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Article

Convergence or divergence? Wind power innovation paths in Europe and Asia

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Abstract

Wind power is increasingly vital for meeting energy challenges and mitigating global climate change and is therefore an important part of renewable energy portfolios in many countries. Given the key and evolving roles of European and Asian countries in driving this sector, this article focuses on two sets of key questions: first, do wind power innovation paths differ between Europe and Asia? If so, how do they differ? Second, do innovation paths reflect different initial conditions in Europe and Asia? Can we expect divergence in the future? We find that although national paths are shaped by a range of national characteristics and therefore differ along key dimensions, the increasing roles of cross-national firm interactions amplify tendencies towards global convergence. These patterns of divergence and convergence can potentially enhance the contribution of wind power to the low-carbon transition but also have implications for the competitive dynamics of the wind power industry.

Key words: innovation path; path creation; globalisation; wind power; Asia; Europe.

1 Introduction

Rapid advances in low-carbon technology are central to global and national efforts to address the challenge of avoiding dangerous climate change. A host of activities—within and across countries and firms—are underway to develop and deploy new technologies, motivated not just by this environmental challenge but also by developmental imperatives and the opportunity to access new and enormous markets that will be created as a result of this low-carbon transition.

Innovation paths for low-carbon transformation may, however, differ markedly between countries because of diversity in policies, endowments and technological capabilities.[1] These differences can derive from variations in national approaches to mitigating climate change and tackling related domestic energy challenges. They can differ in the degree to which low-carbon technologies and solutions become (or are seen as) a source of national competitiveness. Since these innovation paths can have a significant influence on the pace and effectiveness of low-carbon transitions, a better understanding of their main characteristics, the factors that shape them and their relationship to each other may provide insights for national and international climate policy-makers on how to enable and accelerate such a transition.

So far, the EU has been a global frontrunner in many areas of renewable energy through innovation in both policies and technologies. The wind power industry, in particular, plays a key role in the efforts of many countries in Europe to move towards renewables as a significant, even dominant, source of energy. Denmark and Germany were first movers in the wind industry and quickly developed a strategic advantage that led to the dominance of Danish and German firms in the industry worldwide. To date, Denmark and Germany remain lead markets for wind energy. Both countries are widely considered role models in the development of policies to support the expansion and development of the wind energy industry. While it is predicted that the use of wind power for electricity production will more than double in the next generation, the specific paths for its deployment are hotly debated.

At the same time, major emerging economies such as China and India are rapidly catching up, developing their own wind power policy regimes at home while their firms build technological competence through a range of activities, including international acquisitions and technological alliances. China has become particularly focused on green technology, with wind power now designated as one of five strategic high-tech industries. India has invested relatively fewer resources into domestic deployment, but has world-class wind power R&D centres and firms competing in overseas markets. The rapid development of the 'rising powers' influences the global dynamics of the wind power industry (Lema et al. 2013).

Thus, the wind energy sector is in flux both globally and at the level of individual nations. With this in mind, the main purpose of this article is to examine the innovation paths in wind energy in Europe (Denmark and Germany) and Rising Asia (China and India) and understand how these paths have evolved in the face of domestic and global challenges. This article will also shed light on how national and international public policy shapes these innovation paths along with other factors, such as corporate strategies and market evolution.

Since innovation paths in renewable energy unfold in home markets that reflect differing priorities and differing initial conditions in terms of resources and capabilities, the main underlying hypothesis that drives this article is that innovation paths are likely to differ markedly between countries, not least in the area of low-carbon technologies, which depend critically on emergent technological capabilities and politically negotiated objectives.

However, there are forces that may lead to convergence between national development paths, such as 'best practice' and demonstration effects, globalisation of technology, global standards, insertion of national firms into global value chains or national and international climate policy. Furthermore, trajectories may be influenced less by national factors than by technologies and business models adopted by specific firms. In fact, it is uncertain whether it is countries or firms that are innovative.

Accordingly, the research questions for this article are:

- Do wind power innovation paths differ between Europe and Asia? If so, how do they differ?
- Do differing innovation paths reflect different initial conditions in Europe and Asia?
- Can we expect divergence in the future?

Why engage in such a comparative study of innovation paths in wind power? First, as noted above, such a study can help us better understand the dynamics of these innovation paths, especially the interplay of capabilities, markets and institutions in these key countries. It can shed light on possible strategies for technological cooperation between these and other countries and provide guidance for the international efforts towards technology development and transfer. It can also help us to understand how different countries may position themselves in global value chains and find synergies between their environmental imperatives and developmental aspirations.

Wind power, a relatively young industry, is particularly interesting in this regard, because the European leaders (Denmark and Germany) were globally dominant until international competition increased ten years ago, not least from the giant emerging economies of Asia (China and India), thereby changing the rules of the game regarding investment, technological development and production. To explore these questions, this article draws on a set of coordinated studies of innovation paths in Europe (Lema et al. 2014a), China (Dai et al. 2014) and India (Narain et al. 2014). In Europe, Denmark and Germany were chosen as country case studies as they are widely regarded as the forerunners of the wind power industry. China and India are the largest (emerging) economies in the world, and they have both invested heavily in wind turbine markets and have created leading firms in this industry.[2] The countries that were chosen differ significantly in terms of market size, technological capabilities, corporate strategies of champion firms and policy contexts.[3]

Section 2 describes the conceptual underpinnings that underlie this research, addressing the causes of convergence versus divergence in innovation paths. The divergence scenario is buttressed by theories of national innovation systems (Lundvall 1992; Nelson 1993) as well as theories of path dependence and creation (Dawley 2014; Karnøe and Garud 2012; Simmie et al. 2014). The convergence scenario, on the other hand, finds support in arguments emphasising globalisation and the late-comer effect (Dutrénit 2004; Lee 2013; Mathews 2006).

Section 3 examines the innovation paths in the four countries. It finds that although there are many differences between the four countries, the most important differences are between Europe and Asia. At the same time, there are multiple key similarities. We also identify converging trajectories along several dimensions. Section 4 seeks to explain these findings by addressing the roles of country conditions and global flows of technology and knowledge.

Section 5 draws our conclusions with respect to the core questions raised in this article. It brings out the value added to the literature and discusses the implications for international competition and for the diffusion of wind energy as a renewable energy technology.

2 National low-carbon innovation paths in the global economy

2.1 Path dependence and path creation

For the purposes of this article, an innovation pathway can be understood as a technological trajectory at the sector level. Successive sectoral innovations are historically shaped by, and will themselves shape, the path of a given technology. This notion is rooted in evolutionary economics, which emphasises that pathways tend to be cumulative and self-reinforcing because they are continually being influenced by extant infrastructures, institutions and capabilities (Dosi 1982; Nelson and Winter 1982). In other words, innovations are often path-dependent in the sense that they are built upon earlier technologies, experiences and competition strategies (Arthur 1994; David 1985).

The notion of path dependency in evolutionary economics arose as a critique of standard neoclassical economics, in which economic processes are typically seen as formed by efficiency-seeking behaviour, which continually moves particular markets (sectors) towards an optimum state. In path-dependence theory, there is no such single equilibrium. On the contrary, there are typically several possible equilibria, and prevailing paths—the 'dominant designs'—may not be globally efficient. A trajectory depends on initial conditions, contingencies (chance events) and self-reinforcing mechanisms. Path processes may be become subject to 'lock in', whereby the direction of the path becomes so entrenched that the actors cannot change its course.

In recent years, a number of authors have criticised the path-dependency perspective for being overly deterministic. They focus on innovation paths as emergent properties and on how 'mindful deviation' by purposeful actors, such as firms and policy-makers, opens up new paths or changes the direction of existing ones (Garud et al. 2010; Martin and Sunley 2006). Thus, it is not only the initial conditions that determine a trajectory, but also the boundary conditions. It is no coincidence that this debate about path dependence and creation has been particularly prevalent in discussion of low-carbon development. The climate change problem has been perceived as a 'carbon lock-in' (Unruh 2000), and green path creation has emerged as a notion of breaking out (Lema et al. 2014b: 25). The latter depends on 'the possibility of purposefully crafting a desirable path' (Kemp et al. 2001: 269).

