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Innovation Paths in Wind Power

Insights from Denmark and Germany

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Joint project with:

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Abstract

Denmark and Germany both make substantial investments in low carbon innovation, not least in the wind power sector. These investments in wind energy are driven by the twin objectives of reducing carbon emissions and building up international competitive advantage. Support for wind power dates back to the 1970s, but it has gained particular traction in recent years thus opening up new innovation paths. This paper explores the key features, similarities and differences in innovation paths in Denmark and Germany and sheds light on their main determinants.

The paper shows that there are many commonalities between Denmark and Germany when it comes to innovation pathways, both in technological and organisational innovation. In turbine technology, the similarities are the constant increase in turbine size and quality. The key difference to be found is the relative importance of different turbine designs. The ‘Danish Design’ remains the global standard. The direct drive design, while uncommon in Denmark, dominates the German installation base. Direct drive technology has thus emerged as a distinctly German design and sub-trajectory within the overall technological innovation path.

When it comes to organising wind turbine deployment, both countries have moved along broadly similar paths. There are now fewer turbines deployed than at any time in the past 10 to 20 years, but on average these are concentrated in larger projects and the production capacity and total electricity output has increased significantly in both countries. The key difference is in the role of the offshore segment in deployment: Denmark has been a pioneer in the offshore segment, which has hitherto played a much smaller role in Germany.

While this paper shows that there are many common features between the two countries, it also identifies a diversity of pathways, or rather, a co-existence of different sub-trajectories in both core technology and in the organisation of deployment. It is as yet unclear whether the future will bring more convergence or divergence.

To address this, the paper explores specific determinants of innovation paths: government policies, demand conditions, geography, value chains, and the strategies undertaken by firms. It demonstrates that the innovation paths common to both countries have roots in a confluence of determining factors which are mainly due to social and political priorities, preferences and decisions at national level. However, the sub-trajectories, which create variation between Denmark and Germany, differ in this regard. They tend to have roots in ‘given’ geographical conditions and in company-level technology choices. In other words, many of the similarities in innovation paths between Denmark and Germany have common national causes, while company-specific strategies also influence the innovation paths in significant ways. This raises important questions about the national specificity of innovation paths in wind power development.

Finally, the paper briefly addresses the increasing global interconnectedness of wind technology markets and the role of emerging new players, such as China and India.

Preface

Mitigating climate change by reducing carbon emissions is one of the biggest and most complex issues the world has ever faced. Technological innovation plays a major role in taking on this challenge. Old and new industrial powers alike are increasingly reforming their policy frameworks to encourage low carbon innovation, and investments are following.

Evolutionary economics has clearly demonstrated how initial choices of technologies and institutional arrangements preclude certain options at later stages; hence, situations evolve in an incremental and cumulative way, resulting in context-specific technological pathways. Such path dependency implies that technologies and institutions do not progressively converge toward a unique best practice, as neoclassical equilibrium models might suggest. The historical and social embeddedness of such evolutionary processes instead results in a variety of very different technologies and institutions across countries.

The starting assumption of our research was that low carbon technologies depend on politically negotiated objectives and policies to a particularly high degree, mainly due to the failure of markets to reflect environmental costs. The way national governments and industries deal with the low carbon challenge varies greatly depending on levels of environmental ambition, technological preferences (such as different attitudes towards nuclear energy, shale gas, carbon capture & storage), the ways markets are regulated, and the importance attached to expected co-benefits (such as exploiting green jobs or energy security). Consequently, low carbon technologies are more likely to evolve along diverging pathways than other technologies whose development is more market-driven.

To test this assumption we conducted the international research project “Technological trajectories for low carbon innovation in China, Europe and India”. The project explored whether, to what extent and why technological pathways differ across countries. Case studies were conducted in two technological fields, electromobility and wind power technologies, in China, India and leading European countries. Whether a diversity of pathways emerges or a small number of designs becomes globally dominant has important implications. From an environmental perspective, diversity may help to mobilise a wide range of talents and resources and deliver more context-specific solutions. Convergence, on the other hand, might help to exploit economies of scale and thereby bring about bigger and faster reductions in the cost of new technologies. From an economic perspective, diversity may provide niches for many firms, whereas a globally dominant design is likely to favour concentration in a small number of global firms – which may or may not be the established ones. Comparing European incumbents with Asian newcomers is particularly interesting, because China and India might well become the gamechangers – responsible for most of the increase of CO_2 emissions but also leading investors in green technology. In addition, the project explored lessons for international technology cooperation, emphasising ways to navigate the trade-offs between global objectives to mitigate climate change effects and national interests to enhance competitiveness and create green jobs locally.

The project was carried out between 2011 and 2014 as a joint endeavour of four institutions: the German Development Institute / Deutsches Institut für Entwicklungspolitik (DIE), the Institute of Development Studies (IDS) Brighton, the Indian Institute of Technology (IIT) Delhi, and the School of Public Policy at Tsinghua University, with additional collaborators from the Universities of Aalborg, London and Frankfurt. The project was truly collaborative, to the extent that international teams jointly conducted interviews in China, India and Europe which helped to build common understanding.

Eight reports have been published in, or are currently being finalised for, the DIE Discussion Paper series:

1. Schamp, Eike W. (2014): The formation of a new technological trajectory of electric propulsion in the French automobile industry
2. Chaudhary, Ankur (2014, forthcoming): Electromobility in India. Attempts at leadership by businesses in a scant policy space
3. Altenburg, Tilman (2014, forthcoming): From combustion engines to electric vehicles: Implications for technological trajectories. Case study Germany
4. CHEN Ling, Doris FISCHER, SHEN Qunhong and YANG Wenhui (2014, forthcoming): Electric vehicles in China – Bridging political and market logics
5. Lema, Rasmus, Johan Nordensvärd, Frauke Urban and Wilfried Lütkenhorst (2014, forthcoming): Innovation paths in wind power: Insights from Denmark and Germany
6. DAI, Yixin, Yuan ZHOU, Di XIA, Mengyu DING, Lan XUE (2014, forthcoming): Innovation paths in the Chinese wind power industry
7. Narain, Ankita, Ankur Chaudhary and Chetan Krishna (2014, forthcoming): The wind power industry in India
8. Bhasin, Shikha (2014, forthcoming): Enhancing international technology cooperation for climate change mitigation. Lessons from an electromobility case study

On the basis of these case studies, the team is currently working on a series of cross-country comparative analyses to be published in academic journals.

The research team is very grateful for generous funding and the very supportive attitude of the Swedish Riksbankens Jubileumsfond under a joint call with the Volkswagen Foundation and Compagnia de San Paolo.

