RESEARCH PAPER

CO-LOCATION OF INNOVATORS AND FINAL PRODUCTS: CASE OF WIND ENERGY OF GERMANY

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ABSTRACT. This study highlights the importance of understanding the geographical context of innovation processes in industries driven by tacit knowledge, with German wind energy as its object of investigation. The subject of the research is the spatial organization of innovation processes in the wind energy sector, focusing on the co-location of inventors, production facilities, and installed capacities, particularly among locally embedded enterprises. The aim of this research is to characterize the geography of innovation in the German wind energy sector by examining the correlation between innovation departments and installed capacities, the degree of company embeddedness, and the industry's stage of development. The novelty lies in the application of a spatial analysis framework combined with network theory to explore how proximity and embeddedness shape the innovation cycle. The study developed a methodology to quantitatively assess the co-location of company branches and installed capacities over time using influence zones. Findings reveal a strong link between the locations of knowledge-generation sites and installed capacities, especially for embedded enterprises, where co-location coefficients within a 50-km radius range from 1.9 to 2.5. This correlation strengthens over time, particularly from 2000–2009 to 2010–2019. Foreign enterprises show high co-location coefficients for manufacturing sites but not for innovation departments. Further research is needed to explore the interplay of tacit and formalized knowledge in increasingly complex innovation processes and to determine causality in co-location patterns between innovators and installed capacities.

KEYWORDS: knowledge spillovers, tacit knowledge, geographical proximity, company embeddedness, wind energy, Germany

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INTRODUCTION

Innovation plays a pivotal role in regional development, as evidenced by a substantial body of literature. Key concepts such as industrial districts (Marshall 1920; Becattini 1979; 1990), clusters (Porter 1990), innovative milieu (Camagni 1991), regional innovation systems (Cooke 2001), and learning regions (Asheim 1996) underscore the importance of geographical factors in fostering innovation. This growing body of research has led to increased attention to the regional dimension of innovation policy.

The successful implementation of innovation policies, however, depends on several factors, including the specific industrial structure of a region. The regional industrial landscape shapes the nature of innovations, the sources of knowledge, and the degree to which players are embedded in the local innovation infrastructure. Among these factors, the significance of geographical proximity is crucial in determining the effectiveness of innovation processes. Geographical areas act as a place for sharing skills and also affect how effectively knowledge, especially specialized knowledge, is shared.

Since geography greatly affects innovation, it is important to understand the knowledge available, especially tacit knowledge, to create good technology policies. The geography of innovation, including the spatial distribution of knowledge generation and production activities, is crucial for developing targeted support strategies for market participants.

The *object* of this study is wind energy, selected for its reliance on tacit knowledge as a crucial driver of innovation within its production processes. The subject of the research focuses on the spatial organization of various stages of wind energy production, with particular attention to the embeddedness of participants in regional innovation systems. The aim of the study is to characterize the geography of innovation in the German wind energy sector and analyze its evolutionary features in the context of tacit knowledge.

By investigating the relationship between the locations of knowledge-generation hubs and the distribution of installed wind energy capacities, this research seeks to deepen our understanding of how tacit knowledge influences technological innovation. The study further explores the spatial dynamics between production stages and the integration of key actors, providing insights into the role of regional embeddedness in shaping innovation within this sector.

To achieve this aim, the study is structured around three key tasks:

1. To determine whether there is a correlation between the locations of knowledge generation and installed wind energy capacities. This task will identify the geographical patterns of innovation and production in the wind energy sector.

2. To assess the influence of companies' embeddedness in the local regional environment on the spatial organization of innovation activities and installed capacities. This task explores how the degree of integration into the local network affects innovation outcomes.

3. To establish the dependence of the spatial relationship between innovators and final production on the stage of industry development. This task will examine how the evolution of the wind energy sector impacts the spatial distribution of innovation and production activities.

These tasks collectively explore the relationship between spatial factors and innovation in the wind energy sector. The *novelty* of this research lies in its approach, which combines spatial analysis with a network framework to offer a new perspective on how proximity and embeddedness affect the innovation cycle in the wind energy industry.

In contrast to traditional hierarchical models of innovation, which often emphasize top-down control, the network framework focuses on horizontal linkages and decentralized collaboration. While studies such as Jackwerth (2017) have examined the inefficiencies of hierarchical systems in the wind energy industry, this research is the first to investigate the spatial aspects of nonlinear connections between actors in the innovation process. By examining geographical proximity and the spatial distribution of tacit knowledge, this study sheds new light on how localized knowledge spillovers and embedded competencies influence the development of wind energy innovations.

In conclusion, this study's novel contribution lies in its exploration of the spatial dynamics of the wind energy innovation process. The research highlights the critical role of geographical proximity in fostering innovation, with innovation centers often located near existing wind turbines to facilitate access to tacit knowledge. The study also emphasizes how spatially "sticky" competencies within the industry influence the placement of wind turbines, providing a deeper understanding of how tacit knowledge can be formalized and leveraged within the spatial dimension of innovation.

MATERIALS AND METHODS

Literature review

Types of knowledge in the context of sectoral economic activity

There are many approaches that explain the nature of knowledge and its impact on the economy. Charlie Karlsson distinguishes between the concepts of "information" as a form of codified knowledge that is easily transmitted, transferred, and stored at low cost, and "knowledge", which is difficult to codify and interpret due to its inherent complexity and indivisibility, as it is the result of a long period of learning in a specific environment (Karlsson 2012).

Closest to the second one is the concept of "tacit knowledge" which underpins the research paradigm in the works of Michael Polanyi (Polanyi 1958). The transfer of this knowledge between people requires intensive, regular, and trust-based contacts. Such ideas and skills generally arise from experience and are not systematized (Chugh 2015). For example, take the Japanese automobile industry, about which Ikujiro Nonaka wrote: the central element stimulating innovation in a Japanese automobile company is the use of "tacit" and often subjective knowledge, intuition, and guesses of individual employees, which the company tests and utilizes, rather than the "processing" of objective information (Nonaka 2007).

One of the key publications in which innovation processes were explored through the prism of different types of knowledge was the work of a Danish team of authors led by Morten Berg Jensen and Bengt A. Lundvall. They identified two types of knowledge: Science, Technology, Information (STI) knowledge and Doing, Using, Interacting (DUI) knowledge (Jensen et al. 2007). In the first case, the focus is on formal processes within R&D and explicit, codified knowledge, while in the second case, it is about employee learning resulting from informal interactions within and between organizations and the "tacit" nature of knowledge. The first type of knowledge is global, based on "know-what" and "know-why", while the second is local, depending on "know-how" and "know-who". STI knowledge relies on the use of systematized scientific and technical knowledge, whereas DUI knowledge is characterized by informal learning processes and is based on experience.

Bjørn Asheim, Lars Coenen, Meric Gertler, and others offer a more comprehensive view of knowledge, learning, and innovation, shifting away from a binary approach. They identify analytical, synthetic, and symbolic knowledge (Asheim and Gertler 2005; Asheim and Coenen 2005; Asheim 2007).

The analytical knowledge base relies on scientific knowledge grounded in formal methods and codification. Examples of such industries include biotechnology and nanotechnology. The workforce requires research experience or university education. An important form of knowledge application involves the creation of new firms and subsidiaries based on radical innovations.

The synthetic knowledge base relies on the application of knowledge or its combination, typically in response to the need for solving new applied problems (in the form of product or process development). Examples of industries include general and transportation engineering and energy industrial equipment. Cooperation with scientific centers is based on applied research and development, rather than fundamental research. This knowledge is acquired through hands-on learning in professional and polytechnic schools. Innovations are incremental and most often occur within existing companies (Lorenz and Lundvall 2006).