The intention to create new pathways in the energy domain—not least by adding renewable sources, with the ultimate goal of replacing fossil-fuel energy—is a particularly strong example of intentional new path creation. Many countries are trying to reshape their energy sectors by promoting low-carbon alternatives. However, each of them must work with different starting points and constraints. This raises the question of whether these paths will gravitate towards dominant designs or whether multiple pathways will emerge.

Section 2.2 seeks further insights from theory to frame this question. Later sections will address it empirically by examining the wind energy sector in selected European and Asian countries. The wind sector has been studied as an exemplary case of path creation. Existing studies have examined the cases of Denmark (Andersen et al. 2014; Karnøe and Buchhorn 2008), Germany (Fornahl et al. 2012; Simmie et al. 2014) and the UK (Dawley 2014; Simmie et al. 2014). However, only limited attention has been paid to countries outside Europe, with some studies on China and India (Chaudhary et al. 2014; Dai and Xue 2014; Lewis 2007). There has been no work, however, comparing countries from these major regions.

2.2 Divergence and convergence

Green innovation takes place within the boundaries of common global challenges, including the need to decouple growth from resource use, to increase the use of new and renewable energy sources, to increase energy efficiency and to reduce carbon emissions (Lema et al. 2014b). Although these general challenges are shared among nations, specific pathways may evolve in different directions depending on particular national starting points. On the other hand, competitive forces in globalised markets may, over time, create dominant designs—winning technologies and 'best practices' for their adoption and use. Technology choices may also be influenced by international cooperative efforts to meet these climate change challenges jointly. There is, however 'no simple theory that can explain or predict, when innovation paths converge or diverge' (Schmitz and Altenburg 2015, this issue).

On the one hand, innovation paths will likely reflect the systemic characteristics of the countries in which they have evolved (Lundvall 1992; Nelson 1993). Pathways emerge in different countries through a context-dependent process involving interaction between firms and other organisations, influenced by national institutions (e.g. policies and regulations) and the economic and social structures of specific countries. Particular countries may develop their own paths as sectors branch out in different directions (Frenken and Boschma 2007). Altenburg and Pegels (2012) suggest that innovation pathways in sustainability-oriented industries are particularly country-specific, due to the important role of public policies and public finance. The same conclusion can be reached from reviewing existing literature emphasising technological factors, such as the dependence on specific national infrastructures of many carbon-reducing technologies (Jonsson 2000). In other words, there are strong reasons to believe that innovation pathways will be country-specific.

On the other hand, the national factor may be over-emphasised when industries are characterised by global inter-connectedness. National distinctiveness may play less of a role when technologies are mobile and subject to significant international 'transfer' through trade in global value chains, globally-mobile engineers, direct investment from abroad, mergers and acquisitions, and international co-operation for greenhouse gas mitigation. Flagship firms are likely to originate from particular green 'lead markets', but this dynamic home base will often be used as a platform for subsequent diffusion through export initiatives and other cross-border activities (Beise and Rennings 2005). Technologies thus become international, as opposed to country-specific, and this tendency may be reinforced by the adoption of 'best practice' policies within specific domains, which lead to similarity in outcomes or 'path transplantation' (Dawley 2014). In addition to the internal forces that tend to be emphasised in the literature on path creation, such external factors need to be taken into account.

These exogenous mechanisms may be particularly important for the purpose of the present article for two reasons. First, the pressure arising from environmental challenges, especially the climate challenge, is typically considered to require global deployment—and hence diffusion—of environmental innovations. A range of global governance policy mechanisms is being put in place for this end. Such diffusion involves transplantation and adaptation of innovative designs across borders. In commercial terms, first-mover countries are likely to dominate the world market for these innovations (Rennings 2014), which may by extension create similarities across international growth paths. Second, the same logic arises from the context in which late-comer countries seek to catch up. This situation may create inflows of foreign direct investment and associated technological spillovers, and local firms may adopt reverse engineering strategies and licensing (Dutrénit 2004; Mathews 2006). This is likely to facilitate convergence.

Lee (2013: 16) defines 'path-following' catch up as the trajectory by which latecomers follow the same path taken by their forerunners.[4] In the absence of strong capabilities for the creation of their own paths, emerging economies may move along linear 'path-following' trajectories, just as as late-comer firms follow the same path as that taken by their predecessors. In some cases, latecomers may skip stages of development to catch up more quickly, while still following the overall trajectory of the first movers ('leapfrogging'). Echoing ideas from Freeman and Soete (1997), Lee argues that for latecomers, the emergence of new industries and new generations of technologies create particularly good opportunities to break free of the established path and move beyond catch-up. In such circumstances 'a country can construct its own unique path and diverge from that of its forerunners' (Lee 2013: 18).

Given that green technologies are new and emerging, they may provide particularly good opportunities for new path creation and divergence for latecomers.

Most of the literature has concentrated on the causes of path creation (Karnøe and Garud 2012; Martin and Sunley 2006) and, more recently, on why innovation paths diverge or converge (Schmitz and Altenburg 2015, this issue). Less attention has been paid to the manifestation of these paths and the similarities and differences between them, yet the question of how paths diverge (if they do) is particularly important in the context of green technologies. This is because the efficiency of climate change mitigation may differ between different paths and because the nature of the trajectories may provide insights as to who will be the economic winners and losers in the green transformation.

3 Wind power innovation paths in Europe and Asia

Wind energy is the most commercialised and most successful type of renewable energy presently available (International Energy Agency 2015). The wind sector is characterised by ongoing innovation to reduce the cost of energy, so that it can more successfully challenge long-established fossil-fuel energy sources. The industry has become 'strategic' due to its potential as a source of energy generation, job creation and export revenue.

However, these potential benefits are unequally distributed along the wind energy value chain. The nature of activities and the underlying knowledge bases vary along the chain. Consequently, so does the global mobility of production and innovation. The distribution of benefits between nations depends crucially on their respective innovation paths and the degree to which these paths differ.

In the wind power industry, innovation takes place at two different levels: at the core technology level (the wind turbine and associated equipment) and at the deployment level (the installation of turbines). The distinction between core technology and deployment is analytically useful, even though the boundary between the two is blurred in reality. It is used in this article to unbundle the notion of innovation paths. Key indicators for examining innovation paths in wind power are shown in Table 1, which covers aspects of both core technology and deployment.

Different firms tend to specialise in different activities at both levels. Regarding core technology, the main actors are wind turbine generator producers and component suppliers. At the deployment level, the key firms are utility companies or independent power producers, which may be independent firms or cooperatives. A range of other firms also engage in deployment, including planning, construction and logistics firms, consultancy services providers and operation and maintenance (O&M) services providers.

3.1 State of wind energy deployment and industry development

As can be seen in Fig. 1, there are major differences in the historical development of wind power in the four countries. Denmark, an early mover in wind energy, now generates 40% of its electricity by this means. Denmark has also been the world leader in turbine technology for more than 30 years. Danish firms hold 25% of the total global turnover in this industry, with Vestas, the national leader, representing 13% of the global market in 2013. Denmark is also a key location for inbound investment in wind power development activities, such as R&D, testing, and high-quality production. This status has been achieved with the strong support of government policy.

Germany is currently the largest wind energy market in Europe and the third largest in the world, after China and the USA (Bundesverband Windenergie 2012). In 2013, Germany had an installed capacity of more than 34 GW, and its installed capacity and market have been growing continuously since the mid-1990s (Earth Policy Institute 2014). The large majority of Germany's installed capacity is onshore, with only about 253 MW (0.253 GW), less than 1%, offshore as of 2011 (Fraunhofer Institut für Windenergie und Energiesystemtechnik 2012). After years of stagnation and financial crisis, the wind energy sector seems to have recovered, as shown by growing installation trends. This is due to large wind energy capacity being added in areas of low wind speeds in Southern Germany. The leading German firms, Siemens Wind Power and Enercon, had 4.4% and 9.8%, respectively, of the global market in 2013 (Lema et al 2014a).

