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# International Diffusion of Renewable Energy Innovations: Lessons from the Lead Markets for Wind Power in China, Germany and USA

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**Abstract:** The international diffusion of environmental innovations is getting increasing attention as an opportunity to improve competitiveness. Especially in the energy sector, countries use policy support to this end. A recent goal in this context is the formation of "lead markets", which represents the idea that countries can build up first-mover advantages that will increase their competitiveness. Taking the lead in international diffusion of a particular innovation benefits a country's industry through creating increasing returns of technological development and stimulating exports to expanding international markets. Interaction between national and international forces affecting renewable energy innovation and its diffusion has received fairly little attention so far. Here, we investigate the formation of lead markets for wind power technologies in China, Germany and the USA to see whether policy support of renewable energy innovation is capable of improving competitiveness. An extension of the current lead market framework is developed to include supply side factors and technology policy issues. The comparative analysis of lead market potential for wind power indicates a high level of internationalization of the industry with countries holding lead positions in specific parts the supply chain. Competitive advantages were built upon policy support but tended to shift among countries.

**Keywords:** climate change; competitiveness; renewable energy; policy support

## 1. Introduction

Climate change is pushing a transition towards a new energetic system. Since energy use is responsible for about 83% of global anthropogenic greenhouse-gas emissions [1], current patterns of energy production and consumption have to be transformed to avoid dangerous climate change. Driven by technological change in energy sources and use, a transition to a new energetic system requires environmental innovations to take place in a particular pace and direction.

One issue that has not received very much attention is the potential interaction between international and national forces promoting renewable energy technologies. The strong international dynamics of energy markets, not limited by national boundaries, contrasts with policy support in the form of technology policies (e.g., subsidies) and environmental regulation coming mainly from domestic authorities. At the same time, policy to foster innovation in renewable energy technologies is increasingly being framed as serving multiple goals [2–5]. It is expected to not only spur innovation and increase national welfare (through contributing to energy security and affordability, and employment) but also to help conquer a leading position in the global market for renewable energy technologies.

In the last five years, China, the EU15, Japan and USA have all implemented policies aimed at achieving leadership in green technologies [6–8]. The idea is that through environmental and technology policy countries can gather first-mover advantages that will increase their competitiveness. In this case, a country takes the lead in the international diffusion of a particular innovation, benefiting from increasing returns of technological development, economies of scale and exports to expanding international markets. Yet, the factors that affect the potential of policy to improve competitiveness through renewable energy innovation are still poorly understood [3].

Environmental innovation in the energy sector has been historically focused on large-scale supply-side technologies, such as hydro and nuclear power, which concentrate up to 80% of global annual investments in 2011 [9]. Among all supply-side technologies, wind power stands out as one of the most promising by its low environmental impact, fast pace of growth and potential for cost reduction [9–11]. Wind power technologies are already widely diffused and considered mature: they have become price-competitive with traditional fossil-fuel energy sources in specific settings; and subsidies for these technologies are already planned to be phased out in several countries [12,13]. Wind power was responsible for 2.6% of global electricity generation in 2012, and saw its installed capacity grow at an average rate of 24% per year in this last decade [10]. But further growth is required since wind power is expected to provide 15% to 18% of the necessary $CO_2$ reductions in the electricity sector by 2050 [1]. This explains the call for a rapid scaling up of annual installations and investment: from 45 GW in 2012 to 65 GW in 2020, 90 GW by 2030 and 104 GW in 2050, with annual investments going up to USD 170 billion [1].

This study contributes to the conceptual and empirical discussion on whether policy support to renewable energy innovation is capable of improving competitiveness. We examine the formation of lead markets regarding wind power technologies in China, Germany and USA, the three countries with larger installed capacity. For this purpose, we apply and extend the "lead market" approach from Beise and Rennings [14]. The extension aims at analysing supply side factors and policy instruments that address particular aspects of renewable energy innovations. Our analysis has two objectives: to understand how countries' specific contexts and policy responses have affected the development of wind power industries; and to examine the impact of interactions among the three countries with respect to the diffusion of wind power technologies. Whether lead markets were actually formed and have created competitive advantages at the country level are the questions that guide our research. In this way, we intend to contribute to the literature on environmental innovation and sustainability transition studies, in line with the recent calls for addressing spatial factors [15–17].

The remainder of this paper is organized as follows: Section 2 presents the lead market approach, proposes extensions of this framework, and discusses its application to renewable energy innovation. Section 3 uses these indicators to analyse the development of lead markets in the wind power industry. Section 4 discusses the results and derives policy implications. Section 5 concludes the paper.

## 2. Lead Markets for Renewable Energy Innovations

The study of renewable energy has recently received much attention from a new angle in the emerging literature on environmental innovation and sustainability transitions. This approach aims to address social, institutional, political and economic considerations in an integrated manner (for different views, see [18–20]). Two dominant conceptual frameworks here are technological innovation systems (TIS) and the multi-level perspective (MLP). Both of these have, however, been criticized for neglecting, or giving little attention to, the geographical dimension of transition processes [16,21,22]. Considering the global scale of the transition needed, it is relevant to understand the geographic unevenness of innovation processes so that privileged positions and their consequences are better explored. Whether countries or regions can achieve advantages of scale and scope and lead innovation through sheer size, localized concentrations of knowledge and capabilities or other intangible spillover effects is still unclear [16]. The recently developed lead market approach by Beise and Rennings [14] offers an important entry-point for filling this gap since it pays explicit attention to the spatial dimension of technology diffusion. Moreover, it considers the implications of geographic aspects on environmental innovation in tandem with international competition [23].

Taking the concept of dominant design [24] as its central theoretical underpinning, a lead market is defined as the market in which the diffusion of a dominant design first takes place. Following the tradition of innovation studies, dominant design here refers to the mechanism that, by creating standardization, leads competition to take place on the basis of cost, scale and product performance [24]. In the case of wind power technologies, this means that competition is based upon performances in terms of cost (such as costs of inputs and manufacturing process), scale (output increase along the supply chain) and power generation capacity (such as wind turbines, blades and tower sizes and power control mechanisms). The idea is that local preferences and environmental conditions in a specific geographic area favour the development of an innovation design that ultimately may become internationally dominant [14]. The lead market is identified by certain attributes of a geographic area where an innovation has been first broadly adopted, rather than where an innovation was first invented. It emphasizes that technological change is determined not only by sectoral dynamics but also by distribution of innovative activities in different geographic areas [23].

The introduction of a dominant design tends to shift the direction and rate of further technological change [25]. After the selection of a dominant design, the competitive emphasis begins to move towards cost, scale and product performance. The market reaches a point of stability in which products are standardized, or slightly differentiated, and radical innovations from within an industry are less likely to occur due to higher barriers to new entrants and decreasing competition [25]. The early adoption of an innovation can generate learning benefits and economies of scale that are supplemented by a reduction of risk in the investment necessary to perform R&D for innovation. Thus the advantage of setting up a dominant design, as it can build up a competitive advantage to explore international markets and establish technological standards thereby creating a lead market position. As a result, a country would enjoy a first-mover advantage in terms of technology adoption. As such, it benefits from, for example, putting its firms in the forefront of learning curves and market development [14].

In the case of renewable energy innovations, the formation of lead markets is intrinsically related to policy since such economically unlogical innovations critically depend on incentives provided by well-designed environmental and technology policies [4,5,26]. For the international diffusion of renewable energy in particular, the role of policy is even more critical. Because renewable energy sources offer no additional benefits in terms of cost, quality or functionality, their international diffusion has been typically preceded by the international diffusion of the regulation, which induced the original innovation underlying the lead market [14,27]. Lead markets are thus built upon a "regulatory advantage" [28], where the international adoption of a country's environmental regulation paves the way for the diffusion of an innovation. Hence, the interest from policy makers in establishing lead markets in sectors with a strong potential of becoming a technology supplier [6,29]. Within this perspective, the lead market concept is extended to embrace also lead supply [23,30]. The idea is that a lead market represents a competitive advantage built upon a dominant role in both innovation and international markets development [31].