Symbolic knowledge relies on the creation of meanings and desires, as well as aesthetic types of products. These include drawings, images, and symbols (cultural innovations). The dynamically developing creative economy, including fields such as mass media, advertising, design, and branding, has a significant influence on the creation of this type of knowledge (intangible products) (Scott 2007). This type of knowledge requires embedding and understanding the everyday culture of specific social groups. Therefore, acquiring creative skills is associated not with formal university qualifications but with the real practice of the creative process, "know-who" (Asheim et al. 2011). Here, there is also a component of tacit knowledge.

Given the diversity of innovation processes, the strict classification of industries based on knowledge is incorrect. Innovation processes in numerous economic sectors combine elements of all types of knowledge. Each industry can be characterized by the predominance of a particular type of knowledge in its innovation processes (Alhusen and Bennat 2021). How much one type of knowledge dominates depends on the firms, industries, and activities (like research and production). Using both STI and DUI knowledge together can help companies get better results in developing innovations (Carrillo-Carrillo and Alcalde-Heras 2020; Parrilli and Heras 2016). It should be clarified that the idea of differentiating knowledge is not intended to assess differences in competence and technological complexity but to characterize the nature of innovations and their contribution to innovation activities (Moodysson 2007).

Innovation dynamics in regions by different types of knowledge

The geographical context often determines the role of different types of knowledge in the innovation process (Doloreux and Shearmur 2023). Due to various methods of knowledge creation, the dominance of a particular type of knowledge has different spatial dimensions in the interaction of actors. The generation of analytical knowledge is typically less reliant on intensive local collaboration, which promotes the development of global knowledge networks. Simultaneously, there is a belief that the transfer of synthetic knowledge is more effective when participants in innovation processes directly communicate in a common geographic area. (Moodysson et al. 2008). Geographical clustering of inventive endeavors demonstrates the regional character of tacit knowledge.

Traditionally, it was considered that inventions occurred mostly in large cities. However, there is increasing evidence that innovation can also thrive in peripheral locations outside of major urban areas (Eder 2019). Recent research has shown that in advanced economies (Parrilli et al. 2020) and in the context of product innovations (Carrillo-Carrillo and Alcalde-Heras 2020) the importance of DUI knowledge can be noticeably greater, despite the significance of other types of knowledge in innovation processes. The emphasis on this aspect can be found in Marshall-Becattini's early twentieth-century works based on the concept of industrial districts. The basic idea of grouping several small businesses in certain industries that operate at different stages of a shared production process in a specific location is similar to the current idea of tacit DUI knowledge. Marshall identified specialized labor, diffusion of knowledge, and technology transfer as advantages of industrial districts (Marshall 1920). Becattini integrated these characteristics with the actor's social proximity (Becattini 1979). According to a recent study, such districts are better suited to incremental rather than radical innovations (Hervas-Oliver et al. 2021).

The work of Dutch economist and economic geographer Ron Boschma actively explores the geographical aspect that shapes the context of interactions among players. He explains how many forms of proximity between actors (cognitive, organizational, institutional, social, and geographical) define the process underpinning this impact (Boschma 2005). The latter catalyzes other types of proximity but has no direct impact on how actors in innovation interact. Therefore, geographic proximity has an array of effects, all of which operate together to increase the extent of contact between innovation actors. This is especially crucial when discussing tacit DUI knowledge since face-to-face interaction is the only vehicle for this knowledge to be transferred between individuals and is difficult to codify. Therefore, the localized nature of DUI knowledge is characterized by knowledge spillovers between people over short distances.

Asheim and Coenen found that studying five northern clusters in Denmark, Sweden, and Norway showed that different regional innovation systems (RIS) are shaped by different types of knowledge. Consequently, it influences the type of innovation policy that is implemented into practice, depending on the specifics of the industry. The support and enhancement of localized learning in established industrial specializations distinguishes synthetic (engineering) knowledge. This, in turn, reinforces technological trajectories that rely on tacit knowledge, using an ex-post approach. Territorially integrated RISs emerge as a result. In terms of scientific knowledge, the main goal is to support new business ideas that need partnerships between universities and industries. This can be achieved through places like science parks and incubators (ex-ante approach). The regional knowledge infrastructure is essential in both innovation systems. As a result, national innovation systems, or regionally networked innovation systems, are formed. The first one is science-oriented and may have weak interactions with local industries. The last one, which has more advanced technologies than territorially integrated RIS, combines analytical and synthetic knowledge and is market-oriented, making it the most competitive type of RIS known to arise during an industry's growth stage. The ex-post approach enables locally networked innovation systems to address problems incrementally while at the same time providing initial assistance to the industry in surmounting technological barriers (Asheim & Coenen 2005).

Local knowledge spillovers, or "local buzz", often occur in the context of the tacit nature of knowledge "in itself". Tacit knowledge comprises researchers, engineers, and all persons who play a role in maintaining the efficient operation of the DUI industry at all stages of the value chain. Simultaneously, global knowledge transfer channels, or "global pipelines", facilitate the sharing of scientific, technological, and innovation (STI) knowledge. This exchange requires formal links between players involved in innovation and codified forms of knowledge. As Harald Bathelt notes, both types of knowledge spillovers are necessary for the productive creation of innovations (Bathelt et al. 2004). However, differences in their combination indicate the varying roles of localized and global knowledge spillovers in different industries.

For companies that are part of networked innovation processes, it is necessary to supplement their internal knowledge base with another type of knowledge. The primary methods of acquiring new knowledge include attracting human capital with the required competencies in a different knowledge base, as well as internationalizing scientific collaboration, outsourcing R&D, or engaging in external economic activities. All of this increases the focus on various territorial forms of organizing innovation processes, from clusters and innovation systems to global production networks and value chains, where the type of knowledge used is not internal to the industry but rather external knowledge that has been brought into a range of technologies, actors, and industries from outside (Smith 2000). Thus, there is a global trend toward integration and collaboration in the process of knowledge creation and corporate innovation.

Evolutionary researchers emphasize that the spatial pattern of the innovation process also determines the stages of industry development. According to M. Feldman, tacit knowledge is especially important during the early stages of industry formation (Feldman 2010). In such cases, local knowledge is often in demand, "existing in a tacit and non-formalized shape within informal communication networks through trusted interactions between closely located economic agents" (Pelyasov 2012). At the same time, formalized knowledge is characteristic of more mature industries, and global knowledge transfer channels serve to disseminate it more effectively over long distances.

Under the influence of scientific and technological progress, the processes of knowledge creation and innovation are becoming increasingly complex, diverse, and interdependent. Different combinations of knowledge types exhibit spatial diversity. They also appear differently in the framework of innovation evolution.

Table 1 provides a brief description of the differences between the two ideal types of knowledge, considering the rationale for knowledge creation, the methods of its development and utilization, and the sensitivity to geographical factors.

Innovative development of wind energy in Germany as a DUI industry

The subject of the research is the wind energy sector in Germany for several reasons. First, wind energy, as a young industry, is well supported by a wide range of scientific and statistical materials that allow for analysis of its innovative development in its early stages. Second, existing publications on the innovative aspects of its development indicate that wind energy is an industry where tacit knowledge is actively sought after (Binz and Truffer 2017; Rohe 2020; Tsouri et al. 2021). Binz and Truffer also note in their work on global innovation systems that new knowledge in wind energy is formed not only through science but, to a greater extent, through on-the-job training (Binz and Truffer 2017). This is also supported by research from Heidenreich and Mattes (2020), which looks at how local innovation in Germany's wind energy sector relies on sharing tacit knowledge.