India's wind energy sector has grown considerably in the past decade. Total installed wind power capacity reached 20.1 GW by 2013, up from 1.63 GW in 2001–2, thus registering an average annual growth of 28.6%. Although substantial in itself, this is only a small percentage of the estimated potential: the onshore gross potential that can be harnessed from wind energy in India is now estimated at about 103 GW (revised upwards from 49 GW). Wind power is concentrated mainly in the southern state of Tamil Nadu, with an installed capacity of almost 7 GW (as of the end of March 2012), representing about 40% of India's total installed wind energy capacity at that time. Suzlon, the leading Indian wind turbine manufacturer, had 5.3% of the global market in 2013.

The last ten years have witnessed a dramatic development of the Chinese wind industry. China has become the global leader, both in terms of annual installation capacity and total installation capacity, which reached 91.4 GW in 2013. According to China's national plan, nine large-scale wind farm bases of 10 GW installation capacity each will be built by 2020. China has also gained substantial technological capabilities for wind energy. At least 30 turbine manufacturers produce parts, equipment, and wind turbine systems in China, with the top three firms (Goldwind, United Power and Mingyang) together accounting for 18.5% of the global market in 2013.

The four countries studied share a continued and increasing emphasis on wind power industry development and wind power deployment. While there are differences in the innovation paths of these countries, it is striking that countries with such different initial conditions have such strong similarities.

3.2 Innovation path similarities across Europe and Asia

There are four main similarities common to all the innovation paths studied across Europe and Asia. The first similarity is the increasing

Table 1. Key dimensions for analysing innovation paths in wind energy

Dimension	Example of key indicator
Turbine size	Nameplate capacity in MW
Turbine quality	Reliability as reflected in turbine capacity factors, O&M costs
Turbine design	Use of gear versus direct drive models; product diversification
Onshore/ offshore	Share of offshore segment compared to onshore segment
Project size	Project capacity in megawatts and number of turbines

Source: Lema et al. (2014a).

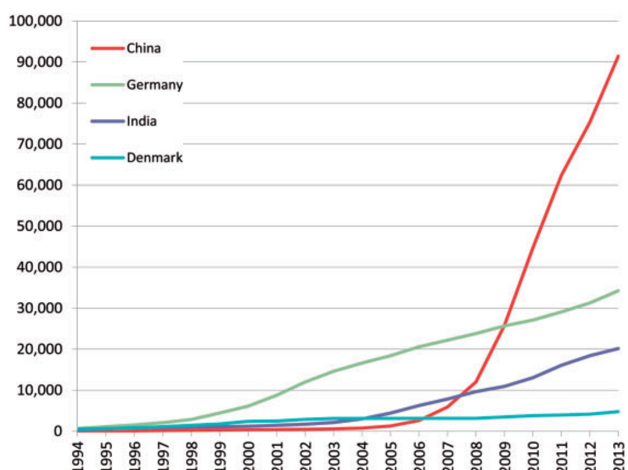

Figure 1. Installed capacity (MW).
Source: Earth Policy Institute (2014).

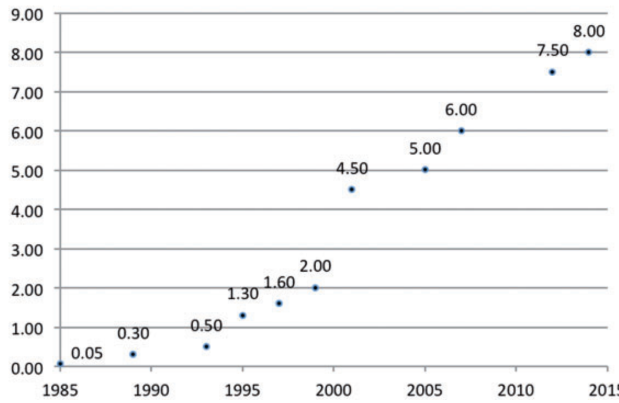

Figure 2. Growth in size of turbine capacity (in MW) since 1985.
Date indicates first year of operation.
Source: International Renewable Energy Agency (2012) and Wind Power Monthly (2014).

Table 2. Examples of large turbines

Manufacturer	Country	Model	Capacity (MW)	Year
XEMC	China	XD115	5	2011
Sinovel	China	SL6000	6	2011
Siemens	Denmark/Germany	SWT-6.0 150	6	2011
Enercon	Germany	E126	7.5	2012
Vestas	Denmark	V164	8	2014

Multi-MW turbines are mainly developed for offshore market.
Source: Wind Power Monthly (2014).

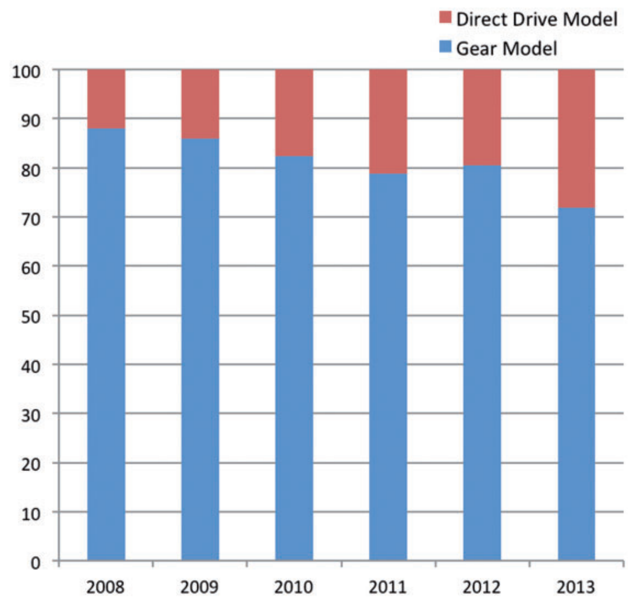

Figure 3. Gear model and direct drive model market shares.
Source: BTM (2014).

size of turbines developed and installed, which is a strong trend in all four locations. Turbine capacity has been increasing dramatically over the years, and all of the leading manufacturers are participating in the race to develop ever larger turbines. The continuous up-scaling of wind turbine capacities, towers, rotors and blades is a prominent characteristic of the innovation paths in both Europe and Asia. Fig. 2 depicts the growth in turbine size over the last 30 years, showing the years in which new larger prototypes were installed and connected to the grid. Table 2 shows that manufacturers from Denmark, Germany and China were key participants in this trend. Technological ability to increase the size of turbines significantly exceeds the growth in demand for larger turbines. Nevertheless, the growth in demand for larger turbines is visible in all four markets. Globally, the average size of turbine connected to the grid in 2013 was 1.9 MW, compared to 1.8 MW in 2012 and 1.6 MW in 2008 (BTM 2014).

The second similarity is the increasing reliability of turbine technology. Improvements in turbine reliability are an important feature of the innovation paths across all cases. While many key informants highlighted the 'quality dimension' during our interviews, this metric is not easily verified empirically. However, one indicator of increased reliability is the reduction of O&M costs, for both scheduled and unscheduled repairs. This reduction holds true across markets: average O&M costs have dropped 38% in the period 2008–12 (Bloomberg New Energy Finance 2012). Such a reduction in costs helps to increase the competitiveness of wind energy significantly in relation to other energy sources. Another indicator is the capacity factors of installed turbines. Capacity factors have increased across all locations studied in this research.[5] This development is further evidence of fast learning for technological progress in wind turbine development.

The third similarity is the existence of a dominant design in turbine technology. Wind turbines with gears—the so-called 'Danish design', using doubly-fed induction generators (DFIG)—are the dominant design in the global wind power industry. Even though several companies, including Enercon, Siemens Wind Power and GE Wind Energy, are adopting direct-drive wind turbines, the Danish design still remains the industrial standard globally. The gear-model design is dominant in the EU at large but, as will be discussed, Germany is an outlier in this regard since the gear model is not predominant there. The gear model is also dominant in China and India. Globally, the DFIG dominates the accumulated installation base, but newly added wind power capacity shows that its dominance might be challenged in the future. Fig. 3 shows the dominance of the gear model amidst the steady rise of the direct-drive design. In 2012, the DFIG model accounted for 80.5% of added capacity, but in 2013 this had dropped to 72%.