Lead markets can be identified by considering particular country-specific indicators that capture the likelihood that a design which first diffused domestically becomes globally adopted. According to the literature, these characteristics can be analysed through so-called lead market factors. Here, we extend the framework with lead market factors as developed in previous studies to address the idiosyncrasies and challenges specific to the international diffusion of low-carbon energy technologies. As discussed below, our framework is based on a set of five lead market factors: demand and supply side of domestic market, policy mix, technological capability and market structure [14,23,30–33].

### *2.1. Demand Side of Domestic Market*

The demand side of a domestic market relates to price and demand advantages. Price advantages come from a relatively low price of one innovation design and are mostly based on economies of scale. These depend on market size and rate of market growth. Countries with rapid market growth can be earlier adopters because the cost of new technology is lower than that of late-comers when the production capacity is extended compared to production process of incumbent technologies. Moreover, faster growth lowers the risk of producers making full use of new investments [32]. Additional sources of price advantage are lower costs of input factors and complementary goods. The price advantage can be considered one of the most significant lead market advantages since large reductions in input cost and prices have played a key role in the global diffusion of many innovations.

The demand advantage refers to a country's market characteristics that improve the demand for an innovation and can be reproduced by other countries later on. Market trends in technological, economical, social and environmental areas serve as an advantage whenever increasing the perceived benefit from an innovation [34]. Policy can affect the shaping of demand advantages in the case of renewable energy innovation. For example, previous research indicates acceleration on the rate of innovation diffusion in the countries that signed the Kyoto protocol [35].

### *2.2. Supply Side of Domestic Market*

The supply side of the market covers demonstration and export advantages. Demonstration advantages are based on a trial effect which extends beyond national borders [32]. Somewhat at odds with the concept of technological transfer traditionally present in innovation studies, demonstration advantages indicate the ability of a country to successfully deploy a new technology and share information about it, thus reducing uncertainty about its initial adoption by firms or consumers in other countries [14]. Sharing of information on the usability and reliability of the innovation design increases the perceived benefits from an innovation for later adopters, including those in other countries. For environmental innovations, for example, data about emissions reduction and implementation schemes are valuable inputs to build interest in foreign countries about the adoption of more restrictive environmental policies. The export advantage refers to a country's ability to respond to consumer needs in other countries [14]. Exports of environmental innovations are fostered, for example, by: similarity with foreign markets in terms of regulation [36], conditions of use [32], and degree of export orientation in a region or country (e.g., local incentives to develop exportable products, internationalization of domestic companies, foreign domestic investment).

### *2.3. Policy Mix*

Here we extend the regulatory advantage as defined in previous studies (e.g., [14,30–33]), to consider the policy mix to support diffusion of renewable energy innovations. Since there is consensus that optimal policies to support environmental energy innovation should combine environmental regulation and technology policy (e.g., [4,5,26]), the analysis here goes beyond the early focus of the lead market approach on environmental regulation to embrace elements of technology policy. Environmental regulation focuses on creating incentives to reduce potentially harmful consequences of economic activities (*i.e.*, environmental externalities), seeking to foster diffusion of environmental friendly technologies. Technology policy, on the other hand, focuses on keeping expensive but promising technological options open and stimulating their innovation through public support for knowledge creation, including public R&D, subsidizing private R&D and stimulating diffusion through market subsidies, technology transfer and capability building. Of course either policy affects the entire set of activities from invention through innovation to diffusion, but the emphases differ.

The combined implementation of such policies increases the likelihood of arriving in the long term at a wide diffusion of the best technology while reducing the overall costs of the entire process [37,38].

A policy mix supporting environmental innovation is increasingly used as a strategic element of economic policy aiming at increasing competitiveness through stimulating first-mover advantages [3,39]. A policy mix to support environmental innovation works as a lead market advantage as it combines incentives for technological change with the setting of regulatory standards followed in other countries [14]. Countries search for a “lead position” through policy support since early compliance by a domestic industry can be used as an advantage to export technology. In this case, the national industry benefits from economies of scale, learning effects and patent protection associated with early compliance, which facilitate the international expansion of the respective industry. As a regulatory advantage, the policy mix refers to the role of policy diffusion in the creation of lead markets for renewable energy innovations.

### *2.4. Technological Capability*

It is widely agreed that technological capabilities influence trade performance at firm, sector and country levels (see [40] for a review). This suggests that the competence of a country to use a lead market for gathering higher competitiveness also depends on its comparative technological capability. On the competitive arena, technological capabilities can serve as barriers to imitation [36]. In the domestic market, local knowledge flows and technology clusters can enhance knowledge spillovers, thus promoting further innovation [41]. Policies to support lead market formation are commonly influenced by the domestic industrial base and related technology capabilities, since the integration of supply-side aspects into the lead market development enhances competitiveness [23]. Markets for renewable energy innovations are then shaped not only by market dynamics, but also by policy. Here, the role of policy in realizing a lead market position lies in the stimulation of innovation and diffusion through fostering continuous development of dynamic capabilities and keeping technological options open so that international competitiveness is maintained.

### *2.5. Market Structure*

The structure and extent of competition in the domestic market can increase pressure to achieve more innovation and lower prices, in turn enhancing the chances of international diffusion. There are different definitions of market competition. A traditional indicator is the degree of market concentration, measured by the number of buyers and suppliers and the market share distribution among them. For example, a large number of suppliers tend to keep prices low and stimulate quality improvements and adoption of new products offering a better cost-benefit ratio. Increased competition at a sectoral level benefits innovation and international diffusion by inducing further market growth [42]. Hence, competition in the domestic market favours the development of lead markets by increasing the likelihood of innovation to appeal globally because of its lower price, superior quality or better cost-benefit relation.

The lead-market approach as developed and applied thus far involves the previous five factors, which are summarized in Table 1. They can be seen to jointly capture the possible advantages of a country in leading the international diffusion of an innovation. These factors are interrelated and can possibly be mutually reinforcing [14]. The precise lead market position not only depends on the presence of these factors but also on the way they interact. Within this lead market framework, we discuss in the next section the development of lead markets for wind power technologies in China, Germany and USA.

**Table 1.** Lead market factors (Based on [14,23,30–33]).

| Factors | Definition |
|---|---|
| Demand side of domestic market | Ability of a country to develop a market earlier than others, creating the possibility to shape foreign markets and serve foreign demand. |
| Supply side of domestic market | *Demonstration advantage* |
| | Demonstration effect derived from the ability of a country to be the first to successfully diffuse a new technology. |
| | *Export capacity* |
| | Ability of a country's industry to respond to consumer needs in other countries. |
| Policy mix | Ability to define policy measures (in terms of environmental regulation and technology policy) that are followed in other countries. |
| Technological capability | Knowledge base and absorptive capability. |
| | Integration into knowledge networks (industrial clusters, research institutions and international partnerships). |
| Market Structure | High competition level in the domestic market enhances pressure to innovate and reduce prices. |

## 3. Lead Markets in the Wind Power Industry

Following the lead market factors mentioned (Table 1), here we analyse wind power technologies in China, Germany and USA. Only onshore wind technologies of commercial scale are analysed since offshore and small scale ones are still in an early development stage and have not been widely diffused. The focus is on the distinctive elements among the countries in order to grasp a better view on possible competitive advantages and signals of lead markets formation. The aim of this comparative analysis is not to extract "best practices", but rather to understand how variations in national contexts and policies have contributed to build wind power domestic industries, as well as to identify the contribution of interactions between countries.