Therefore, the wind energy innovation system is characterized by its *regional embedding*. Based on research in related fields, the authors conclude that the development of wind energy still primarily relies on DUI knowledge, which contrasts with the general trend toward a shift to STI knowledge in other industries over time. Meanwhile, in the process of creating value chains within global innovation systems, suppliers in offshore wind energy, according to the study by Tsouri, Hanson, and Normann, represent a wide variety of firms that produce products, components, and services and are to some extent involved in the development of innovations in the STI knowledge mode (Tsouri et al. 2021). Some of these firms also have experience in supplying the oil and gas industry, which relies on both DUI and STI modes of innovation (Hanson J. et al. 2021).

In studies on technology life cycles, it is noted that geographical proximity to users only weakens in the case of mass energy technologies (such as today's solar photovoltaic systems). In contrast, for innovators of complex technologies like wind energy, geographical proximity remains significant (Huenteler et al. 2015; Barua 2012). This must also be considered in the implementation of technological policies: subsidies for market deployment in wind energy are more effective when combined with measures to promote learning and the knowledge spillovers between producers and researchers (Kamp et al. 2004; Tang and Popp 2015). Hence, *the hypothesis arises that there is a high degree of concentration of all links in the value chain within the industry in one place, from invention and product creation to practical use*.

M. Bednarz and T. Broekel scrutinize the industry from the perspective of its reliance on demand and supply factors (Bednarz and Broekel 2020). They compare two types of models: one that shows how supply influences the installation of wind turbines and another that illustrates how demand attracts companies that manufacture wind turbines. The researchers believe that in Germany, the demand factor is more important, especially when looking at regional policy in the context of ex-post approach. This means that the co-location of innovation centers and installed capacities may be driven by consumer demand for innovations in regions with favorable conditions for the development of wind energy.

Thus, wind energy is an industry with a distinctive mode of innovation creation, where certain types of knowledge (tacit, applied, engineering, DUI) play a crucial role. This aligns with findings by Alle et al. (2017), who argue that the localized exchange of tacit knowledge is critical for fostering innovation in complex industries like wind energy, particularly in regions with high embeddedness. Individuals generate this knowledge by acquiring practical skills in the workplace at various stages of the value chain. The dissemination and exchange of this kind of knowledge are most effective within the framework of the spatial concentration of actors. Given *that the degree of embedding can positively influence the role of local tacit DUI knowledge in the innovation processes of companies, this aspect is given special attention in the work. The research question is articulated as follows: How does tacit applied knowledge influence the spatial distribution of wind energy throughout the innovation process, and is the proximity of innovators to final products essential for the effective development of innovations in the industry?*

Against the backdrop of the German government's interest in actively integrating renewable energy sources into the national energy system, embedded companies may receive a particular stimulus for innovative growth alongside the development of institutional structures and framework conditions in the country.

Table 1. Differences between STI knowledge and DUI knowledge

Characteristics	STI knowledge	DUI knowledge
Possibility of formalization	Formalizable	Difficult to formalize, "tacit"
Level of theorization	Theoretical	Applied
Research centers	Fundamental	Experimental
Type of innovator	Scientists	Engineers
Nature of innovations	Radical	Incremental
Scale	Global	Local

METHODS

Studying Germany in the context of innovation's development has methodological advantages. First, the country has strong statistical support, including in the field of spatial data, which enhances the quality of research and expands the possibilities for using various methods. Second, the country's continuous and densely populated space, with a uniformly high level of transport infrastructure development, helps minimize statistical deviations in identifying correlations, a benefit that classics of location theories utilized a century ago.

To test the hypotheses, a methodology was developed to quantitatively characterize the spatial distribution of knowledge generation locations in the field of wind energy and installed capacities. The essence of the methodology is to compare a company's share of installed wind energy capacities within an n-radius from a company branch to the company's share of installed capacities nationwide. Essentially, this indicator functions as a localization coefficient, utilizing radii around company branches instead of regions. These radii can be characterized as *gravitational fields or influence zones* of company branches (Eq. 1):

$$\frac{C_n/G_n}{C_a/G_a} \quad (1)$$

where C_n represents the company's installed capacities within radius n, G^n represents the total installed capacities in the country within radius n, C_a represents the company's installed capacities nationwide, and G^a represents the total installed capacities nationwide. Values of the coefficient significantly greater than 1 suggest a spatial correlation between installed capacities and company branches, indicating a relationship in their placement. The index also shows how much more attractive the placement of generating capacity is within a specific radius of a company branch compared to the national average.

To assess the gravitational fields, various types of company branches were considered. The primary ones are *innovation centers*, where key processes for creating new technological solutions occur. The study also analyzed the spatial distribution of installed capacities in relation to *headquarters*, which are branches with key organizational innovations. Production sites of wind energy companies can also impact innovation processes as repositories of engineering knowledge and serve as indicators of the market supply of wind turbines. The geographical coordinates of the key market players' branches were determined through an analysis of wind energy companies' websites.

Various distances (25, 50, 75, 100, 125, and 150 km) were used as radius values to track at what distance the influence zones of company branches weaken. For each type of company branch, a matrix of coefficients was created to show the level of interdependence between their locations and the company's installed capacities. GE Wind does not have innovation centers or headquarters in Germany, so in two cases, the matrices contain 4 columns instead of 5.

The study covers the period from 2000 to 2019. This range was chosen to avoid statistical deviations that arose during the COVID-19 pandemic and to conduct the research within the framework of the "Renewable Energy Sources Act". Additionally, this interval allows for a comparison of the phenomenon of co-location across two decades: 2000–2009 and 2010–2019. Equal time frames help to determine whether the role of co-location increased as the industry developed or, conversely, decreased. Some company branches were established in the 2010s, but they were included in the calculations along with earlier wind turbine installations. This is possible because the study examines not just the impact of one factor on the location of the other but their *mutual influence*. It is assumed that the installed wind turbines could have influenced the location of new company branches due to the emergence of a local innovation environment in that area, formed based on tacit and applied knowledge.

To confirm the results obtained and to identify more detailed relationships, a cartographic research method was used. Maps showing the locations of innovation activity centers allowed for the identification of the specifics of their localization at the regional level (e.g., northern and southern Germany) and the urban level (e.g., large or small cities). Additionally, supplementary maps were created to either confirm or refute the results obtained from the index calculations. To visualize the relationship between the locations where companies generate knowledge and where they implement their products, the maps showing the density of wind turbines installed by various companies were overlaid with the locations of the major wind turbine manufacturers' branches. The analysis was conducted using the QGIS tool called Heatmap (Kernel Density Estimation). The weights of the points were based on the wind turbine capacities, and a bi-quadratic kernel shape was used for the calculations and the creation of the maps.

Information about the coordinates of wind turbines, their capacities, and manufacturing companies was obtained using the MaStR[1] database, the register for the German electricity and gas market. This database contains information about wind turbines installed in Germany since 1990, including the company under whose brand the turbine was manufactured, its capacity, and its location (geographical coordinates). On the one hand, this database helps identify the key companies active in the German wind energy market. On the other hand, the inclusion of geographical coordinates for the wind turbines allows for the application of the aforementioned methodology.

This approach may not be appropriate for all industries: wind energy, in particular, has a final product that is anchored in space, allowing for quantitative spatial assessment. The methodology is novel in that it attempts to statistically measure the geographic component of the interconnection between innovators and the final product, allowing for the evaluation of the impact of tacit forms of knowledge on the innovation process.

