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Gone with the Wind? An Assessment of Germany's Onshore Wind Industry Amid Rising Chinese Competition

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Abstract: This paper studies the relative competitiveness of Germany's onshore wind industry compared to China's and investigates whether an equally drastic value chain relocation, similar to Germany's solar PV industry, is likely. Based on a comprehensive study of Germany's domestic market, international competitiveness indicators like the world trade share (WTS), revealed comparative advantage (RCA), and relative export advantage (RXA), as well as an expert interview, we found that Germany's industry has lost competitiveness in recent years, supply chain shifts to China are observable, and Chinese manufacturers are poised to enter the German market. However, the German onshore wind industry is still competitive, has a strong basis in its domestic market, and, with the right energy policy framework, it could brace the storm. The novelty of this study is threefold: it offers a comprehensive comparison of the German and Chinese wind industries, presents the first analysis of the 2017 EEG reform's impact on Germany's wind industry, and is the first study to trace the evolution of domestic and foreign market shares in Germany's onshore wind market.

Keywords: onshore wind; energy transition; Chinese wind turbines competitiveness; industrial policy

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1. Introduction

The energy sector is responsible for approximately 75% of global greenhouse gas emissions and is thus a major driver of climate change [1]. The transition to green energy is, therefore, imperative to ensure sustainable development that reconciles social, economic, and environmental aspects and meets the needs of future generations [2,3].

At the forefront of this transition is the wind industry, which has become the most economically competitive source of renewable energy [4]. Germany has emerged as a leader in this sector, having invested early in its wind power market and the development of a strong domestic industry [5]. As a result, the country currently boasts an installed onshore wind capacity of 58.1 GW, accounting for 17.3% of its overall energy supply in 2022 [6,7]. For comparison, the installed global wind power capacity (on- and offshore) in 2022 was 906 GW, whereas in 2021, only 12.6% of the global energy consumption came from wind and solar PV [8]. Moreover, Germany's wind industry is recognized for its technological leadership on a global scale [9].

However, in recent years, the German wind industry has faced increasing economic pressure, compounded by increasing competition from China [10,11]. This competition has not only economic but also geopolitical implications, particularly in the context of the Ukraine war. Energy security is now defined not only by the availability, accessibility, acceptability, and affordability of energy but also by the secure access to green energy technologies [12]. The European Commission emphasizes that the resilience of future energy systems will depend on secure access to the technologies that power these systems [13]. This raises concerns about a potential substitution of the reliance on Russian gas with dependency on Chinese technology imports, a serious issue for policymakers. Such concerns are further amplified by Germany's previous experience of losing its leadership in the solar PV industry to China [14]. Consequently, pressing questions emerge: How competitive is the German onshore wind industry in the face of Chinese rivalry? And is it at risk of following the path of Germany's solar PV industry and relocating to China [15,16]?

These questions intersect with the broader theoretical debate on competitiveness and industry location within the renewable energy sector. In this context, the solar PV and wind industries have often been studied side by side because, although they were subject to similar policy support schemes, they have evolved very differently [17–21]. Despite acknowledging the dynamic nature of competitive advantages in the wind industry, recent studies on the topic from an economic point of view are scarce [4,22,23]. The most up-to-date research only covers 1995–2013, leaving it unclear whether domestic demand-side policies continue to create a sustained competitive advantage. Given the strong demand-side support in Germany, the current struggles of its wind industry suggest that these policies may no longer be as effective. Furthermore, the 2017 revision of the Renewable Energy Law (EEG) led to a wind energy expansion crisis, affecting the industry [6]. To the best of our knowledge, no research has examined how this crisis has impacted the industry's competitiveness, particularly in the context of Chinese rivalry.

Technology life-cycle theory posits that strong domestic demand enhances industry competitiveness and localization by fostering innovation through local learning [21,24]. This is supported by prior research by Lewis and Wiser [25]. Thus, Hypothesis 1 (H1) states that if domestic demand is strong, then Germany's wind industry is competitive both domestically and internationally. In a similar vein, the theory of Global Innovation Systems (GIS) highlights the industry's reliance on tacit knowledge from suppliers, the engineering know-how from local "legacy sectors", and user–producer interaction for innovation, suggesting it is less likely to relocate in the presence of domestic demand [19,26,27]. This leads to Hypothesis 2 (H2), which asserts that no strong signs of relocation for the German wind industry should be observable in the presence of domestic demand. However, increased price competition, the standardization of turbines, and the rise of international quality standards raise concerns about Germany's long-term competitiveness, leading to Hypothesis 3 (H3), which, according to the GIS framework, proposes a gradual decline in competitiveness over time [19,28].