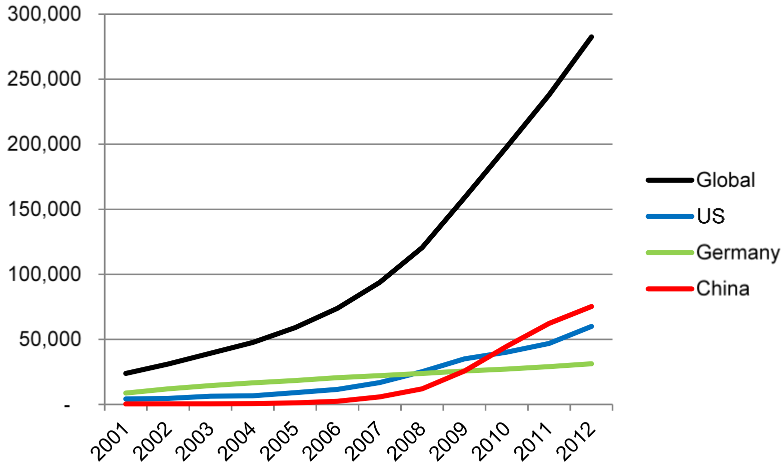
### *3.1. Demand Side of Domestic Market*

The domestic demand represents an advantage as it nurtures the development of a national renewable energy industry and enables competence building in terms of deployment of new technologies. Moreover, the ability of a country to develop a market earlier than others opens up the possibility of shaping foreign markets and benefiting from foreign demands [30]. Following previous studies (e.g., [43–45]), we use installed capacity and installation costs as indicators of domestic market advantage. We employ costs instead of prices to enable the comparison among the three countries. International comparison of wind power prices provide little insight to understand innovation diffusion since it is predominantly driven by electricity market regulation.

The contribution of domestic demand for the wind power industry development has been acknowledged by different studies (e.g., [44–47]). Growing demand in protected domestic markets creates opportunities for experimentation and testing, as well as for cost reduction through learning-by-doing and economies of scale [2,48].

From 2001 to 2012, China, Germany and USA have dominated the wind power market, accounting for an average of 53% of the global installed capacity. Leadership, in terms of installed capacity, initially belonged to Germany, which was taken over by USA in 2008 and by China in 2010 (Figure 1).

**Figure 1.** Total installed wind power capacity (MW) (Source: [49]).

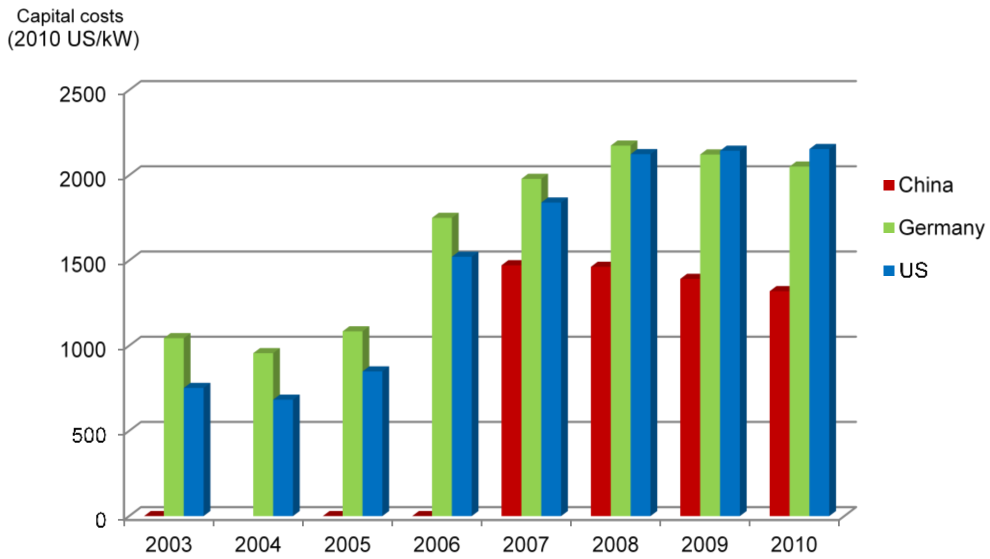



In 2008, the leadership shift from Germany (only 7% additional installed capacity) to USA (50% additional installed capacity) came together with a decline of onshore turbine price estimated at 33% [13]. This price decline is attributed to the end of shortages of supply of turbines and components (e.g., gear boxes, blades and bearings), as well as declining prices of materials (especially steel and copper). China's leadership beginning in 2010 was based on a wider jump: 73.4% of installed capacity added, compared to 14.5% in USA and 5.6% in Germany [49]. Yet, cost can be seen as a main driver again. With yearly growth rates of added wind power capacity over a 100% between 2005 and 2009, the Chinese wind industry achieved strong cost reductions, and kilowatt electricity prices reached values between 35% and 55% below those in other countries [50]. In contrast, the expected advantage of scale has not always been realized in the wind industry. Between 2002 and 2008, global installed capacity doubled twice, while wind project costs in USA rose by more than 50% [51]. In this case, the 30% cost decline projected by the learning curve was neutralized by the increase in wind power capital cost due to supply side factors, such as rising commodity and raw materials prices, increased labour costs, improved manufacturer profitability, and turbine upscaling [7].

Examining the evolution in terms of capital costs of wind power systems (composed by wind turbine, tower, foundations and grid connection components) enables further insights (Figure 2). Capital costs cover: wind turbine (production and transportation), grid connection (cabling, substations and buildings), construction (transportation and installation of wind turbine tower, construction of wind turbine foundation, and building roads and other related infrastructure required for installation of wind turbines) and other (development and engineering costs, licensing procedures, consultancy and permits, data management and monitoring systems). The capital costs for wind power systems vary significantly depending on the maturity of the technology and the local capital cost structure. The first, because internationally established, is considerably uniform; whereas the later provides a clear advantage for

China and to a lesser extent for USA. Both these countries are expected to benefit from economies of scale due to the large number of new systems being installed in the coming years. Yet, China has an additional advantage in terms of lower labour costs [52] and lower quality standards which reduce production costs and use of raw materials [53]. An important reason for low prices of wind power systems in China until now has been low turbine efficiency. The Chinese market suffers from weak incentives to efficiency improvements due to the measurement of the renewable portfolio standard in kW of generation capacity, rather than realized production, and high levels of curtailment [45].

**Figure 2.** Onshore wind power system capital costs (2003 to 2010) (Source: [52]).




A main factor driving the cost increase experienced by German installations between 2004 and 2008 (Figure 2) is the development of new turbine designs to improve adaptation to local wind conditions. German wind power system technology, compared to USA and Chinese ones, have higher power and larger hub heights. They are better suited to German wind conditions because they enable better wind capture and involve less land use, but they raise costs due to, among others, increased materials use and transport costs [54]. From 2009 onwards, Germany has benefited from subtle cost decreases explained mainly by economies of scale of production due to the diffusion of these larger power systems towards other countries, such as USA [55]. Higher costs of installed capacity in the North-American market follow the same trend of an increase in turbine size as experienced in Germany in previous years. Still, by following the German innovation, USA wind power industry is benefiting from lower costs of larger turbines (compared to those of the initial development in Germany).

Considering the prospects for the near future, China is expected to maintain its advantage in terms of domestic market. According to the IEA [13], by 2018, China will be the country with the largest cumulative capacity worldwide, with an estimated total of 185 GW wind power, followed by the United States (92 GW), Germany (44 GW) and India (34.4 GW). Chinese dominance is expected to be reinforced by the fact that the most significant factors associated with wind power price reduction in China are related to cumulative installed capacity: joint learning from technology adoption and learning-by-doing, and economies of scale [56]. However, since it is based on low quality turbines, instead of investing in turbines development, the Chinese market seems to be driven by the benefits of imitation, simply reproducing turbines developed in foreign markets. These advantages of scale are also being pursued in USA. Recent reports point to turbine price reductions of as much as 33% for contracts signed by USA developers in 2011. This is considered to result partly from increases in manufacturing investment, production capacity, and industry growth in the national market, as well as a brief period of relative federal policy stability [57]. As well, both China and USA are expected to benefit from further reductions in operation and maintenance (O&M) costs, attributed to increasing turbine efficiency and additional economies of scale from very large wind farms.