Bonn, April 2014 Tilman Altenburg

Contents

Annex

Figures

Tables

Boxes

Abbreviations

BMU	Bundesministerium für Umwelt (German Federal Ministry for the Environment)
BMUB	Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit (German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety)
BMVi	Bundesministerium für Verkehr und digitale Infrastruktur (German Federal Ministry for Traffic and Digital Infrastructure)
BMWi	Bundesministerium für Wirtschaft und Energie (German Federal Ministry for Economic Affairs and Energy)
BNEF	Bloomberg New Energy Finance
BWE	Bundesverband WindEnergie (German Wind Energy Association)
CCS	Carbon capture and storage
CHP	Combined heat and power
CSP	Concentrated solar power
DD	Direct drive
DEA	Danish Energy Authority
DFIG	Doubly-fed induction generator
DTU	Danish Technical University
DVES	Danish Wind Electricity Society
DWIA	Danish Wind Energy Association
EEG	Erneuerbare Energien Gesetz (Renewable Energy Law, Germany)
ETS	Emission Trading Scheme
EU	European Union
EUDP	European Union Demonstration Project
EWEA	European Wind Energy Association
FDI	Foreign direct investment
FIT	Feed-in tariff
GHG	Greenhouse gas
GW	Gigawatt
GWEC	Global Wind Energy Council
GWh	Gigawatt hour
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IPCC	International Panel on Climate Change
IPRs	Intellectual property rights
IWES	Institute for Wind Energy and Energy Systems (Fraunhofer)
KIBS	Knowledge-intensive business service
km	Kilometre
kW	Kilowatt
kWh	Kilowatt hour
LCOE	Levelised cost of energy
LORC	Lindoe Offshore Research Centre
MNC	Multinational corporation
m	Metre
m/s	Metre per second
MW	Megawatt
NGOs	Non-governmental organisations

O&M	Operation & maintenance
OECD	Organisation for Economic Co-operation and Development
OEM	Original equipment manufacturer
PMDD	Permanent magnet direct drive
PV	Photovoltaics
R&D	Research & development
RE	Renewable energy
SME	Small and medium-sized enterprises
S&T	Science and technology
SET	Strategic Energy Technology Plan (Europe)
SOE	State-owned enterprise
TSO	Transmission system operator
UK	United Kingdom
UNFCCC	United Nations Framework Convention on Climate Change
US	United States
VDMA	Verband Deutscher Maschinen- und Anlagenbau (German Engineering Federation)
WEC	Wind energy converter
WTG	Wind turbine generator

1 Introduction

Innovation paths for low carbon transformation are likely to differ markedly between countries because of the diversity in policies, endowments and technological capabilities. These pathways will differ in the approach to, and effectiveness of, mitigating climate change and tackling related domestic energy challenges. But they will also differ in the degree to which low carbon technologies and solutions can become a source of national competitiveness.

There is widespread agreement that the European Union (EU) has so far been a global frontrunner lowering carbon emissions through innovation in policies and technologies. It has created momentum in new green industries such as the wind power and the electric vehicle industries. The wind power industry in particular is at the front end of the low carbon transformation as it plays a key role in the efforts of European countries to use more renewable energy. Wind energy is the most commercialised and most successful type of renewable energy presently available. This paper examines the innovation paths that can be observed in Denmark and Germany, the leading wind energy nations in the EU.

These two countries 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 global industry. To date, Denmark and Germany are leading innovators and markets. Both countries are widely considered as role models in the development of policies to support the expansion of wind energy. However, if national and European targets for wind energy are to be reached, these countries cannot rest on past success. 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 deployment are hotly debated due to the many interests at stake.

At the same time, emerging economies such as China and India are rapidly catching up in the industry, developing their own policy regimes at home while buying up firms and forming technological alliances abroad. China has become particularly focused on green technology, with wind power now designated as one of five strategic high-tech industries. India has invested fewer resources for 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.[1]

The wind energy sector is thus in a flux both globally and nationally. It is not yet apparent how distinct national pathways will be; how they will look; and how fast they will change the local energy systems. To advance our knowledge, the main purpose of this paper is to examine the low carbon innovation paths in Denmark and Germany. It addresses in particular the role of public policy in shaping these innovation paths, but also seeks to examine other factors such as corporate strategies and market evolution.

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[1] For an assessment of how China is influencing the wind power industry, see Lema / Berger / Schmitz 2013.

1.1 Research questions

This paper examines the innovation paths of Denmark and Germany, the global forerunners of wind energy, to explore how these innovation paths have evolved in the face of domestic challenges combined with global competition and collaboration with new powerful wind energy actors from India and China. The research questions for this paper are the following:

- What are the key features, similarities and differences in innovation paths in Denmark and Germany?
- What explains these similarities and the differences?

Examining these questions, the paper presents research on the wind energy innovation paths in Denmark and Germany and summarises the key findings from fieldwork in both countries. Complementary research was undertaken on the new economic powers of China and India in order to allow comparison of these trends across regions and countries at various different levels of economic and technological development.

1.2 Innovation paths

Green innovation takes place within the boundaries of common 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. 2014). Although these general challenges are shared between nations, specific pathways may evolve in different directions depending on the national starting points. Evolutionary economics suggest that specific innovation pathways emerge as technological trajectories, i.e. as ‘branches’ in the evolution of a technological paradigm (Dosi 1982).

The pathways tend to be cumulative and self-reinforcing because they are continually being shaped by extant capabilities and infrastructures. In other words, innovations are often path-dependent in the sense that they are built upon earlier technologies, experiences with innovation, and with competition strategies (David 1985). Innovation paths are likely to reflect the properties of the countries in which they have evolved. Such a notion arises from the theory of national innovation systems (Nelson 1993; Lundvall 1992). Pathways in different countries emerge as a context-dependent process involving interaction between firms and other organisations, influenced by the national institutions (e.g. policies), the properties of the underlying technology, and the economic and social structures of specific countries. 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 literature emphasising technological factors such as the dependence on specific national infrastructures in many carbon-reducing technologies (Jonsson 2000). In other words, there are strong reasons to believe that innovation pathways will be country-specific.

However, there are forces and dynamics which may pull in different directions. First, path dependence at the national level is not destiny. History is rich in examples of intentional path creation or shifting (Garud / Karnøe 2001). Innovations can be 'path-creating' when new constellations are moving in the direction of new techno-economic paradigms or new designs within emerging sub-trajectories. Firstly, innovation paths are emergent properties, shaped by a myriad of processes including interactions between firms and by public organisations seeking to steer their direction (Garud / Kumaraswamy / Karnøe 2010). Second, while national institutions and system-level factors are important, the role of individual firms tends to be overlooked. Where rival technological standards exist, dominant designs are often decided in the battles of particular lead firms. In other words, innovation paths may be company-specific rather than country-specific. Third, the national level 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 global trade, globally mobile engineers, foreign direct investment, or mergers and acquisitions. 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 / Rennings 2005). Thus technologies become international, as opposed to country-specific, and this may be reinforced by the adoption of 'best practice' policies within specific domains, which lead to similarity in outcomes. Against this backdrop, the paper examines what the dominant trends are in the European wind power industry. It seeks to unravel to what extent, how and why the innovation paths are different or similar in the Danish and German wind industry.