RESULTS

Specifics of the development of the corporate structure of the wind power market in Germany

In the 1980s, as the potential of wind power became increasingly clear, Germany attempted to develop powerful turbines with the support of government programmers (Ohlhorst 2009). This approach proved less effective than the model of neighboring Denmark. The Danish technology here was developed by local manufacturers. These companies were located in rural areas in regions with steady and strong winds. In the beginning, the firms met the needs of local communities, but they gradually consolidated and expanded, while the state only provided a favorable institutional environment without directly intervening in the innovation processes of the industry.

[1]https://www.marktstammdatenregister.de/MaStR/Einheit/Einheiten/ErweiterteOeffentlicheEinheitenuebersicht#stromerzeugung

This environment then emerged in northern Germany, where the conditions for wind energy development (wind speeds and rural electricity needs) are similar to those in Denmark (Ohlhorst 2009). Here, the first locally embedded German wind turbine manufacturers emerged. The latter is defined through the prism of their evolution: the longer the manufacturer's branches are located in a particular country or region, the more embedded the company is in the local environment. In addition, a company's focus on selling its products primarily domestically reinforces this quality.

The country has the status of a technological leader in the sector. Today, three of the top 10 global wind turbine manufacturers have German roots[2]. German wind power plays a leading role in electricity generation among all energy sources: in 2023, almost 140 TWh of electricity was generated by wind power, accounting for 32% of the country's total electricity, and about 17% of wind generation was provided by offshore installations[3]. Following the Fukushima accident, the German government has established a consistent policy of abandoning nuclear power and increasing reliance on renewables, the development of which is particularly influenced by the feed-in tariff mechanism. The law enshrines the goal of increasing the share of renewable energy sources in the electricity supply to 80% by 2050[4].

The most successful German wind turbine manufacturer on the domestic market is Enercon. The headquarters and largest production site of the company are located in Aurich. Other production sites are also located mainly in the north of the country. In 2014, an innovative research and development center and a test center were opened in Aurich. The management notes that the location was chosen based on its proximity to the production units in order to take advantage of the innovative benefits of co-localization and to contribute to the further development of technology and innovation in the company[5]. Enercon's current share of wind turbines in the German market is around 40%.

The second company in terms of production localization is Nordex. Despite the fact that it was founded in Denmark in 1985, after 6 years, the company moved to the town of Rerik in the federal state of Mecklenburg-Western Pomerania, and then in 1999, with the expansion of production, to Rostock. The company's headquarters, main production site, and innovation center are now located here, while management and the employee training center are localized in Hamburg. However, in the last decade, Nordex management decided to intensify its presence in global markets and merged with another energy company, Spain's Acciona, forming the conglomerate Nordex Group in 2016. It now accounts for about 7% of the German wind turbine market.

The Spanish-German wind energy company Siemens Gamesa Renewable Energy (SGRE) also built its first production site in Denmark. In 1980, Danregn, a Danish company, became involved in the production of wind turbines. In 2004, it was sold to Siemens AG, one of Germany's largest industrial conglomerates. As a result, its headquarters, as a sales and project management center, moved to Hamburg. In doing so, the company chose a different strategy from Enercon, which was focused on the domestic onshore wind energy market and carved out a significant niche for itself in foreign markets. For this purpose, the turbine manufacturer under Siemens has been opening its own production sites around the world, acquiring other companies, and developing offshore wind power. The biggest expansion came in 2016: Siemens and Spanish wind energy company Gamesa announced their plan to create a merged company with a 59 percent stake in Siemens and a 41 percent stake in Gamesa. In 2019, SGRE agreed to acquire for €200 million the European service park of Hamburg-based Senvion, which, before the deal, provided 10% of the German wind energy market, including offshore wind turbines.

The key foreign company in terms of installed capacity in Germany is Denmark's Vestas, the world leader in wind power (with a German market share of more than 20%, the same as SGRE's). Vestas, despite its foreign roots, is present throughout the entire value chain in neighboring Germany, including R&D. Another world leader in the wind power industry, a division of American General Electric (GE Wind Energy), is less active in Germany. The main research departments of the company are not located in Germany, so GE Wind Energy takes almost no part in local innovation processes. It accounts for about 6% of the German wind energy market.

In total, these five companies provide almost the entire German wind energy market (Fig. 1): German Enercon, German-Spanish Siemens Gamesa Renewable Energy (SGRE), and Nordex Group, as well as Danish Vestas and American GE Wind Energy (headquartered in France).

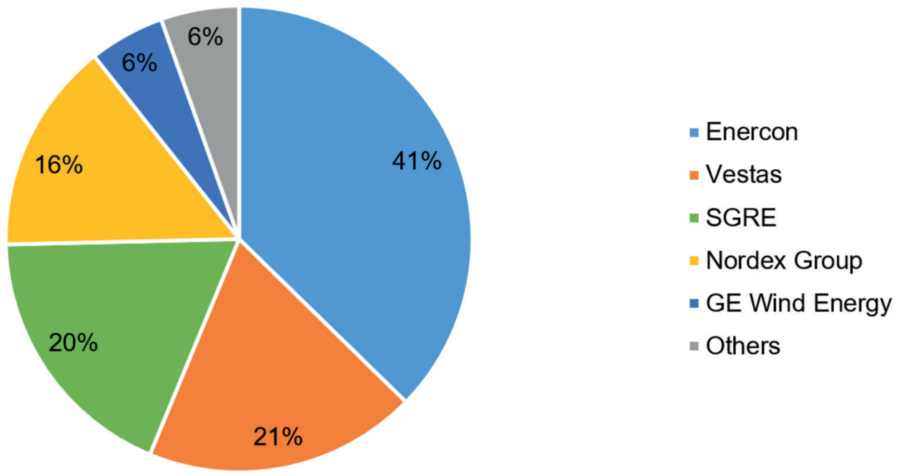


Fig. 1. Shares of wind turbine manufacturers in the German market by installed capacity[6]

[2] https://energydigital.com/top10/top-10-wind-turbine-manufacturers
[3] https://www.energy-charts.info/downloads/electricity_generation_germany_2023.pdf
[4] https://www.bundesregierung.de/breg-de/schwerpunkte/klimaschutz/wind-an-land-gesetz-2052764
[5] https://www.enercon.de/unternehmen/
[6] https://www.enercon.de/en/company/market-share/

Location of fundamental and applied research institutes

Although companies are increasingly taking over the R&D functions of research institutes and universities, their role in innovation processes in Germany remains significant. The location of company-independent R&D centers was analyzed in two research-oriented categories: fundamental and applied. Scientific organizations aimed at fundamental research in the field of the wind power industry (DLR, WindForS, and ForWind) are located in cities with decent universities (Fig. 2). In fact, two geographical areas can be allocated: Lower Saxony and Southern Germany (the states of Bavaria and Baden-Württemberg). This shows that fundamental knowledge can arise not only in the locations where wind turbines are directly operated. At the same time, applied research institutes (Fraunhofer IWES, DEWI, and FuE-Zentrum FH Kiel) are located only in the north, where knowledge is put into practice.