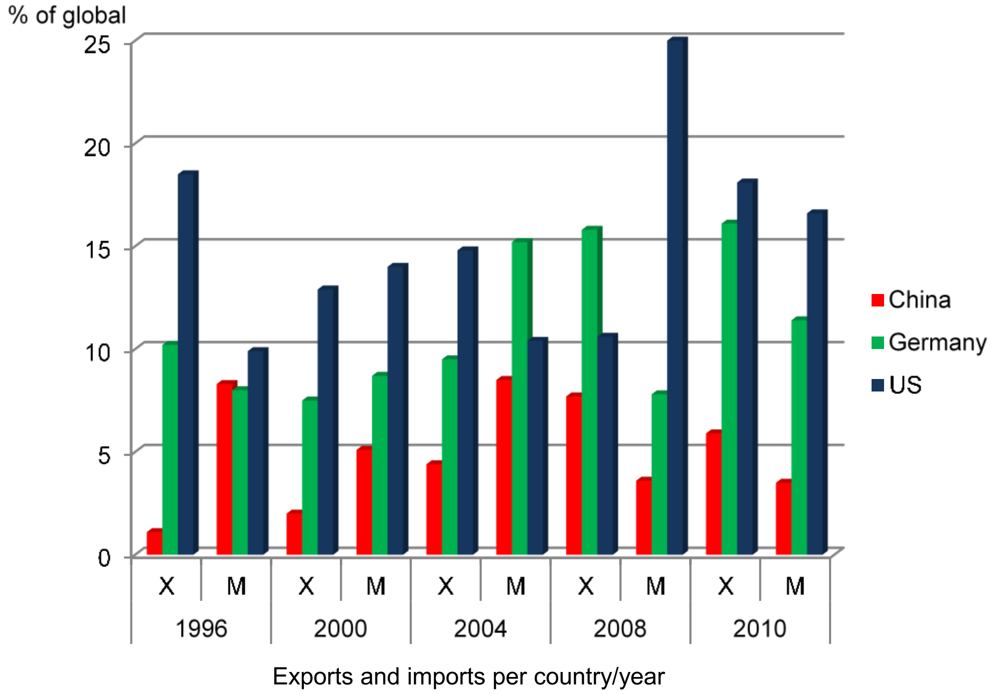
### *3.2. Supply Side of Domestic Market*

The supply side of the market takes into account the demonstration and export advantages. Demonstration advantages are based on a trial effect [32]. It indicates the ability of a country to successfully establish a new technology and share information about it, reducing uncertainty about its initial adoption in other markets [14]. The export advantage stays for the ability of a country to respond to consumer needs in other countries [14]. Here we seek to assess the export and demonstration advantages by comparing the performance on exports of wind power technologies by China, Germany and USA. We consider the demonstration and the export advantages together because, in the cases studied, countries started exporting wind technologies only after their initial deployment in domestic markets and mostly together with projects of technology transfer. Due to the high complexity characteristic of wind power technology, its deployment requires a minimum level of technological capabilities [58]. Exports of wind power technologies have involved not only the parts and engines required to build a wind power systems, but also the information and knowledge needed to safely deploy them [59,60].

Production of wind technologies in both China and USA has been directed mainly at the national market. Exports are a secondary goal, been strongly influenced by changes in their respective domestic markets. Factors that have commonly led to increases in exports are a production capacity surplus due to market entry of turbine and components manufacturers, a decrease in the annual rate of growth in the number of domestic installations, and higher turbine prices in the domestic market [49,57]. Germany’s production of wind technology, on the other hand, was traditionally focused on international markets, with export rates reaching up to 80% of production [61].

Comparing the global share of exports and imports of wind technologies by China, Germany and USA (Figure 3) provides further insights. The higher shares of participation by USA and Germany, both in global exports and imports, indicates the effort of these countries to build a global position as a wind technology supplier as well as the benefits of building a local supply chain, in line with previous studies (e.g., [62,63]). China, on the contrary, appears to keep its wind technology industry prioritizing the national demand, which potentially explains its reduced involvement in foreign trade [64].

**Figure 3.** Percentage of global wind technology exports (X) and imports (M) (Source [65]).




### *3.3. Policy Mix*

Policy support works as a lead market factor by establishing domestic rules and market dynamics that later on influence international standards in policy design. Since policy typically paves the way for renewable energy diffusion, the first countries to adopt it tend to get a first mover advantage in terms of innovation and deployment [14,27]. As is typically the case with environmental innovation, the regulation schemes to support renewable energy technologies evolved in tandem with the geographic diffusion path of wind power. The benefits from regulation towards the formation of lead markets in China, Germany and USA have developed differently depending, among others, on the timing and pace of diffusion in each country. Hence, the comparison of policy mixes takes these various features into account in determining their contribution for lead market formation. Building upon previous research, first date of implementation, uncertainty level, and scope are among the main criteria analysed (see [38,63] for reviews).

Germany was a first mover, establishing a feed-in tariff (FIT) scheme to support wind power generation already in the early 1990s, and is perhaps the only country without any interruption in its feed-in tariff scheme since then [61]. Germany's FIT scheme is considered one of the most efficient in the world [66]. It is highly flexible due to a mechanism to adjust the FIT to the location, which increases the viability of projects in sub-optimal locations, promoting a more balanced geographical distribution of wind power generation. It also seeks to foster technological progress and cost reduction. Payment bonuses are offered as incentive to repowering and to increases in generation capacity, as well as adoption of the most efficient grid connection technologies [67].

An additional advantage of policy support in Germany derives from its low uncertainty level. The stability and long term horizon of FIT together with priority dispatch and reimbursement for curtailment have reduced the risk of investment in wind power and kept costs of capital low. In addition, the national bank, KfW, has directly invested in projects and provided funds for commercial banks to finance wind power projects at low, fixed interest rates and with grace periods of up to 5 years [68]. Altogether, this policy measures created a large renewables market in the country, fostered the development of domestic R&D capacities and consolidated the wind industry as a cluster. However, the creation of similar support schemes in USA and China in the last decade (Table 2) has shifted, at least partially, the initial advantages from Germany.

**Table 2.** Selected policy support instruments (Source: [49,69,70]).

| Support Instrument Used by Country/Year of 1st Implementation | China | Germany | USA |
|---|---|---|---|
| Feed in Tariffs | 2009 | 1991 | |
| Premium or Adder System | | 2012 | |
| Auction or tendering system | 2002 | | |
| Tax based (electricity) production incentives | | | 1992 |
| Spot market trading | | 2008 | |
| Investment subsidy or tax credit | | | 1981 |
| Tradable Green Certificate | | | 1998 * |
| Concessionary finance through government supported agencies | 2001 | 1989 | 1992 |
| Concession on import duty | 2003–2010 | | |
| Renewable energy Portfolio Standard or Purchase Obligation | 2006 | | 2002 * |
| Federal or state-level targets (binding or indicative) for electricity generation | 2007 | 1991 | 2002 * |
| Project siting guidelines | | 1997 | 2002 |
| Project permitting process | 2001 | | 2005 |
| Priority access to the grid | 2009 | 1991 | |
| Grid code | | 2008 | |

Note*:* * At the State level, e.g., California.