1.3 Examining innovation paths in wind power

In the wind power industry, innovation takes place at two different levels: at the core technology level (the wind turbine) and at the deployment level (the installation of turbines).[2] Different firms tend to specialise in different activities at both levels. In core technology, the main actors are wind turbine generator (WTG) producers such Danish Vestas or German Enercon and component suppliers such as LM, a Danish blade manufacturer. At the deployment level, the key firms are utility firms such as Dong Energy (Denmark) or RWE (Germany) 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 and consultancy services providers and operation as well as maintenance (O&M) services providers. There is no strict division between the two levels. For example, turbine manufacturers partake in deployment in various ways, usually in O&M. Thus, different paths may emerge at both different levels. While in core technology there are rival turbine designs, there is also a variety of deployment models. The latter exhibit key differences in siting (on or offshore and micro-siting within farms)[3], turbine size, wind farm size, business models, and

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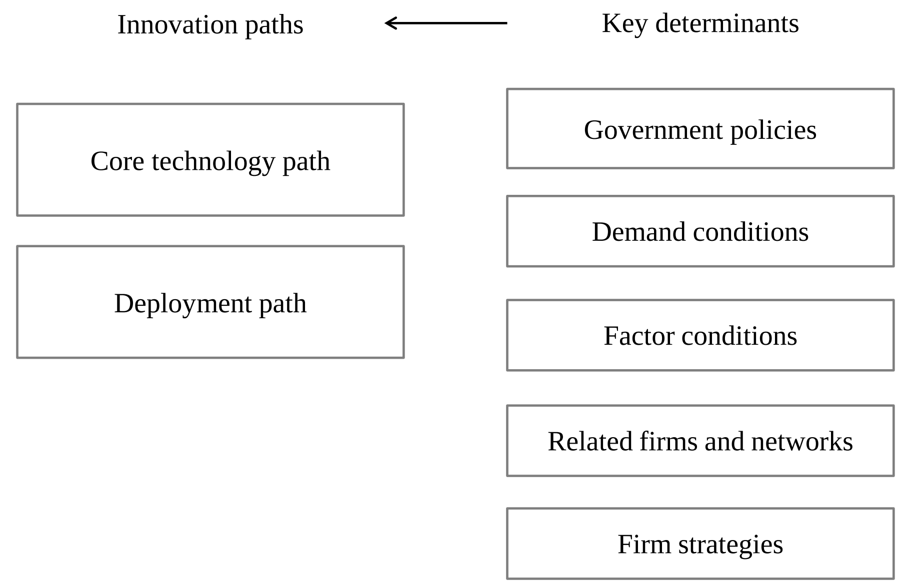
[2] See Lema et al. 2011, Section 2.2. and Figure 2.1.

[3] Wind farm siting has two elements: Macro-siting (or just siting) refers to the identification of the most suitable locations for the installation of wind parks. It involves an investigation of the most suitable location where the park can be located, considering a range of relevant factors. Micro-siting refers to

integration into the electricity system. The distinction between core technology and deployment is analytically useful – even though the boundary between the two is blurred in reality.[4] It is used in this paper to unbundle the notion of innovation paths (technological trajectory), as shown on the lefthand column of Figure 1.

As mentioned, much contemporary theory emphasises the importance of the national level in shaping innovation paths and distinct sources of competitiveness (Schmitz / Altenburg 2014). Porter (1990) emphasised 'the diamond factors': demand conditions, factor conditions, firm networks, and individual firm strategies. Government policies were initially seen as semi-external to the diamond model, as their function was to influence the four core determinants. But many observers have pointed out that government policies tend to influence the four factors to such an extent that policies alone could sometimes be used to analyse patterns of specialisation. While the diamond factors are suitable for a rapid appraisal of determinants, government policies must be given at least equal weight. As shown in Figure 1, these will be used to structure the analyses of the determinants of innovation paths.

Figure 1: Conceptual framework for the study



Source: Own compilation

Table 1 provides the specific criteria for dealing empirically with innovation paths in wind power, covering both core technology (first three criteria) and deployment (last three criteria). Table 2 provides the main elements for examining the determinants. In this way, the five determinants can be unbundled – an essential step towards detecting

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the investigation of the park's layout, which includes investigating the relevant technological and economic factors. It thus refers to the careful placement of each turbine. The specific position of each turbine is important because a small difference can potentially double output (Ntoka 2013). Note that siting also has an alternative spelling as 'sitting'.

[4] For example, the quality of the core technology (i.e. the turbine) can only be finally assessed when deployed.

the myriad of ways in which they influence innovation paths. While we address the general influence of these factors throughout this section, the summary subsection at the end of the chapter will establish the links to specific paths most explicitly.

Table 1: Specific criteria for analysing innovation paths in wind energy

Turbine size:	• Nameplate capacity in MW
Turbine quality:	• Reliability as reflected in actual turbine capacity factors
Turbine design:	• Use of gear versus direct drive models
Onshore/offshore installation:	• Share of offshore segment compared to the onshore segment
Project size:	• Project capacity in megawatts and number of turbines
Deployment services:	• Operation and maintenance (O&M) services content of new deployment projects

Source: Own compilation

Table 2: Main elements for analysing determinants of innovation paths

Government policies:	• Demand-side policies • Supply-side policies
Firm strategies:	• Vertical and horizontal strategies and focus areas • Focus on domestic/export market
Demand conditions:	• Volume of demand • Nature of demand
Factor conditions:	• Geographical endowments • Factor costs
Related firms and networks:	• Value chains • Industrial clusters

Source: Own compilation

1.4 The country cases

Denmark has been the world leader in turbine technology for more than thirty years. Danish firms hold 25% of the total global turnover in this industry. Denmark is also a key location for inbound investment in wind power development activities, such as research and development (R&D), testing, and high-quality production. This status has been achieved with the strong support of government policy. Today, wind energy constitutes more than 30% of electricity consumption in Denmark. A 2012 agreement concluded by all major parties in parliament stipulates that 50% of the electricity consumption in Denmark shall be supplied by wind power by 2020.

While Denmark has historically been the global first mover in wind energy, Germany is today Europe's largest, and the world's third largest, wind energy market after China and the United States (BWE 2012). Germany had an installed capacity of more than 30GW by the end of 2011 and its installed capacity and market has been growing continuously since the mid-1990s (BWE 2012; IEA 2013). The large majority of installed capacity is onshore, with only about 253MW (0.253GW), less than 1%, being offshore in 2011 (IWES 2012). After years of stagnation and financial crisis, the wind energy sector seems to have recovered with growing installation trends. This is due to the so-called 'second spring' with large wind energy capacity being added in areas of low wind speeds in southern Germany (BWE 2012). The German government has targets in place for 35% of the total electricity to come from renewable energy by 2020, 50% by 2030 and 80% by 2050, of which wind plays an important role.

1.5 Data collection

Interviews were conducted in Denmark and Germany. For Denmark, substantial parts of the material contained in this paper draw on interviews in the first quarter of 2013. These interviews were conducted by Rasmus Lema and Søren Møller Andersen and focused mainly on the innovation paths. Prior interviews were made to establish the context and trends. These first rounds were undertaken with Shikha Basin (April 2012) and with Yixin Dai, Yuan Zhou and Ankita Narain (May 2012) (see Box 1).

Box 1: Interviews in Denmark

Representatives from the following organisations were interviewed in Denmark:

- BTM Consult,
- Danish Energy Authority (DEA, Ministry of the Environment),
- Danish Wind Design (turbine design),
- Danish Wind Energy Association (DWIA, business association),
- Dong Energy (utility firm),
- DTU/Risø Research Centre on Renewable Energy,
- Envision (turbine manufacturer),
- LM Wind Power (the world's largest supplier of turbine blades),
- Mita-Teknik (supplier of control system equipment and business services),
- Norwin (turbine design and consultancy),
- Danish Energy Association (business association),
- Vestas (turbine manufacturer),
- Windar Photonics (sensor technology).