The fourth similarity moves us from core technology to deployment. This is the increasing shift to utility-scale deployment, which is becoming a major trend in all four countries. Individual projects are becoming larger, with more turbines in each project, particularly in new offshore projects but also onshore. This development has been associated with a shift in ownership structures: over the last 5–10 years, large utility companies and independent power producers have entered the market to a much greater extent than before. Convergence has occurred along this dimension. The difference between the first movers in Europe and the rest of the world has largely disappeared in recent years, so that ownership structures are very similar globally. In terms of trajectory, this is a break away from the 'Nordic' Danish and German wind power models, which were based on private equity investment and popular participation in tax-driven projects.[6] In China, large, state-owned utilities have dominated wind project development since the emergence of the industry. The trend is visible in India, but it is slower due to the historically dominant role of independent power producers.

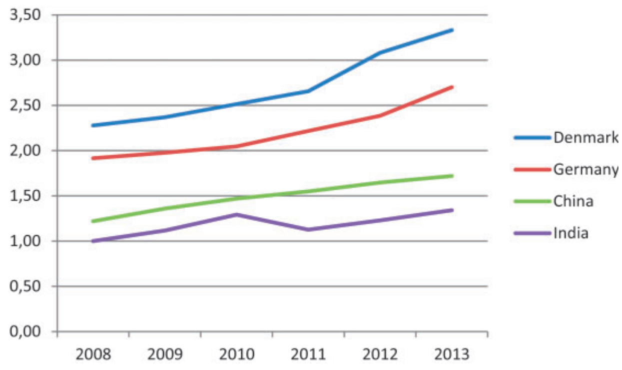

Figure 4. Average size of turbines (in MW) installed each year.
Source: BMT Navigant (2014: 46).

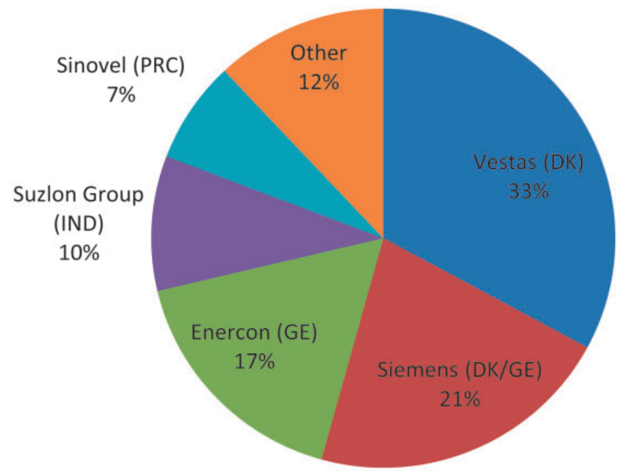

Figure 5. Leading suppliers in multi-megawatt size class (2013).
Source: BTM (2014).

3.3 Innovation path differences and variations across Europe and Asia

This subsection will now identify differences and variations in innovation paths between Europe and Asia. The first difference is a variation in the size of the turbines that are in use, which continues to exist across the countries studied despite the shared tendency towards larger turbines. The data shows that on average, deployed turbines are larger in Europe than in Asia. Fig. 4 shows that in 2013, the average sizes of turbines were 2.7 to 3.3 MW in Europe (Germany and Denmark, respectively) compared to 1.3 to 1.7 MW in Asia (India and China, respectively). Among major markets, India has the lowest average size of turbines in use, which is mainly due to the logistical challenges of transporting large turbines to wind sites. The size difference is also due in part to the fact that offshore turbines tend to be larger than onshore turbines, and India has not yet developed an offshore market.

The continental differences are also related to the technological profiles of national firms. As shown in Fig. 5, European champion companies (Vestas, Siemens and Enercon) dominate the sale of large turbines. The multi-megawatt segment (defined as turbines larger than 2.5 MW) is a European mainstay, although champion firms from India and China (Suzlon and Sinovel) have also entered the market segment on a smaller scale.

Similarly, despite the shared trend in quality enhancements, the second variation pertains to reliability differences between Europe and Asia. Asian turbines tend to be lower cost compared to European turbines, but the difference in the cost of electricity generated by these wind turbines (the levelized cost of energy) is not as great as the difference in the upfront costs of the turbine. The reason is technological. Due to a higher quality of turbine (better reliability, longer lifespan etc.) combined with better siting, each turbine in Europe produces more electricity than its Asian counterpart (normalized for turbine size). Table 3 shows that capacity factors are significantly higher in Europe than in India and China, not least in offshore projects.

Thirdly, there are differences when it comes to turbine design. One element of this is the tendency in Asia to design low-cost turbines. As shown in Table 3, the typical capital costs for onshore farms in 2010 were US$ 1850/kW in Europe and US$ 1300/kW in China/India. The turbines are the major budget item. The price difference is not only a reflection of factor cost differentials. The Chinese turbine manufacturers tend to rely more on licensing of standardised designs than do European firms. This creates economies of scale in the component supply layer in China and drives down the cost. Another element is the dominance of European firms in the proprietary design of turbines, not least for the offshore market.

Table 3. Typical new wind farm cost and performance in 2010

	Installed cost (US$/kW)	Capacity factor (%)	Levelized cost of energy (US$/kWh)
China/India	1300–1450	20–30	0.06–0.11
Europe	1850–2100	25–35	0.08–0.14
Europe (offshore)	4000–4500	40–50	0.14 –0.19

Source: International Renewable Energy Agency (2012).

This dominance of Europeans firms in the design of turbines tailored for offshore installation is closely related to a fourth difference. Offshore deployment is a very strong pathway for deployment in Europe, whereas that has not been the case in Asia so far. As emphasised by Andersen (2014), the offshore wind segment is an example of an industry that has branched out from its roots in the traditional onshore wind energy industry. However, this branching process has been largely confined to Europe. More than 90% of worldwide installed capacity is in Europe. As shown in Fig. 6, the UK leads on offshore wind with 54% of offshore capacity, followed by Denmark (18% of world offshore capacity) and Germany (7%). Five percent of worldwide offshore capacity is installed in China, while India does not yet have any offshore wind farms. China has adopted a range of ambitious policies to expand the offshore segment. [7] However, China is facing a series of barriers to the development of offshore wind, both in terms of policies and technologies. Specifically, China has technical problems in almost all aspects involving infrastructure, turbines, foundations, installation and operations (Beyer 2014); this dampens China's prospects for offshore wind in the near future. India has only recently started exploring offshore opportunities, with the intention of mapping the possibilities of this wind resource.

Fifth, despite the trend towards larger project size, there are variations along this dimension. One variation is in the location of new large projects. As seen in Table 4, megaprojects are installed offshore in Europe, but onshore in China and India. For example, compare the European offshore projects of 400–630 MW with the Asian onshore projects of 500–1,000 MW. The table shows that Asia surpasses Europe when it comes to megaprojects, particularly onshore projects. The increasing size is associated with a shift from turbine manufacturers to independent power producers and utilities which has occurred in all of the countries studied.

This subsection has identified a number of significant differences and variations between Europe and Asia. Some of these differences are likely to converge in the future, while others may remain different or even diverge further. We return to this point in Section 4. In the meantime, Section 3.4 seeks to disentangle the innovation paths further by identifying a number of sub-trends that add further complexity to the picture.

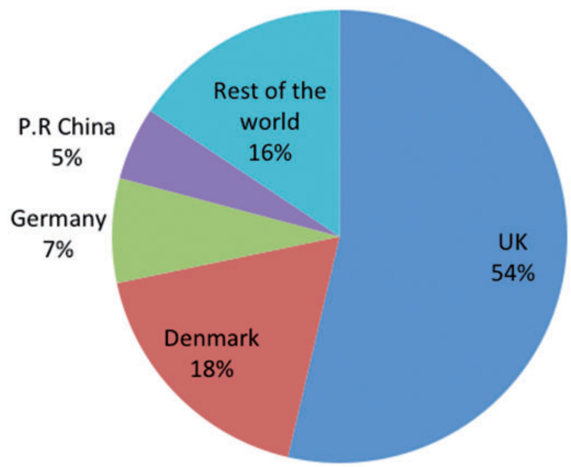

Figure 6. Worldwide offshore wind power (2013).
Source: BTM (2014).

3.4 Innovation path experimentation and branching

So far, a relatively clear picture has emerged showing that certain innovation paths are shared between Europe and Asia, while others remains distinct (see Table 5). Similarities are particularly strong in core technologies, while most of the differences relate to peculiarities in the deployment trajectories, which then have an influence on the innovation path. However, several complexities become apparent if one pays attention to exceptions and sub-trends or 'branches' of the innovation path. Such an analysis shows that: experimentation may create new branches in the future, a number of sub-trends can already be identified, and co-existence between some paths and branches is likely to continue.