In China, regulation of wind played a key role promoting a transition from imitation and cooperation to indigenous innovation [58,71]. While the Tenth and Eleventh Five-Year Plans (2001–2005; 2006–2010) put a strong focus on the R&D and innovation capabilities, the current Twelfth Five Year Plan (2011–2015) increased support to demonstration and diffusion activities to achieve the target of 11.4% of total energy use based on non-fossil sources [72,73]. Moreover, in 2013, China's public investment in renewable energy amounted to USD 56 billion, more than that in the whole EU (USD 48 billion) and USA (USD 36 billion) [11]. Challenges still to be addressed by policy support in China are the domestic supply of high-end components and grid connection technologies. In 2012, the Chinese market imported at least 50% of the high-added-value critical parts and components used, such as control and hydraulic systems [73]. Along the same line, further policy support is required to improve wind power connections to the grid and dispatch efficiency. In 2011, a third of wind capacity installed in China was not connected to the grid [49]. Up to now, there has been no incentive for a better distribution of wind farms within the country. For reasons of attractive land prices, the largest capacity has been installed at long distance from locations with the highest demand for electricity. Addressing these issues could create opportunities for China to further expand its wind power industry and, hence, to exploit additional advantages from public investment directed at wind power diffusion.

In USA, Renewable Portfolio Standards (RPS) targets, set at both state and federal levels, have been the main driver of diffusion of wind power. To meet the current RPS targets an average annual increase in renewable energy production of 3 to 5 GW between 2013 and 2020 is estimated to be necessary, well below the 16 GW of total renewable capacity added in 2012 (of which 13 GW were of wind power) [57]. This indicates important limitations of USA RPS programs to drive future wind power development. At the federal level, the past experience of stop-and-go wind energy support in the United States brings additional constrains to further increases in deployment. Since the early 1990s, federal support mechanisms (notably, the Investment Tax Credit, ITC, and the Production Tax Credit, PTC) have been erratic for political reasons. For example, between 1992 and 2010, USA Congress let the PTC for wind expire four times before eventually extending it again, contributing to wind deployment following cycles of boom-and-bust [74]. Even though this market uncertainty has not stopped local investments in wind manufacturing (possibly because of the large long-term market potential), it has affected the competitiveness of the local industries and prevented these from enjoying gains of scale and planning [75].

The comparison of selected policy instruments to support wind energy among the three countries illustrates the diversity of policy, in terms of instrumental design as well as timing. In Germany, policy support was initially developed in the 1990s, whereas the United States and China followed later, in the beginning and middle of 2000, respectively. From the 15 instruments analysed, only two are present in all three countries, namely concessionary financing through government supported agencies and targets for electricity generation. Concessionary financing is generally made through a loan provided at terms substantially more generous than those of market loans. The concession is achieved through interest rates below those available on the market, grace periods, or a combination of these [76]. The adoption of priority access to the grid by China following the standards first established in Germany is the only clear example of a lead market advantage in wind power mainly built upon policy support. German companies have been the main suppliers of grid connection and management technologies for the Chinese market since the regulation of grid access was implemented [49]. However, no pattern of reproduction of instruments could be identified among the three countries, thereby no clear lead market advantage. This is in line with research showing that the design of policy support for renewable energy changes significantly to be adapted to local conditions, such as wind intensity, land availability, community acceptance.

### *3.4. Technological Capability*

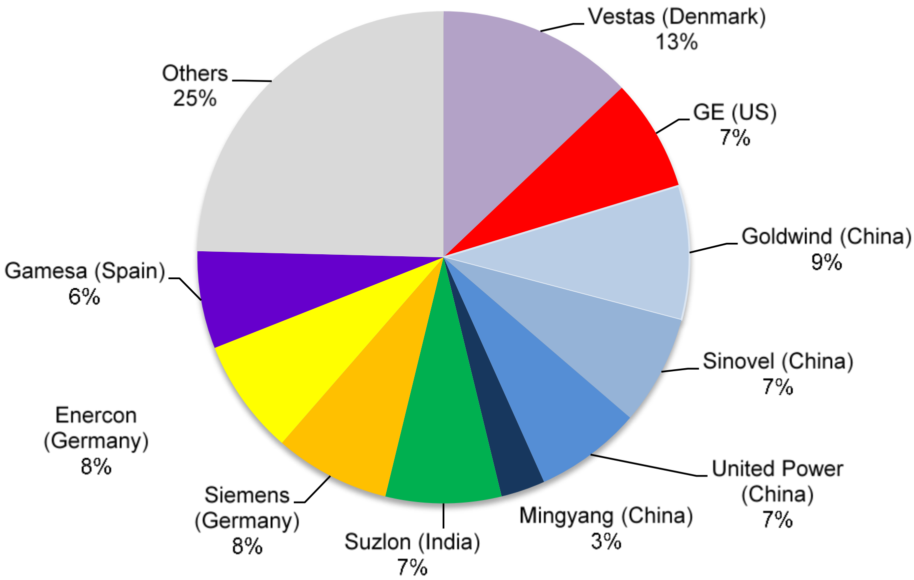
Technological capability refers to the ability to generate and manage change in technologies and is largely based on specialized resources [77]. As a lead market factor, it represents an advantage in terms of dynamic efficiency that is difficult to imitate and requires deliberate investment and time to build since it does not follow automatically from the acquisition of foreign capital embodying new technology, nor from the accumulation of related operating know-how. Superior technological capabilities can form the basis of long-lasting first-mover advantages especially for technologies characterized as knowledge-intensive and highly dynamic, as is the case of wind power [30,78]. Thus, a country with a comparatively higher technological capability has an advantage in developing a lead market due to superior dynamic efficiency in technology management.

Here we use the share of domestic content of wind power facilities as an indicator of technological capabilities since the location of production involves availability of skilled technical personnel, information on available technologies and social institutions that reduce transactions costs. Previous studies have shown that countries with local supply networks have stronger technological capacities [79]. Moreover, technological capabilities facilitate local knowledge spillovers from international trade and foreign domestic investment, and thus contribute to knowledge diffusion within the domestic country [59]. Additionally, knowledge spillovers play a significant role in stimulating innovation in wind power technologies, both at the intra and inter-sectoral levels [80], together with foreign direct investment [81].

All the three countries studied present a high degree of domestic content of the wind power installations indicating strong technological capability building. Certain components, such as control systems and bearings, are supplied by firms from a wide range of countries as is also the case with leading wind turbine producers around the world [81]. In 2011, USA local industry supplied 67% of the turbines and components installed in the country-up from less than 25% before 2005 [51]. German domestic wind equipment manufacturers supplied over 77% of the domestic market in 2009, while it exported 80% of total German-made wind power equipment [61]. In China, since the adoption of a law on "local content requirements" in 2003, on average about 80% of all components of wind turbines installed in the country have been locally manufactured and assembled [56].

In global terms, the importance of German and Chinese wind technology manufacturers is also clear. In 2011, Chinese firms were responsible for 26% of global installations, followed by German ones with 16% (Figure 4). General Electric (GE), the only USA based firm among the main global players, had a reduced share of global installations, 7% of total. In contrast, GE accounted for 38.2% of USA market [82], pointing to the influence of national installations on building up global market players. Such a market share distribution (Figure 4) also indicates higher degree of internationalization of German and Chinese firms if compared to North-American ones. For example, from the 8% of global installations of turbines by Siemens in 2011, 20% took place in USA.

