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Pulled or pushed? The spatial diffusion of wind energy between local demand and supply

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Abstract

This article contributes to and connects the literature on spatial innovation diffusion, entrepreneurship, and industry life-cycles by disentangling the relevance of local demand and supply in the adoption of wind energy production. More precisely, we evaluate the strength of local supply–push effects with those of local demand–pull over the course of the evolution of an industry and its main product evolution. By using Bayesian survival models with time-dependent data of wind turbine deployment and firm foundation for 402 German regions between the years 1970 and 2015, we show that the spatial evolution of the German wind energy industry was more strongly influenced by local demand–pull than local supply–push processes. New producers are found to emerge in proximity to existing local demand for wind turbines. No evidence was found for producers being able to create local demand for their products by pushing the adoption of the technology in their regions.

JEL classifications: Q21, R12, O33, O31

1. Introduction

A growing literature is investigating the emergence and evolution of industries across space and time. The economic geography and regional science literature usually focuses on the role of the (local) supply side in the emergence and evolution of industries, emphasizing agglomeration externalities, path dependence, windows of local opportunity, and related variety (Bergek and Jacobsson, 2003; Boschma and Wenting, 2007; Fornahl *et al.*, 2012). Notably, while the demand side has received much less attention in the field, its relevance has been highlighted in the diffusion of innovation literature originating from Rogers (2003) and Hägerstrand (1952, 1965a,b). More recently, the (primarily sociological) literature on technology transition has underlined demand processes as crucial for the emergence and expansion of industries and their products[1] (Geels, 2004). In particular, in this literature, local demand (in combination with local institutions) is argued to create (market) niches within which new industries and products can grow before facing the "full" competitive forces of nonlocal markets (Schot and Geels, 2008).

Hence, both lines of argument emphasize the role of local demand and supply processes for the emergence and growth of industries. However, while a substantial empirical literature exists that assesses the role of regional supply-

1 For the sake of readability, we stick to the term "product." However, our argumentation is also valid for new technologies.

side factors for industries' emergence, empirical findings on the importance of local demand are less extensive. In addition to both literature streams paying more attention to the early stage on industries' developments, empirical studies in these fields rarely analyze demand, and supply factors side-by-side (Justman, 1994). Accordingly, it is still not well understood how local demand relates to the emergence and concentration of industries, and to what extent industries may themselves contribute to the activation and formation of local demand.

This article contributes to this debate by investigating how industries' evolution is shaped by local supply-side conditions (i.e. manufacturers) and the spatial distribution of demand. In the context of grand societal challenges, such as climate change and the associated transition toward renewable energies, demand becomes particularly important as it enables producers to learn about these new and changed consumer needs as well as shifts in their preferences (Martin *et al.*, 2019). Therefore, this paper evaluates the (statistical) impact of local wind turbine producers on regional wind turbine installation and the extent to which existing regional wind turbines stimulate the emergence and extension of local wind turbine production. Extending the work at the level of product innovation (Brem and Voigt, 2009), we compare the contribution of local supply–push and local demand–pull processes to the emergence and evolution of the industry over multiple stages of its life-cycle.

For our empirical analysis, we use data on wind turbine deployment and firm foundation for 402 German regions for the years 1970–2015 and employ a Bayesian event-history analysis (Zhou and Hanson, 2018). To analyze both the supply and demand side, we first explain the spatial diffusion of wind turbines considering the location of manufacturers. Second, we investigate the location decisions of manufacturers using the (regionally) existent and future installments of wind turbines as approximations of local demand. Our results show that manufacturers emerge more frequently in places with already existing wind turbine installations. Hence, local supply–push factors, in the form of local niche building, are identified to be less relevant while local demand–pull plays a greater role.

The paper is structured as follows: Section 2 gives an overview of the underlying theoretical arguments, building on the literature of economic geography, innovation, and transition studies. Section 3 describes the evolution of the German wind industry. The empirical design of our study is presented in Section 4. Section 5 shows the results and Section 6 concludes with a discussion of the results, shortcomings, and future research.

2. The emergence and evolution of industries in time and space

2.1 Emergence

To explain the spatial origins of new industries, Scott and Storper (1986) and Storper and Walker (1989) developed the Window of Locational Opportunity (WLO) concept. Here, the so-called "trigger events" mark the starting point for the emergence of new industries in specific locations. The industry's initial locations are distributed relatively arbitrarily and unpredictably, as their needs in terms of resources and skills are diverse and distinct from the older existing industries (Boschma and Lambooy, 1999). Consequently, emerging industries are characterized by relatively high degrees of freedom in terms of location. In later extensions of the concept, the assumption of the randomness of locations was revised with greater importance assigned to regional conditions (Boschma and Lambooy, 1999; Fornahl *et al.*, 2012). In particular, scholars have argued that the likelihood of new industries emerging in regions grows when related industries are already present (Boschma and Frenken, 2011). Technological relatedness thereby refers to a certain but not complete cognitive overlap, similarity, and complementarity of core technologies, and potential shared development history (Frenken *et al.*, 2007). The presence of related industries ensures the availability of required skills, human capital, infrastructure, and collaboration partners. The process of industry emergence and expansion on the basis of regional technologically related industries is referred to as regional branching (Boschma and Frenken, 2011) and manifests itself through various diversification mechanisms (Asheim *et al.*, 2011; Buenstorf *et al.*, 2015). For example, the diversification of existing firms from related industries has been highlighted as a catalyst for the first regional entry of new industries (Helfat and Lieberman, 2002; Klitkou and Coenen, 2013). Regional branching processes are also fueled by spin-off activities with entrepreneurs from related industries (Boschma and Wenting, 2007; Klepper, 2007). Both mechanisms, related diversification and spin-offs, have a strong regional dimension in that firms tend to establish new activities near to existing operations, and spin-offs tend to be located close to their parent company. Other processes fueling regional branching are spatially limited labor mobility and knowledge diffusion in social networks, which are also more intense within relatively small-scale areas and among related industries (Asheim *et al.*, 2011).

2.2 Concentration

While some regions manage to become the initial locations of new industries, they do not necessarily benefit from their subsequent growth as industrial concentration processes frequently lead to industrial agglomeration in only a few regions. But which regional characteristics favor such concentration processes? The literature addresses this question among others with concepts such as industrial districts (Marshall, 1920), Italian industrial districts (Pyke *et al.*, 1990), clusters (Porter, 1998), and innovative milieus (Camagni, 2005).[2] In evolutionary economic geography, spin-offs and agglomeration externalities are emphasized as explanatory mechanisms (Arthur, 1994; Klepper, 2006). Spin-off processes are transmission channels in which routines and knowledge diffuse from parent organizations to new enterprises. The mechanism has features of a self-reinforcing, snowball-like process, as the likelihood of further spin-offs depends on the number of existing firms in a region. The importance of spin-off dynamics in the emergence of regional industry clusters has been demonstrated by numerous examples, such as the information and communication technology industry in Silicon Valley (Saxenian, 1994) and the automotive industry in Detroit (Klepper, 2007).

In addition to spin-off processes, agglomeration externalities may play significant roles in regional industry concentrations. These externalities emerge from the colocalization of economic actors (Neffke *et al.*, 2011) and represent the spatial connotation of increasing returns (Krugman, 1991). It is customary to differentiate between Jacobs and Marshall externalities, where the first refers to externalities resulting from the spatial concentration of economic actors in different activities and the latter relates to effects resulting from the agglomeration of firms in the same sector (Boschma and Wenting, 2007). In addition, urban regions may offer advantages to young industries, as their size and greater economic diversity make firms more able to find generic resources, among which are human capital, services, and infrastructure (Hoover and Vernon, 1962). The discussion of these types of externalities has recently been extended to include a more dynamic approach, which considers industries not only being exposed to regional conditions but also being able to contribute to their development. This is taken up in the concept of related variety, which highlights concentration-promoting externalities that often emerge from the agglomeration of existing, related industries (Boschma and Wenting, 2007; Boschma and Frenken, 2011). It highlights mutual adaptation processes between new industries and their regional environment. For example, research and development (R&D) investments generate industry-specific knowledge and employees gain industry-specific skills through on-the-job learning. As an industry becomes more established, the specific resources that are created increase in importance and may even reach a critical mass such that increasing demand for them leads to the emergence of an efficient "local production environment" (Boschma and Lambooy, 1999). This may stimulate regional branching processes or attract further firms from related industries and, hence, may give rise to self-reinforcing processes according to the principle of cumulative causation (Myrdal, 1957). From studies covering the multiple development phases of industries, it has been observed that the relevance of the different processes and factors (i.e. branching, related variety, spin-offs, and agglomeration externalities) changes. Moreover, the effect of spin-off processes with an industry-specific background is less relevant for industry concentration in the development phase of an industry due to the (still) low potential of the parent companies—at this stage, related industries are more significant (Boschma and Wenting, 2007). A large number of empirical studies confirm these processes, showing the path-dependent emergence and development of industries in space (Balland *et al.*, 2013; Breul *et al.*, 2015). For instance, Neffke *et al.* (2011) show that young industries benefit from Jacobs externalities, whereas more mature industries profit more strongly from Marshal externalities.

2.3 The creation of local technological niches

The literature reviewed in the previous subsection noticeably pays more attention to "supply" or "push" dynamics. That is, the likelihood of industry emergence and spatial concentration are primarily explained based on the availability of "input factors" such as human capital, infrastructure, resources, knowledge, and the presence of related competencies. While not absent, local demand and supply factors have received less explicit attention in theoretical arguments as well as in empirical studies. For instance, the presence of local customers, for example, in the form of related industries positioned at later stages of the value chain, is clearly acknowledged in the discussions on related diversification and urbanization externalities. Yet, few discussions are found in this literature stream on the presence

2 It is beyond the scope of the present paper to present and discuss these concepts. An overview can be found in Brenner and Mühlig (2013: 482ff.).

of potential end-users in regions and how these may contribute to the emergence of an industry or its spatial concentration.