In terms of turbine size, the main path is towards ever larger designs, even if adoption is slower, so that the turbines in use are smaller than the largest available, particularly in Asia. These paths concern the main markets for onshore and offshore turbines in the main utility-scale markets. However, there is also a sub-trend of small and micro-turbines aimed at distinct markets that are gaining increasing attention, particularly off-grid installations and minigrids in rural areas. China and India may have initial conditions that present the best 'fit' for such turbines. Indeed, China is the lead market globally for small-scale wind power (Rueter 2014).[8]

Regarding turbine quality, a number of observers have emphasised the reliability differences between European and Asian turbines. Such differences seem to be widespread, according to interviews, but the gap is probably closing and the shared trend is

Table 4. Large wind farms in Asia and Europe

Name	Capacity (MW)	Location	Country	No. of turbines	Turbine model	Operator
Jaisalmer Wind Park	1064	Onshore	India	N/A	Suzlon 350 kW to 2.1 MW	Suzlon Energy
London Array	630	Offshore	UK	175	Siemens 3.6 MW	DONG Energy
Dabancheng Wind Farm	500	Onshore	China	300	Goldwind 20 kW to 3.0 MW	Xinjiang Tianfeng Wind Power
Anholt	400	Offshore	Denmark	111	Siemens 3.6 MW	DONG Energy
Bard Offshore 1	400	Offshore	Germany	80	Bard 5.0 MW	Bard

Source: Dai et al. (2014), Lema et al. (2014a), Narain et al. (2014).

Table 5. Innovations paths in Europe and Asia: Summary of findings

	Innovation path similarities between Europe and Asia	Innovation path variations between Europe and Asia	Innovation path experimentation, branching and flux
Turbine size	• Increasing average turbine size in all cases	• Turbines in use are larger in Europe than in Asia	• Coexistence of micro turbine paths in all cases
Turbine quality	• Increasing reliability of turbines in all cases	• Reliability differences between Europe and Asia	
Turbine design	• Dominant designs established in both Europe and Asia	• Low cost turbines mainly in Asia • Tailored offshore turbines mainly domain of European firms	• Coexistence of competing designs in all cases • Direct-drive models dominant in Germany
Onshore/ offshore		• Offshore deployment largely confined to European cases	• Some offshore experimentation in China
Project size	• Increasing average project size	• Megaprojects are offshore in Europe but onshore in Asia	• Higher degree of distributed deployment in Europe
Deployment services			• Experimentation and co-coexistence of a variety of service provision models

towards increasing reliability of turbine technology overall. However, the question is whether there will be room for market segmentation, with demand preferences for different price–quality constellations. If so, Europe may have advantages in 'high end' markets. The quality drive was highly visible in all of the micro-level innovation cases across the countries under study, but particularly in Europe, where firms have had more time to journey along the learning curve.

When it comes to turbine design, it is clear that the focus on product diversification is growing, so that specialised turbines are developed for maximum output in low wind speed areas, in different climatic conditions (altitude and temperature) and under different regulatory environments, such as height restrictions or the need to avoid radar interference. Most of these are minor innovation path 'branches' growing from the main designs. When it comes to these main designs, there is a co-existence between gear models and direct-drive models, which is a common feature of all the countries. However, the development of the direct-drive is a German innovation, first developed by Enercon, and the direct-drive model is dominant in Germany, with a market share above 60%. Gear-model wind turbines are prevalent among the wind turbines installed in Denmark.[9] The existence of competing designs is now a global phenomenon with European roots, and competition between these designs also plays out in Asia. In China, different lead firms back different technologies, with Sinovel backing direct-drive and Goldwind backing the gear model (Zhou et al. (2015, this issue)). The same situation exists in India. Both the gear models and direct-drive models are being deployed within the India market, with a growth in the market share of gearless technology over the past few years. Although the gear models promoted by Suzlon had a near-monopoly until a few years ago, a number of Indian firms are now seeing growth in the direct-drive concept, particularly Wind World India (formerly known as Enercon India), which displaced Suzlon as the Indian market leader in 2013 and promotes direct-drive technology (Narain et al. 2014).

When it comes to deployment, there is also a diversity of paths, not least in trends in project size. The main trend is an increase to utility-sized projects (including offshore projects), but there is also a continuing sub-trend of smaller-scale deployment. This second segment is driven by distributed generation and new deployment service patterns.

The smaller projects are scattered and distributed more evenly in geographic terms. Therefore centralisation and decentralisation trends co-exist, with the decentralised-generation phenomenon growing (in absolute terms) within the overall rapidly-expanding wind market. Both Denmark and Germany had a decentralised-generation structure during the 1980s and 1990s, but the shift in these countries has been towards utility-scale projects. Asia, particularly China, saw 'stage skipping', whereby large utilities such as Longyuan became dominant from the outset.

There has long been a debate over the prospects for decentralised deployment in China and India. So far, the technological advance in small wind turbines and decentralised deployment has been very limited in those countries. The Chinese government is currently devising support for distributed energy provision (i.e. energy that is generated onsite or near energy end-users, including for small wind turbines) (China Greentech Initiative 2014). In China, the 12th Five-Year Plan of Wind Energy (2012) thus stipulates an increase in distributed wind power to a total of 15 GW in 2020,[10] while India has no specific targets for distributed wind power.

Given these countries' socio-economic contexts, one might have expected more investment and progress in India and China. In Asia, particularly in India, decentralisation is hindered by infrastructure problems (transporting turbines to the point of installation), by the problem of grid volatility and by the economics of deploying and maintaining small wind power systems. However, this pattern may be reversed if China and India find breakthroughs in mini-grid and off-grid technologies, which may be particularly relevant to electrification in rural communities or for other areas where the grid supply remains limited. In India, there was a programme to set up off-grid micro wind-electric generators (5 kW) in the late 1980s, but there were problems with installation, maintenance and integration with other energy sources, which may indicate that the system capabilities were not in place at the time. In China, there are now specific targets for off-grid deployment of wind. While there are successful wind–solar hybrid systems used for road lamps, highway monitors and communication stations, there are only a few systems in place for residential and commercial use in remote areas and on islands (Chen et al. 2011).[11]

Future research should examine why there was so little technological advance and increase in off-grid deployment. Both China and India have huge off-grid pockets where energy is greatly needed, yet the existence of these regions (often remote but sizable) has not translated into major public policy initiatives and/or private innovation efforts. Some progress in improving technology and deployment has been made, but it seems only minor and slow. The main reason may be a lack of purchasing power, combined with the extra costs involved in remote deployment. Another important issue is that concern with energy security and industry development have been major drivers behind the expansion of wind energy in China and India, and these concerns have only benefited on-grid technological development and deployment.

4 National versus global drivers and shapers

This section discusses the reasons for the observed innovation paths, starting in section 4.1 with the role of home markets. Unsurprisingly, it suggests that sector trajectories are significantly moulded by national settings. The differences identified in the previous sections are indeed reflections of national innovation systems, particularly policy regimes designed for either catching up or staying ahead. While it is impossible to lay out the specific constellations of factors which have shaped all the different elements of the observed innovation paths, it is possible to provide an account of how some key 'determinants' have helped shape elements of identified paths. Section 4.2 then considers the role of cross-national interactions in shaping innovation paths. It shows how many dimensions of the innovation paths emerged first in Denmark and Germany, and then became adopted in and diffused through China and India. However, this process is driven from both sides, as national champion firms increasingly engage in the organisational decomposition of innovation.[12]

4.1 The role of the home market in shaping national innovation paths

Innovation paths reflect national context and characteristics, not least the supply and demand conditions of home markets. On the demand side, the size and nature of the home market is a key factor. During the recent financial crisis, the volume of demand in Europe has *st*agnated somewhat while it has grown in Asia, especially in China. Equally important is the nature of demand—demand for particular types of projects (e.g. onshore/offshore) or technologies (e.g. gear model or direct-drive model), with different contractual emphases (e.g. upfront vs. lifetime costs), different standards etc.