**Figure 4.** Turbine manufactures share of global installations (2011) (Source: [62]).




In contrast, turbine size shows a different pattern of change in technological capabilities. In 2006 the average size of turbines in China was 830 kW, with 600–850 kW turbines accounting for 80% of the market share. On the other hand, the average turbine size in Germany and USA was 1634 kW [83]. In 2011, the average turbine size had grown in all three countries, to 1.5 MW in China, 2.5 MW in Germany and 2 MW in USA [49,55,57]. Here Germany leads the technological development. Wind turbines with nominal powers above 3 MW are rapidly penetrating the German market and already represented 16.8% of newly installed wind power generating capacity in 2011–up from 6% in 2010 [55]. China and USA clearly lag behind. In 2011, the expansion of upgraded technology in China was still driven by 2 MW models, which accounted for 14.7% of newly installed capacity, and models with a power of over 2.5 MW accounted for only 3.5% [49]. In USA, turbines with 3 MW or above represented less than 8% of newly installed capacity [57]. Further reasons to consider the Chinese industry as lagging behind are problems with high levels of curtailment (up to 23% of wind energy production) and a below-average capacity load factor, the proportion of actual electricity produced compared to installed capacity (of 22% compared to 33% in USA). These figures indicate that China is still struggling to catch up with Germany and USA.

As wind power technologies are entering maturity, turbine model life cycles are becoming longer. In the German market, for instance, the wind turbines with nominal power up to 500 kW were dominant for 3 years, from 1990 to 1993, whereas the 1 to 2 MW class were dominant for almost six years, from 1998 to 2004, and current classes of wind turbines are dominating for even longer, since 2004 [55]. This slowing-down of technological change may favour catching up by Chinese and USA industries, as it means more time for building up capabilities while past technological trajectories in other countries facilitate international knowledge spillovers.

### *3.5. Market Structure*

The market structure as a lead market factor refers mainly to the degree of competition. We do not focus here on competition within electricity markets since previous research indicates that electricity market conditions have little effect on renewable energy innovation (e.g., [35,84]). Competition has been considered a crucial stimulus for innovation by researchers such as Schumpeter [85] and Dosi [40]. Based on the idea of creative destruction, the argument is that competition increases the pressure for technological change as innovations cause certain incumbent organizations, technologies, skills, and equipment to become obsolete which then creates opportunities for newcomers. Lead markets are usually highly competitive because competition speeds up technological development [42] which enhances the adaptability of innovation to diverse market conditions [86].

Despite the fact that wind power is commercially deployed in 83 countries [12], it has a high level of market concentration in terms of geographical distribution: by the end of 2013, the top 10 countries accounted for 85% of the total global capacity, namely China (28.7%), US (19.2%), Germany (10.9%), Spain (7.2%), India (6.3%), UK (3.3%), Italy (2.7%), France (2.6%), Canada (2.4%), Denmark (1.5%) [87]. Market concentration at the geographical level is especially notable for competition in wind power, because of systems' cost composition and companies' organizational structure. 64% to 84% of the investment cost of an onshore wind power system is the cost of the wind turbine (including turbine production, transportation and installation), of which raw materials respond for 60% to 90% [12]. Of the remainder turbine costs, labour makes up 5% to 7%, while transportation costs 2% to 8%, depending on the wind turbine size [82,88]. This combination of low labour input, internationally standard commodity prices and relatively high transportation costs create barriers for turbine producers to realize further cost reductions by shifting production sites to low-cost locations. Hence, investments in turbine production are expected to remain market-seeking, *i.e.*, to follow demand location, and remain geographically dispersed.

On the organizational level, the vertical integration of most wind turbine manufacturers, with internalized parts production and O&M services, spreads local competition to the supply chain. Geographical proximity of suppliers offers advantages of cost reduction through supply chain management based on techniques such as component commonality, just-in-time stocking and shorter lead times [12]. In addition, local sourcing of wind power parts may benefit compliance of local-content rules and insulate from exchange rate fluctuation and customs duties.

Led by wind turbine manufactures, the supply side of the wind power industry is highly concentrated within China, Germany and USA (Table 3). Market contraction due to declining prices of gas in USA and carbon in Europe and China, as well as a global reduction of public support, created a situation of over-capacity of supply and led the wind power industry to consolidation and higher concentration. Germany turbine makers experienced a decline in market share within China, where domestic suppliers constituted over 93% of the market in 2013, up from 28% just six years earlier, and some (e.g., Bard and Fuhrländer GmbH) filled for insolvency in late 2013 [54]. In the United States, there were factory closures and layoffs due to a shortage of new turbine orders [57]. China is expected to follow the same trend, with current predictions pointing to a reduction of two thirds in the number of wind turbine makers in the next five years [89].

**Table 3.** Renewable power capacity in 2013 (Source: [90]).

| Technology/Power Generation in GW | China | USA | Germany |
|---|---|---|---|
| Bio-power | 6.2 | 15.8 | 8.1 |
| Geothermal power | 0 | 3.4 | 0 |
| Solar PV | 19.9 | 12.1 | 36 |
| Concentrating thermal power (CSP) | 0 | 0.9 | 0 |
| Wind power | 91 | 61 | 34 |

Regarding a lead market advantage, the local production and companies' headquarters location show important differences among the three countries. The German and the Chinese markets are dominated by national companies, which in both cases were responsible for more than 70% of the market. In contrast, only 40.3% of USA market was supplied by national players in 2013 (Table 4). A possible explanation is the difference in terms of policy support within the three countries. Whereas in Germany and China there was strong policy support for the initial stages of the innovation process (through R&D financing in the former and through technological transfer and acquisition in the later), USA policy was focused rather on the demand side (e.g., through Renewable Portfolio Standards). The lower degree of local production in USA probably follows the fact that most top 10 companies are of foreign origin, since the initial development of wind power manufacturing has historically been synchronized to domestic demand. On the other hand, USA market has an estimated 550 locally based manufacturers selling wind power equipment in the national market in 2012 [91]. The large number of players in USA may be connected with the fact that the local industry benefits from a well developed financing system and from public incentives to wind power development, which foster entrepreneurship [57] and mean a less risk-averse approach than in China and Germany.

**Table 4.** Market share of 10 top turbine manufacturers (annual installations in 2012) (Sources: [49,57,60]).

| Germany | | | | China | | | | USA | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Company** | **HQ** | **LF** | **%** | **Company** | **HQ** | **LF** | **%** | **Company** | **HQ** | **LF** | **%** |
| Enercon | Germany | Yes | 49.6 | Goldwind | China | Yes | 23.3 | GE Wind | USA | Yes | 38.2 |
| Vestas | Denmark | Yes | 20.0 | United Power [2] | China | Yes | 9.3 | Siemens | Germany | Yes | 20.1 |
| Repower [1] | Germany | Yes | 16.2 | Ming Yang [3] | China | Yes | 8.0 | Vestas | Denmark | Yes | 13.8 |
| Nordex | Germany | Yes | 8.4 | Envision | China | Yes | 7.0 | Gamesa | Spain | Yes | 10.2 |
| Siemens | Germany | Yes | 1.3 | XEMC-Wind | China | Yes | 6.5 | Repower | Germany | No | 4.5 |
| GE Wind | USA | Yes | 1.2 | Shanghai Electric | China | Yes | 6.3 | Mitsubishi | Japan | No | 3.2 |
| Others | | | 3.3 | Sinovel | China | Yes | 5.6 | Nordex | Germany | No | 2.1 |
| | | | | CSIC-Haizhuang | China | Yes | 4.9 | Clipper | USA | Yes | 1.9 |
| | | | | Dong Fang | China | Yes | 3.6 | Acciona | Spain | No | 1.5 |
| | | | | Zhejiang Windey | China | Yes | 3.4 | Suzlon | India | No | 1.4 |
| | | | | Others | | | 22.2 | Other | | | 3.0 |
| ***Top 6 sum*** | | | ***96.7*** | ***Top 10 sum*** | | | ***78.8*** | ***Top 10 sum*** | | | ***97.0*** |

Notes: HQ: Headquarters country. LF: Local factory; [1] Since 2014, renamed Senvion, subsidiary of Suzlon Group; [2] Before being restructured as a state-owned enterprise in 2007, United Power was Longwei Power Generation Technology Service, a joint venture with the US company Westinghouse between 1994 and 1998, and a joint venture with Siemens from 1998 to 2006; [3] A joint venture with German Aerodyn Energie Systeme Gmbh.

