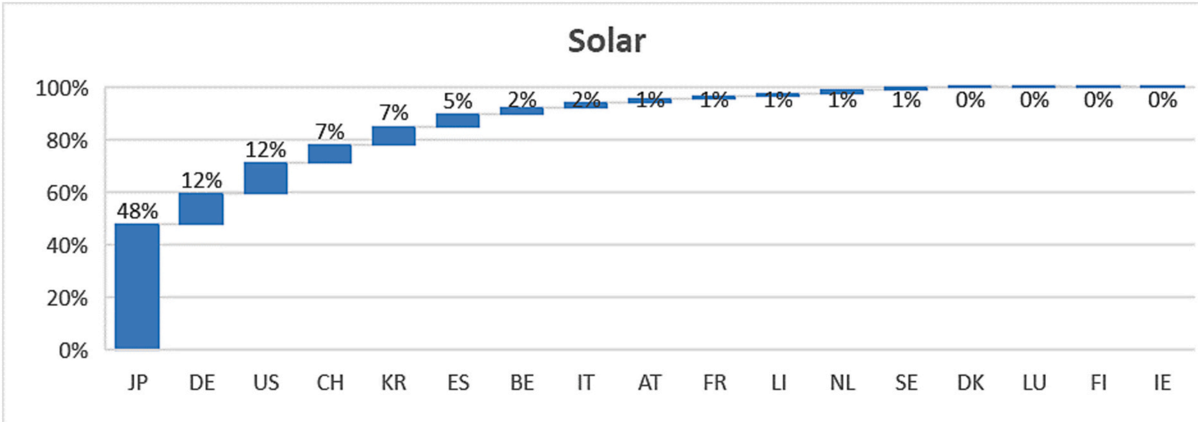

Fig. 2. Breakthrough by country (solar PV).

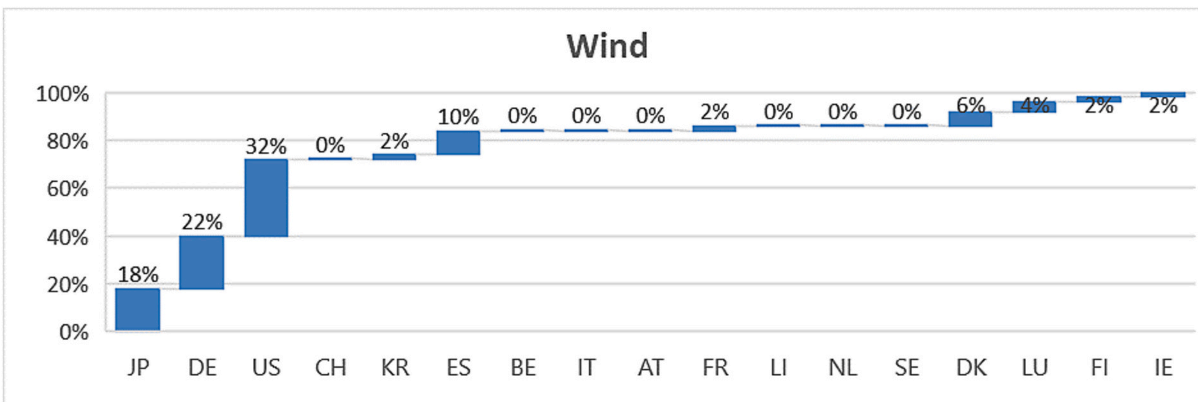

Fig. 3. Breakthrough by country (wind).

(cumulated) share over the years that were taken into account. In both technologies, the peak in the number of citations is reached in the second year.

For each of the distributions, we calculate the mean and standard deviation of (truncated) forward citation counts. In accordance with our definition of a breakthrough patent, we first calculate the mean count of received citations per patent for the 3-digit technology classes a technology belongs to. For instance, there are 17 classes for solar PV technology and 5 classes for wind technology. To the mean count we add three standard deviations. In general, other studies apply 3–5 standard deviations (Della Malva et al., 2015). The result is the minimum value of received citations to qualify as a breakthrough patent. For solar PV this number is 4–7 citations and for wind energy it is 4–6 citations. Based on these numbers, we identified all patents that received a number of citations that equals or exceeds these thresholds. This resulted in 80 patents for photovoltaic and 49 patents for wind technology. This represents a share of 4.4 % in wind technology and 3.5 % in solar PV of all cited patents.

By looking at the analysis of breakthrough patents by country (Figs. 2 and 3), we see that there is large variance across countries. In solar PV it is Japan, the US and Germany that are leading and in wind technologies it is the US, Germany and Japan that are most successful in breakthrough inventions.