In Germany, the fieldwork involved interviews with 12 key actors. These actors were (wind) energy firms, business associations, research organisations and government agencies. The aim was to assess the trends of the German wind energy sector with regard to innovation paths and specific innovation milestones. The interviewees were selected based on leading positions in their organisations and their expertise in relation to the German wind energy sector. The German interviews were conducted by Frauke Urban and Johan Nordensvärd in the third quarter of 2012 at various sites in Germany (see Box 2).

Box 2: Interviews in Germany

Representatives from the following organisations were interviewed in Germany:

- AREVA (wind energy firm),
- BMU (German Ministry for the Environment),
- Bosch Rexroth (supplier firm),
- CEwind (research organisation),
- Enercon (turbine producer),
- EWE (energy firm),
- ForWind (research organisation),
- REpower (wind energy firm),
- Vattenfall (energy firm),
- VDMA Power Systems (business association),
- Vensys (wind energy firm),
- Vestas (wind energy firm).

Secondary data comes mainly from reports of sectoral organisations, notably the German Wind Energy Association (BWE), the Danish Wind Energy Association (DWIA), the European Wind Energy Association (EWEA), and the International Energy Agency (IEA).[5]

The interview questions were based on semi-structured questionnaires. The questions followed an interview schedule, which was used for all four case study countries involved in the overall project: Denmark, Germany, China and India. The interviews in Denmark and Germany were (mostly) conducted in the local languages and then translated into English to ensure consistency with the overall project. Information which is not referenced in this report is derived from the interviews.

1.6 Paper structure

The body of the paper is structured according to Figure 1, covering the contextual setting in Denmark and Germany, the innovation paths, and the key determinists. The outline is as follows:

- Section 2 identifies key characteristics of the innovation paths in Denmark and Germany, covering both the core technology and the deployment dimension. It does so by examining the development trends along the six ‘indicators’ specific to the wind energy industry when it comes to the technological-sectoral pathway in this industry. The section shows that there are many common features of the innovation paths in

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[5] Additional policy information was derived from desk research in Phase 1 of the project which aimed to analyse national climate change mitigation policies, energy policies, and industrial policies relevant for the wind sectors. This involved a review of existing literature and data for assessing the key policies and strategies in place at the national level (and the regional level for the EU) to achieve climate change mitigation, particularly in relation to wind energy. See the outputs and reports from Phase 1 for details (Urban et al. 2012).

both countries, but also some notable differences, both in core technology and deployment.

- Section 3 discusses the main determinants that shape the innovation paths in these two European countries. It focuses on what explains the similarities and differences, drawing heuristically on the factors identified by Schmitz and Altenburg (2014), who in turn draw on Porter (1990) in his attempt to understand the competitive advantage of nations. The section shows that the similarities between the innovation paths have roots primarily in factors that are socially and politically determined. The differences, on the other hand, tend to have roots in firm-level technology choices and given geographical conditions.
- Section 4 pulls together the key findings of our research and provides a discussion of the innovation paths in Denmark and Germany. It sums up the insights with regard to how one can explain the similarities and differences between these two countries. Against this background it then discusses the nature and degree of national specificity in innovation paths, the role of globalisation, and firm-level factors in this regard and finally puts forth questions for a future research agenda.

The paper includes six ‘innovation cases’, which are described in text boxes. These are included to provide some flesh and to illustrate aspects of the pathways at the case level. Although the case boxes are distributed between different sections of the paper, all of these cases illuminate multiple aspects of the innovation pathways. The sources for these cases are interviews with company representatives, company documents and media reports.

Table 3 shows which aspects of innovation pathways the cases illuminate. Some of the case boxes also shed light on the drivers/determinants of these paths, but this is only addressed explicitly in some of the cases.

Table 3: Innovation cases addressing different aspects of the innovation paths

	Turbine size	Turbine quality	Turbine design	Onshore/ offshore installation	Project size	Deployment services
Vestas V112	✓	✓	✓			
Enercon E126	✓		✓			✓
Horns Rev II				✓	✓	
Alpha Ventus				✓	✓	
Envision 128	✓	✓	✓			
Vensys 2.5			✓			

Source: Own compilation

2 Innovation paths in Denmark and Germany

In order to show what paths innovations in Denmark and Germany have taken in recent years, this section draws on interviews, but also brings in secondary data. As noted in the introduction, we distinguish between the core technology path and the deployment path. Specific criteria for the analysis were identified in Table 1. They will be further specified and elaborated in this chapter. The summary section brings out the key differences and similarities between Denmark and Germany.

2.1 Turbine size

There are many reasons behind the overall rise in wind power output in Denmark and Germany and more importantly the growth paths taken – the trajectories which lie behind the aggregate numbers have both similarities and differences. This section examines the development in the nameplate (or nominal) capacity of turbines.[6] One of the major sectoral trends is the increasing size and capacity of wind turbines that are developed and sold. Turbine capacity has been increasing dramatically and all of the leading manufacturers in Europe are taking part in the race to develop ever bigger turbines. This is one important element of the quest to make wind energy compete head-to-head with conventional energy by reducing the levelised costs of energy (LCOE) from wind.

This race is partly related to the increasing shift in market growth from onshore to offshore projects, as offshore turbines tend to be larger than onshore turbines. Hence the shift from onshore to offshore (as discussed below) does not only constitute a deployment trend – there are also different core technologies involved. However, onshore turbines are also increasing in average size, meaning that up-scaling is a general trend in both the onshore and offshore segment.

As shown in Figure 2 there is large variation in the average size of installed turbines in different markets. Average turbine sizes are larger in Europe than in the United States and in Asia. Denmark and Germany are both in the global Top Three when it comes to installing large turbines. Denmark is topping the list due to major offshore projects in recent years.

As Figure 3 shows, the current European market (United Kingdom, Denmark, Germany and Spain) is characterised by turbines in the range from 2.0 to 2.5MW. All of the producers are well capable of supplying this demand in terms of turbine size and most have turbines on offer that are above the average range, e.g. Vestas 3.0MW (V112).