In terms of competition with other renewable energy sources, wind power is the main renewable energy source by installed power capacity in China and in USA (Table 3). In Germany, even though with a slightly lower installed capacity than solar PV, wind power is ahead in terms of share in final energy supply with 16.2% compared to 6.4% for solar PV and 1.9% for solar thermal energy [92]. These high shares of power capacity installed in all three countries give wind power technologies an advantage to compete with other renewable energy sources. For instance, the need to realize the forecasted return on investment of such installations builds up the pressure for priority of grid connections and adaptations suitable to wind power.

From the data analysed here, no clear lead market advantage for any of the three countries studied follows. In fact, quite the opposite holds for USA, where a lack of strong national players may mean little opportunities to compete with Germany and China since domestic investments in wind power expansion can be used to foster technological development of foreign companies. For instance, USA investment can increase the benefits gathered by German players from technological capabilities acquired through a long path of technological development, which occurred jointly with domestic market formation and the emergence of public support. German companies, despite being highly concentrated in terms of turbine production (the top 2 companies hold 65.8% of the national market—Table 3), are experiencing a trend towards outsourcing of manufacturing activities and increasingly focusing on O&M activities [54]. These provide steady revenues even when sales are falling, and can add value to turbine sales. For China, new benefits can possibly come from a global integration of wind industry value chains.

With increasing components commonality, the production of some wind power system components (notably, those relatively easier to transport, such as bearings and gearboxes) can become more centralized, thus benefitting from economies of scale. As such, China has the advantage of comparatively lower costs, mainly in facilities for iron cast and forging [49]. Still, experts suggest that USA perhaps can build up a lead position in provision of financial services to wind power installations and grid infrastructure connection [57,70]. If this is true, it seems to suggest a situation with opportunities for the three countries to develop comparative advantages in different activities in the wind power value chain.

## 4. Comparison of Lead Market Factors

The analysis of lead market factors for wind power in China, Germany and USA delivers no clear "winner". However, USA seems to have the weakest position. It has no clear advantage for any lead market factor relative to the other two countries. Advantages can be identified for China in terms of demand side of domestic market and policy mix, and for Germany in terms of supply side of domestic market and technological capability (Table 5).

**Table 5.** Summary of lead factors for each country.

| Lead Market Factor | China | Germany | United States |
|---|---|---|---|
| Demand side of domestic market | ++ | 0 | + |
| Supply side of domestic market | + | ++ | 0 |
| Policy mix | ++ | + | 0 |
| Technological capability | 0 | ++ | + |
| Market Structure | + | + | 0 |

Note*:* ++: strong advantage; +: low advantage; 0: no advantage.

In comparison to Germany, the demand side of domestic market advantage for China and to a lesser extent for USA, come with no surprise since these last two countries have larger energy markets (in total consumption), have higher $CO_2$ emissions rates in global terms and have started to scale up wind power energy more recently. Moreover, as discussed earlier (Section 3.1), China has the highest growth forecast and the best conditions for cost reductions in the short run (due to competitive costs of inputs-mainly labour and raw materials transformation). Still, if China or USA will lead further wind power deployment remains an open question that seems to be better answered by policy support rather than by technological change. Reducing uncertainty of policy support for the wind power industry in USA could increase investment and technological innovation through risk reduction and better profit prospects. At the same time, changes in Chinese policy design to optimize incentives for higher efficiency on power generation could fasten repowering and upscaling, adding a further impulse to domestic demand growth.

Within this context, China's stronger position in terms of policy can become a compounding advantage towards market leadership. In the last years, China not only made the largest amount of public investment, but also the largest expansion in foreign markets. Policy support for Chinese companies to adopt the so-called "Go Global" strategy have pushed foreign direct investment overseas from around USD 15 billion in 2005 to over USD 67 billion in 2011 [70]. Chinese manufacturers invested more in electricity generation than in manufacturing bases or commercial subsidiaries, with 63% of the funds directed to the first [53]. This strategy is aimed at securing markets for Chinese companies, which also started to suffer with oversupply in the global market and higher quality standards from foreign competitors. In the national market, Chinese companies enjoy an additional advantage with market reserve assured by the local content regulation and weak competition of foreign funded companies due to their comparatively higher price [49].

In contrast, the German leadership in terms of supply side of the domestic market and technological capability seems to raise more promising advantages for leading the industry, especially in terms of innovation. The German wind power industry has been built upon stringent environmental policy, a strong industrial base and a high degree of integration in international trade [58], which are all difficult, if not impossible, to reproduce in the short to medium run. The German Wind Energy Association (BWE) has more than 20,000 members, making it the largest association of its kind in Germany and one of the world's largest associations in the field of renewable energies [90]. Currently, the focus on modernizing transmission lines [93] and repowering [94] reinforces the German leading position on technological capabilities development. Moreover, the rapid pace of technological change in wind power technologies works as an additional barrier for China or USA to catch up with Germany. Even though lacking appropriated policy support, technological development in USA wind power industry is considered to be closely following the Germany in terms of wind turbines technologies [57]. Furthermore, powered by competitive energy as well as labour costs and exchange rates [95], the recent trend of rebuilding of manufacturing activities in USA can be an additional push for wind power development in the country.

## 5. Assessment of Lead Market Potential

Altogether, the lead market factors analysed for China, Germany and USA show no clear indication of a stable lead market position for any of these countries. First-mover advantages seem to almost necessarily shift to different countries along the path of wind power diffusion. After all, the assumption of the lead market approach that a lead market is a development in a single country can be problematic in the case of wind power technologies. In the same way that previous studies concluded that technology learning in wind power is deemed to have both national and global components [96], so does market dynamics. Hence, the difficulty of isolating factors in terms of geographical space to determine a country's competitive position within an industry and a market which work in a global scale. The comparative analysis of the lead market factors in China, Germany and USA points rather to an international structure of the wind power industry, with countries occupying different lead positions within the supply chain. In line with previous studies, these results suggest that an international specialization within the production chain of wind turbines is under way, and that it is strongly connected to domestic policies supporting low-carbon technology diffusion [44,97].

As a result, further diffusion of wind power technologies at the global scale tends to be led by countries that occupied lead markets positions in the early phases of diffusion. In this case, lead market factors can serve as indicators of future areas of specialization. As global diffusion brings wind technologies into maturity, the paces of change and of profitability growth are reduced. As a consequence, countries can increasingly benefit from competitive advantages formerly acquired to exploit the new market boundaries. The recent expansion of wind power in new markets such as in Brazil, India, Malaysia and Indonesia reinforce this perception. China and Germany have been playing a key role on the diffusion of wind power in these countries, notably in areas related to their respective lead market advantages. The German share in companies supplying grid connection equipment and grid management tools is growing, whereas China is becoming one of the main exporters of wind turbines and other wind power related components [11,54].

Interaction of wind power industries among countries may affect their performance on certain lead market factors and provide further impetus for shifts in competitive advantage of the wind power industry. If one country performs better in terms of any of the lead factors, this will have an impact on other countries. Within the last decade, the most significant interactions occurred between Germany and USA, and more recently between China and the previous two. Germany and USA have mutually benefited from different developments of the wind power industry at national and international levels. Advantages from demand growth in either market have spilled over between the countries generating cost reductions due to economies of scale and reduced times of product development (Section 3.1). Furthermore, in the middle 2000's, the installation by German companies of wind power systems in USA have reduced the domestic problem of supply shortages (see Section 3.5) and benefited Germany by increasing its return to scale of technological development. On another hand, China has benefited from diffusion of technological capabilities from Germany and market demand from the US (Sections 3.4 and 3.5). The later has been more recently explored through a strategy of going global from Chinese companies, as a reaction to limitations of demand in the national market. Technological capabilities previously developed by Germany have contributed to rapid cost reductions achieved by the Chinese wind power industry. Chinese companies saved time and resources focusing on manufacturing and implementation, rather than on product development from the ground up.