This study employs a comprehensive data analysis of Germany's onshore wind power industry to evaluate these hypotheses, comparing domestic and international competitiveness indicators between Germany and China from 2000 to 2022. In line with previous research, data are sourced from specialized databases, such as "The Wind Power", UN Comtrade, and WTO Stats [24,29,30]. Additionally, an expert interview provides valuable qualitative insights. The results indicate notable trends in the competitiveness of the German and Chinese wind industries. While German manufacturers continuously dominate the domestic onshore market, with no Chinese turbines installed as of yet, China has steadily increased its world trade share (WTS) and specialization, thus narrowing the gap with Germany. Competitiveness indicators such as the WTS, revealed comparative advantage (RCA), and relative export advantage (RXA) show that although Germany remains strong, China's wind sector is catching up, aligning with H3 regarding intensified competitive pressure. In contrast to H1, the correlation analysis reveals a mildly negative relationship between domestic demand and competitiveness indicators, suggesting that strong domestic demand may have channeled production internally, thereby limiting export capacity. This effect was further compounded by instability from the 2017 EEG reform [30]. Expert insights highlight ongoing changes in the structure of the value chain, with anticipated pushes from Chinese suppliers due to their price advantages and technological advancements. Although immediate production relocation, especially for turbine manufacturers, seems unlikely, Chinese suppliers have been making strong inroads into the German market. Hence, consistent with H2, a comprehensive relocation of turbine manufacturers, similar to that of German solar PV producers, is not to be expected. However, concerning component suppliers, the picture is more nuanced, and policymakers should consider the increasing market share of Chinese competitors.

The novelty of this study is manifold: It is the first comprehensive analysis of Germany's onshore wind industry spanning from 2017 to 2022, capturing the impact of the 2017 EEG reform on the competitiveness of the German wind industry. Furthermore, in terms of the competitiveness indicators analyzed, it is the first study to directly compare the German and Chinese wind industries. Most importantly, it is the first study to analyze the wind market share evolution of domestic and foreign producers in Germany over time. Achieving success in domestic markets is crucial for securing a competitive position in the international wind industry, making this task highly significant [25].

The rest of this paper is structured as follows. Section 2 summarizes the relevant research on the topic and delineates the research gap in more detail. It also presents the theoretical frameworks for industry localization and competitiveness in the wind industry, derives hypotheses for analysis, and describes the research design. Section 3 presents and discusses the results, and Section 4 concludes this paper.

2. Materials and Methods

2.1. Research Gap

Political and scientific interest in the competitiveness of Germany's onshore wind industry is significant, with concerns that rising Chinese competition is considered an "existential threat" [31], potentially driving the industry toward "the abyss" [10,11,32], similar to the decline of the German solar PV sector [15,16]. This concern has been explored in the scientific literature focusing on competitiveness and industry localization in wind energy, with parallels drawn to the solar PV sector. Studying these two industries side by side is valuable both from a practical and a theoretical perspective. In practical terms, the re-conceptualization of energy security has given rise to a vested interest in maintaining strong renewable energy industries in Europe [12,13]. Therefore, Germany's struggling wind industry preoccupies policymakers, and the fate of Germany's solar PV industry is salient in the political debate [16,32]. From a theoretical viewpoint, the comparison of the two industries is compelling because both have received similar political support measures but have followed different trajectories. As will be elaborated in this subsection, the reasons for these disparate developments also have implications for competitiveness and industry relocation. This subsection provides an overview of the research and history of the German and Chinese solar PV and wind industries to contextualize the debate [17–21].

The literature highlights that demand-side policies are crucial for fostering domestic market formation and driving industry localization in the wind sector. Lewis and Wiser [25] showed that notable support policies are essential for achieving successful localization, with the Chinese wind industry being a prime example of growth induced by a policy-driven home market [33]. In contrast, solar PV sectors often develop without strong domestic demand, as noted by Groba and Cao [20], where the Chinese solar industry thrived internationally despite a limited home market. This divergence between solar PV and wind industries is supported by Huenteler et al. [24], who demonstrated that these sectors follow distinct technology life cycles. Solar PV, characterized by mass production, moves from product innovation to process optimization, while wind turbines, as complex goods, remain in a phase of continuous product innovation due to their intricate component structures. This complexity demands greater tacit knowledge and interaction between users and producers, making the wind industry more dependent on physical proximity to domestic markets, as opposed to the "footloose" nature of the solar PV sector, which more easily relocates to low-cost countries [19]. However, Binz and Truffer [19] challenged the static nature of these frameworks through their Global Innovation Systems (GIS) model, which emphasizes that an industry's position in terms of innovation and valuation is not fixed, but dynamic. Wind industries, once driven by performance improvements, are becoming standardized and price-driven, potentially leading to global competition rather than being confined to domestic markets. Studies by Menzel [30] and Dai et al. [34] reinforced this shift, highlighting the increasing commodification of wind turbines.

The implications for industry localization and competitiveness, especially in the case of Germany's wind sector, remain underexplored. While Germany has historically been a leader in wind energy, recent developments, including the 2017 EEG reform, have intensified competition from China and generated concerns about the sustainability of Germany's competitive edge [4,16]. Policymakers are wary that, much like the solar PV industry, the wind sector may relocate to China. Thus, this paper addresses the following key research question: How competitive is the German onshore wind industry in the face of rising Chinese competition, and what is the probability of it relocating to China? We analyze this considering the established relationship between domestic demand and competitiveness in the context of evolving global market dynamics.