In the neoclassical models of Weber (1909) and later Myrdal (1957), it is argued that demand is an important factor for the location decision of firms and hence for the spatial distribution of industries. However, both argue that demand is an indirect factor for location decisions as demand has a positive effect on supply-side factors. More recently, a more dynamic view of the demand side has been put forward in transition studies (Geels, 2004; Schot and Geels, 2008). Transition studies build upon the notion of institutional embeddedness in socio-technical systems (STS). These include three elements: production, diffusion, and the use of technology including both supply and demand (Geels, 2004). These subsystems shape and are shaped by the actions of actors on three different but interrelated levels: the *technological niche*, the *socio-technical regime*, and *landscape* (Geels and Schot, 2007). Geography enters by combining the socio-technical dimension with that of socio-spatial embeddedness (Truffer and Coenen, 2012). More precisely, it takes a "spatially informed, coevolutionary transition model" (Ibid: 11) that considers the evolution of new industrial niches as an asymmetric process of regional development. Hence, when analyzing the emergence of new technological niches, not only the regime and technological landscape need to be looked at, but the regional context in which the niches are built up as well.

When new products are pushed into the market (*supply–push* or *technology push*) (Brem and Voigt, 2009), the new technology is usually superior to existing products in some way and therefore has the potential to create its own demand. However, few customers are willing to buy and test the product. Only "innovators" or "early adopters" are willing to take a risk by spending money on unknown products (Rogers, 2003: 22). Consequently, demand is usually too low (e.g. due to high production or utilization costs) for new products to sustain themselves in fully competitive environments (Geels and Schot, 2007). The emergence of "technological niches" is therefore critical for their survival. These "technological niches" are a kind of protected area and include a network of supportive actors (Schot and Geels, 2008). Jacobsson and Johnson (2000) called these actors partly "prime movers," who contribute to niches by raising awareness, undertaking investments, providing legitimacy, and facilitating the diffusion of new products. In particular, inventors and producers of new products play a decisive role in the formation of those supportive networks and niches as they "shape the selection process itself by setting up special programs in R&D settings or demonstration projects" (Schot and Geels, 2008: 539).

Support networks tend to be place specific, as geographical proximity between contributing actors facilitates interaction and coordination possibilities, which in turn help the network to form and grow. If successful, a support network will expand in size (in terms of actors and space) and establish its own local institutions, routines, and dynamics (Coenen *et al.*, 2012) after which the niches might reach the stage of a regime (Essletzbichler, 2012). Besides supportive networks, geographic proximity is also important for the local demand side because prime movers frequently create new niche markets that are geographically separated from the main market by establishing "*local practices*" (Geels and Deuten, 2006). Hence, markets for new products are likely to be located in geographic vicinity to their producers, as these may have created the markets themselves. Moreover, lacking established marketing and distribution channels, the diffusion of knowledge about these new products tends to be hampered by geographic distance (Hägerstrand, 1965a,b). In some instances, this may be strengthened by new products' limited transportability when product-specific transportation infrastructure is required and needs to be established first. Hence, in the early stages, the possibilities of serving geographically large-scale markets may be significantly reduced. Over time, infrastructure and distribution, as well as marketing channels, will be built up, and consumers at larger geographic distances can be served. As a prerequisite, the establishment of local technological niches including local demand is essential. In this case, it is the emergence of new products that create their own local demand and thereby shape the spatial distribution of industries. Put more bluntly, these arguments suggest that the spatial distribution of supply shapes the subsequently developed spatial distribution of demand. Noticeably, the creation or activation of local demand by the supply side is particularly relevant in the early, emergence stage of a product or industry. However, another relationship between demand and supply may be of greater importance in other stages.

2.4 Regional demand as a pull-factor

According to the STS literature, demand rises when a certain socio-technical regime is not in a state of equilibrium, in other words, the current technology does not fit or satisfy user preferences. Such an imbalance might originate from the socio-technical landscape (e.g. new dominant lifestyles) which can "modify the direction of development paths and innovation activities" (Geels and Schot, 2007: 406). According to Essletzbichler (2012: 798), these landscapes are "[...] multiple selection environments operating on various spatial scales" (). Part of the variations in landscapes is regional differences in demand and consumer preferences. Understanding these preferences is important for the success of a product and its producer. The producer may learn about consumer preferences and their changes through interactive and collaborative learning with consumers and users (Martin *et al.*, 2019). This is particularly the case for industries in which innovation processes are strongly linked to doing, using, and interacting (Jensen *et al.*, 2007). This applies to the early phases of the development of the wind industry when synthetic knowledge was combined with experience-based skills and crafts. This "bricolage" process is described in Garud and Karnoe (2003).

For instance, the size of regions may matter in this context. If potential early adopters make up a small share of the population, the absolute initial regional demand for products will scale with the size of the population. Moreover, given the smaller distances between potential consumers, information about a new product will diffuse faster within the region. Put differently, larger local technological niches (at least from a demand perspective) are more likely to be formed in urban areas than in rural ones, which is in line with the work of Hägerstrand (1965a,b). However, size is not the only regional characteristic that may matter in this context. Regions also differ in accumulated experiences and the presence of tacit knowledge with respect to products, as well as in actors' propensity share this knowledge among producers (Martin *et al.*, 2019). In addition, existing infrastructure, natural resource endowments, social and cultural capital, wealth and culture may also translate into regional differences in demand, making specific regions more attractive for producers.

Being proximate to demand is particularly attractive when transaction and transportation costs are significant. In such cases, firms may choose to locate close to the demand to maximize profit and, hence, demand may "pull" firms to specific locations (Weber, 1909). However, transportation costs have been decreasing on average in recent decades for most products, suggesting that this argument might have lost significance. However, this is not true for all goods. If trucks and heavy-duty transportation are necessary, for example, if the buyer is located in an inaccessible location or if the transport infrastructure is inappropriate, transportation costs may still be of relevance (Ashwill, 2003). In addition, if components are fragile and upheaval might damage the product, transportation costs tend to rise as well (Kammer, 2011). Accordingly, for some goods and locations, transportation costs are still highly relevant. In these cases, it is economically more favorable for manufacturers to produce in geographical vicinity to demand.

Other factors that can influence the location decision process of firms are the public sector and policy. First, these may create additional demand, such as through public tenders or procurement (Edler and Georghiou, 2007). Second, by offering tax reductions and subsidies, policymakers can support the development of specific industries. For instance, public tenders that are combined with "local-content requirements" are direct monetary effects that shape the location decisions of manufacturers. These have been successfully used by the provincial government of Quebec, Canada when setting up a 1000 MW wind farm (Lewis and Wiser, 2007), with the winning company General Electric (United States) establishing three manufacturing facilities in Canada as a result. Naturally, public policy is especially likely to support industries in this way when they are associated with providing solutions for societal issues such as climate change and sustainability.

Another process that may lead firms to "follow" demand can be found in the entrepreneurship literature. Some entrepreneurs set up their company to satisfy their own demand. That is, driven by an unsatisfied personal need, inventors initiate the production or development of new products. If the innovation is adopted by further actors, such as family or friends, the inventor might become aware of its business potential and eventually found a company. Shah and Tripsas (2007) call this "user entrepreneurship." Entrepreneurs frequently set up their companies close to their home (Boschma and Martin, 2010). Accordingly, it can be argued that it is the initial (individual) demand which decides the location of industrial emergence.

Previously, we have presented arguments for the supply side being able to impact the spatial distribution of demand and thereby being relatively more impactful on the spatial distribution of an industry in its emergence phase. When looking in the opposite direction, a less clear statement can be made. Some aspects (such as entrepreneurs satisfying their own demand) are of great relevance in the emergence phase of an industry as well. Transportation costs and regional variations in demand seem to be less specific to a particular stage of an industry's development. While arguments can be made that the "discovery" of the optimal location in terms of minimizing the distance to demand takes some time and requires the product to have somewhat matured, the issue of inappropriate transport infrastructure is likely to be reduced over time. Hence, it is up to empirical analyses to shed light on these processes.

3. The evolution of the German wind industry

To empirically disentangle the contribution of local demand and local supply on the spatial evolution of industries, we take the German wind industry as an example. This is motivated by a number of reasons. First, renewable energy industries are of high importance for policymakers to achieve the established climate goals and the new industries promise numerous new jobs (Burton *et al.*, 2011). In addition, the decentralized structure of renewable energy systems generally opens up an interesting research area for geographers (Dewald and Truffer, 2012). Second, the wind industry in its modern form is only a few decades old, which increases the availability of data for the early stages of this industry. Moreover, the geographically fixed installation of wind turbines and the obligation to report every new plant in Germany until 2015 allow for approximating the geographic (and temporal) distribution of their demand. This is a very appealing feature of this industry because, generally, little information on local demand is available for emerging industries. Third, the production of wind turbines does not require specific natural resources or regional characteristics implying that (in principle) firms in this industry are relatively unconstrained when choosing their location (Kammer, 2011). Moreover, some of the industries that the wind industry is strongly related to and that might spur related diversification processes belong to the mechanical engineering sector (Ibid). Despite significant regional variations, it can be assumed that basic competences in mechanical engineering are existent in the vast majority of regions in Germany and, hence, the set of potential locations for the industry's emergence is substantial. Accordingly, the WLO covers a significant number of regions. Fourth, the wind industry is characterized by very high transportation costs, which on average amount to 7–10% of total costs (Ashwill, 2003). Should complex or problematic situations lead to higher idle times for trucks, costs can even increase to 20% of the total investment (Kammer, 2011). Proximity to demand is therefore a non-negligible locational advantage.