Moreover, the turmoil promoted by the Chinese competition in the wind (and solar) markets in the last years points to the fallibility of lead markets as a policy goal. Efforts made by Germany, and other countries such as Denmark, to build up lead market advantages did not prevent a latecomer like China to dominate the market. Because manufacturers of Chinese wind technologies achieved batch supply capability, there was oversupply in the market and competition was intensified, leading to price decreases over the last years [49]. This resulted in a global restructuring of the wind industry, involving mergers and acquisitions, as well as companies going bankrupt. Foreign-funded companies located in China initially benefited from the emergence of Chinese wind power market, notably as it was characterized by a lack of severe competition due to insufficient supply of equipment. But these companies had to end their operations or were absorbed by other, mainly Chinese, companies when the prices started to fall in 2010. Previous advantages of lead market formation that, directly or indirectly, financed the internationalization of European and USA companies, were reversed into an over-capacity problem. From these companies, only the large ones survived, mainly because they benefited from a better reputation and were more trusted, both in terms of reliability of their products and O&M services.

Ambitious policy support for environmental innovation is expected to help industries to achieve technological leadership, thereby improving the competitiveness of the national economy. However, the innovation dynamic of environmental innovation in the energy sector is necessarily subject to international forces. At the supranational level, global climate policy informs the desired pace of energy system transformation by setting targets of GHG emission reductions. The innovation dynamics that follows takes place within the international competition for low-carbon technologies, based on national industrial policies. National suppliers in this sector are also usually exposed to international competition and the domestic markets are driven by this combination. Therefore, the difficulty of building domestic policies to achieve a lead market position at the industry level. Restricted to a national sphere and lacking control over costs (determined at the international level), governmental policies aiming at the creation of lead markets in low-carbon technologies, e.g., renewable energy, suffer of limited foresight and impact.

Despite the lack of a clear lead market formation, China, Germany and USA share some conditions that may have contributed for these countries to approach lead market positions within this last decade. From all five lead market factors analysed, two conditions seem pervasive on strengthening the three countries positioning: policy design and adaptation to different stages of wind power global technological trajectory. In all three countries policy was designed to support different elements of wind power technologies depending on the respective national industry characteristics and technological trajectory. For Germany, early market entrance and strong technological base made the initial focus on technological development and exports a rentable option. In USA, the stop-and-go cycles of policy support have pushed the industry towards a technology follower position, taking advantage of the combination of imitation and economies of scale due to its large domestic market. In China, the 10th and 11th Five-Year plans (2001–2005; 2006–2010) offered the initial support to build a national wind power industry, whereas the 12th Five-year plan (2011–2015) is expected to increase exports of goods with a higher value added, such as wind power system technologies. These cases offer further evidence to the literature in environmental policy where the technology aspect of policy support is increasingly recognized as a defining element of policy effectiveness.

## 6. Concluding Remarks

This paper has examined lead markets for wind power associated with three countries. This involved extending the existing framework for studying lead markets, and analysing the lead market potential of wind power in China, Germany and USA. The empirical analysis enables three types of conclusions. First, in response to our initial guiding questions: even though lead markets are difficult to be clearly defined at the country level, there is enough evidence that policy support for environmental innovation can help to create competitive advantages. The observed advantages for China and Germany in terms of particular lead market factors show a strong connection with policy support in each of these countries, while the comparatively weak position of USA appears to be closely connected to the lack of consistent policy support over time. In China and Germany, developing a lead market in wind power was clearly formulated as a policy goal, which served a broad policy framework encompassing objectives such as energy security and achieving international market dominance. Between 2008 and 2011, Germany (together with the European Commission, other member States and industry) have worked to carry out the action plans for six lead markets, one of them renewable energy, including wind power. The Lead Market Initiative (LMI) for Europe was launched by the European Commission following the EU's 2006 Broad based innovation strategy. The scope of the LMI, the selection of the six markets and the action plans were approved in the Competitiveness Council of May 2008 [98,99]. Between 2010 and 2013, Germany also developed a project on lead markets sponsored by the funding initiative "Economics for Sustainability" from the Federal Ministry of Education and Research [55]. China's Twelfth Five Year

Plan (2011–2015) defines renewable energy, including wind, as one of the strategic emerging industries (SEI) to be stimulated. One of the goals is to be an "international leader" by 2030, not only in terms of market share but also state of the technology [100]. This explains the long-term horizon of the policies implemented (e.g., contracts for feed-in tariffs for 15 to 20 years, Five Years Plan). Meanwhile, in USA, exploitation of gas intensified, fostering rapid growth of the related industry, and receiving increased policy support. Due to the strategic role of energy, the policy mix to support environmental innovation and competitiveness is often linked to a country's geopolitical positioning.

A second conclusion concerns the impact of the policy mix in terms of environmental regulation and technology policy on technological trajectories. The assessment of lead markets for wind showed the relationship among the stage of wind power international diffusion, the technological trajectory at the country level, and policy design. In Germany, the diffusion of wind power coincided with early stages of its international expansion. At this moment, technological change and scaling up were occurring at a much faster pace than ever before. Benefiting from its already established supply capacity of technologies complementary to wind power, Germany was able to stimulate a rapid path of technological development in the industry. This involved building up advantages in terms of technological capability, knowledge flows and supply chain, while promoting domestic demand through strong subsidies for wind power generation. On the other hand, the diffusion of wind power in China started almost 30 years later than in Germany, at a moment when economies of scale had become more important and technological change started to slow down. The main lead market advantages of China–domestic market and policy mix–were developed in a context of rapid market expansion with high rates of growth and falling prices, strongly supported by policies stimulating deployment in national and international markets.

A third conclusion regards supranational interactions. The international dynamics of the energy markets, as well as the "race" for leadership in green growth, make innovation in renewable energy a necessarily supranational issue. In this case, interactions among countries have effects that go beyond the traditional risks of spillovers involved the innovation process. As demonstrated by the massive growth of the Chinese wind (and solar) manufacturing capacity, investment in diffusion can backfire. The rapid market expansion led to industry consolidation that has destroyed benefits of earlier (and more costly) investments, with the risk of an undesirable reduction in technological diversity and slowing down technological progress in the industry.

Striving for lead markets in wind power, although not clearly beneficial to any of the three countries studied, has contributed to the international diffusion of wind power technologies. As technology diffusion sets through, the cost gap between renewable and traditional fuel sources narrows, making renewable energy sources a more attractive option in countries where it so far was too expensive. The benefits of pursuing a lead market position by one country spill over to other countries, as renewable energy technologies become more affordable. In a similar way, the benefits of reducing emissions through higher renewable energy use also spill over to contribute with the global challenge of climate change mitigation.

The extended framework for lead market testing highlights the importance of spatial conditions to the international diffusion of renewable energy innovations. The differences among the lead factors for China, Germany and USA indicate the diversity of local characteristics relevant to wind power development. Therefore there is a need for a policy mix that addresses multiple goals. The position of a country's wind power industry on the curve of innovation, its technological trajectory and knowledge base play a key role in defining the most suitable policy mix. In terms of future research, it would be good to have a clear understanding of how important different lead market factors are, what is their relative weight, and the extent to which they contribute to spur renewable energy innovation and to sustain competitiveness.

## Author Contributions

Juliana Subtil Lacerda performed the research, compiled the data, prepared the manuscript, and created the graphics. Jeroen van den Bergh suggested the topic and co-wrote the paper.

## Conflicts of Interest

The authors declare no conflict of interest.

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