2.2. The Development of the Onshore Wind and Solar PV Industries in Germany and China

2.2.1. Germany's Solar PV and Onshore Wind Industries

The historic development of the solar PV market was deeply influenced by policy, mainly due to its lack of competitiveness with fossil fuels in its early stages [35,36]. Germany's initial advantage stemmed from a combination of R&D support and demand-side initiatives, such as the 100,000 rooftops program and the EEG's feed-in tariff (FiT), which fueled rapid market growth and positioned Germany as a global leader in solar PV from 2000 to 2008. By 2007, Germany housed the world's largest solar cell manufacturer, Q-Cells, and held a 21% global market share [14,37]. However, German producers struggled to meet domestic demand and failed to cut costs, leaving them vulnerable. Chinese manufacturers, supported by favorable policies that enabled low-cost and high-volume production, capitalized on this weakness [38]. As a result, they filled supply gaps in the German market and outcompeted local firms, further helped by the lack of protectionist measures in Germany's subsidies. The 2008 financial crisis exacerbated the situation, with German firms unable to secure investments to remain competitive amid falling global prices. By the early 2010s, most German solar manufacturers, including Q-Cells, went bankrupt or were acquired by Chinese companies [37]. Critics argue that Germany's policies created a demand for solar PV but failed to establish a competitive domestic industry [39,40].

Germany's onshore wind industry evolved through four distinct phases, shaped by the interplay of policy, market dynamics, and industrial development. The first phase of technology exploration began in 1974, following the oil price shock. In response, the German Ministry for Research and Technology launched various R&D initiatives, culminating in the GROWIAN project of 1979. This ambitious attempt to build the world's first 3 MW onshore turbine, although later regarded as a failure, highlighted the significant technological gap between Germany and more advanced wind industries in the U.S. and Denmark [5]. Throughout the 1980s, smaller R&D programs were introduced to accelerate domestic technological advancements. The second phase, market and industry formation, was initiated in 1989 with the launch of the 100 MW (later 250 MW) subsidy program and the Electricity Feed-in Law. These policies, particularly the Feed-in Tariff (FiT), spurred rapid expansion in the wind energy market, propelling Germany to become the world's largest onshore wind market at the time [5]. Domestic manufacturers thrived, with 67% of the turbines subsidized under the program German-made, while the accompanying Scientific Measurement and Evaluation Program (WMEP) helped improve innovation and competitiveness. By the 1990s, the German wind industry, alongside Denmark, was a dominant force globally. With the introduction of the Renewable Energy Sources Act (EEG) in 2000, Germany entered a period of steady market and industry growth in the third phase. Despite more restrictive zoning laws slowing the pace of capacity expansion, the country's onshore wind capacity still grew by an average of 2.72 GW annually between 2000 and 2017. During this period, the industry's domestic market share reached up to 70%, and exports accounted for approximately 70% of production, cementing Germany's reputation as a key player in the global wind sector [30]. However, the industry faced a sharp downturn in the fourth phase following the 2017 EEG reform, which introduced a competitive auction system. Wind park developers were now required to win public tenders, with bids often being won by those demanding the least subsidies, thus intensifying price competition [30]. The initial low auction volumes signaled a slowdown in market growth, leading to a significant drop in capacity expansion, averaging just 1.7 GW annually from 2018 to 2022 [6]. Furthermore, bureaucratic permitting processes and zoning restrictions hindered new project developments [1]. As a result, high production capacity met dwindling domestic demand, leading to industry consolidation. By 2021, the number of German turbine manufacturers had plummeted from 14 in 2014 to only 3, with their global market share shrinking accordingly [30].

The introduction of a public tender system has drastically reduced demand for new turbines, with a 62% drop in capacity increases [41]. Additionally, the slow designation of wind park zones and lengthy, bureaucratic permitting processes have further stunted growth [1,42]. Low subsidies under the new EEG, especially given rising production costs, have made many projects unprofitable, leaving some permitted projects unimplemented [11]. This imbalance between supply and demand has created intense price pressure, with many manufacturers operating below capacity and at a loss [43]. Exporting turbines is also difficult due to local content regulations in other countries. Rising production costs, driven by supply chain disruptions, the Ukraine war, and inflation, have worsened the situation, as manufacturers struggle to fulfill old orders placed at lower prices [44,45]. The result has been job losses, with employment dropping from 160,000 to 100,000 between 2016 and 2020, and a shift in value chains, especially in rotor blade production, which ceased in Germany in 2017 [9].

2.2.2. China's Onshore Wind Industry

China's wind industry development resembles Germany's, with four distinct phases. The first phase (1986–1994) saw early demonstrations and technology transfer, beginning with the Malan Wind Farm, which relied entirely on imported turbines [34,46]. The second phase (1995–2004) involved the introduction of industrial exploration, spurred by the 863 program and public funding. Domestic producers emerged but relied on technology transfers, particularly from German companies [5,47]. The third phase (2005–2011) was marked by rapid expansion, driven by local content guidelines and the 2005 Renewable Energy Law. The Chinese wind market grew exponentially, and domestic manufacturing surged, reducing imports from 75% in 2004 to 12% by 2010. The fourth phase (2012–2020) saw overcapacity, curtailments, and efforts to stabilize the industry, alongside international expansion, such as Goldwind's acquisition of Germany's Vensys [21]. The fifth phase (2021-present) is characterized by grid parity and a shift toward sustainable development [46].