Table 6. Key geographical differences between case countries

	Landmass (km^2)	Coastline (m)	Population	Coastline/area ratio (m/km^2)	Coastline per capita (m)
China	9,326,410	14,500,000	1,355,692,576	1.55	0.01
India	2,973,193	7,000,000	1,236,344,631	2.35	0.006
Germany	348,672	2,389,000	80,966,685	6.85	0.03
Denmark	42,434	7,314,000	5,569,077	172.4	1.31

Source: CIA World Factbook.

Table 7. Wind incentives in case countries

Country	Feed-in tariff
Denmark	Onshore wind receives a subsidy of DKK 0.25/kWh (€0.033/kWh) on top of Nordpool market price for electricity during first 22,000 hours of full load operation. Market price of NordPool varies from DKK 0.26/kWh to DKK 0.38/kWh (€0.034/kWh – €0.050/kWh)
Germany	Feed-in tariff rate for onshore projects begins at €0.098/kWh, which is paid for at least five years. Projects may receive additional bonuses for grid compatibility and repowering. After five years rate is reduced in stages, depending on site productivity. Tariff is received for a total of 20 years
China	China has been divided into four regions, based on varying qualities of wind resources present, and fixed feed-in tariff rates vary accordingly, ranging from CNY 0.51/kWh (€0.061) for best wind-speed areas up to CNY 0.62/kWh (€0.075) for poorest. Competitive bidding is used for offshore projects
India	India operates a system of preferential feed-in tariffs determined by regulators, available in 13 Indian states. Feed-in tariff price ranges from INR 3.2 – 6.14/kWh (€0.045 – 0.086/kWh), and tariffs are offered for a varying number of years, depending on state. Government has announced it plans to bring back additional funding via Generation-based Incentive

Source: BTM (2014: 146ff).

The case of China shows how rapid market expansion combined with relatively loose demand specifications meant that the initial pathway was characterised by lower cost and, often, less reliable technology (Dai and Xue 2014). Thus, much of the policy focus was on rapid capacity increase through 'less demanding' deployment. It was not until recently that the Asian giants shifted from policies intended to increase installed capacity to so-called generation-based incentives focusing on electricity output. Generation-based incentives were only introduced in 2009 in both India and China (Dai et al. 2014; Narain et al. 2014). European countries have come further in creating demand-policy frameworks that create incentives for improving quality (e.g. the market price-based variable feed-in tariff in Denmark and the tapering feed-in tariff used in Germany) (see Table 7). Demand conditions have also shaped the up-scaling trends in most countries, as regulations and incentives, such as tendering requirements, have been put in place for larger turbines (Lema et al. 2014a).

On the supply side, the nature of the innovation path depends critically on the existence of national champion firms with production and innovation capabilities. There are enormous differences between lead firms from Europe, China and India with regard to market strategy, business models, internationalisation strategy and innovation capability (Dai et al. 2014; Narain et al. 2014). The strongest capabilities are still embedded in firms and innovation systems in Europe, which tend to have a higher degree of investment in R&D, more advanced testing facilities etc.. This helps to explain the remaining differences in reliability. The role of supply-side capabilities in supplying technologies is evident in the case of the offshore trajectory in Europe. Here, the industry was able to draw on the national maritime competencies needed for offshore wind deployment. A policy focus on offshore wind arose to due to geographical conditions (i.e. high-wind coastlines) (see Table 6). This focus could develop from accumulated wind capabilities onshore combined with maritime capabilities arising from the shipping industry and experiences in natural gas exploitation. These initial market conditions propelled Denmark to become the world leader in offshore wind.

The high per-capita investments in wind energy deployment as well as public and private support for capability building in Northern Europe, combined with highly developed innovation systems, created platforms for innovations that set the course for future pathways. However, the 'Asian giant' countries have been strengthening their innovation systems to catch up in quality. In China, the regulatory environment and firm-level capabilities and priorities were conducive to cost innovations and business models that could facilitate a more rapid uptake of wind turbine technology globally, but the government is now also supporting R&D in the wind power sector to increase technological development (Lewis 2013). In India, policy has focused more on diffusion, although the government created the National Institute of Wind Energy with the intention of strengthening wind power in the country through R&D, wind-resource mapping, standards, testing and certification (Narain et al. 2014).

Thus, there are indications of a strong influence of 'home markets' in shaping national innovative paths. Such home markets are politically constructed and reflect underlying priorities. In Denmark and Germany, wind power markets have been driven by environmental and industrial development concerns. Firms and policy-makers were the first movers to develop a quality drive in the development of the industry, and these actors were also pioneers in the establishment of a sectoral system of innovation that supported and directed technological development (Lema et al. 2014a). In China and India, it was mainly energy security imperatives that led to policies that created a demand for wind energy (Dai and Xue 2014; Urban et al. 2012). In the case of China, industrial policy—aimed at catching up and building competitive industries—also played a role, as evinced by early support through the '863' program of the Ministry of Science and Technology (Dai and Xue 2014).

While home market conditions are important, it is clear that the importance of national market demand is changing over time. As will be shown in Section 4.2, home market demand is highly important for Chinese and some Indian firms today, but less so for European firms and Suzlon in India. The location of a firm's headquarters is important, but most firms now operate globally, both in terms of sales and/or of innovation.

4.2 Wind power innovation: From national paths to globalisation?

When starting this research, we expected that national determinants would lead to distinct innovation paths, and that these would differ from country to country. However, it became increasingly apparent that this is not necessarily the case, as the firms operating in these national spaces also operate internationally and have their own distinct firm-level trajectories. In other words, new research questions emerged about national paths versus company-specific and international paths.

It is clear that national determinants (national governments, national lead markets, national innovation systems and national factor conditions etc.) are relevant. As described above, they explain many of the dominant trends as well as country-specific variations, but there are also cases where the suitability of using only a national lens can be insufficient.

Particular tracks of wind energy innovation often have a distinct company-specific element. Most notably, the difference between gear models and direct-drive models reflects the firm-level choices of the key players. In this case, it seems that public policies have played a key role in ensuring a high level of innovative activity, but have had less influence on the specific nature of innovation. Some pathways also have a distinct international element. To grasp this, it is useful to adopt a dynamic perspective and distinguish between the initial national technology path creation, and subsequent international technology path diffusion. This means that locally created technologies and solutions (i.e. those originating in Denmark and Germany) become 'diffused' outside Europe (Beise and Rennings 2005). In other words, European technologies have become global technologies over time and hence gradually lost their national distinctiveness. Firms in China and India have leveraged technology and technical capabilities from other countries and are selling their turbines across the world.

Our study of key lead firms has shown this clearly. The dominant design epitomized by the Vestas portfolio can be traced back to Danish inventions and improvements preceding the firm, but the design is now globally dominant and used by hundreds of firms outside Denmark. Similarly, the Vensys case shows how direct-drive technology has diffused outside Germany. Vensys has been bought by Goldwind, a Chinese corporation, and plays an integral part in the R&D of Goldwind's international products. Vensys is most famous for developing turbines with permanent magnetic direct-drive, which are now used in China. This diffusion process of 'transplanting' pathways from Denmark and Germany to other parts of the world and vice versa is important in its own right, but there are other discernible trends that have to be taken into account.

Since many of the processes that shape these pathways are becoming truly global, the question arises as to the implications for the development of these sectors within individual countries. This is a question that extends beyond what has been addressed empirically in this research, but it is possible to provide insights to frame future research. We do this by considering the increasingly global nature of some of the key determinants, viewed mainly through the lens of lead firms. These determinants are intrinsically intertwined, but it is useful to separate them analytically.