3.1 The rise of the wind energy system

The wind industry started to emerge in the late 1970s in Germany when the first societal and political rethinking of the energy system took place, stimulated by the energy crisis (Simmie *et al.*, 2014). Before then, Germany's energy regime had relied on coal and nuclear power but the crisis led to the first proposals demanding a change to renewables (Jacobsson and Lauber, 2006). R&D expenditures somewhat rose in favor of renewable energy and led to the first development projects, initiating the growth of specialized knowledge (Johnson and Jacobsson, 2003). Within this experimental phase, producers were individuals living in rural areas and building all the necessary infrastructure on their own. Simultaneously, global companies like Boeing or MAN began entering the market (Kammer, 2011).

In these first years, new firms were spread all over West Germany (Kammer, 2011). In Lower Saxony (North-Western Germany), a small core of regional producers and suppliers evolved (see Figure 1). Former shipbuilders started to manufacture towers and rotor blades for wind energy plants. Gearboxes were produced in South Germany and in the Ruhr Area, as expertise in mechanical engineering was necessary (Kammer, 2011).

From the mid-1980s onwards, events at the socio-technical landscape started to put additional pressure on the dominant regime of energy production: the accident of Chernobyl in 1986, the general climate change debate, and the reunification of Germany (Jacobsson and Lauber, 2006; Kammer, 2011). Policymakers eventually acknowledged changing societal attitudes toward sustainability and renewables, which, amongst others, led to the introduction of the electricity feed-in tariffs law in 1990. This law provided financial certainty for investors by guarantying relatively high feed-in tariffs for a long time period (Kaldellis and Zafirakis, 2011). Moreover, on the product level, the design of three-bladed turbines became the dominant design (Johnson and Jacobsson, 2003). This led to the standardization of production and a cost reduction per kilowatt of 29% between 1990 and 2004 (Kammer, 2011).

During these events, the wind turbine industry experienced its first *take-off* and started to grow and diffuse across the country. For instance, the world's first fair on wind energy, "Husum Wind," took place in Lower Saxony in 1989. From 1990 onward, German reunification opened up new manufacturing locations in Eastern Germany (Kammer, 2011 and Figure 1) and some firms started to establish their first sales offices outside of the country.

In a typical fashion for an emerging industry, this was a turbulent phase with product standards not yet being defined, consumers still being skeptical, and the well-established energy regime of coal and nuclear power energy producers putting pressure on the new market entrants (Jacobsson and Lauber, 2006; Kammer, 2011). Consequently, many newcomers producing wind turbines quickly exited the market by either filing for bankruptcy or merging with other firms (Kammer, 2011). For example, in 1989, Vestas Wind Systems bought the Danish producer Danish Wind Technology (Ibid: 153). Crucially, in this phase, such mergers and exits were not part of an industry-wide

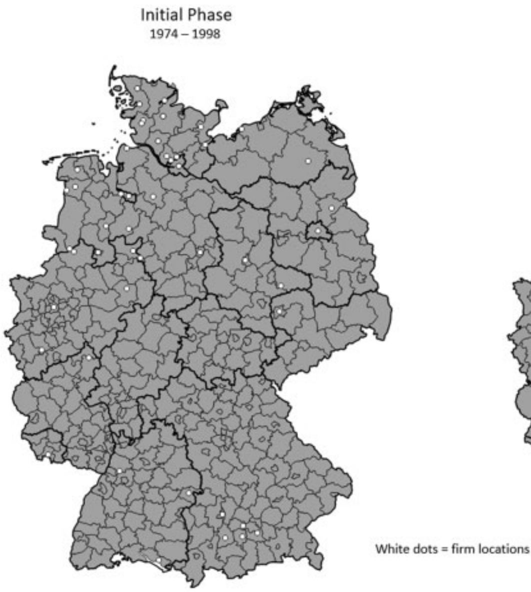

Figure 1. Spatial development of the wind energy industry in Germany, 1974–2010. *Source*: Own visualization and www.gadm.org (version 2.8, November 2015).

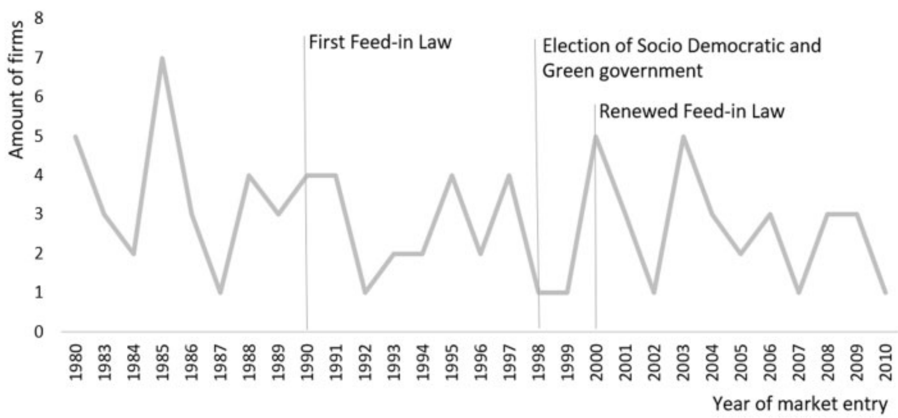

Figure 2. Number of firms entering the wind market per year and selected political events (own visualisation).

consolidation process but rather part of the explorative character of innovation and entrepreneurial processes in this phase of the industry's development.

Political support for wind energy and other renewables was significantly strengthened when the Social Democratic/Green coalition gained power in 1998. The coalition-initiated market formation programs for renewable energies such as eco-taxes on energy. Further indirect support came from the decision to phase out nuclear power (Jacobsson and Lauber, 2006). In addition, and most importantly, the nationwide feed-in tariff law was reformed and renewed by adopting the Renewable Energy Sources Act in 2000. This implemented long-term financial support for new renewable energy production and increased investment security (tariff schemes were guaranteed for 20 years), which greatly stimulated the installation of wind turbines (Johnson and Jacobsson, 2003). The industry's growth in this phase led to established manufacturers setting up regional production plants and additional start-ups entering the market (Kammer, 2011 and Figure 2).

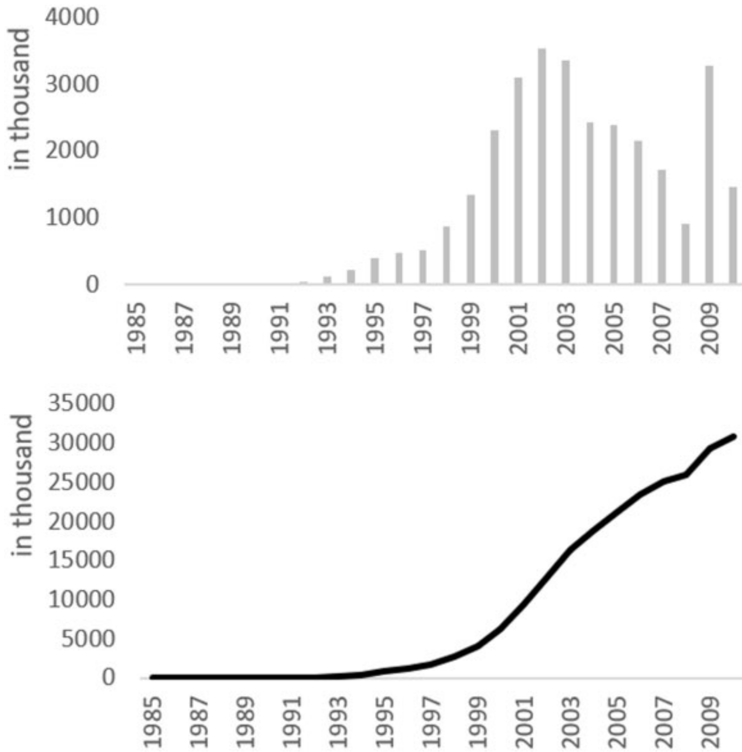

Figure 3. Annually installed (top) and cumulated nominal capacity (bottom) in Germany (1995–2010) (*Source*: Energy-map.org).

3.2 The wind industry life-cycle

The German wind energy industry has passed through multiple life-cycle phases so far. Based on the work of Klepper (1997), we divide its evolution into three stages: initial, growth, and maturity. This is usually done based on the firm's entry and exit rates. However, as the wind industry is highly subsidized (see Johnson and Jacobsson, 2003), political influence strongly biases these rates (see Figure 2). We, therefore, define the industry's life-cycle phase based on the development of its primary product—wind turbines. To abstract from technological specifics and incremental innovation, we capture it by the installed capacity of energy generation from wind.

The cumulated installed capacity shows the expected S-Curve of diffusion (see Figure 3). Until the end of the 1980s, only several hundred kilowatts were installed every year. From 1989 onward, the typical take-off becomes visible. In 1991, for the first time, more than 10,000 kW were installed. In line with this, Neukirch (2010) assigns the years from 1973/1975 to 1991 as the pioneering phase of the industry. Ohlhorst (2009) identifies the years from 1990 to 1995 as the breakthrough years, which was followed by a short decline in growth during the years 1996–1998 (see also Figure 2). In line with Klepper (1997), we combine the pioneering phase (the mid-1970s to 1991) and the take-off stage (1992–1998) into the *initial* stage.