However, all of the interviewed manufacturers work under the assumption that market demand will shift towards even bigger turbines in the future. At 7.5MW, the Enercon 126 is a clear example of this trend. REpower has built the world’s largest offshore turbine currently in operation with a size of 6MW. Similarly, all of the producers work on designs for giant turbines, such as the Vestas V164 offshore turbine with a capacity of 8.0MW. This turbine has recently been sold to an offshore project developed by Dong in the United Kingdom

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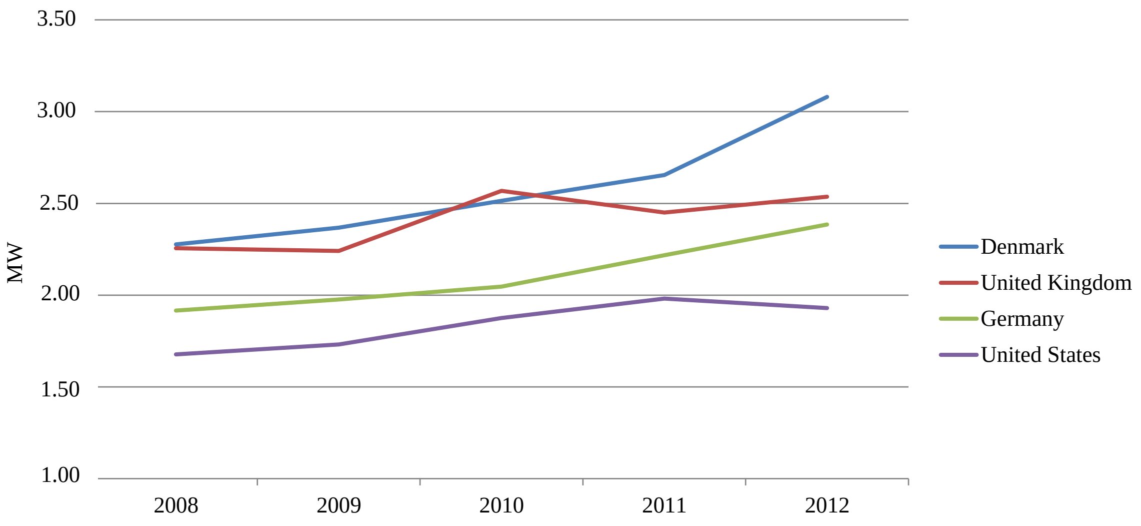
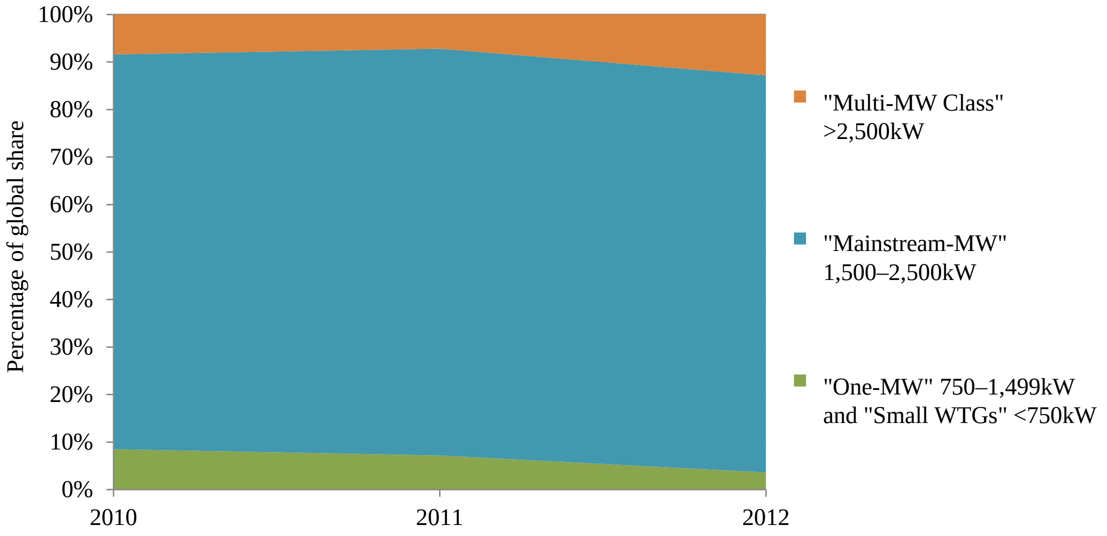
[6] This refers to the intended technical full-load sustained output of a turbine and is measured in megawatts (MW).

Figure 2: Average size of turbines installed each year



Source: BTM Consult – a part of Navigant – 2013, 35

Figure 3: Turbine size classes by global market share



Note: Small WTGs constitute a minor share ranging from 0.1% to 0.6%.

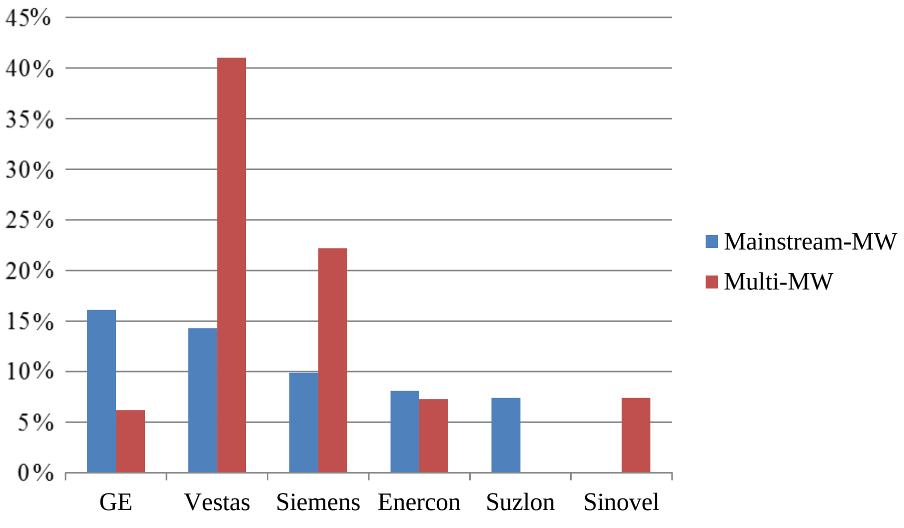
Source: BTM Consult – a part of Navigant – 2013, 53 at the Burbo Bank Extension Offshore Wind Farm. Several firms are currently conducting R&D for up-scaled turbines of about 10 to 20MW, including Enercon, Vensys, REPower and Siemens. DONG Energy and Vestas have concluded a cooperation agreement to test the V164-8.0MW wind turbine at the Test Centre Østerild in Denmark.

The increasing turbine size has ramifications for deployment because few firms have the experience, equipment and solutions for the transportation and installation of giant turbines offshore. Dong plans to radically increase the size of the offshore turbines it will install, from 3 to 4MW currently to 8 to 10MW between 2016 and 2020.

The up-scaling of wind energy turbines is expected to make wind energy more financially viable, both offshore and onshore and in areas with both strong and weak winds. The continuous up-scaling of wind turbine capacities, towers, rotors, and blades is an on-going innovation path in both Denmark and Germany.[7]

Figure 4 shows the market shares for turbines of different size. There is still a very small market for turbines below 750MW (0.1% of total sales and not included as a separate category). As seen, the mainstream market of 1.5 to 2.5MW turbines is by far the largest segment at 83.5% in 2012. The multi-MW market (turbines above 2.5MW) grew to 12.8% in 2012. Vestas has the largest market share globally within the multi-MW market segment.

Figure 4: Market shares in mainstream and multi-MW markets



Source: BTM Consult – a part of Navigant – 2013, 53

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[7] In Germany, the up-scaling trend has been discontinued. A period of rapid up-scaling of wind turbines from small kW-turbines to MW-turbines occurred in the 1990s. These large turbines were called GROWIAN (GROsse WIndenergieANlagen – large wind energy turbines). Nevertheless, the massive up-scaling of turbine capacities failed in the 1990s. As a result, the wind energy industry took a step back and developed smaller turbines, then improved and perfected them step-by-step, until the technology and the industry were mature enough to gradually up-scale the turbine capacities.