In terms of policies and regulation, the European leaders are truly global firms embedded in, and influenced by, multiple and differing policy frameworks and innovation systems. However, the main point addressed here is the globalisation and standardisation of the regulatory frameworks themselves. Our underlying research shows that national policy frameworks differ markedly in certain respects, but that there is also a certain degree of imitation and adoption of 'best practice' (Dai et al. 2014; Narain et al. 2014). For example, as shown by Menzel and Adrian (2013), international wind energy standards published by the International Electrotechnical Commission (IEC) have become increasingly influential over the last ten years. They have been adopted by national governments or used as a basis for defining national standards. Many international standards are used across countries as a part of the IEC 61400 system, but the enforcement—the certification methods—often differ across markets, according to nationally specific government regulations. Future research needs to untangle these dynamics. European practice is often core to the formulation of standards in other parts of the world. Drawing on experiences from Europe and other parts of the world, Vestas has worked closely with the R&D arm of China State Grid to define a grid code that facilitates the integration of turbines. Similarly, firms such as Garrad Hassan have specialised in certification, drawing on global experiences and intensive knowledge of standards

When it comes to demand conditions, the globalisation of wind power markets is central to the discussion of the divergence versus convergence of innovation paths. While historically, the local lead markets in Denmark and Germany have been important, their relevance is now decreasing with a shift in demand to other countries such as the USA, China and India (Lema et al. 2013). This shift in demand means that firms are not necessarily or primarily innovating for the home market. Vestas is an example of a truly global firm in terms of number of markets served, the proportion of sales made outside Denmark and the globalisation of production facilities (see Fig. 7). Moreover, the ownership structure of Vestas is such that it is majority-owned by investors located outside Denmark. Enercon differs in that this firm produces most of its products in-house and the key market is the German home market itself. Although the vast majority of sales are in Germany, Enercon still sells in more than 20 markets across the globe.

As discussed, Danish and German innovations are diffusing globally, thereby influencing the innovation paths of other countries. This may be understood as the globalisation of an innovation path that emerged from innovation nested in Denmark and Germany. At the same time, it is also clear from interviews that the wind power industry is witnessing a globalisation the innovation process itself. The European lead firms have set up R&D offices in Asia. The Asian lead firms are increasingly undertaking innovation activities in European lead markets as they acquire engineering firms and collaborate with providers of technology services. This evolution has involved a shift from licensing to co-design relationships between Asian and European firms (Dai et al. 2014; Lema et al. 2013). So far, this has been a convergence factor, enabling Asian firms to catch up along the technology path defined in Europe. For example, a firm like Suzlon, which has built its success upon international acquisitions, is very similar to European firms in terms of products and competitive strategy. Therefore Suzlon has R&D/design facilities in Germany, the Netherlands, Denmark and India (and in fact, the

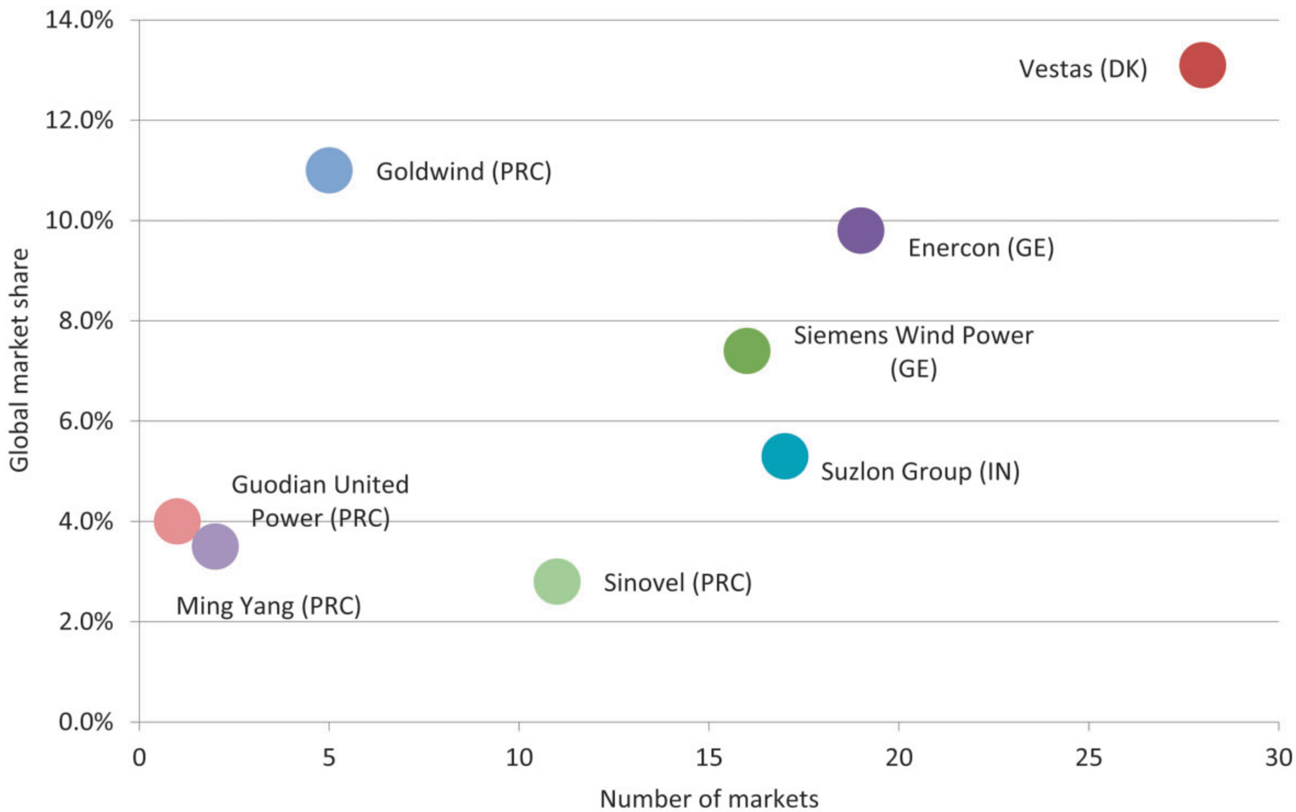

Figure 7. Globalisation of lead firms in four case countries.
Source: Adapted from BTM (2014).

R&D headquarters of its technology group is in Hamburg, Germany).

The globalisation of the innovation process is likely to lead to path-following convergence for the foreseeable future. Zhou et al. (2015, this issue) show that European lead firms have knowledge bases that are broader and deeper than those of their Asian counterparts (although Indian Suzlon is partly an exception in this regard as it has a stronger knowledge than Chinese lead firms). This reflects the European firms' leadership in the search process at the technological frontier. However, in the long run that this may change. For example, the Chinese firm Envision has established a design team in Denmark with engineers headhunted from Vestas and Siemens. This team is working on radically different turbine designs, particularly the two-bladed partial pitch turbine. This shows that Asian firms may combine their own financial resources with radical ideas and European capabilities to move beyond mere catch-up in technology development.

5 Conclusions

This article has examined innovation paths within and across countries, identified similarities and differences between them and examined the extent to which they reflect country-specific conditions and whether they are likely to converge or diverge in the future. Unsurprisingly, the paths unfold in socially-constructed markets specific to particular country conditions.

The research was motivated by the notion that, at present the advancement of low-carbon sectors fundamentally depends on politically negotiated support that may differ markedly between countries. This is consistent with the existing literature on wind energy path creation, which tends to emphasise the specific circumstances leading to path creation in a particular country (Dawley 2014; Karnøe and Garud 2012; Simmie et al. 2014). When it comes to China and India, the literature on innovation in wind energy tends to emphasise state guidance and the importance of the national innovation system (Kristinsson and Rao 2008; Lewis 2007, 2013). There is no shortage of national studies, but little research that compares innovation paths across Europe and Asia in a systematic manner or contrasts the national and global drivers of innovation paths. This is what we have sought to do in this article and the remainder of this final section seeks to bring out the new insights.

Do wind power innovation paths differ between Europe and Asia? If so, how? Section 3 emphasised that distinguishing between core technology and deployment is important when it comes to innovation paths in wind energy. It then showed that there are important similarities between the four countries, particularly in core turbine technology. The broad directions of core technology innovation paths are similar, especially in terms of enhancement of technology (size, efficiency, and reliability of turbines) and in terms of dominant designs. Interestingly, core technology patterns differ more between particular lead firms than between European and Asian countries. Section 3 also showed that that all four countries examined in this study are undertaking significant activities in the development and deployment of wind energy and that there are important differences in the patterns of deployment (e.g. in the size and nature of deployment projects and the presence of offshore installations). Overall, there are key differences in the scale, speed and direction of the observed deployment patterns. As might be expected, these differences are particularly pronounced when comparing Europe and Asia, since there are particularly big differences in the size, nature and location of new energy projects.