From 1999 onwards, 1 million kilowatts were installed yearly (except for during the financial crisis of 2008). Given this qualitative jump in installed capacity, we define the years 1999–2010 as the *growth phase* of the industry. Since the yearly installed capacity continued to grow linearly until the end of our observation phase, we cannot identify the industry moving into its maturity phase. This is in line with other studies that argue the industry has not yet reached this stage (Kammer, 2011). Moreover, if we look at the mean values of market entries for both phases, we observe a value of 3.05 for the initial phase and a value of 2.6 for the growth phase. However, the first value is biased by the year 1985 when seven firms entered the market. Excluding this value, we obtain a mean of 2.8, only slightly higher than in the growth phase. For the maturity phase, we would expect a smaller number of market entries (Klepper, 1993).

4. Empirical approach

4.1 The data at hand

The first data set we use is the wind turbine database ("EEG Anlagenregister"). In Germany, every new renewable energy facility had to be registered in this database by the grid operator until the end of 2015. Most importantly, it includes information about the time of activation, place of deployment, and capacity. Energy-map.org reviewed this information and added the geolocation of all facilities. Amongst others, the database lists all onshore wind turbines starting from 1983 to 2015. On this basis, we observe the time of the first and all subsequent wind turbine installations for every NUTS3 region in Germany. We use this information as an approximation of the regional demand for wind turbines. In particular, we identify which regions where the first to install wind turbines at all.

To model the supply side, we conducted detailed web research to identify all wind turbine manufacturers in Germany that existed at some point between 1970 and 2015. We started with the list of manufacturers gathered by Kammer (2011) and extended it by searching on the manufacturers' own websites and on business registers like *unternehmen24.info*. In addition, websites such as *Wind-turbine.com* and www.wind-turbine-models.com were helpful for acquiring an overview of the industry. In total, we identify 103 manufacturers and collected their date and place of foundation. This includes the location of the firms' first production facility, as well as the additional production facilities they opened over the years in different regions.

Before presenting the empirical variables constructed on this information in Sections 4.3 and 4.4, we first introduce our empirical model.

4.2 Bayesian spatial survival analysis

The adoption of innovations and the foundation of firms are events taking place at certain moments in time. In the case of innovations, their timing dependents on the innovation itself, the adopter's characteristics, and environmental conditions (Rogers, 2003). With respect to founding a firm, regional characteristics tend to impact the time of establishment (Sternberg, 2003; Boschma and Wenting, 2007). Therefore, we model the founding of a firm in a location as an event in time, which is related to the prior emergence of its industry at another time and location. To identify the determinants influencing the occurrence of this event, we make use of survival analysis methods.

Survival models originate from medical research and seek to explain how the risk, or hazard, of an event occurring (e.g. death) is conditioned by covariates of theoretical interest (e.g. medication) (Fox and Weisberg, 2011).[3] Recently, these models have been used to study the diffusion of events in time and space. For instance, Darmofal (2009) applies spatial Bayesian survival models to explain the diffusion of political ideas in the United States and Perkins and Neumayer (2005) make use of a Cox proportional hazard model to study whether emerging countries adopt new technologies faster due to smaller investments in prior technologies.

Generally, a survival model consists of the following elements:

$$p_{(t)} = p_0(t)\ \exp(\beta^T x(t)),$$

where $p_{(t)}$ is the probability of an event at time t (e.g. death), $p_0(t)$ is the exogenous baseline hazard, that is the probability of an event occurring independently of any covariates. $x(t)$ is a vector of covariates (e.g. drugs) affecting the baseline hazard and β^T is the corresponding vector of parameters (Perkins and Neumayer, 2005).

A specific reason to use survival analysis instead of standard regression models is the *censoring* inherent to longitudinal data. Censoring defines the possibility that events may lie outside the observation time; called *left censoring* if the event occurs beforehand and *right censoring* when the event takes place after the observational period (see Figure 4). In contrast to survival models, standard regression models do not consider censoring and thereby miscalculate the average time it takes for an event to happen (Mills, 2011).

Survival models differ in the distribution of their baseline hazard. For instance, the semiparametric Cox model does not assume any baseline hazard, that is it has no intercept (Cox, 1972). In contrast, the calculation in Weibull or Gompertz model is based on a specific baseline hazard. Consequently, researchers must decide between the flexibility of a Cox model and a more precise parametric model, whereby the latter requires the assumed baseline to be correct (Box-Steffensmeier and Jones, 2004).

3 Survival models are also known as "event-history analysis" in sociology or "failure-time analysis" in engineering.

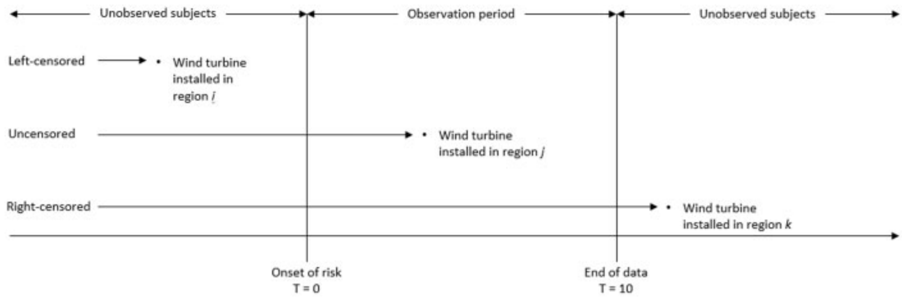

Figure 4. Left-censored, uncensored, and right-censored subjects.

Another issue in the use of survival analysis is potentially missing variables influencing the baseline hazard. These are called random effects or frailties. Box-Steffensmeier and Jones (2004) show that omitting such covariates leads to the underestimation of the factors positively influencing the hazard rate and to an overestimation of the factors negatively relating to it. In our case, such factors are most likely related to specific locations and their relations to others. We account for these unobserved factors by means of including frailty terms into the model. These can be either individual or shared frailties. The first accounts for unit-specific effects and the second incorporates the effects relating to the clustering of observations, that is observations sharing the same region.

To do this, we make use of a Bayesian framework, which is particularly useful when applying survival models in spatial settings, that is when the observations are organized in a finite number of spatial units such as regions (Zhou and Hanson, 2018). This is the case in our study, as we assign all observations to the 402 German districts (NUTS3). Subsequently, we implement spatial dependencies through the inclusion of an intrinsic conditionally autoregressive (ICAR) element. The ICAR represents a spatial neighborhood matrix E, with an element e_{ij} being 1 if observations i and j are neighbors and 0 otherwise. Hereby, we consider the possibility of neighboring observations having similar risk propensities based on unobserved covariates (spatial autocorrelation) (Darmofal, 2009).

The quality of the models is compared by the Log Pseudo Marginal Likelihood (LPML) and the Deviance Information Criterion (DIC). A model is superior if its LPML value is larger and if its DIC value is smaller than another model.

4.3 Empirical variables

4.3.1 Supply–push

We model local supply–push by the time it takes for the first wind turbine to be installed in region i with **FIRST TURBINE**$_{t\rightarrow e,i}$[4] being our dependent variable. This event is explained with the following independent variables.

To measure the effect of existing producers on the likelihood of wind turbine deployment in region i, we create the variable **PRODUCER**$_{e-5}$. This counts the number of producers that exist within a radius of 25, 50, 75, or 100 km from the first turbine in region i. We decided to work with a radius instead of administrative region borders (e.g. NUTS3) because wind turbines are often deployed at the borders of such regions (Broekel and Alfken, 2015) and we expect producers to have an effect on the deployment in neighboring regions as well. Moreover, we introduce a time lag of 5 years, that is we count the producers that entered the market at least 5 years before the observed deployment. This is justified because the decision process of installing and the installation of a wind turbine itself take around 3–7 years (Kammer, 2011). Therefore, a time lag is needed when investigating whether wind turbine manufacturers create a technological niche and push the product into the regional market, allowing the manufacturer to plan, manufacture, and install the wind turbine.

We also include the number of existing wind turbines within a radius of 20 km (**TURBINES**$_{i,e-5}$) with a time lag of 5 years. The variable summarizes all wind turbines deployed 5 years before the event e, that is it captures the installation of prior wind turbines in region i. Considering this variable allows us to model two effects in the growth phase: learning and aversion. On the one hand, the existence of wind turbines can signal learning effects, which in

4 Start of the observation time is 1 year before the first event occurs.

turn imply reduced planning and construction time for further wind turbines. On the other hand, if several wind turbines already exist, citizens might prefer to prevent the installation of further wind turbines, leading to longer planning times. The chosen distance is in line with the current literature (Broekel and Alfken, 2015).

4.3.2 Demand–Pull

With the local demand–pull model, we are interested in analyzing the effect of local demand on the propensity of wind turbine manufacturers emerging in region *i*. That is, we seek to explain the time it takes for a new company being founded in region *i*, which is captured by the dependent variable **FIRST PRODUCER**$_{t \rightarrow e,i}$.[5]

The first explanatory variable **TURBINES**$_e$ measures the number of wind turbines within a radius of 25, 50, 75, or 100 km existing in the year of the founding of a wind turbine manufacturer. It approximates the demand conditions 5 years ago, which might have been the time at which the manufacturer made the decision to eventually found a firm. Planning and installing wind turbines, as well as establishing a business, is a long process usually requiring multiple years. Second, we approximate current demand conditions by counting the number of wind turbines installed in the 5 years following the emergence of a wind turbine manufacturer (**FUTURE TURBINES**$_{i,e+5}$). We make use of the same radii as with TURBINES$_e$. Due to the planning time of up to 7 years, it seems likely that these turbines are publicly announced approximately 5–6 years before they start to operate. Hence, they are considered as current as well as short-term future demand that a manufacturer can satisfy.