China leads the world in onshore wind capacity with 335 GW in 2022, the highest growth rate, and the largest turbine industry globally [46,48]. Nine of the top fifteen turbine manufacturers are Chinese [16]. However, this dominance is largely due to its vast domestic market, where imported turbines made up just 4.2% of the total in 2018. Historically, Chinese turbines struggled internationally due to outdated technology, high failure rates, reliability issues, and a lack of certification [34,49,50]. In 2018, only 1.8% of China's turbines were exported, mostly to countries without strong wind industries [49]. However, this is now changing for two reasons: intense domestic competition is pushing Chinese manufacturers abroad, and Chinese technology has advanced significantly, with MingYang and Sany launching world-leading turbines [51,52]. While Chinese firms still lag in software-driven innovations, such as smart turbines that adjust to grid load and predict failures, their global presence is growing [34]. Sany, for example, has announced Germany as its top priority for European expansion [52].

2.3. Theoretical Framework and Hypotheses

The preceding sections highlight divergent perspectives within the literature concerning industry location and competitiveness. To clarify these issues and address the research questions, this subsection derives competing hypotheses grounded in the technology life-cycle theory and Geographic Innovation Systems (GIS) literature. These hypotheses are subsequently analyzed in the empirical sections.

2.3.1. Technology Life-Cycle Theory and Hypothesis 1

Technology life-cycle theory links demand-side policies and domestic markets to industry localization and competitiveness in the wind sector. This relationship is influenced by the technological complexity of wind turbines, which shapes learning and innovation processes. Figure 1 illustrates this mechanism.

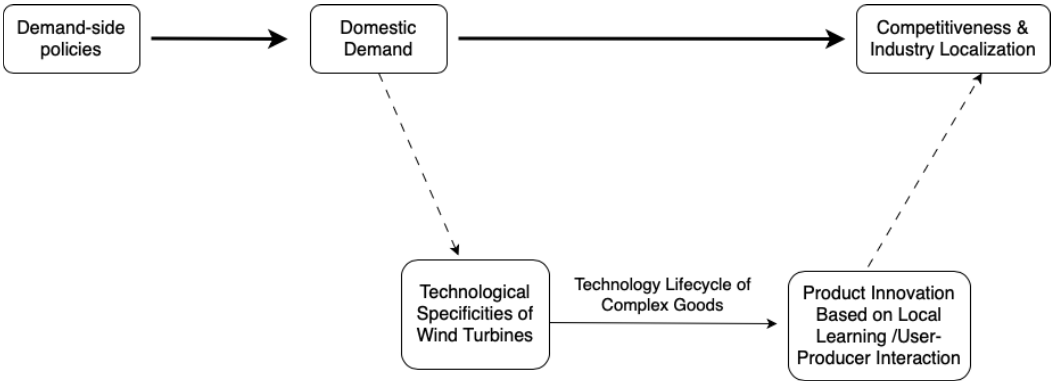

Figure 1. The mechanism between domestic demand and innovation in the wind industry. Adapted from [18,21,24].

The theory suggests that domestic demand impacts localization and competitiveness through innovation, driven by wind turbines' complexity. With about 8000 components, system imbalances caused by improvements in one part often require further adjustments [24,29]. The proximity between operators and manufacturers is crucial for addressing these issues through user-producer interactions [21].

Studies have confirmed that a strong domestic market is essential for successful localization and correlates with industrial competitiveness [4,21,25]. Accordingly, we propose the following hypothesis:

Hypothesis 1. *If domestic demand is strong, Germany's wind industry will be competitive both domestically and internationally.*

2.3.2. GIS Theory and Hypotheses 2 and 3

GIS theory accommodates the dynamic nature of the wind industry, offering insights into Germany's competitiveness and potential relocation risks.

An industry's GIS configuration depends on its innovation and valuation modes. In science and technology (STI)-driven industries like solar PV, innovation is based on codifiable knowledge, enabling easy international transfer and making production relocation more feasible. In contrast, the wind industry, which relies on complex engineering and tacit knowledge from sectors like shipbuilding and metalworking, is innovation-driven by "learning by doing, using, and interacting (DUI)". This territorial embedding makes the industry "spatially sticky" and less likely to relocate [19].

Valuation modes also differ. Standardized products like solar panels compete on price in global markets, while wind turbines must adapt to local conditions, relying on trust and regional networks [19]. Though wind turbines have become more commodified and price-driven over time [34], local adaptation remains key.

Thus, we formulate the following two hypotheses:

Hypothesis 2. *Industry relocation is unlikely.*

Hypothesis 3. *A gradual decline in competitiveness is observable over time.*

2.4. Research Design

This study evaluates the hypotheses through a comprehensive data analysis of the German wind power market, alongside a comparison of competitiveness indicators between Germany and China. The findings are supported by expert interviews and a literature review of the wind sectors in both countries.

2.4.1. Data

The cross-sectoral nature of the wind industry makes comprehensive statistics rare [9]. To address this, data are sourced from specialized databases like "The Wind Power", UN Comtrade, and WTO Stats [29,30,53]. An overview of the studied variables is given in Table 1.

The data from [54] contain comprehensive information on Germany's domestic market for onshore wind power. For each wind park, it lists the capacity in MW, the turbine manufacturer, the year of commissioning, and, if applicable, the year of decommissioning. Combined with data from the same source about manufacturer countries, it is used to track market share trends by manufacturer country in Germany and proxy demand-side policies. Countries with historically large (Denmark, Germany, and the U.S.) or recently increasing market shares (India) are explicitly listed, whereas the rest are summarized in the category "Rest of the World". Turbines by Siemens-Gamesa also fall under this category, as their headquarters are in Spain [30]. Missing values and offshore parks are excluded. With 209 out of 11,574 observations (1.8%) or 415.39 MW (0.7%) of total capacity, this concerns a negligible amount of data points. The creation of separate datasets for each year (2000–2022) enables visualization of market share trends. Data on annual market growth, impacted by missing values, were supplemented manually.