4. Econometric approach

After having identified the breakthrough patents within each technology class, we can now go on and develop a regression model. The dependent variable, breakthrough invention, is a count variable so we could for instance use a Poisson regression method. However, we are mainly interested in the probability of generating a breakthrough invention at all. That is why we opted for a pooled logistic regression model (1) to estimate occurrence probabilities with R's pglm package. Although OLS is unbiased for count data, it rarely provides the best fit for dependent variables with a limited set of (non-negative integer) values across all values that the independent variables can take (Wooldridge, 2015).

As described in our hypotheses, we take the number of non-patent literature citations an organization has made as our first independent variable. However, beside these NPL-citations there are possibly other factors that have an influence on the dependent variable and hence need to be controlled for. First, there is typically a capacity effect, which relates to the size of the firm. Larger firms may have a higher probability for generating breakthrough patents. Therefore, we take the size of a firm into account, which is approximated by the absolute number of patents a firm applied for each year and represented by the variable *pat_all*. Second, R&D intensity might be an influential factor. However, different studies have shown that an increase in R&D intensity at the firm level goes together with an increase in the use of public research which is already captured in the variable for *pat_npl* (Laursen and Salter, 2004; Mohnen and Hoareau, 2003). Furthermore, the average number of participants in patent creation (*share_psn*) might be relevant for the breakthrough outcome. Here, multiple people's involvement in the process might provide e.g. the availability of more ideas, the possibility of a critical discussion as well as a broader knowledge-base. At least in academic research a higher number of authors is often associated with both, a better outcome and a higher quality of research (Levitt, 2015). Also, the tendency of an organization to produce patents in international cooperation (*coop_int*) might have a positive impact on the probability to produce a technological breakthrough, which can arise from synergies created by such a cooperation (Schade, 2009). We further included the technological range of the patent applicants by looking at the number of different IPC-subclasses in which they are patenting. As breakthroughs are commonly seen to "materialize from recombining disconnected but pre-existing technology subclasses" (Arts et al., 2013), a broad technological knowledge portfolio might influence the chance of creating a breakthrough patent. Another common control variable regarding patent quality and value is the citation frequency of a patent (Harhoff et al., 1999). We here include backward and forward citations as a control variable by looking at the average number of backward and forward citations per patent for each actor. Following the literature, a high number of backward citations can be seen as an indicator for a higher value of the patent (Harhoff et al., 2003), though it also is a sign for a more incremental invention. On the other hand, forward citations are commonly seen as a good indicator for breakthrough patents (Trajtenberg, 1990; Kaplan and Vakili, 2015). As an additional variable, the average number of claims per patent for each actor is used, which mainly indicates the quality and economic value of a patent (Squicciarini et al., 2013; Lanjouw and Schankerman, 2004) as well as its general importance (Srivastava and Gnyawali, 2011).

Considering the mentioned variables, our model can be formulated as follows:

$$\begin{aligned} log\left(\frac{p}{1-p}\right) &= \beta_0 + \beta_1(pat\_npl) + \beta_2(pat\_all) + \beta_3(share\_psn) \\ &\quad + \beta_4(coop\_int) + \beta_5(tech\_range) + \beta_6(avg\_claim) \\ &\quad + \beta_7(avg\_citing) + \beta_8(avg\_cited) \end{aligned} \tag{1}$$

with

$log\left(\frac{p}{1-p}\right)$ – occurrence probability of the estimated breakthrough invention
pat_npl – number of nonpatent literature citations of the organization
pat_all – absolute number of patents a firm applied for
$share\_psn$ – average number of participants in patent creation of the organisation
$coop\_int$ – tendency of an organization to produce patents in international cooperation
$tech_{range}$ – number of different technological fields the organisation is patenting in
avg_{claims} – average number of claims per patent
avg_{cit_backw} – average number of patents cited per patent
avg_{cit_forw} – average number times a patent is cited from another patent

We start with a list of firms that had at least a single patent in the respective technology field during the observation period (≥2000) and retrieved all patents in the respective technology field for these firms. Next, we estimate the pooled logistic regression model (Maximum Likelihood Estimation) for the three standard deviations case, taking the years 2000–2010 into consideration. Tables 4 and 5 show the count breakthrough patents and non-breakthrough patents per year in the solar PV and wind energy industry.