The resulting spatial pattern of fundamental and applied research institutes corresponds to the peculiarities of the industry's development at a very early stage. The initial innovation impetus in the country did not originate in the north of Germany, where the main wind power capacities are installed today, but in the south, in Stuttgart, where aerodynamics research was conducted at the local technical university. By 1957, one of the first wind turbines in the world had been commissioned under the direction of aeronautical engineering professor Ulrich Hütter. It was built on the principles of aeronautical engineering: "Anything that rotates should be as light as possible, but also as strong as necessary (Maegaard et al. 2020)". So, the radical innovation within the industry originated in a fundamental university environment rather than in places with favorable natural conditions for the implementation of wind energy. Soon, the character of innovation transformed from radical to incremental, and innovation activity in the German wind industry shifted from the south of the country to the north, where there are more opportunities for obtaining applied knowledge.

Co-location of R&D departments, production sites, headquarters, and installed capacity

R&D Departments

The calculations show a clear relationship between Enercon's R&D department and its installed capacity (Table 2). The index values correlate with the degree of the company's embeddedness in the local environment. Enercon dominates the domestic market, but its level of presence in global markets is lower than that of other companies[7]. High index values (above 1.25) persist up to a distance of 125 kilometers, with a maximum of 2.50 within a radius of 25 kilometers. Enercon is a key wind energy company in Lower Saxony, the German federal state with the highest wind energy potential.

The example of Enercon's data shows that our hypothesis of *decreasing interdependence in the location of innovation centers and wind generation capacity as the industry reaches maturity* is confirmed only at larger radii of 75, 100, 125, and 150 km (these indices are lower in the 2010s compared to the 2000s). At the same time, at distances of 25 and 50 km from the R&D department, the coefficient in 2010 was higher (2.66 and 2.38) than in the 2000s (2.21 and 2.08). Evidently, the role of tacit knowledge in innovation processes of embedded firms at

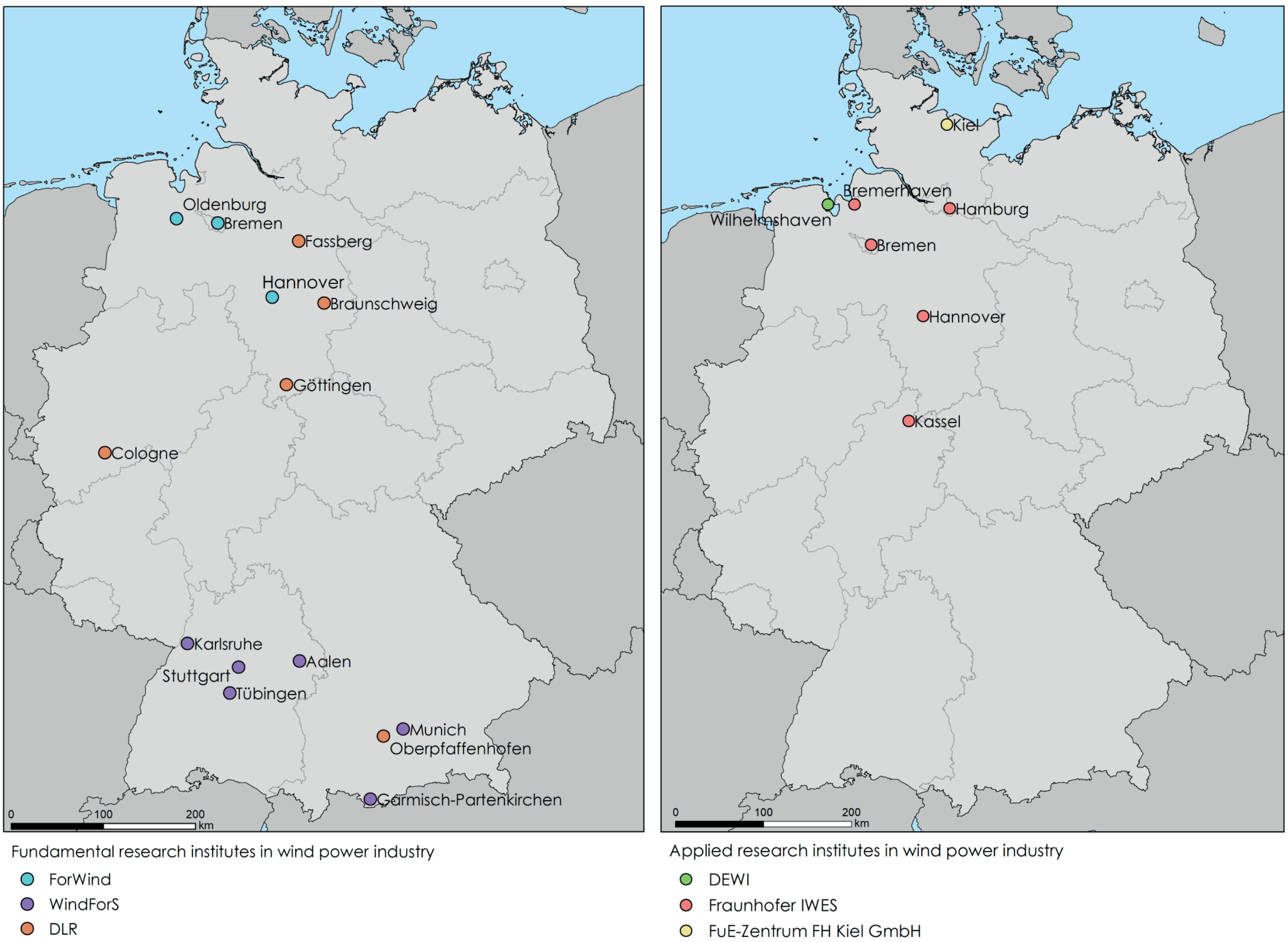


Fig. 2. Location of the main fundamental and applied research centers in the German wind energy industry

[7] According to the ranking of global wind energy companies: https://energydigital.com/top10/top-10-wind-turbine-manufacturers

Table 2. Coefficient matrix of co-location of R&D departments in key companies and installed capacities

	R&D departments							
Radius to department, km	Enercon		Nordex Group		SGRE		Vestas	
	2000–2009	2010–2019	2000–2009	2010–2019	2000–2009	2010–2019	2000–2009	2010–2019
25	**2.50**		**2.31**		**1.53**		**0.12**	
	2.21	2.66	2.18	2.40	0.66	1.44	0.16	0.00
50	**2.27**		**1.92**		**1.50**		**0.10**	
	2.08	2.38	1.60	2.09	1.73	1.37	0.19	0.00
75	**1.64**		**1.16**		**1.38**		**0.45**	
	1.89	1.59	1.42	1.09	1.80	1.24	0.52	0.35
100	**1.27**		**1.06**		**1.34**		**0.53**	
	1.79	1.16	1.43	0.94	1.79	1.20	0.60	0.43
125	**1.31**		**1.14**		**1.23**		**0.54**	
	1.61	1.24	1.56	1.02	1.58	1.13	0.58	0.51
150	**1.17**		**0.98**		**1.30**		**0.55**	
	1.42	1.07	1.35	0.87	1.46	1.24	0.62	0.50

close distances does not weaken. The multiplicative effect of the mutual intensification of spatial gravity contributes to the increase in the degree of co-location throughout the development of the industry. This means that there are two trends in the evolution of innovation processes: "localization", which promotes increased concentration in small radii, and "deconcentrating". The latter is characterized by a decrease in the importance of co-location at farther radii (Fig. 3).

It should be noted that Enercon's success is largely due to the inventive skills of the company's founder, local "self-made" entrepreneur and innovator Allois Wobben. He was born in Rastdorf, graduated from the University of Oldenburg, and his career path is similar to that of Stanford University students W. Hewlett and D. Packard[8]. By 1984, A. Wobben was in Aurich and had established Enercon, a company that later became one of the leaders of the German wind energy industry. Wobben's activities were compactly concentrated in the north-western part of the federal state of Lower Saxony, indicating a high degree of embeddedness for both the company and its founder in the local environment.