2.2 Turbine reliability

Improvements in turbine reliability are an important feature of the innovation paths in Europe. While many interviewees highlighted the quality dimension, the latter is not easily subjected to empirical verification. This section examines ‘turbine quality’ primarily in terms of reliability of the turbine. Increased reliability is equal to the higher actual electricity yield of a turbine over its lifetime and hence to higher electricity output. On average, this creates lower costs of wind-generated electricity, although the effect depends on the related investment costs.

Wind energy is on the path to reach cost parity with conventional energy in the electricity market. In Denmark, the cost per kilowatt hour (kWh) has been driven down by 80% over the last 20 years (DWIA 2014).[8] There are many contributing factors. In addition, the increased reliability of turbines means that O&M costs are reduced; hence it is necessary to take lifetime variable costs into account. O&M includes scheduled and unscheduled maintenance work as well as replacement costs for components including gearboxes, blades and generators. O&M costs typically constitute 20 to 25% of the total cost of wind energy (Kirkegaard / Hanemann / Weischer 2009). This issue is explored further in Section 2.6. Here the focus is on the innovation process that increases the quality of the turbine and how it results in higher capacity factors.

In theory, large turbines increase power output per turbine and reduce the cost of energy because the number of turbines per project, foundations, and the number of O&M visits is reduced. However, in reality, the relationship is more problematic if larger turbines are less time-tried and because costs can increase compared to mature technologies if there is a higher incidence of faults and breakdowns.

While the point about the turbine quality/reliability was made by several interviewees, the data to back up the reliability claims are scarce and tend to be confidential. However, according to Bloomberg New Energy Finance, the O&M costs have come down rapidly in recent years.

> *“Average prices for operation and maintenance contracts in the wind sector have dropped 38% in the last four years, boosting the sector’s competitiveness significantly … The wind energy sector is making significant improvements not just in the capital cost and performance of its turbines, but also in the ongoing cost of operating and maintaining them once installed” (BNEF 2012, 1).*

The Bloomberg data collected from project owners suggest that Enercon, Vestas and Siemens are the best O&M providers in terms of promptness and quality of service. The full service contract from Enercon was 20% below average market price. The European wind services market is expected to reach EUR 4.5 billion in 2020 from EUR 2.3 billion in 2011 (Deloitte / Touche 2012).

Some insight into the issue of turbine quality can be gained by examining capacity factors. The capacity factor is an indicator of how much energy a particular wind turbine generates (WEC 2013). 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

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[8] This trend is likely to continue and result in a fully competitive energy source within 10 years (DWIA 2014).

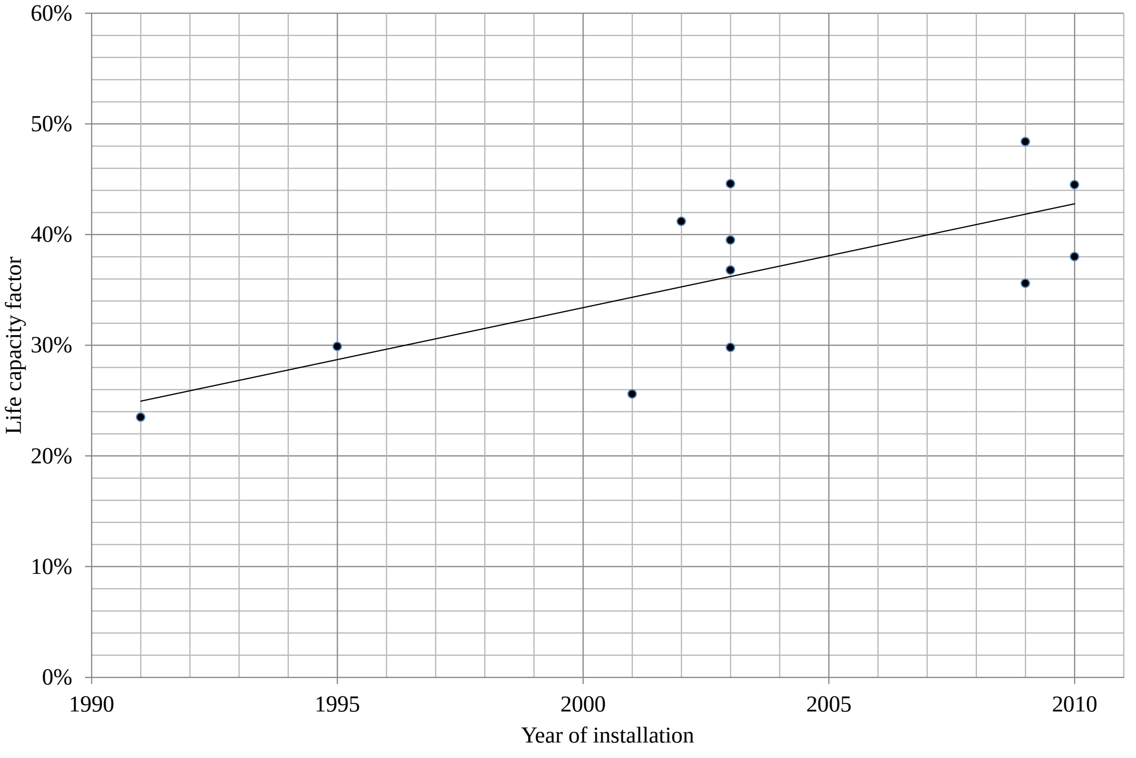
time, to its potential output if it were possible for it to operate permanently at full nameplate capacity.[9]

This is determined by wind conditions as well technological factors. Improvements on both the deployment side (siting of farms and micro-siting of turbines) and the core technology side have affected the net capacity factor of turbines over the years. Reflecting on prior average increases from 13% in 1985 to 24% in 2001 (in California), Boccard maintains:

> *"This is obviously due to technological progress in wind turbines design and possibly to better sitting [location and position]. This hard fact is proof that the learning curve was at work for WPG* [wind power generators] *during the 80s and 90s. Over the last decade, the wind power industry has noticed an even stronger development"* (Boccard 2008, 5).

Figure 5 shows the capacity factors of offshore wind farms in Denmark. It demonstrates a clear trend: the average capacity factors have increased significantly since the early 1990s. There is a big difference in the capacity factor of Horns Rev II at 48.4% (installed 2009) – for 2012 alone it was as high as 52.0% – when compared to Vindeby 23.5% (installed 1991). New wind projects and the turbines within them are now much more efficient, which has a significant impact on the levelised cost of wind energy. The newest turbines may regularly hit a 50%-capacity factor due to technological changes (Shahan 2012).

Figure 5: Danish offshore capacity factors



Note: The figure shows lifetime capacity factors at Danish offshore wind farms installed between 1990 and 2010. Lifetime capacity factors are the average annual capacity factors recorded from the time of installation until the present time (2013).

Sources: Calculation based on Energy Numbers 2013 and data from DEA 2013

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[9] To calculate the capacity factor, take the total amount of energy the plant produced during a period of time and divide by the amount of energy the plant would have produced at full capacity.