Our hypotheses state, that to create breakthrough inventions, science closeness is either more important in the solar PV industry compared with the wind industry (where other factors such as embeddedness in local networks or customer interaction might be more important H1a) or that closeness to science is more important in the wind industry where scientific knowledge can have a stronger impact since inventions are typically based on analytic knowledge-bases (H1b). Thus, our main explanatory variable is the science closeness of a firm. We expect that firms that have relatively many NPL citations in their patent portfolio are close to the forefront of technology. In particular, we are therefore interested in information about citations to non-patent literature (NPL). NPL includes scientific journals articles, book chapters, conference papers and others. First, we created a list of patents that are citing NPL in the respective technology field. Next, we were looking for firms that applied for patents that are citing NPL the respective technology field. As main independent variable we take the number of NPL citations for each year. To control for a capacity effect we take the size of a firm into account, which is approximated by the absolute number of patents a firm applied for each year.

Regression results show that the science orientation, characterized through a large number of NPL, significantly increases the chances for creating breakthrough inventions in the wind industry (Table 7). However, for the solar PV case, as illustrated in Table 6, the parameter *pat_npl* is not significant even though it is positive, indicating that there is no significant influence of science orientation on creating breakthrough inventions in the solar industry. Consequently, we find confirmation for hypothesis 1b while hypothesis 1a has to be rejected. Further, in both, wind and solar industry, a decrease of people involved into the patenting process does significantly increase the probability of creating a breakthrough patent. Regarding a firm's tendency of international cooperation, the production of breakthrough patents is significant and positively correlated in the field of wind energy. However, the creation of a breakthrough patent in the technology field of photovoltaics is independent from international collaboration. Technological range has significant influence on the ability to create breakthrough innovations in both industries. This influence shows to be positive in the field of wind energy and negative in the field of photovoltaics. The effect of the average number of forward and backward citations is in both cases significant and similar for both industries. While backwards citations have a negative impact on the capability to create breakthrough patents, the impact is positive for forward citations. Finally, the results further indicate, that the average number of claims per patent has a significant negative impact for both, wind and solar industry.

5. Discussion and conclusions

The solar PV industry is based on the analytic knowledge-base while the wind industry has been more strongly focused on the synthetic knowledge-base. However, it has been acknowledged that also in the wind industry further technological progress requires stronger science focus and thus scientific knowledge-bases to better understand, for instance, blade aerodynamics. Our result indeed confirms that those wind energy firms, which are more closely related to science, have better chances to stand out and to generate breakthrough inventions. In this regard, one additional citation of NPL is associated with a 1.29 % increase in odds ratio for a breakthrough patent. However, this is not the case for solar PV firms, where research closeness is generally higher and therefore does not significantly affect the capacity to generate a breakthrough invention to the same extent as in the wind industry. These aspects might also explain the results regarding the relevance of international cooperation on breakthrough patent creation. While photovoltaics is a field in which technological advancement is well documented through scientific publications, further international cooperation for knowledge exchange has no significant additional effect on the creation on breakthrough patents. In contradiction, advancements in wind industry are mainly characterized by smaller enhancements on site, which are often based on tacit knowledge and therefore lack a specific documentation. In this case, an international cooperation might be especially valuable for breakthrough creation, as it allows bringing together new knowledge. Here each additional citation of NPL increases the odds ratio by about 0.72 %. Regarding the impact of the technological range, a deeper technological specialization supports breakthrough creation in photovoltaics while a broader knowledge base is more advantageous in the wind energy sector. This seems reasonable, as the construction of wind turbines requires knowledge from different fields such as mechanical, electrical and civil engineering, while

Table 4
Breakthrough patents in solar PV.

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
0	5311	5311	5313	5308	5309	5309	5306	5310	5312	5311	5316
1	6	6	4	9	8	9	11	7	5	6	1

Table 5
Breakthrough patents in wind energy.

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
0	1636	1634	1635	1632	1631	1634	1627	1630	1632	1633	1636
1	0	2	1	4	5	2	9	6	4	3	0

photovoltaics are technically more concentrated. The significant positive influence of forward citations as well as the significant negative impact of backward citations are consistent with literature (Trajtenberg, 1990; Kaplan and Vakili, 2015), whereas the significant negative correlation of patent claims on breakthrough creation is somewhat surprising. However, this result might be explained by the lesser need of innovation delimitation for breakthrough patents, as they are more likely to cover a new broader field in contrast to more incremental patents. Another at first glance surprising result is the negative impact of the average number of inventors on the creation of breakthrough patents. This might be explained with the finding, that rather smaller groups (or even individuals) serve as a nucleus for unconventional ideas (Wu et al., 2019). Finally, the results demonstrate that in both considered technologies, the likelihood of generating a breakthrough patent is positively associated with the overall patenting intensity. In this regard, the odds of producing a breakthrough in the wind and solar sectors increase by 0.37 % and 0.48 %, respectively, with each additional patent. These results are plausible as they reflect the cumulative nature of innovation in the wind and solar sector. The positive link between the likelihood of breakthrough patents and overall patenting intensity might be driven by the growing body of prior knowledge and the increased investments and competition in these fields. This dynamic relationship underscores the pivotal role of patenting intensity in driving transformative technologies in renewable energy.