A German wind turbine manufacturer close to Enercon in terms of its embeddedness is Nordex. In recent years, the company has embarked on a course to expand its markets worldwide by creating the German-Spanish Nordex Group. The values of the index also reflect its slightly lower focus on the German consumer compared to Enercon. Nevertheless, it shows high results in the 25- and 50-km radius (2.31 and 1.92), indicating the large influence of localization within the northeastern region of Germany. However, already at the 75-km radius, the index decreases significantly. The indices for the different periods reflect similar trends as in the case of Enercon: in the 2010s, the indices were significantly higher at 25- and 50-km radii and lower at 75-, 100-, 125-, and 150-km radii. This suggests the *50-km radius as the 'gold standard' for the processes of sharing tacit DUI knowledge in the German wind industry in the case of locally embedded companies.*

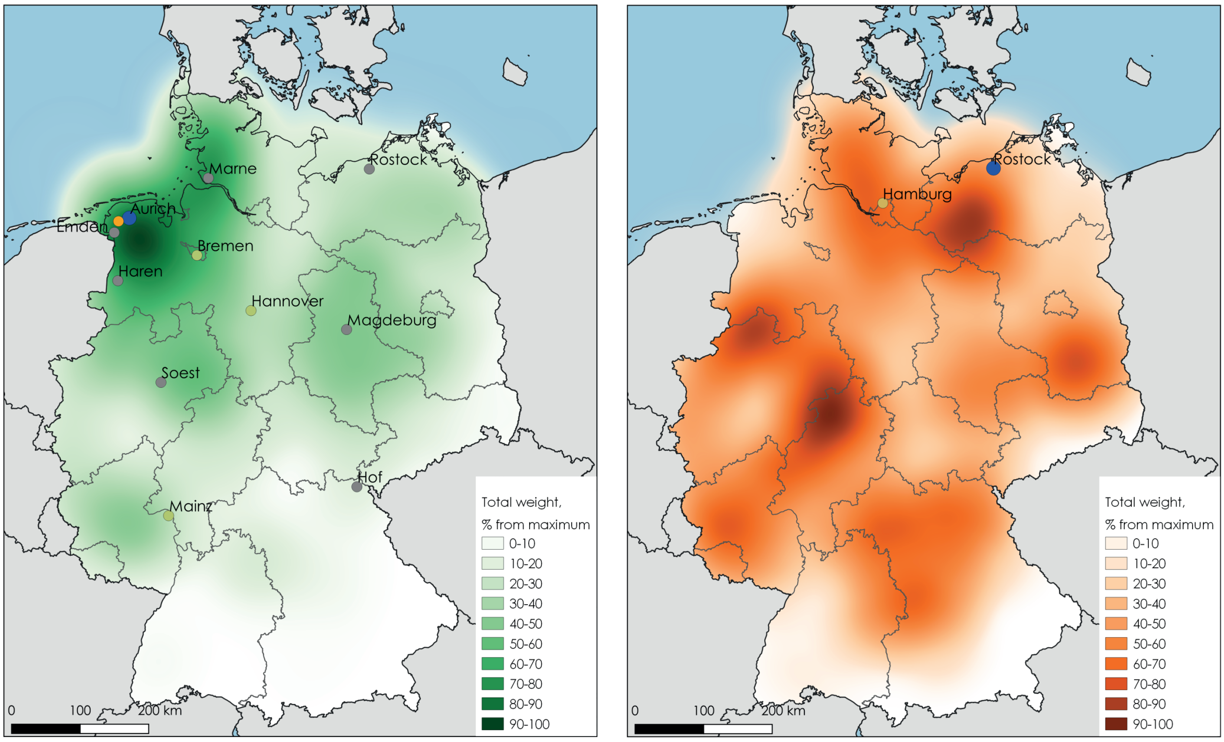
Like Nordex Group, SGRE is a German-Spanish conglomerate, but its roots in Germany are even weaker. This is partly due to the fact that the company was Danish for quite a long time. With the merger in 2016 with Spain's Gamesa, the company became a global company specializing in large wind power projects, including offshore projects. With a significant share of the German wind energy market (more than 20%), the company shows high index values (above 1.25) up to a 150 km radius, but in the closest radius from innovation centers, the company is behind Enercon and Nordex (Fig. 4).

Starting from the 50-km radius for SGRE, a decrease in the localization coefficient was observed in the 2010s compared to the previous decade. This reflects SGRE's less localized approach to the location of innovation centers compared to Enercon and Nordex. At the closest distance (25 km radius), however, the previously identified logic of increasing mutual attraction of innovation centers and installed capacity persists: in the 2010s, the coefficient values in the 25 km radius became higher than in all other radii (1.44). This indicates that even in a weakly embedded firm, the role of tacit knowledge in innovation processes persists.

For the foreign company Vestas, whose main innovation activity takes place outside Germany, the value of the localization coefficient was significantly lower than 1 at all radii. Thus, there is a spatial disintegration of its economic operation. The company's R&D activities are conducted in Denmark, where its headquarters and main innovation centers are located. In Germany, the company has only located one innovation center in Dortmund during the study period. Here, Vestas has advanced S&T competencies, but there is no demand for a local environment with tacitly applied wind energy knowledge, as there are no locations for generator installations in the highly urbanized Ruhr Area. The low coefficient values (<0.2) for radii of 25 and 50 kilometers are related to this.

Vestas installs wind turbines in East Germany to fill a niche that German manufacturers do not occupy. After the

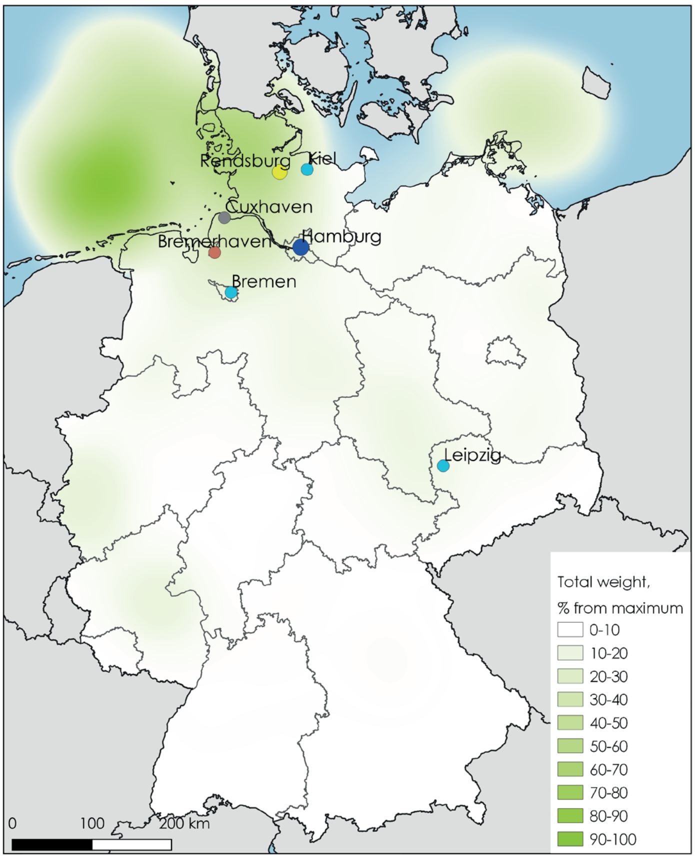
[8] https://www.deutschland.de/de/taxonomy/term/40/der-pionier-aus-dem-norden
https://successstory.com/people/aloys-wobben



Enercon
- HQ, main production site, R&D department
- Foundary
- Production site
- Sales office

Nordex
- HQ, main production site
- Management, employee training centre

Fig. 3. Density maps of installed wind turbines of embedded companies (Enercon and Nordex) and the location of their main branches



SGRE
- Head office, service centre, R&D department
- R&D department, service centre, sales office
- Production site
- Service centre
- Sales office

Fig. 4. Density maps of installed SGRE wind turbines and the location of their main branches

country's reunification, due to the lower population density and increased investment attractiveness of new projects (including through institutional support from regional authorities), this part of the country is characterized by a high potential for the industry's development (Fig. 5). Germany seems to downplay tacit knowledge for the company, unlike its home country. There is also a decrease in the localization ratio in the 2010s compared to the 2000s, confirming the weakening of the relationship over time.