Recent studies have shown that the emergence of new firms and industries greatly depends on spatial clustering and the existence of related variety (Porter, 1998; Boschma and Wenting, 2007). We construct the variable **PRODUCER**$_{i,e}$ that sums all wind turbine manufacturers already existing in region *i* when a new manufacturer emerges. A positive finding for this variable is in line with the idea of spatial clustering being important for a firm's emergence. The potential impact of related variety is capture by **RELATED**$_{i,e}$, which approximates the technological relatedness of the wind industry to other industries. It is based on the cosine similarity of the 4-digit IPC class F03D ("Wind motors") with all other IPC classes. More precisely, in a common manner, we estimate the cosine similarity based on the co-occurrence frequencies of 4-digit IPC classes on patents to obtain a measure of technological relatedness of each IPC class pair. In a second step, we calculate the revealed technological advantage (RTA) for each IPC class and region. If the RTA > 1 for IPC class F03D in region *i*, it reveals that this region patents more wind motors than the average region (Hidalgo *et al.*, 2007). The two matrices, technological relatedness and RTA, are then multiplied with each other to obtain the aggregated relatedness coefficient for F03D and each region (see Neffke *et al.*, 2011).

4.3.3 Control variables

The diffusion of wind turbines is likely to be impacted by additional factors that are not in the focus of this paper. Crucially, the average wind speed in region *i* (**WIND**$_i$) is a natural candidate in this respect. The higher its level, the more electricity can be produced by the wind turbine and, hence, profitability increases making the installation more likely (Burton *et al.*, 2011). The likelihood of installing wind turbines in regions is also determined by available space (**AREA**$_i$). Wind turbine installations need space to build up the necessary infrastructure, such as foundations and network access. Second, wind turbines have to be distant from other objects like buildings or trees, allowing for unhindered wind flow and avoiding externalities (Burton *et al.*, 2011). We obtained data on the extent of residential areas and forests in regions from the German Federal Institute for Research on Building, Urban Affairs and Spatial Development (BBSR). We subtract from the total area of region *i* the areas already in use and the areas not available for wind energy due to natural constraints like rivers. As this variable is not measured on a yearly basis and the first figures are available for 1996, we decided to use its values from the last available year in each industry life-cycle phase, because we assume the available space decreases over time. On this basis, we estimate two values for the variables AREA for each NUTS3 region. The first represents these conditions in the initial phase of the industry (the year 2000)[6] and the second those at the end of the growth phase (the year 2010).

Moreover, we consider the political preferences toward sustainable energy in a region, which is crucial for the installation of wind turbines (Theyel, 2012). We approximate this with the share of votes for the Green party in federal

5 Start of the observation time is 1 year before the first event occurs.

6 There were no values for 1999.

elections (**GREEN**$_{i,e}$). Further regional factors are the population density (**POP**$_{i,e}$) and gross domestic product (**GDP**$_{i,e}$). In less populated regions it might be easier to plan and activate wind turbines as fewer people feel distracted by them. At the same time, a larger population represents more potential entrepreneurs that can establish wind turbine manufacturers. All three variables were gathered from the German database "GENESIS."

Moreover, for the demand–pull models, we control for regions being in the north of Germany (**NORTH**$_i$). More precisely, NORTH$_i$ is a dummy variable having the value of one if region i is part of the federal states of Hamburg, Bremen, Lower Saxony, Schleswig-Holstein, or Mecklenburg-Western Pomerania, and is zero otherwise. While we exclusively consider onshore wind turbines, the offshore business has become important for wind turbine manufacturers in recent years. Consequently, offering direct access to the sea is a beneficial attribute of North German regions (Fornahl *et al.*, 2012). Finally, in the supply–push models, we consider the potential peculiarities of East Germany with dummy variable **EAST**$_i$ which is zero for all regions in West Germany and one for all East German regions. The variable controls for the East German regions becoming accessible to manufacturers at a later time and these regions being characterized by economic catching-up processes in the 1990s.

4.3.4 Time dependency

Many of our covariates changed over the years. For example, GREEN changes every 4 years with the parliamentary elections. We therefore model time dependencies as described in Zhou *et al.* (2020) and Therneau *et al.* (2017). That is, we organize the data in time intervals that are defined in a way that variables' values change between intervals but not within. For the 1980s we lack data for several variables (see Table 1) and therefore define variables' values based on the earliest available observation.

5. Results

Before coming to the actual results, note that we do not report P-values but rather the 95% confidence intervals, which are more common when using Bayesian event models (Darmofal, 2009; Craioveanu and Terrell, 2016). Moreover, the variable capturing spatial dependencies (ICAR) is significant in all estimations, justifying the choice of our empirical approach.

5.1 Initial phase

5.1.1 Supply–push

The results for the initial phase are presented in Table 2. The models explain the effect of local supply on the creation or activation of local demand (supply–push), that is the likelihood of wind turbine installations.

WIND$_i$ is significant and positive, implying that regions with high wind speeds are likely to be among the first to install wind turbines. If wind levels increase by 1 m per second, the probability of a first wind turbine being installed increases by 124%. This finding supports the idea of turbines being expensive and having low degrees of efficiency in the industry's initial phase (Neukirch, 2010; Kammer, 2011). This made early installments more attractive in regions with high wind speeds.

POP$_{i,e}$ is also significant and positive. This contradicts our expectations that wind turbines are more likely to be installed in less populated regions to reduce land-use conflicts (see e.g. Short [2002] and the "nimbyism" discussion). However, as our models explain the timing and not the number of wind turbines, we see this finding to be in line with the technology diffusion literature. This literature argues that new technologies are more likely to emerge in urban regions and that their diffusion starts from more central places (Hägerstrand, 1952).

GDP$_{i,e}$ is significant and negative, that is regions with large gross domestic products per capita are less likely to be early locations for wind turbine installations. This fits with the northern German regions, which were found to be more likely locations for wind turbines.

In the model considering a radius of 100 km, PRODUCER$_{e-5}$ is significant and negative. This suggests that the presence of wind turbine producers tends to increase the time needed to install the first wind turbine in a region. This result is surprising because we observe a relatively strong overlap between producers' and wind turbines' locations in North Germany (see Figure 5). However, again, our models capture the timing of turbine installations and their locations. Accordingly, this finding suggests that the earliest wind turbines' locations were not proximate to those of

Table 1. Variable operationalization and source

	Variable	Description	Operationalization	Source	Year
Dependent	FIRST TURBINE$_{t\rightarrow e,i}$	Wind turbine	Time of first wind turbine installed in region i (NUTS 3)	Energy-map.org	Year of event (t)
	FIRST PRODUCER$_{t\rightarrow e,i}$	Wind farm producer	Time of first producer entering the market in region i (NUTS 3)	Various websites	Year of event (t)
Independent	TURBINES$_e$	Existing wind turbines	Existing wind turbines within a radius of 20 km at time e	Energy-map.org	Year of event (t)
	TURBINES$_{e-5}$		Existing wind turbines within a radius of 25, 50, 75, or 100 km at time $e-5$	Energy-map.org	$<t-5$
	FUTURE TURBINES$_{i,e+5}$	Future wind turbines	Wind turbines within a radius of 25, 50, 75, or 100 km at time $e+5$	Energy-map.org	$t+1$ to $t+5$
	DISTANCE$_{P,FT}$	Distance in km	Distance between new producer and future wind turbines		
	PRODUCER$_{e-5}$	Existing wind farm manufacturers	Wind farm producers within a radius of 25, 50, 75, or 100 km at time $e-5$	Various websites	$<t-5$
	PRODUCER$_{i,e}$		Wind farm producers in region i (NUTS 3) at time e	Various websites	Year of event (t)
	DISTANCE$_{T,P}$	Distance in km	Distance between new turbines and existing producers		
	WIND$_i$	Average wind speed	Above average wind speed (ger.: Windhöffigkeit) in region i	German weather service	1981–2000
	AREA$_i$	Available space	Available space in region i useable for wind turbines	Regional database Germany	1998; 2010
	GREEN$_{i,e}$	Votes	Above average percentage of votes for Bündnis 90/The Greens in federal elections in region i at time e	Regional database Germany	1994; 1998; 2002; 2005; 2009
	GDP$_{i,e}$	Regional GDP	Above average gross domestic product in region i at time e	Regional database Germany	1992–2010
	POP$_{i,e}$	Population density	Above average population density of region i at time e	Regional database Germany	1992–2010
	RELATED$_{i,e}$	Patent relatedness of region i	Co-occurrence of IPC classes with class F03D ("Wind motors") in a patent and location quotient for region i at time e	PATNET	1974–2010
	NORTH$_i$	Regions of North Germany	Dummy variable: 1 if region i belongs to Hamburg, Bremen, Lower Saxony, Schleswig-Holstein, or Mecklenburg-Western Pomerania, otherwise 0		
	EAST$_i$	Region in East Germany	Dummy variable: 1 if region i belongs to Mecklenburg-Vorpommern, Brandenburg, Saxony, Saxony-Anhalt, and Thuringia, otherwise 0		

producers, which is supported by the fact that the average distance between producers and wind turbines is 81 km. Hence, while they share the general location of northern Germany, early turbines were not installed directly at the producers' locations but in more suitable places in the wider surroundings.