There seems to be no major difference in capacity factors between Danish and German offshore wind farms. While many farms are so new that capacity factors cannot yet be calculated, data show that for example Alpha Ventus and Horns Rev II have similar factors of around 50%. Alpha Ventus has a capacity factor of 50.8% (LORC 2014).

Interviewees suggested that there was little difference in the reliability of turbines between Denmark and Germany however it was not possible to obtain company-level data on the reliability of equipment. Even when it comes to commissioned projects (onshore) there is no readily available data to compare the two countries. However, the overall trend is one of increasing quality, as discussed in this section.

The quality drive was highly visible in all of the micro-level innovation cases. Even at the engineering stage, calculations were made based on cost-of-energy estimates that pinpoint the optimum technology in the trade-off between size and reliability. The cases show how increasing the reliability is a key focus area of equipment development and how European turbine developers factor in both the capital and operation costs in their design calculations.

The Vestas V112 example illustrates several of the paths discussed in this and the prior section. It is a part of the multi-megawatt group of turbines of 3MW and above and has been subject to the most comprehensive testing process in the industry performed to increase reliability. It is also an example of a ‘bundle of innovations’ which drives up efficiency and reliability (see Box 3). While originally built for the onshore market, it has now been developed further into different versions for different conditions, including for offshore deployment.

Box 3: Innovation case – Vestas V112

The V112-3.0MW wind turbine is currently the most popular one in the Vestas line-up. It was launched in the latter part of 2010 and has since been sold to more than 30 customers all over the globe. The V112-3.0MW reflects the dominant ‘Danish’ design in the industry, a design that Vestas has fine-tuned over the years. This includes the blade design, nacelle design and cooling systems with thousands of components being tested to ensure highest reliability.

While the design cannot be tweaked significantly to suit the needs of different customers, the customer *can* choose different standardised ‘add-ons’ to meet local weather conditions or local legislation regarding height, etc. Continuous improvement is achieved through these add-ons: if new and better solutions are discovered, these are only implemented after internal verification in Vestas and take the form of minor improvements to the core design.

The V112 was developed over a two-and-a-half year period before the first prototype was erected in Lem, Denmark. Three further prototypes have been installed: one in Spain at a location with extreme weather conditions; one in Germany due to demand from a customer; and one was set up at an offshore location close to Aarhus, Denmark. After installing the V112 prototypes in western Denmark and Spain, small pilot projects were initiated. The turbines on these projects are still running.

Vestas seeks to distinguish itself by having the most advanced test facilities where every component can be tested extensively. Vestas maintains a database on every turbine sold and this enables the firm to identify what types of errors may occur, when they are likely to occur, and how to handle these errors.

The V112 turbine now covers all three wind classes (IEC I, II and III wind speeds) as well as offshore. The potential market is therefore promising. It is different from another popular wind turbine also produced by Vestas, the V90-3.0MW, which is designed to operate in high wind speeds only. The V112 was developed to perform onshore in low (7.5m/s (metre per second) on average) to medium (8.5m/s on average) wind speeds. However it was soon discovered that the turbine could easily be altered to perform offshore within high wind speeds (10.5m/s on average) with only minor changes to the design.

Box 3 (cont.): Innovation case – Vestas V112
Another spin-off of the V112 turbine is the V126-3.0MW, which was designed to yield maximum power production in low-wind conditions. This turbine is almost identical to the V112: the only difference is a minor alteration to the gearing, some small design changes in the rotor, and the wider rotor diameter. The greater rotor diameter on the V126 makes it very efficient in low-wind settings. The similarity between the V112 and the V126 is as high as 99%. The original V112-3.0MW has therefore enabled Vestas to introduce two new turbines (the V90-3.0MW and the V126-3.0MW) to the market in a relatively short period of time. The 'design reserves' of the V112 enabled Vestas to develop these additional turbines. 'Design reserves' for example stem from the fact that the gearbox is more robust than what was demanded in the original V112. It can therefore survive greater loads while the same gearbox, with minor alterations, can be installed in other turbines.
Sources: Interviews with company representatives, company documents and media reports

2.3 Turbine design

Wind turbines with gears are the dominant design in the wind power industry. Gear-model wind turbines are prevalent amongst the wind turbines installed in Denmark, while direct drive models form the majority in Germany with a market share above 60% (IWES 2013).[10] The 'Danish Concept' design originates from developments dating back to the 1890s when Danish scientist Paul la Cour received a grant from the Danish government to construct a turbine for electricity generation. With the help of government funding, he founded the Danish Wind Electricity Society (DVES) in 1903 and over the next years more than 30 turbine generators were introduced. The next wave came in the 1950s when the Gedser wind turbine was erected. This was a pioneering design, which laid the foundation for modern turbines.[11]

Researchers from Risø National Laboratory and firms such as Bonus and Vestas were central to the development of this turbine design:

> *"They perfected a heavy-duty version of the wind turbine – and it has become the Microsoft Windows of the wind power industry. ... these sturdy Danish designs had little of the aerodynamic flash of the earlier U.S. wind turbines; they were simply braced against the wind with heavier, thicker steel and composite materials. They were tough, rugged – and they worked"* (Fairley 2002, 42).

The Danish design evolved during the 1990s with pitching of blades and power electronics and became embedded into the standard Danish drivetrain design. 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

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[10] Fraunhofer Institute for Wind Energy and Energy System Technology (IWES), Wind energy report, Germany 2011, 25.

[11] The majority of turbines that are installed worldwide are based on the Danish design and contain gears. Alternative lighter designs backed by US government research support were largely unsuccessful due to 'over-engineering' and, after the crisis due to the so-called 1980s 'California gold rush', the American lighter design vanished from the market landscape allowing the heavier Danish turbine to become dominant.

industrial standard. Vestas maintains that the Danish design and their future models will also be based on a construction containing gears.

The development of the direct drive is a German innovation, first developed by Enercon (see Box 4). Enercon uses a ring generator/synchronic generator, which creates a magnetic field electronically, rather than using permanent magnets such as Siemens (Offshore), GE Wind Energy (Offshore) and Vensys do. The main advantage of the direct drive is that is uses fewer parts than the gear model thus reducing the need for maintenance and repair, while the main disadvantage is higher cost.

Box 4: Innovation case – Enercon E126

Enercon is Germany's most important and well-established wind energy firm with a market share of over 60% in Germany and has been operating for over 25 years (BWE 2012). The most significant innovation of Enercon is the development, deployment and commercialisation of the first direct drive turbine to the mass market. This process started in the early 1990s, with the world's first direct drive being developed by the Enercon founder, Aloys Wobben, in 1992. The direct drive is used in all of Enercon's turbines and plays a key role for the E-126.

Enercon relies significantly on a business model with a high degree of vertical integration, producing almost all of its components in-house. Enercon is the firm that has gone the furthest to push a full-package approach to wind energy and seeks to market itself as a full-package supplier. Enercon often operates its own wind parks, undertakes the installation of turbines, organises the logistics, conducts service, operation and maintenance, has its own insurance and thus sells the entire wind package. Selling "the availability of energy" requires customers to sign a partner agreement with Enercon. 90% of Enercon's customers in Germany and abroad sign these agreements.