Thus, for a foreign company, we should not speak about the lack of connections in the co-location but about the *opposite* nature of such connections. The location of the Vestas wind turbine generators was due to the low density of settlement in the East German lands (on a German scale). The location of the innovation center, on the contrary, was due to its gravitation towards a densely populated environment with a large number of universities and people who are carriers of explicit formalized knowledge.

Headquarters and production sites

The thesis about the different influences of the local environment on national and foreign companies is also confirmed by the coefficients for their headquarters (Table 3). For Enercon and Nordex, they do not differ from the coefficients calculated for innovation centers, which indicates that innovation and management processes are embedded in the same environment. In the case of the transnational SGRE, lower rates persist for HQs as for innovation centers; the centrifugal tendency when comparing the 2000s and 2010s is evident to the same extent as for innovation centers. A low degree of co-location is also observed for the Danish Vestas (indicator values are strongly below 1).

At the same time, American GE Wind has neither headquarters nor innovation centers in Germany, which demonstrates the exclusive role of the demand factor for wind turbines in terms of capacity placement under this brand.

The coefficients calculated for the production sites confirmed it (Table 4). The figures were highest for foreign companies Vestas and GE Wind. Within a radius of 100 kilometers, values consistently exceed 1.4. Moreover, for the geographically more isolated American GE Wind, they are much higher than for the Danish Vestas. Co-location of production centers and installed capacities is also common among embedded companies. The coefficients are comparable to those of innovation centers and headquarters. Such co-location also favors the diffusion of tacit knowledge within the local environment.

The study yielded three main findings. The research revealed a positive correlation between the locations of knowledge generation and the capacities installed by companies.

Furthermore, the higher the level of embeddedness, the greater the impact on innovation co-location and end-product manufacturing within the firm. Close proximity fosters intensive intra-firm exchange of tacit knowledge (doing-using-interaction mode), an effect that is most visible within a radius of 50 km (co-location coefficients range from 1.9 to 2.5). At the same time, foreign enterprises only have high co-location coefficients (2.2–3.9) at manufacturing sites. In this instance, market demand – rather than tacit knowledge embedded in the local environment – determines the location of installed capacities and corporate branches.

Over time, the correlation between knowledge generation locations and their application for embedded

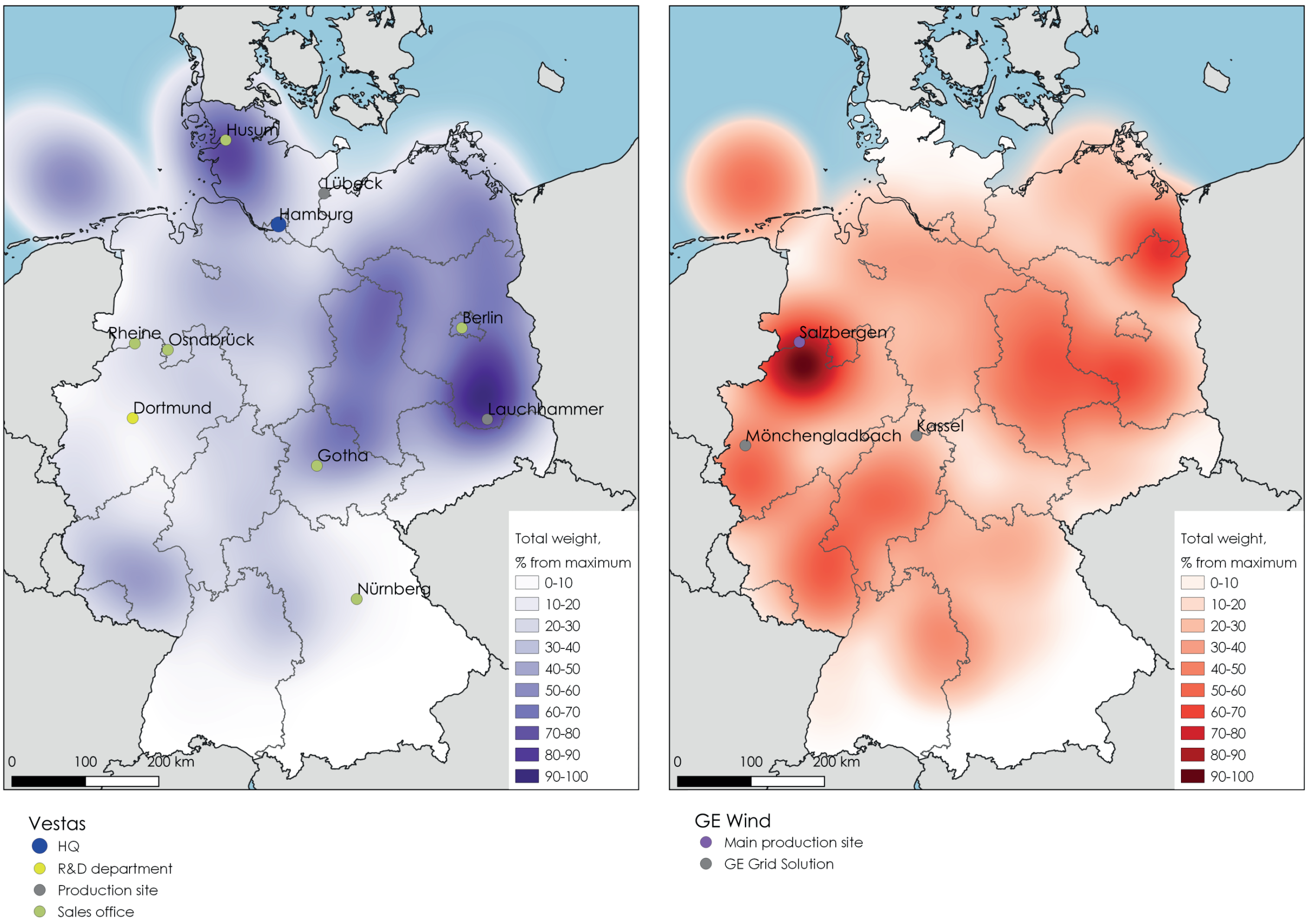


Fig. 5. Density maps of installed wind turbines of foreign companies (Danish Vestas and American GE Wind) and the location of their main branches

Table 3. Coefficient matrix of co-location of headquarters in key companies and installed capacities