For the international competitiveness indicators, export/import data on wind power technology (HS code 850231) were taken from Comtrade [55] for Germany, China, and the global market. Due to the wind industry's cross-sectoral nature, this HS category does not capture all of the exports/imports related to wind power technology. However, it is the only category that can be assigned to turbines and contains transportable components, making it suitable for the study of exports and imports. Furthermore, this code is the most reliable and frequently cited source [35,53]. In line with the literature, data from WTO Stats (2023) were used for information on the manufacturing exports/imports of Germany, China, and the global manufacturing market [29] (Table 1).

Table 1. Variables in the German wind power market dataset.

Variable	Explanation
ID	Identifies each wind park
Manufacturer	Turbine manufacturer
Total Power	Total electricity production capacity in kW
Commissioning Date	Year the wind park was connected to the grid
Decommissioning Date	Year the wind park was shut down (if applicable)
Offshore Distance	Distance from shore (if applicable); otherwise, set to "No"
Manufacturer Country	Country of turbine manufacturer (Germany, China, U.S., India, or Rest of the World)
Year of Observation	Year of market share observation
Annual Market Growth	Growth in installed capacity in Germany each year

2.4.2. Operationalization

To test the hypotheses, competitiveness and demand-side policies need to be operationalized. As the data lack proxies for industry relocation, this aspect is explored through an expert interview.

Kuik et al. [4] defined competitiveness as the capacity to effectively sell products and maintain a strong standing in international arenas. Although direct measurement is challenging, outcomes such as market shares and export advantages can be assessed. This study compares competitiveness indicators for Germany and China's onshore wind industries, including their world trade share (WTS, 2000–2022), market share in Germany (1997–2022), revealed comparative advantage (RCA), and relative export advantage (RXA) [29,35,53].

The **world trade share (WTS)** measures a country's share of worldwide exports of wind power technology in a given year. It ranges from 0 to 1 and is calculated by dividing a country's wind power technology exports by total global exports. j indexes the product groups within the manufacturing industry and i indexes the country:

$$\mathrm{WTS}_{i,j} = \frac{a_{i,j}}{\sum_i a_{i,j}}$$

where $a_{i,j}$ = the exports from country i in product group j and $\sum_i a_{i,j}$ = the exports across countries in product group j.

The **relative export advantage (RXA)** measures the export specialization of wind power-related technology in a given year. It is defined as the ratio of a country's wind power-related exports to worldwide exports in this product category, divided by the ratio of the country's manufacturing exports to global manufacturing exports:

$$\mathrm{RXA}_{i,j} = 100 \cdot \tanh\left(\ln\left(\frac{(a_{i,j}/\sum_i a_{i,j})}{(\sum_j a_{i,j}/\sum_{i,j} a_{i,j})}\right)\right)$$

where $a_{i,j}$ = the exports from country i in product group j; $\sum_i a_{i,j}$ = the exports of all countries i in product group j; $\sum_j a_{i,j}$ = the exports of country i across all product groups j; and $\sum_{i,j} a_{i,j}$ = the total exports across countries and product groups.

The **revealed comparative advantage (RCA)** shows whether domestic wind power technology is more successful in the international market than foreign wind power technology is in the domestic market in a given year. It does so by dividing the ratio of a country's wind power exports to imports by its manufacturing exports to imports:

$$\mathrm{RCA}_{i,j} = 100 \cdot \tanh\left(\ln\left(\frac{(a_{i,j}/e_{i,j})}{(\sum_j a_{i,j}/\sum_j e_{i,j})}\right)\right)$$

where $a_{i,j}$ = the exports from country i in product group j; $e_{i,j}$ = the imports of country i in product group j; $\sum_j a_{i,j}$ = the total exports of country i across all product groups j; and $\sum_j e_{i,j}$ = the total imports of country i across all product groups j.

Both the RXA and RCA are normalized on a scale from -100 to 100, with values above 0 indicating a competitive advantage [35].

Demand-side policies are proxied by the annual increase in installed capacity (MW). This follows the approach of Dechezleprêtre and Glachant [56], which ensures validity via the strong correlation of 0.98 between capacity and generation for OECD countries. Competitiveness indicators are then correlated with annual domestic installations using Kendall's Tau to test H1.

2.4.3. Expert Interview

To enhance the data analysis and explore industry relocation prospects, an expert interview was conducted. Requests were sent to turbine manufacturers, suppliers, industry associations, and think tanks, among which only one positive response was received. Although the number of interviews is a clear limitation of this study, we nonetheless believe that the interview provides a valuable contribution, as it provides context for the quantitative analysis. Furthermore, the expert was a spokesperson from a leading industry association in which all major turbine producers and suppliers are organized. As such, they not only had intimate knowledge of the industry but also a broad understanding of the regulatory framework, which is key for this study. The semi-structured and object-centered format of the interview offered several advantages. Semi-structured interviews provide depth and new insights by allowing open-ended responses. Fully structured questions might not capture the experts' extensive knowledge, and the object-centered approach ensures relevance and focus [57].