To test the robustness of our results, we calculated additional models with an alternative time lag of 3 years and alternative radii of 25 and 75 km. The results are reported in the first two rows in Table 5 in

Table 2. The regional supply model in the initial phase

	Local supply–push initial phase (1983–1998)	
	50 km radius	100 km radius
Supply–push		
PRODUCER_{e-5}	0.0079 (−0.184, 0.194)	**−0.359 (−0.503, −0.211)**
$\text{DISTANCE}_{T,P}$	–	–
TURBINES_{e}	–	–
Regional characteristics		
$\text{WIND}_{i,e}$	**0.492 (0.337, 0.675)**	**0.808 (0.552, 1.039)**
$\text{AREA}_{i,e}$	0.003 (−0.011, 0.07)	0.045 (−0.031, 0.114)
GREEN_{i}	−5.743 (−1.42, 2.371)	−4.517 (−15.4, 5.097)
$\text{GDP}_{i,e}$	**−0.008 (0.0003, 0.0031)**	**−0.01 (−0.015, −0.0043)**
$\text{POP}_{i,e}$	**0.0017 (0.0003, 0.003)**	**0.0025 (0.0002, 0.005)**
EAST	−0.384 (−0.025, 0.387)	**−1.777 (−2.656, −0.683)**
ICAR	**1.641 (0.718, 2.975)**	**10.79 (5.71, 18.00)**
Survival model	Proportional hazards	Proportional hazards
LPML	−527	−432
DIC	1051	812
N|events	2159|152	2159|152

Coefficients in bold are significant at 95%. Lower and upper bounds of confidence intervals given in parentheses.

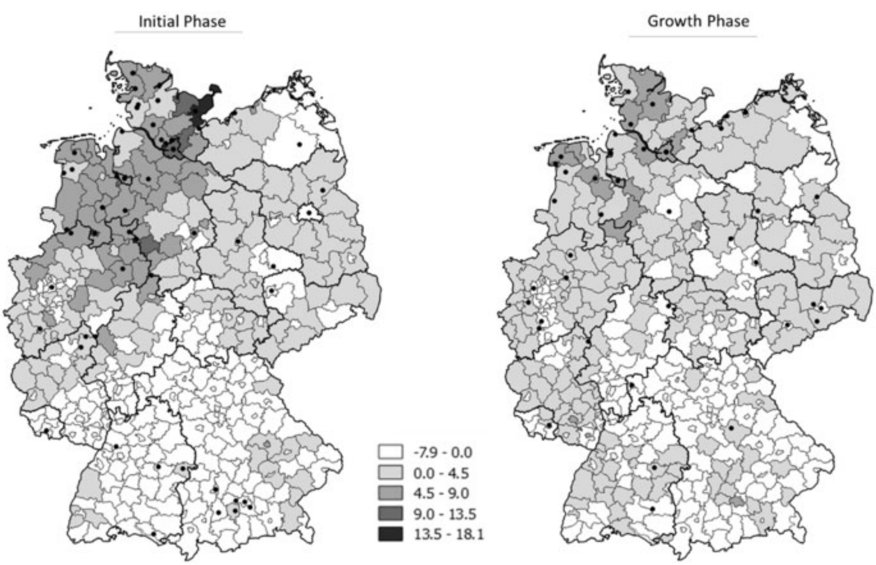

Figure 5. Spatial distribution of wind turbines in Germany (dark gray: high propensity of installation, white: low propensity, black points: producer).

the Appendix. Our results are robust with respect to the specification of the time lag; there are no visible differences when using 3 or 5 years. By and large, these models also confirm our main findings with PRODUCERS_{e-5} being negative and significant. PRODUCERS_{e-5} remains insignificant in the models in which we consider wind turbine installations within a radius of 25 and 50 km to district centers. However, this is explained by the fact that few wind turbines exist within a 50 km distance of producers, as the average minimum distance between wind turbines and producers is 81 km (Table 7). We also tested an alternative specification considering the distance between the first wind turbine and the closest existing producer.

Table 3. Demand–pull results of the initial phase

	Local demand–pull initial phase (1974–1998)		
	50 km	100 km	Distance
Demand–pull			
FUTURE TURBINES$_{e+5}$	**0.0053 (0.0008, 0.009)**	0.0009 (−0.0004, 0.003)	–
DISTANCE$_{P,FT}$			−0.003 (−0.008, 0.0013)
TURBINES$_e$	−0.032 (−0.086, 0.012)	−0.017 (−0.0493, 0.024)	–
Related variety			
PRODUCER$_{i,e}$	–	–	–
RELATED	**0.014 (0.006, 0.002)**	**0.0014 (0.0005, 0.002)**	**0.0014 (0.0006, 0.003)**
Regional characteristics			
NORTH$_i$	**1.329 (0.329, 2.205)**	**1.353 (0.177, 2.454)**	**1.329 (0.177, 2.454)**
GREEN$_{i,e}$	2.970 (–1.288, 1.730)	2.308 (–0.162, 0.179)	2.308 (–16.29, 0.177)
GDP$_{i,e}$	−0.003 (0.008, 0.002)	−0.004 (−0.01, 0.0016)	−0.0042 (−0.0101, 0.0016)
POP$_{i,e}$	0.0002 (−0.002, 0.002)	0.0003 (−0.002, 0.003)	0.0003 (−0.0018, 0.0022)
ICAR	**0.775 (0.05, 2.97)**	**2.919 (0.042, 12.855)**	**0.676 (0.06, 2.591)**
Survival model	Proportional hazards	Proportional hazards	Proportional hazards
LPML	−235	−222	−236
DIC	468	441	470
N|events	7288|57	7288|57	7288|57

Coefficients in bold are significant at 95%. Lower and upper bounds of confidence intervals given in parentheses.

Unfortunately, these models did not converge. For this reason, we also calculated a Cox proportional hazard model with the same frailties (see Table A1).

5.1.2 Regional demand

We now turn toward the question of whether local demand for wind turbines attracts the emergence of producers. The results of our estimations are shown in Table 3.

RELATED$_i$ has a significantly positive coefficient. Regions with a related patent portfolio have a higher likelihood of wind turbine producers emerging. This confirms existing works on the impact of relatedness of regional diversification and firm foundation (Neffke *et al.*, 2011). It also fits with Kammer (2011) who highlights that the German wind turbine producers benefited from the shipbuilding industry and with Breul *et al.* (2015) who also find a positive relationship between technological relatedness and the time of local manufacturers' emergence. Accordingly, our study adds further support for the importance of relatedness for industrial development.

Furthermore, we find more favorable conditions for this industry's development in northern regions, which we captured with the variable NORTH$_i$. This variable is significantly positive and indicates that the likelihood of the first manufacturer entering a region increases by a factor of three when the region is located in the north of Germany. We interpret this as an indication of the relevance of access to offshore activities for wind turbine manufacturers' locations and for the generally more wind turbine-friendly conditions in northern Germany (a more suitable landscape and more sparsely populated) that are not captured by the other variables in our model.

In contrast to PV manufacturers that appear to prefer urban regions as locations (Breul *et al.*, 2015), population density remains insignificant in our investigations and thus appears to be irrelevant for wind turbine manufacturers. With all other factors equal, new facilities have equal chances of being located in urban and rural regions. Consequently, these regions do not appear to offer any particular locational benefits or disadvantages. The latter is somewhat surprising, as the transportation of towers and rotor blades would seem to be more cumbersome and expensive in urban environments and hence, make these locations less attractive.

With respect to the relevance of a local demand–pull effect, we look at the coefficients of FUTURE TURBINES$_{e+5}$, DISTANCE$_{P,FT}$, and TURBINES$_e$ that approximate a local demand–pull effect. FUTURE TURBINES$_{e+5}$ is significantly positive in the 50 km model with the coefficients of DISTANCE$_{P,FT}$ and TURBINES$_{i,e}$ remaining insignificant. The emergence of a producer is 0.5% more likely in regions that see one more additional

Table 4. Supply–push results for growth phase

	Local supply–push growth phase (1999–2010)		
	50 km	100 km	Distance
Supply–push			
$PRODUCER_{e-5}$	0.198 (−0.493, 0.001)	−0.374 (−0.124, 0.068)	
$DISTANCE_{T,P}$			**0.033 (0.0195, 0.0401)**
$TURBINES_e$	−0.017 (−0.043, 0.008)	−0.012 (−0.026, 0.001)	−0.019 (−0.409, 1.361)
Regional characteristics			
$WIND_{i,e}$	**0.261 (0.083, 0.531)**	**0.247 (0.051, 0.384)**	**0.40 (0.212, 0.739)**
$AREA_{i,e}$	**0.333 (0.201, 0.453)**	**0.252 (0.190, 0.335)**	**0.434 (0.351, 0.544)**
$GREEN_i$	**−7.72 (−14.24, −0.445)**	−6.169 (−0.139, 0.658)	−6.151 (−19.51, 2.831)
$GDP_{i,e}$	**−0.009 (−0.013, −0.006)**	**−0.009 (−0.013, −0.004)**	**−0.015 (−0.0202, −0.0103)**
$POP_{i,e}$	0.0015 (−0.0003, 0.003)	0.0013 (−0.0006, 0.006)	**0.0032 (0.0013, 0.0049)**
EAST	−0.014 (−1.466, 1.162)	0.487 (−0.347, 1.757)	0.378 (−0.434, 1.215)
ICAR	**23.084 (3.724, 39.045)**	**7.804 (1.257, 16.046)**	**53.24 (39.941, 69.899)**
Survival model	Proportional hazards	Proportional hazards	Proportional hazards
LPML	−510	−572	−400
DIC	906	1101	655
N|events	1940|204	1940|204	1940|204

Coefficients in bold are significant at 95%. Lower and upper bounds of confidence intervals given in parentheses.

wind turbine being installed over the next 5 years. The finding provides some support for the idea that local demand stimulates the emergence of wind turbine producers. Note that the effect appears smaller than in reality because wind turbines are often installed in larger numbers at the same time, which multiplies this effect.