Our results have some important economic and political implications. Regarding the former, wind technology firms are advised to invest more into their R&D units, which is a precondition to developing the necessary absorptive capacity to understand recent scientific discoveries published in journals and books and presented at conferences. Also, collaboration with research institutes or universities can be a valuable measure to gain access to the scientific community and its knowledge. For solar PV, where the general level of science relatedness is already higher, other factors such as exploratory research might be more relevant. Since breakthrough inventions can have a significant economic impact, there is also a policy dimension of our result. We have shown that the application of academic research increases the breakthrough potential of wind technologies, which (as shown in previous research) helps firms performing better than firms that are less science focused. Therefore, when it is in a national government's best interest to have well performing domestic firms, then funding of academic research is necessary to generate new knowledge for firms to source from. Moreover, innovation support programs could be designed in a way that firms are incentivized to collaborate with research institutes and universities.

The observation that breakthroughs require a stronger science orientation could indicate a general pattern according to which a technology field goes through a transition phase from a synthetic towards a more analytic knowledge-base. While in the beginning, innovation is more based on experience and practical exchange (with users) in later stages of technology development, breakthrough inventions require a stronger science orientation since, so to speak, the low hanging fruits have already been harvested. Thus, firms that are capable of absorbing scientific knowledge, which typically requires them at least to conduct some own R&D and run their own lab, are in a comparatively better position. We expect that this pattern not only holds for the wind industry but also for other industries that started out on the basis of synthetic knowledge and that have a product architecture that includes elements that require strong scientific knowledge to become significantly improved in terms of some performance measure. However, as our empirical analysis is so far limited to the wind and solar technology and it would be interesting to see in the future if other technologies show

Table 6
Estimation results solar PV.

	Estimate	Odds ratio	Std. error	t value	Pr(>t)
(Intercept)	5.79E-06	1.00001	2.09E-04	0.0278	0.9779
pat_total	4.78E-03	1.00479	1.87E-04	25.5834	<2.20E-16 ***
lag(pat_npl, k = 1)	−6.94E-04	0.99931	5.50E-04	−1.2609	0.2073
share_psn	−1.47E-03	0.99853	2.25E-04	−6.5274	6.79E-11 ***
coop_int	8.35E-04	1.00084	1.45E-03	0.5753	0.5651
tech_range	−8.09E-05	0.99992	1.28E-05	−6.2926	3.16E−10 ***
avg_claim	−1.25E-03	0.99875	8.18E-05	−15.2251	<2.20E−16 ***
avg_cit_backw	−1.67E-03	0.99833	1.50E-04	−11.0805	<2.20E−16 ***
avg_cit_forw	5.29E-02	1.05432	5.12E-04	103.3238	<2.20E-16 ***
	Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1				

Table 7
Estimation wind energy.

	Estimate	Odds ratio	Std. error	t value	Pr(>t)
(Intercept)	−1.06E-03	0.99894	3.32E-04	−3.1904	0.001423 **
pat_total	3.73E-03	1.00374	1.50E-04	24.9376	<2.20E−16 ***
lag(pat_npl, k = 1)	1.28E-02	1.01288	1.24E-03	10.3208	<2.20E-16 ***
share_psn	−1.67E-03	0.99833	5.12E-04	−3.2528	0.001145 **
coop_int	7.12E-03	1.00715	3.32E-03	2.1434	0.032096 *
tech_range	1.37E-04	1.00014	1.73E-05	7.9349	<2.24E-15 ***
avg_claim	−7.10E-04	0.99929	1.63E-04	−4.3492	<1.38E-05 ***
avg_cit_backw	−1.54E-03	0.99846	3.28E-04	−4.6954	<2.68E-06 ***
avg_cit_forw	4.21E-02	1.04300	6.79E-04	61.9666	<2.20E-16 ***
	Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1				

similar patterns. Moreover, our analysis is limited to the level of the invention, which means that is remains unclear to what extent breakthrough inventions are actually transformed into products that significantly improve a technology.