The interview guidelines, developed following recent literature, were organized into topic-based blocks [58]. Each block started with a general question followed by specific ones. The guidelines allowed for some flexibility to clarify and deepen responses. To ensure scientific quality, questions were designed based on Diekmann's and Lehmann's criteria [58,59]. They were (1) short, precise, and unambiguous; (2) free from normative or polarizing language; (3) non-suggestive; (4) focused on a single topic; (5) relevant to the expert's knowledge; and (6) avoided potentially embarrassing content.

The guidelines were crafted to keep the interview under one hour, considering the typical human attention span [57,58]. The interview was recorded with the participant's consent and transcribed for analysis. The guidelines and transcript can be found in Appendix A.

3. Results

3.1. Discussion

3.1.1. Data Analysis

The analysis of the WTS, RCA, and RXA only approximates the development of competitiveness in the Chinese and German wind industries, as only one wind power product group was analyzed. Despite current political concerns, no Chinese turbines were identified in the German onshore market. Instead, German manufacturers dominated the domestic market throughout the study period and even expanded their market share in recent years (see Figure 2). Although their share declined from 60.3% in 1998 to a low of 52.5% in 2003, this was primarily due to market growth requiring more imports, as seen in the U.S. market's share increasing from 1.8% to 11.7% in the same period. Since then, German manufacturers have strengthened their position, with their market share rising to 64.6% in 2022. Danish producers' market share declined from 40.6% in 1997 to 27.5% in 2018, while U.S. producers' share also decreased after peaking at 11.7% in 2003, stabilizing at 6.3% in 2013. Indian producers and other nations remained insignificant throughout the study period. Thus, German turbine manufacturers have excelled in the domestic market, with no sign of Chinese competition as of yet.

These trends suggest that, consistent with H2, Germany continues to maintain its domestic strength. However, with Chinese turbines still absent from the German market, the competitive pressure appears to be more of a future concern than a current reality.

In the global market, the picture is more nuanced (see Figure 3). Germany's share of wind power technology exports fell to 1.9% in 2002 but rose steadily to 38.4% in 2008. Strong fluctuations followed, ranging from 42.4% in 2012 to 23.4% in 2017. These fluctuations are partly attributed to data accuracy issues. Since the same export data for wind power-related goods were also used to calculate the RXA and RCA, these considerations and caveats also apply to the fluctuations and divergences observed there. However, after 2017, Germany's WTS stabilized, fluctuating between 29% and 35%, reaching 31.2% in 2022. China, which had a WTS of less than 1% until 2006, continuously increased its share, reaching 19% in 2022. The WTS trends of Germany and China showed convergence over the observed period. Additionally, a regression with Germany's WTS as a dependent variable and China's WTS as an independent variable was run. With a coefficient of 0.89 and a p-value of 0.029, the relationship was positive and statistically significant. This means that if China's WTS grows, so does Germany's. But as the coefficient was >1, this means that Germany's WTS grew less strongly than China's, confirming the notion that they are converging.

The convergence in the WTS supports H2, indicating increasing competition from China in global markets. Furthermore, the data show that both countries are increasingly competitive internationally, confirming that China has made considerable strides in catching up.

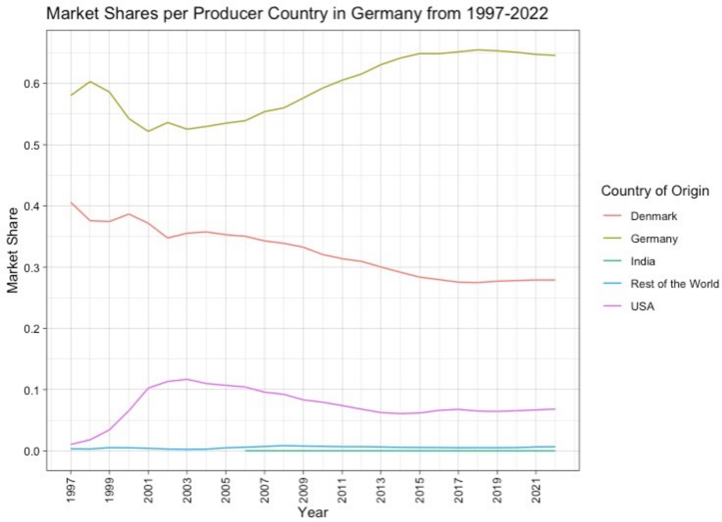

Figure 2. Market shares of relevant producer countries in Germany, 1997–2022.

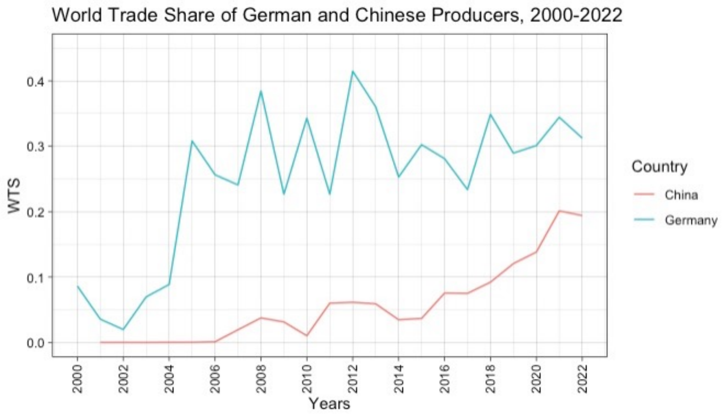

Figure 3. World trade share of China and Germany for wind power-related goods (HS code 850231), 2000–2022.