5.2 Growth phase

5.2.1 Regional supply

During the industry's growth phase, the installation of wind turbines was impacted by favorable natural conditions, which is shown by the significantly positive coefficients of wind speed $WIND_i$ and available space $AREA_i$ (see Table 4). Higher wind speeds and more available space decreases the time until the installation of a first wind turbine. Over time, the relevance of $AREA_i$ increases as available open spaces became scarcer and therefore potentials of utilization conflicts grew (Burton *et al.*, 2011). As in the initial phase, $GDP_{i,e}$ is significantly negative: wind turbines are installed earlier in economically weaker regions.

Interestingly, in the model considering a 50 km radius to wind turbines, $GREEN_{i,e}$ is significant but negative, that is, regions with larger shares of green voters needed more time to install their first wind turbine. This seems contradictory at a first glance as wind power is a renewable, "green" energy source. However, voters favoring ecological behavior and thus voters of green parties are more frequently found in South German cities, such as Freiburg, Stuttgart, or Munich. They are significantly under-represented in the northern regions where most wind turbine installations took place. In addition to a strong south–north discrepancy, voting for the Green party is also much more frequent in the largest cities. Accordingly, this variable may also capture that wind turbine installations are much less common there. Moreover, wind turbine installations also represent interference with local ecological systems, which these types of voters likely oppose. As the variable captures multiple aspects, its relatively large coefficient is not surprising (coefficient: −7.72). Given that GREEN's value ranges between 0.02 and 0.29, an increase in 1% in votes decreases the likelihood of a first wind turbine installation in a region by about 7%.

$PRODUCER_{e-5}$, which approximates local supply–push processes, is insignificant in both models. However, the distance to the next producer, $DISTANCE_{T,P}$ is significantly positive. Hence, it takes more time for the first wind turbine to be installed in a region proximate to an existing manufacturer. This clearly does not correspond to a significant local supply–push effect in this phase. Rather, the contrary appears to hold, the first wind turbines are installed

Table 5. Demand–pull results of the growth phase

	Local demand–pull growth phase (1999–2010)		
	50 km	100 km	Distance
Demand–pull			
FUTURE TURBINES$_{e+5}$	0.001 (−0.004, 0.005)	−0.003 (−0.002, 0.0009)	
DISTANCE$_{P,FT}$	–	–	**−0.073 (−0.144, −0.009)**
TURBINES$_e$	0.0001 (−0.016, 0.015)	0.005 (−0.007, 0.018)	0.0009 (−0.013, 0.013)
Related variety			
PRODUCER$_{i,e}$	**0.692 (0.186, 1.244)**	**0.601 (0.239, 0.951)**	**0.610 (0.242, 0.941)**
RELATED	0.0006 (−0.002, 0.003)	0.0004 (−0.002, 0.002)	0.0005 (−0.001, 0.002)
Regional characteristics			
NORTH	1.084 (−0.114, 2.227)	**1.275 (0.418, 2.142)**	**0.987 (0.166, 1.805)**
GREEN$_{i,e}$	−7.417 (−22.53, 5.228)	−8.637 (−20.69, 3.630)	−7.580 (−20.78, 3.497)
GDP$_{i,e}$	0.0008 (−0.003, 0.0044)	0.0002 (−0.004, 0.004)	0.0007 (−0.003, 0.004)
POP$_{i,e}$	**0.0023 (0.0002, 0.004)**	0.002 (−0.0003, 0.003)	0.0018 (−0.00009, 0.0037)
ICAR	**1.608 (0.1347, 5.7041)**	**0.067 (0.005, 0.195)**	**0.080 (0.006, 0.464)**
Survival model	Proportional hazards	Proportional hazards	Proportional hazards
LPML	−192	−191	−188
DIC	378	381	375
N|events	4648|46	4648|46	4648|46

Coefficients in bold are significant at 95%. Lower and upper bounds of confidence intervals given in parentheses.

at greater distances to manufacturers. However, this result could be driven by some producers being located far away from wind turbines' early locations, that is in the south of Germany.

Therefore, as a robustness test, we included only regions of North Germany. The coefficient of DISTANCE$_{T,P}$ becomes insignificant (Table A2). In any case, the finding clearly suggests that better possibilities to build local support for wind turbines or lower transportation costs to potential wind turbine locations did not matter at this stage of the industry's life-cycle since more suitable natural conditions for wind turbine installations were more important.

5.2.2 Regional demand

The results for the growth phase are also reported Table 5. The number of existing producers in a region (PRODUCERS$_e$) is significantly positive, which indicates that the industry is concentrating in space as existing producers attract further producers. This may be either due to spin-off processes (Klepper, 2006) or because of the increasing relevance of Marshallian externalities (Neffke *et al.*, 2011). As RELATED$_i$ is insignificant it implies the irrelevance of related industries at this stage. This phase of the industry's life-cycle is also characterized by firms opening up second production locations with little to no R&D activities (Kammer, 2011). For these, the presence of related knowledge is less relevant than advantages linked to shared infrastructure and labor pooling effects.

POP$_{i,e}$ is significant and positive in one model (50 km radius) meaning that regions with higher populations are more likely to be the first to witness an early firm entry. This result fits with the urbanized regions having larger potentials of entrepreneurial activities (Boschma and Wenting, 2007).

TURBINES$_{i,e}$ and FUTURE TURBINES$_{i,e+5}$ remain insignificant in these models. The number of existing wind turbines and those that will be built in the next 5 years within a certain distance to the producer does not explain producers' emergence. However, we do find a significantly negative coefficient of DISTANCE$_{T,P}$, which supports the demand–pull hypothesis. During the growth phase, new producers are more likely to emerge early in regions geographically proximate to future wind turbines. With every additional kilometer a region is more distant to future wind turbines, the probability of a producer emerging decreases by about 7%. This is likely because firms seek to minimize the transport costs of their final products. In fact, Klepper (2006) presents evidence of firms in the automobile and tire industries locating new production facilities in geographic proximity to customers to save transportation costs. In the case of wind turbines, these costs are even higher and therefore production facilities located close to demand are more valuable. However, it may also be the case that firms will locate near demand to better interact with

Table 6. Main results of the robustness test

Model	Phase		Producers (25 km)	Producers (50 km)	Producers (75 km)	Producers (100 km)	Distance
Supply–push	Initial	3 years and earlier	Insignificant	Insignificant	**Negative Significant**	**Negative Significant**	Not converged
		5 years and earlier	Insignificant	Insignificant	**Negative Significant**	**Negative Significant**	Not converged
Supply–push	Growth	3 years and earlier	Insignificant	Insignificant	**Negative Significant**	Insignificant	**Positive Significant**
		5 years and earlier	Insignificant	Insignificant	**Negative Significant**	Insignificant	**Positive Significant**
Model	Phase		Future turbines (25 km)	Future turbines (50 km)	Future turbines (75 km)	Future turbines (100 km)	Distance
Demand–pull	Initial	Within 3 years	Insignificant	Insignificant	Insignificant	Insignificant	Insignificant
		Within 5 years	**Positive Significant**	**Positive Significant**	Insignificant	Insignificant	Insignificant
Demand–pull	Growth	Within 3 years	Insignificant	Insignificant	Insignificant	Insignificant	Insignificant
		Within 5 years	Insignificant	Insignificant	Insignificant	Insignificant	**Negative Significant**

their customers and understand their preferences (Fabrizio and Thomas, 2012). Crucially, while there are benefits to geographic proximity, manufacturers do not need to be immediately colocated with wind turbine locations, as the insignificance of $\text{TURBINES}_{i,e}$ and FUTURE $\text{TURBINES}_{i,e+5}$ underlines. This finding is reasonable given that wind turbines require open space and a certain distance to settlements.

6. Discussion and conclusion

The aim of this paper was to analyze whether and to what extent local supply–push or local demand–pull mechanisms characterize an industry's spatial evolution. We have combined supply-side arguments from the field of economic geography (Weber, 1909; Myrdal, 1957; Frenken *et al.*, 2007; Boschma and Frenken, 2011) with more demand-oriented arguments from the literature on technological systems (Geels, 2004; Geels and Schot, 2007). In particular, we argued that the relevance of local supply–push and demand–pull factors changes over the life-cycle of an industry.

These arguments were tested using the example of the German wind turbine industry and its spatial evolution over its initial and growth phases. Empirically, we made use of data on manufacturers' founding dates and their locations. This was merged with information on the installation time and geographical locations of wind turbines. We employed Bayesian survival models to test the relative importance of the local supply–push and local demand–pull hypotheses.

The local supply–push models, which analyze the spatial diffusion of wind energy turbines, highlighted the importance of regions' natural conditions. To maximize turbines' revenues, the first turbines are installed in regions with high wind speeds and with available open spaces. We find these natural conditions to be more important for the success and diffusion of this technology than manufacturers establishing local supportive niches in the initial and growth phase of the industry. Accordingly, local supply–push induced by manufacturers appears to be less relevant for this industry's evolution. However, this is not to say that these processes have not been present at all, for instance, some regions can be seen as testing areas for early wind turbine installations (Kammer, 2011). According to our results, this does not seem to have been essential for the evolution of the industry spatially.