Do innovation paths reflect different initial conditions in Europe and Asia? Can we expect divergence in the future? Section 4 suggested that, to a large extent, the existing differences are reflections of national settings. Wind-sector trajectories are moulded by national innovation systems, country-level endowments and specificities of national markets and policies, which create variations in sectoral trajectories across countries. The differentiated national investment in the offshore paths is a clear example. Another example is the emergence of the direct-drive turbine design, which is a reflection of particular engineering and design capabilities in Germany. That said, Section 4 also showed that even though country conditions matter, there are forces that have driven technological similarities. The section showed how sector-level technological specificities have been transplanted as a part of the global diffusion of technologies. In other words, the paths depend on national conditions manifested in their respective innovation systems, but these systems are increasingly open, and cross-national linkages have shaped the technological trajectories in important ways. In effect, European first movers have created dominant designs, which have later been adopted in Asia.

The picture that emerges is that Europe has tended to be the main locus of 'path creation', while rapid catching up in China and India has mainly been 'path-following' (in the sense of Lee (2013)). So while catching up is in itself an innovative process, the diffusion of wind power in emerging markets has mainly followed existing techno-organisational paradigms. Although bounded by certain fixed or slowly changing endowments, globalisation and late-comer effects have promoted convergence. Licenses, foreign direct investments and acquisitions of foreign companies have been key elements in an organisational decomposition of the innovation process in the sector, which has, in effect, transplanted core elements of given innovation paths.

This bounded convergence of innovation paths across Europe and Asia runs contrary to initial expectations. At the outset of this research, we hypothesised that low-carbon innovation paths in Europe and Asia would diverge significantly due to policies that reflect country-specific political priorities, as well as different initial conditions in terms of technological sophistication, demand conditions and national economic growth rates. In this respect, the present study has qualified the initial hypothesis by unveiling the important role of firm-level trajectories. Convergence and divergence processes were largely driven by firms that compete and innovate both in Europe and Asia (and the rest of the world), and these firms use particular technologies to exploit, and seek advantages in, national and global markets. Innovation paths thus differ in some specific respects, which matters when firms bid for contracts, but these differences do not change the overall picture of cross-national convergence in this sector. In other words, there is more divergence at the company level than at the country level.

What are the implications for the shift from high- to low-carbon development? Who will be the economic winners and losers in this green transformation? We suggest that the patterns of convergence and divergence identified in this article can enhance the contribution of wind power to the low-carbon technology transition in these (and other) countries in a number of ways, while having an important influence on the competitive dynamics of the wind power industry:

- There are already established innovation paths in leading Asian and European countries, with the development of both firm- and national-level capabilities in technology development and deployment-related resources (e.g. policy design, wind-resource mapping, financing, project management and operations). These paths are likely to continue and deepen in the foreseeable future with significant positive implications for the deployment of wind energy in these countries.
- The interaction and convergence between the paths in Asia and Europe—enabled and driven by global flows of knowledge and technology—can serve to further enhance technological development in the sector, since these trends expand the number of firms and personnel engaged in the innovation process. The speed and skill with which developing-country firms have leveraged wind-technological capabilities outside their national borders and built upon them bodes well for the ability of these countries to engage in the low-carbon technology transition.
- Global market expansion and the already-emerging convergence in innovation paths may result in growth opportunities for lead firms in both Europe and Asia. Although there is a certain degree of protectionism at play in all countries, the business opportunities are likely to grow both for Asian firms in Europe and other countries, and for European firms in Asia and other countries.
- There are significant issues of national competitiveness in green technologies, but sub-trajectories identified in this article (e.g. offshore technology, direct-drive technology or small turbines), constitute niche markets in which competiveness in global markets can be gained.
- The emergence of a wider base of players globally and associated economies of scale is helping to bring down the cost of wind energy and help it compete with fossil-fuel-based electricity on a global scale. While this is good news for the climate, it also puts turbine developers under pressure. Prices have already been brought down, as they have been in advanced economies, but the future may see consolidation in the market with larger firms arising from cross-continental takeovers. The losers are likely to be European firms that are unable to reduce their prices and Asian firms unable to increase and maintain quality.
- Synergies between these innovation paths should also underpin collaboration in these areas as part of the international efforts in technology transfer and cooperation. Global initiatives are likely to concentrate increasingly on low- and lower-middle-income countries. Asian pathways shaped by large rural communities and pockets of poverty have not yet emerged. However, new global initiatives could bring together capabilities and resources across the globe to increase access to electricity in poor countries. New collaborative business models for decentralised rural electrification may create entirely new innovation paths in developing countries.

This last point relates closely to one important finding of this research. One would have expected the development of strong trajectories in China and India for developing small-scale and off-grid technologies, yet such trajectories were not identified. Given the relevance of such technologies for China and India and the potential for export to other countries, this is surprising. The reasons for this lack deserve further research, which should seek to identify how international support for such technological developments can be designed to increase international technological collaboration and new models of renewable energy provision.

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Notes

1. In this article we use the term ‘innovation path’ to mean the trajectory of technology development and deployment, which incorporates both the nature of the technology as well as activities surrounding its development and deployment.
2. In this article when referring to ‘Europe’ we mean Germany and Denmark, and when referring to ‘Asia’ we mean India and China. Where appropriate, we refer to the differences between the two European and Asian countries. We are aware of further differences between other countries in Europe and Asia, but the purpose of this article is to seek insights from the selected comparisons.
3. A total of 50 interviews were conducted in China, Denmark, Germany and India, with key informants in lead firms, suppliers, trade organisations and government organisations. Interviews were conducted by cross-national research teams in the period 2012–14. Secondary sources were essential and are referenced. Market data derives from BTM (2014) if nothing else is indicated.
4. Lee (2013) uses these terms to refer to both firm-level catch-up (e.g. Samsung, Hyundai) and national industry-level catch-up (consumer electronics, automotive) in South Korea.
5. The capacity factor is an indicator of how much energy a particular wind turbine generates in relation to the theoretical maximum (Renewable Energy Research Laboratory 2015). It is the actual net output as opposed to the nameplate capacity. To be more precise, the capacity factor of a wind farm is the ratio of its actual output over a period of time to its potential output, if it were possible for it to operate continuously at full nameplate capacity.
6. However, there is a recent trend towards reviving community ownership of smaller projects as a means to create popular acceptance of wind power development in Denmark. The UK is currently seeking to emulate this strategy to combat NIMBY-ism (Harrabin 2014).
7. China has set ambitious offshore wind targets of installing 5 GW by 2015 and 30 GW by 2020. China’s National Energy Administration has, however, admitted that it is unlikely to meet its 2015 5 GW offshore target. At the end of 2013, there was only about 0.5 GW installed, and the majority of this is in ‘near-shore’ projects (Carbon Trust 2014). In 2014 China launched the construction of projects amounting to roughly 1.5 GW (Chinese Renewable Energy Industries Association 2014).
8. As yet, it is unclear whether experimentation in this field will feed into a major boost in rural electrification in China and whether this can provide a platform for exports to developing countries. There is some work in India on small turbines (e.g. <http://www.unitronenergy.com> accessed 1 Feb 2015), although this constitutes a very small portion of the overall wind energy landscape in the country at present.
9. Co-existence between the gear model and direct-drive model is likely to continue, and there is as of yet no clear trend with regard to the future success of the newer direct-drive model. Competition between the two standards is likely to be a source of European strength as the major lead firms continue to invest heavily in R&D to improve the performance of the respective designs.
10. Distributed wind power is defined by the Chinese government as projects generating less than 50 MW that are connected to a distribution grid line of less than 110 kV.
11. At the project ownership level, there are stark differences between China and India when it comes to the distribution of ownership. In China, ownership is concentrated in a handful of state-owned utilities, while in India, it is much more widely distributed between various types of investors, including manufacturers and independent power producers (Surana et al. 2014).
12. This refers to the trend in which innovation activities that used to be carried out in-house at headquarters are increasingly located at subsidiaries or are carried out by key collaborators, including suppliers of knowledge-intensive business services. See Schmitz and Strambach (2009) and Lema et al. (2015) for discussions of this notion of the ‘organisational decomposition of the innovation process’ (ODIP).

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