Germany's RXA showed a strong increase in export specialization for wind power-related goods compared to its general manufacturing industry between 2000 and 2005 (see Figure 4). Initially negative, it rose from a low of −94.2 in 2002 to 75 by 2005 and has remained positive, fluctuating between 59.1 and 86.0. In contrast, China's RXA was negative throughout the period. However, this needs to be interpreted in the context of China's overall dominance in the manufacturing industry, as the RXA measures the wind industry's relative export specialization compared to the overall manufacturing sector, not its absolute export strength. Nevertheless, the continuous improvement in China's RXA, which neared zero in recent years, indicates that China's wind industry is increasingly gaining strength within the export sector. While Germany has retained its export advantage, China's gradual progress is notable.

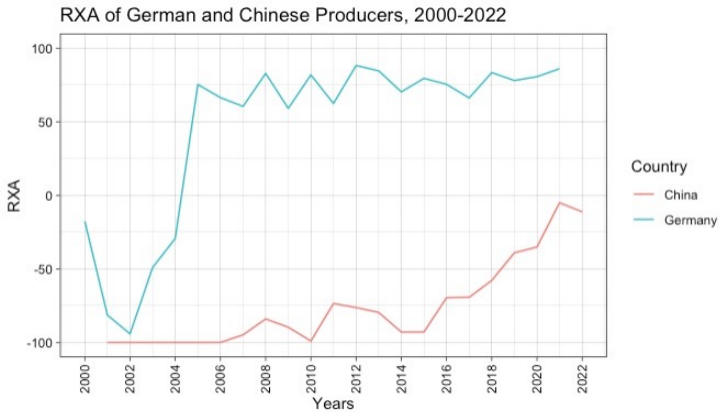

Figure 4. Relative export advantage of Chinese and German producers, 2000–2022.

Germany's RCA also developed positively, with greater fluctuations than its RXA (see Figure 5). After rising from −99.8 in 2002 to 97.4 in 2012, the RCA fluctuated greatly, peaking at 97.4 in 2012 and then falling to 50.9 in 2018, while remaining strongly positive. China's RCA grew sharply after 2007 and, with a few exceptions, stayed close to 100, surpassing Germany's RCA from 2009 to 2019. This indicates that China has become a strong competitor in export markets and supports the convergence identified in H2.

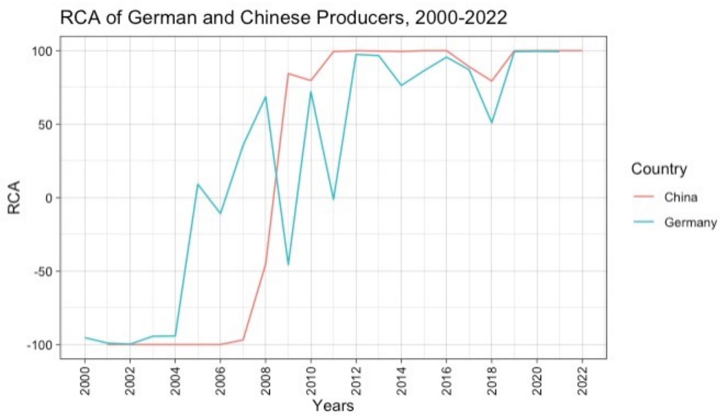

Figure 5. Revealed comparative advantage of Chinese and German producers, 2000–2022.

The correlation analysis indicates that, contrary to earlier literature, domestic demand-side policies have a mildly negative correlation with all competitiveness indicators for the German wind industry (see Table 2). The WTS correlation is more negative than others, likely due to peaks in domestic demand crowding out exports and limiting market share expansion. This finding challenges the first hypothesis (H1), which suggested that domestic demand would enhance competitiveness. Instead, the negative correlation aligns with more recent literature, suggesting that high domestic demand can hinder exports due to capacity being directed inward. Additionally, the 2017 EEG reform likely disrupted stable demand, creating uncertainty for manufacturers and reducing export focus.

Table 2. Correlation between domestic demand-side policies and competitiveness indicators for the German wind industry.

Competitiveness Indicator	Kendall's Tau
Domestic Market Share	−0.019
WTS	−0.158
RCA	−0.063
RXA	−0.095

3.1.2. Expert Interview

The expert interview provided additional insights into the challenges facing Germany's wind industry. According to the expert, the economic situation is strained, with manufacturers operating at a loss, especially after the 2017 EEG reform, which led to a drastic decline in demand. As a result, production is below capacity, and companies face significant losses. The expert highlighted how the long lead times for turbine production exacerbate the problem, as orders fulfilled now were placed when prices were much lower, and costs have since increased due to inflation, the energy crisis, and supply chain disruptions from the COVID-19 pandemic.

The expert also noted value chain shifts, including the cessation of rotor blade production in Germany in 2017. Components are increasingly sourced from Asia, with 50–60% of parts now coming from there or often from non-European suppliers who benefit from cost advantages and privileged access to raw materials.