Radius to HQ, km	Headquarters							
	Enercon		Nordex Group		SGRE		Vestas	
	2000–2009	2010–2019	2000–2009	2010–2019	2000–2009	2010–2019	2000–2009	2010–2019
25	**2.50**		**2.31**		**1.31**		**0.31**	
	2.21	2.66	2.18	2.40	1.24	1.28	0.00	0.42
50	**2.27**		**1.92**		**1.13**		**0.86**	
	2.08	2.38	1.60	2.09	1.79	0.97	1.24	0.60
75	**1.64**		**1.16**		**0.98**		**0.75**	
	1.89	1.59	1.42	1.09	1.69	0.80	1.12	0.49
100	**1.27**		**1.06**		**1.06**		**0.80**	
	1.79	1.16	1.43	0.94	1.61	0.93	1.02	0.71
125	**1.31**		**1.14**		**0.99**		**0.83**	
	1.61	1.24	1.56	1.02	1.30	0.93	0.97	0.74
150	**1.17**		**0.98**		**1.00**		**0.90**	
	1.42	1.07	1.35	0.87	1.24	0.95	0.91	0.89

Table 4. Coefficient matrix of co-location of production sites in key companies and installed capacities

Radius to PS, km	Production sites									
	Enercon		Nordex Group		SGRE		Vestas		GE	
	2000–2009	2010–2019	2000–2009	2010–2019	2000–2009	2010–2019	2000–2009	2010–2019	2000–2009	2010–2019
25	**1.95**		**2.31**		**1.19**		**2.55**		**3.86**	
	1.60	2.14	2.18	2.40	2.30	0.96	2.28	2.73	4.35	3.45
50	**1.78**		**1.92**		**1.18**		**2.16**		**2.37**	
	1.47	1.96	1.60	2.09	1.79	1.02	2.16	2.06	1.84	2.74
75	**1.50**		**1.16**		**1.11**		**1.67**		**1.82**	
	1.39	1.56	1.42	1.09	1.56	0.97	1.58	1.64	2.03	1.54
100	**1.31**		**1.06**		**1.30**		**1.41**		**1.43**	
	1.32	1.31	1.43	0.94	1.31	1.21	1.41	1.34	1.61	1.18
125	**1.26**		**1.14**		**1.55**		**1.24**		**1.07**	
	1.26	1.27	1.56	1.02	1.54	1.46	1.24	1.20	1.25	0.80
150	**1.18**		**0.98**		**1.55**		**1.18**		**0.87**	
	1.22	1.10	1.35	0.87	1.32	1.49	1.18	1.14	1.11	0.60

enterprises declines over greater distances but strengthens within a 50-kilometer radius (at this distance co-location coefficients increase from 1.6–2.5 in 2000–2009 to 2.1–2.7 in 2010–2019). Thus, for local producers, the hypothesis that the relevance of tacit knowledge declines as the industry matures is only partially supported.

DISCUSSION AND CONCLUSIONS

Geographical aspects of innovation processes play a crucial role in sectoral studies, particularly when viewed through the lens of different types of knowledge. In industries like wind energy, where tacit knowledge (in the doing-using-interacting mode, or DUI) is central to innovation, the importance of geographical proximity becomes particularly pronounced. A wealth of literature supports this view, highlighting the innovation characteristics specific to the wind energy sector (Binz and Truffer 2017; Moodysson et al. 2008; Rohe 2020; Tsouri et al. 2021; Heidenreich and Mattes 2022). Access to tacit knowledge can be significantly enhanced when innovators are co-located with the places where final products are implemented. This study, for the first time, examined and confirmed the hypothesis that there is a correlation between the locations of knowledge generation and installed capacities in wind energy.

The analysis of co-location between company branches and installed wind power capacities revealed that the degree of spatial mutual influence strongly depends on the level of embeddedness in the local environment. Companies that are locally embedded demonstrate a clear pattern of co-locating their knowledge centers and production sites. This observation underscores the importance of the local environment in the wind energy industry, where much of the production chain – from wind turbine development to installation – takes place. In these settings, innovation processes are heavily shaped by tacit knowledge exchange. The phenomenon of co-location is most pronounced within a 50 km radius, which reflects the importance of local proximity in fostering tacit knowledge sharing. According to Asheim and Coenen's classification, this makes the German wind energy sector closely aligned with territorially embedded regional innovation systems (RIS) (Asheim and Coenen 2005).

This study also provides a novel contribution by examining the evolution of innovation processes in the wind energy industry. It challenges the prevailing idea that the role of DUI knowledge diminishes over time due to the formalization of knowledge (Feldman and Kogler 2010). The hypothesis was not fully supported in the case of German wind energy, where the synergistic effect of knowledge concentration within a small radius (50 km) often outweighed the tendency toward formalizing knowledge. While there was evidence of a "localization" effect (increased co-location at small radii), there was also a "deconcentrating" trend at larger radii, indicating a growing importance of other factors beyond geographic proximity.

This dual process – localization within small radii and deconcentration at larger scales – suggests a nuanced understanding of the spatial dynamics of innovation. For embedded companies, such as Enercon and Nordex, the proximity to tacit knowledge sources in the local environment is crucial. In contrast, foreign firms, which are less embedded in the local context, show a weaker reliance on local tacit knowledge and instead focus on accessing STI knowledge and market niches. This observation verifies the conclusion that the division of industries based on distinct types of knowledge (STI vs. DUI) is overly simplistic (Bathelt et al. 2004; Hanson et al. 2021; Tsouri et al. 2021). The innovation processes of foreign companies in the German wind energy sector align more with STI processes, where the spatial pattern of innovation centers and installed capacities is driven by access to specialized knowledge and market demands, rather than tacit knowledge embedded in the local environment.

Despite these findings, several aspects remain unexplored and warrant further research. The complexity of the wind energy innovation process, coupled with increased skill recombination and outsourcing of certain production stages, results in a mix of knowledge types, blurring the distinction between DUI and STI knowledge. This study did not fully address this phenomenon, but it presents an important avenue for future inquiry.

Additionally, the proposed methodology does not resolve the question of which comes first in co-location: the innovators or the installed capacities. In some cases, the emergence of innovation centers may drive the expansion of installed capacities in close proximity, as innovators seek to observe the practical outcomes of their work. Alternatively, the installation and operation of wind turbines may create the tacit knowledge environment that attracts innovation centers to the region. Furthermore, the study does not account for other potential factors influencing co-location, such as the institutional environment, which could also shape innovation patterns in wind energy.

The practical implications of this study lie in its ability to inform more effective innovation policies for the wind energy sector. The findings suggest that for industries like wind energy, where tacit knowledge plays a central role, a policy approach that reinforces local connections and builds on existing regional innovation systems (RIS) would be most effective. In particular, an ex-post approach, which strengthens existing development trajectories and focuses on the reinforcement of embedded RIS, would likely yield better results. In this context, the emphasis should not be on integrating governmental research centers into the established innovation structures, but rather on reinforcing intra-regional connections between key innovators and local suppliers, who carry critical tacit knowledge.

For regions like northwestern Germany, which lie between the innovation core and the periphery, specialized innovation growth based on embedded tacit knowledge could help establish thriving local innovation systems. This contrasts with broader, one-size-fits-all innovation policies that focus on generic factors such as increased R&D spending or human capital development. These generic approaches often overlook the importance of medium-sized regions, which may lack the critical mass of resources but can still play a key role in localized innovation.

As noted by Zemtsov and Baburin (2017), this is particularly relevant for Russia, characterized by a pronounced spatial polarization in its innovation potential. Our findings indicate that innovative development is also achievable in non-leading regions, creating opportunities for long-term innovation-driven growth in most of Russia, beyond the influence zones of the largest agglomerations. ■

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