In the local demand–pull models that analyze the spatial evolution of wind turbine manufacturers, we observe the expected processes typical for the industrial phases of emergence and concentration. In the initial phase of the industry, manufacturers are more likely to emerge in regions with related knowledge, for example, in which the

Table 7. Average values of turbines and producers within a given radius (median values in brackets)

Model	Phase		Producers (25 km)	Producers (50 km)	Producers (75 km)	Producers (100 km)	Distance (km)
Supply–push	Initial	3 years and earlier	0.16 (0)	0.69 (0)	1.49 (1)	2.48 (2)	77.39 (62.54)
		5 years and earlier	0.15 (0)	0.62 (0)	1.35 (1)	2.23 (2)	81.72 (68.41)
Supply–push	Growth	3 years and earlier	0.31 (0)	1.11 (1)	2.41 (2)	3.79 (3)	57.41 (48.83)
		5 years and earlier	0.27 (0)	0.98 (1)	2.158 (2)	3.42 (3)	62.46 (52.73)
Model	Phase		Future turbines (25 km)	Future turbines (50 km)	Future turbines (75 km)	Future turbines (100 km)	Distance (km)
Demand–pull	Initial	Within 3 years	4.45 (0)	17.45 (0)	39.31 (2)	68.98 (3)	131.23 (51.81)
		Within 5 years	34.54 (0)	77.63 (2)	136.00 (6)	104.63 (11)	104.62 (31.33)
Demand–pull	Growth	Within 3 years	20.17 (10)	79.7 (50)	178.4 (122)	311.2 (227)	13.97 (10.92)
		Within 5 years	28.82 (15)	114.30 (78)	256.00 (194)	446.00 (359)	11.45 (9.17)

shipbuilding industry was present. Over time, relatedness becomes less important and new firms tend to emerge in geographic vicinity to already existing manufacturers, which fosters the industry's spatial concentration. In addition, local demand–pull becomes more relevant: with every additional kilometer to demand (future wind turbine installations), a new producer is less likely to emerge in a region. In summary, we confirm the importance of related variety, urbanization, and industrial agglomeration shaping the industry's spatial distribution. In addition to providing further evidence for this, our paper highlights the significant role of local demand.

These characteristics of the wind industry are in line with the argumentation of Binz and Truffer (2017) who define four kinds of global innovation systems (GIS). In particular, they classify the wind industry as a *spatially sticky GIS*. Accordingly, the wind industry is built upon specialized user needs and experience-based skills that are hard to copy and that are unlikely to diffuse in space. Other examples of such industries are biogas, luxury watchmaking, or legal services (Ibid). Crucially, in the growth phase, these industries' spatial distributions remain similar to those of the initial stage. With the exception of East Germany expanding the set of potential locations in 1989, our study supports this view, as the spatial distribution of producers remained similar over time and as the existence of local producers was identified to contribute to the establishment of new producers. In contrast, the photovoltaic industry, which was subject to similar politically support as the wind industry (Jacobsson and Lauber, 2006; Dewald and Truffer, 2012; Breul *et al.*, 2015), is characterized as a *footloose GIS* (Binz and Truffer, 2017). This implies that regions diversifying into the PV industry at an early stage of this industry's life-cycle are much more in danger of losing their initial market dominance. In fact, this is what happened in Germany, where regions with an initial advantage in this industry were overtaken (and almost completely eliminated from the market) by other locations in Asia that entered the industry at a later stage. Consequently, any generalization of our results is conditional on such differences between industries and the respective GIS.

Our empirical study has several shortcomings, which may lead the way for future research. First, the German wind industry has specific and partly unique characteristics; it is an industry highly supported by the government implying that its evolution is strongly related to decisions made in politics (Johnson and Jacobsson, 2003; Kaldellis and Zafirakis, 2011). We are confident that this did not significantly impact producers' and wind turbines' precise locations, as nationwide tax and tariff schemes have been mostly used as policy tools in Germany. These shaped demand and supply in general but not their spatial distributions. Future research should nevertheless re-evaluate the arguments using industries more independent of policy influence. Second, to generate a quantitative empirical setting, we focused on the push and pull mechanisms of technology. However, the literature emphasizes technology transitions entailing an interplay of societal rules, norms, market preferences, and policy (see Schot and Geels, 2008). Moreover, Fabrizio and Thomas (2012) discovered that in the pharmaceutical industry, access to local demand changes firms' patterns of innovation as it eases understanding local peculiarities in customer needs. Hence, looking in more detail into these processes is likely to reveal further interesting procedures that remain hidden in our research design. Third, we did not explicitly consider the main product of the industries (wind turbines) to be heterogeneous and evolving over time as well. While certain features of wind turbines can be regarded as a dominant design (three-blade rotor), there are substantial technological variations (e.g. gear vs. gearless designs). Treating all wind turbines to be alike therefore represents a significant assumption on which our empirical study is built. Fourth, we lack the information of which wind turbines were manufactured by which producers. With such information at hand, it would be possible to test if producers only create local demand for their own products or whether they also open markets for competitors. Lastly, our quantification of local demand by means of wind turbines installed in regions in subsequent periods does not directly reflect the demand curve. Rather it may represent the point of supply and demand levels being equal. Accordingly, we might underestimate actual demand in regions in which it exceeds supply capacities. However, we argue and provide evidence for supply being spatially mobile to some extent. This is particularly true when looking at longer time periods. In these cases, manufacturers may emerge or relocate in proximity to demand which implies that the equality of supply and demand levels in subsequent periods may also reflect the "excess" of demand in previous periods. How to properly approximate and quantify demand at the local level needs to be addressed by future research in more detail. With improved access to novel and more precise data in the future, we are confident that the demand side will receive more attention in studies investigating the evolution of industries in time and space.

Accordingly, while this paper represents an additional step in disentangling the interplay between demand and supply in industry's evolution in time and space, we are still far away from fully understanding these processes.

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Appendix

Supply–push models

Our main variable PRODUCERS stays always negative and significant, however, in some models it is insignificant (Table 6). This is true for the 25 and 50 km radii. When taking a look at Table 7, we see that the average minimum distance between an installed turbine and producer is at least 57 km. Accordingly, the number of producers within 25 or 50 km is generally very low, which is the most likely reason for its frequent insignificance.

There is no difference in results with respect to the time lags of 3 and 5 years.

Table A1. Results of the Cox proportional hazard models

	Local supply–push initial phase (1983–1998)			
	Distance (3 years lag)		Distance (5 years lag)	
	Coefficient (SE)	*P*-value	Coefficient (SE)	*P*-value
Supply–push				
$\text{DISTANCE}_{T,P,e-3}$	−0.002 (0.002)	0.403		
$\text{DISTANCE}_{T,P,e-5}$			−0.0012 (0.002)	0.525
Regional characteristics				
$\text{WIND}_{i,e}$	0.504*** (0.063)	<1e−3	0.505*** (0.064)	<1e−3
$\text{AREA}_{i,e}$	0.058*** (0.019)	0.003	0.059*** (0.019)	0.002
GREEN_{i}	−10.78*** (3.864)	0.005	−10.76e*** (3.855)	0.005
$\text{GDP}_{i,e}$	−0.007*** (0.002)	<1e−3	−0.007*** (0.002)	<1e−3
$\text{POP}_{i,e}$	0.001*** (0.001)	0.014	0.001** (0.001)	0.016
EAST	2.226*** (0.318)	<1e−3	2.218*** (0.318)	<1e−3
ICAR	−0.011 (0.001)	<1e−3	−0.011*** (0.987)	<1e−3
Concordance	0.821		0.821	
Likelihood ratio test	257 on 8 df		212 on 8 df	

$^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$.

Table A2. Robustness check of distance

	Local supply–push growth phase (1999–2010)	
	Distance (3 years lag)	Distance (5 years lag)
Supply–push		
$\text{DISTANCE}_{T,P,e-3}$	−0.013 (−0.035, 0.009)	
$\text{DISTANCE}_{T,P,e-5}$		−0.016 (−0.039, 0.016)
TURBINES_{e}	0.006 (−0.007, 0.019)	0.006 (−0.016, 0.031)
Regional characteristics		
$\text{WIND}_{i,e}$	0.243 (−0.123, 0.605)	0.281 (−0.186, 0.624)
$\text{AREA}_{i,e}$	**0.152 (0.071, 0.237)**	**0.165 (0.064, 0.352)**
GREEN_{i}	−5.545 (−1.783, 7.790)	−7.854 (−24.45, 8.782)
$\text{GDP}_{i,e}$	**−0.005 (−0.009, −0.0002)**	**−0.006 (−0.011, −0.001)**
$\text{POP}_{i,e}$	0.0001 (−0.002, 0.002)	0.001 (−0.002, 0.003)
EAST	0.865 (−1.286, 3.006)	0.831 (−1.402, 3.506)
ICAR	**3.503 (0.9452, 8.4271)**	**3.61 (0.5127, 12.6271)**
Survival model	Proportional hazards	Proportional hazards
LPML	−42	−60
DIC	61	104
N|events	169|68	169|68

Data only includes regions of North Germany (i.e. regions of the states Hamburg, Bremen, Lower Saxony, Schleswig-Holstein, or Mecklenburg-Western Pomerania). Coefficients in bold are significant at 95%. Lower and upper bounds of confidence intervals given in parentheses.

Demand–pull models

The Demand–pull models show different results when it comes to 3- or 5-year time lag and our main variable FUTURE TURBINES. The 3-year model of the initial phase has only insignificant values. We trace this result back to the fact that only very few turbines are deployed within 3 years (see Table 7). Again, there is no difference in the direction of significance.