Regarding Chinese competition, the expert emphasized that, although Chinese turbines have not yet entered the German market, it is only a matter of time. Chinese turbines are cheaper, with price advantages of 30–50%, and their quality is comparable to European products. Indicators of this growing competitive pressure include the presence of a major Chinese manufacturer at the prestigious "Husum Wind" fair in Germany and several projects with Chinese turbines planned in Europe. The expert concluded that the future competitiveness of Germany's wind industry will depend on the political framework and clear support signals from policymakers, consistent with H2's projection of rising competitive pressure from China.

Amid the Ukraine war and shifting global energy priorities, green energy, particularly wind, is increasingly vital for energy security [13]. Germany's wind industry plays a key role, but China's growing influence presents a competitive challenge.

3.1.3. Results Outlook

The results highlight key trends in the competitiveness of the German and Chinese wind industries. In Germany, domestic manufacturers dominate the onshore market, with no Chinese turbines installed. Meanwhile, China has steadily increased its global wind power exports, narrowing the gap with Germany. Competitiveness indicators like the world trade share (WTS), revealed comparative advantage (RCA), and relative export advantage (RXA) show that China is catching up, supporting the second hypothesis (H2) that China's competitive pressure is growing, although it has not eroded Germany's leadership through price competition. Contrary to the first hypothesis (H1), which expected higher domestic demand to boost Germany's wind industry competitiveness, the correlation analysis showed a mildly negative relationship between domestic demand and competitiveness (WTS, RCA, and RXA). Increased domestic demand could limit export capacity, compounded by policy instability following the 2017 EEG reform. Thus, H1 is not supported. The expert interview revealed economic challenges in Germany's wind industry, including cost pressures and value chain shifts due to the 2017 EEG reform. While Chinese turbines have not yet entered the German market, they are expected to increase competition. This supports the third hypothesis (H3), although concerns about Germany's wind industry following the fate of its solar sector have not materialized due to high transport costs and local expertise reliance.

4. Conclusions

This study compares the competitiveness of the German and Chinese onshore wind power industries from 2000 to 2022. While Germany maintains strong domestic performance—with a high world trade share (WTS) and revealed comparative advantage (RCA)—China is closing the gap. Chinese manufacturers, although not yet present in Germany's turbine market, already supply 50–60% of components from Asia, signaling increasing competition. China's participation in events like Husum Wind further underscores its ambition and growing influence in the global wind industry.

Our findings reveal that domestic demand in Germany negatively correlates with competitiveness, likely due to industry maturation and the destabilizing effects of the 2017 EEG reform. While Germany still holds a strong domestic position, suppliers are pressured by Asian imports, and internal issues such as low production volumes, insufficient tender volumes, and planning delays pose significant challenges.

From a practical perspective, the wind industry is unlikely to relocate to China as the solar PV sector did due to high transport costs and the need for local expertise. However, Chinese manufacturers are eyeing the German market, and their growing influence abroad should be the focus of policymakers.

While concerns about relocation may be overstated, Germany's wind future will depend on policy efforts to boost domestic demand, reform tender processes, and strengthen competitiveness. Proactive measures are needed to address internal inefficiencies and adapt to evolving global dynamics. As China continues to advance, Germany must take strategic actions to sustain its leadership in the wind sector, ensuring energy security and contributing to the global transition to green energy.

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Appendix A. Interview Guidelines

Block 1: Introductory Questions/General Situation:

1. What is your area of responsibility, and how are you involved with wind energy?
2. The current market environment is characterized by inflation and price pressure. Recently, there have also been some factory closures and significant losses for manufacturers. How do you assess the current economic situation of German onshore turbine manufacturers in light of these developments?
3. How do you evaluate the situation of German supplier companies?

Block 2: Impact of the 2017 Renewable Energy Act (EEG) Amendment on the Competitive Situation in the Domestic Market (Expansion Goals & Price Pressure):

1. The 2017 EEG amendment, particularly the introduction of the auction system, has significantly changed the German wind energy market. For example, the expansion rates in the onshore sector have dropped considerably. What impact has this decline had on the economic situation of German manufacturers and suppliers?
2. In the auction system introduced by the 2017 EEG, price is the decisive factor. Price and competitive pressure in the German onshore market have increased significantly. How does this affect the competitive position of German turbine manufacturers in the domestic market, especially regarding more affordable foreign competitors?
    (a) What are the implications for the supplier industry? Is there evidence of increased reliance on cheaper components from abroad?

3. According to current EEG expansion targets, approximately 10 GW of onshore wind energy needs to be installed annually. Does the German wind industry, especially considering the low expansion rates in recent years, have the production capacity to meet this demand? Or could there be a gap between supply and demand that is increasingly filled by foreign producers?
    (a) If so, would the competitors more likely be established manufacturers from the USA and Denmark, or producers from China or India?

Block 3: Competition from China:

1. How would you assess the competitiveness of Chinese onshore turbine manufacturers compared to German manufacturers in terms of quality and price?
2. What is the approximate cost difference between Chinese and German onshore turbines?
3. In the wind energy sector, software innovations for fault prediction, operational optimization, and wildlife conservation (e.g., BirdVision) are becoming increasingly important: "You don't make money by just selling commodities." How important is digital innovation in the onshore wind energy sector, and how well are German manufacturers positioned compared to Chinese competitors?

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