Data availability

Data will be made available on request.

Annex A. Annex

Photovoltaics (PV)	IPC
. . . Devices adapted for the conversion of radiation energy into electrical energy	H01L027/142
. . . Devices adapted for the conversion of radiation energy into electrical energy	H01L031/02%
. . . Devices adapted for the conversion of radiation energy into electrical energy	H01L031/03%
. . . Devices adapted for the conversion of radiation energy into electrical energy	H01L031/04%
. . . Devices adapted for the conversion of radiation energy into electrical energy	H01L031/05%
. . . Devices adapted for the conversion of radiation energy into electrical energy	H01L031/06%
. . . Devices adapted for the conversion of radiation energy into electrical energy	H01L031/07%
. . . Devices adapted for the conversion of radiation energy into electrical energy	H01G009/20
. . . Devices adapted for the conversion of radiation energy into electrical energy	H02N006/00
. . . . Using organic materials as the active part	H01L027/30
. . . . Using organic materials as the active part	H01L051/42
. . . . Using organic materials as the active part	H01L051/44
. . . . Using organic materials as the active part	H01L051/46
. . . . Using organic materials as the active part	H01L051/48
. . . Assemblies of a plurality of solar cells	H01L025/00
. . . Assemblies of a plurality of solar cells	H01L025/03
. . . Assemblies of a plurality of solar cells	H01L025/16
. . . Assemblies of a plurality of solar cells	H01L025/18
. . . Assemblies of a plurality of solar cells	H01L031/042
. . . Silicon; single-crystal growth	C01B033/02
. . . Silicon; single-crystal growth	C23C014/14
. . . Silicon; single-crystal growth	C23C016/24
. . . Silicon; single-crystal growth	C30B029/06
. . . Regulating to the maximum power available from solar cells	G05F001/67
. . . Electric lighting devices with, or rechargeable with, solar cells	F21L004/00
. . . Electric lighting devices with, or rechargeable with, solar cells	F21S009/03
. . . Charging batteries	H02J007/35
. . . Dye-sensitised solar cells (DSSC)	H01G009/20
. . . Dye-sensitised solar cells (DSSC)	H01M014/00
Wind	**IPC**
Wind energy	F03D%
. . Structural association of electric generator with mechanical driving motor	H02K007/18
. . Structural aspects of wind turbines	B63B035/00
. . Towers	E04H012/00
. . Wind Motors	F03D%
. . Propulsion of vehicles using wind power	B60K016/00
. . . Electric propulsion of vehicles using wind power	B60L008/00
. . Propulsion of marine vessels by wind-powered motors	B63H013/00

Interview with wind energy experts of the Center for Solar Energy and Hydrogen Research Baden-Württemberg (12 October 2017)
Questions (Translated from German)
What are the central drivers of technology development?

- Role of product and process innovation?
- Role of basic research?
- Role of federal funding?
- Role of standards/dominant designs?
- Which countries drive technology development the most??

Characterization of the innovation environment - Actors

- Which main actors are involved in the innovation process? (Internal actors, cooperations, university facilities …?)
- Can the technology be classified as user-driven? (Bring users own ideas? Are users driver of innovation?)
- Do cooperations in the context of technology development mainly take place on a local or global level?
- Can be differentiated between radical and incremental innovations?

Characterization of the innovation environment - Companies

- Is the sector shaped by new or established companies?
- Do strong market entry barriers exist? (at least technology or know-how related?)
- Do rather large or small companies drive technology development?

Technological development:

- Where does relevant development potential exist? Which might be disruptive? E.g. further progress in material efficiency
  - How are cost reductions realized (Learning curve effects or e.g. new materials, processes, higher full load hours, etc.)?
- What are other goals of technology development besides cost reduction (higher full load hours, provision of control energy, flexibility, exchange rare earth/critical metals/recyclability?)
- How to evaluate the influence of spillover effects?
- Is technological development characterized by incremental or rather disruptive (or external) innovation?
- Which components have the greatest influence on technological development (focus on future development)?
  - Are the key parts produced domestically?
- Can one or more technological development paths be identified?
  - Strengths/weaknesses of the individual paths

Enforcement of innovation

- What are the barriers to introducing the newly developed technology?
- Are there acceptance problems? If so, what are the reasons for rejecting the technology?
- Which political or regulatory frameworks are required to successfully establish the technology in the market??
- What role do the federal government and the state play (e.g. funding agencies, legislators or similar)?
- Digitization: What role does it play for the technologies?

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