Enercon currently has small-size turbines below 1MW in its portfolio, such as the E-44, E-48 and E-53, as well as medium-sized turbines in the range of 2 and 3MW and large-sized turbines, such as the E-126. The up-scaling of turbines at Enercon is based on learning from the experience of building smaller turbines, improving technologies, improving innovation and production processes and then up-scaling these turbines in terms of installed capacity, rotor diameter, tower heights and wind speeds (Enercon 2012a).

The E-126 has thus developed evolutionarily out of earlier turbines and technological learning processes. The first Enercon turbine, the E-15, was developed in 1984 and had a capacity of 55kW. It formed the basis of many subsequent turbine innovations at Enercon including the E-126. The E-126 was installed for the first time in 2007 in East Frisia, northern Germany, close to Enercon's headquarter in Aurich.

Enercon has focused most of its research and development toward upscaling its onshore wind energy models. A reason for this innovation path could be the leap in technology, but also the change in the market: much of the onshore potential in Germany has already been exploited which means there is a move towards offshore, up-scaling of turbine sizes, as well as limited technological improvement.

Enercon is leading the up-scaling of turbines on the German market and has prices up to 30% higher than non-Enercon turbines. E126 has an installed capacity of 7.58MW. There are currently R&D activities for increasing the capacity of Enercon's turbines for 10MW and more. The E-126 has a rotor diameter of 127 metres (m), a hub height of 135 m; it is gearless and has the direct drive, single-blade adjustment and its cut-out wind speed is 28–34m/s. It has therefore been made for withstanding even stormy conditions (Enercon 2012a).

Sources: Interviews with company representatives, company documents and media reports

Turbines with a direct drive have been marketed for many years now, but have only gained a commercial foothold quite recently. The attractions are the potentially increased reliability, the lower costs derived from 'engineering out' the gearboxes (removing them from the turbine design) and their refurbishment and overall lower O&M costs. Enercon is the firm best-known for manufacturing direct drive turbines. Vensys is smaller but has become important as a technology centre for Goldwind. There are variations in the direct drive technologies of the two firms, which are related to the generator component. Enercon has a new system (annular multiple poles generator) which supposedly decreases the use of moving components in the turbine. Goldwind has a technology based on permanent magnet direct drive. Other firms, such as Envision, Siemens Wind Power and GE Wind Energy, are shifting from gearbox turbines to permanent magnet direct drive turbines. The production of permanent magnet generators involves rare earth materials, which is sometimes seen as a disadvantage.

Vestas has in-house design competence in direct drive and had initiated a research project on direct drive technology for their large turbines, which ran in parallel with the geared-model project. In the end, the firm stuck to the ‘Danish design’ which can use increasingly reliable gearboxes from key suppliers and which has been proven and fine-tuned over a period of thirty years. It considers the direct drive model as ‘not proven’ (Vestas 2013).

According to GlobalData, a global business intelligence provider, direct drive turbines jumped from around 18% of the overall market in 2006 to 22% in 2011. The firm estimates that the market share will increase to 29% in 2020 (GlobalData 2012). Roughly half of these turbines have so far been produced by Enercon.

Co-existence between the gear 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 investing heavily in R&D to improve the performance of the respective designs. This is primarily a competition between Denmark and Germany (with some involvement of Chinese companies on both sides).

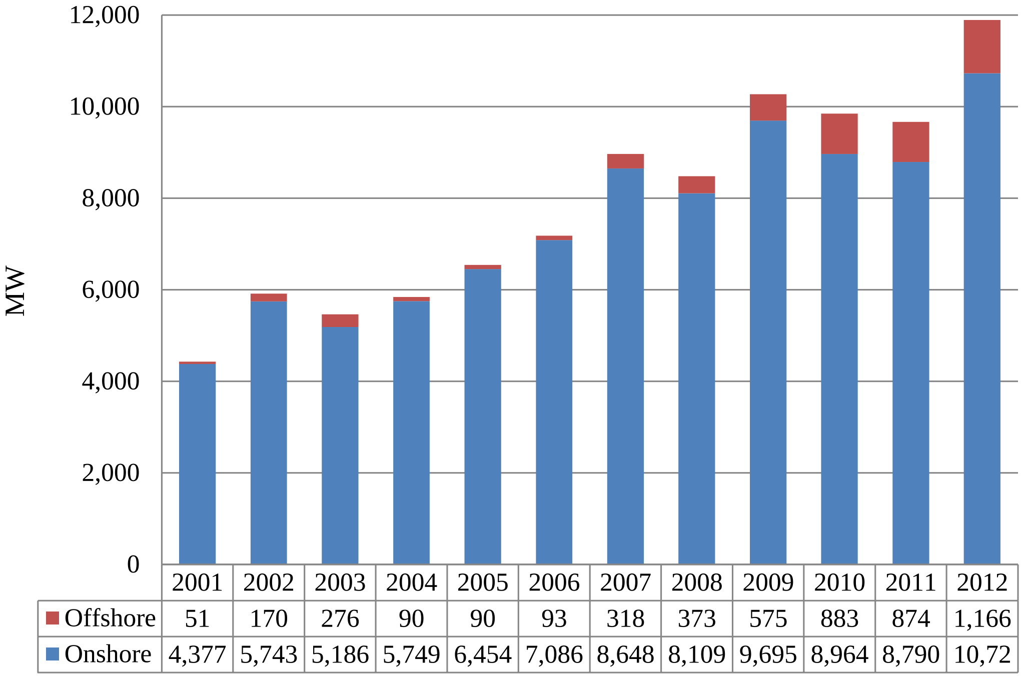
2.4 Onshore/offshore installation

In recent years, a trend can be observed towards the rapid growth of the offshore wind sector. In Europe the offshore market now constitutes 10% of the overall market (see Figure 6). In 2012, 1,166MW of new capacity were connected to the grid, a new record for offshore installations. Denmark is the pioneer offshore, but Germany is catching up rapidly. As shown in Table 4, the offshore share of installed capacity was 22% in Denmark compared to just 1% in Germany.

In terms of global shares this equates to 16% of global offshore capacity in Denmark and 6% in Germany (Figure 7). However, the United Kingdom has the biggest installation base. Despite public R&D in the offshore field, the United Kingdom has little manufacturing and private sector research capacity.

When it comes to offshore wind farms, Denmark is the leading country. With the establishment of Horns Rev I in 2002, Nysted (Rødsand 1) in 2003, Horns Rev II in 2009 – the world’s largest offshore wind turbine farm when it was inaugurated – Rødsand II in 2010 and with several major future projects, Denmark is setting the pace for offshore wind farms (see Box 5). The expected future development in the industry in Denmark indicates that the majority of wind turbines will be installed offshore; this is underlined by the fact that a total of 450MW offshore was installed in Denmark in 2010 compared to 250MW onshore wind turbines. The overall capacity of offshore wind turbines installed in Denmark is 870MW.

Figure 6: Annual onshore and offshore installations in Europe



	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
🟥 Offshore	51	170	276	90	90	93	318	373	575	883	874	1,166
🟦 Onshore	4,377	5,743	5,186	5,749	6,454	7,086	8,648	8,109	9,695	8,964	8,790	10,72

Source: EWEA 2013, 10

Table 4: Onshore and offshore capacity in Denmark and Germany (2012)

	Onshore	Offshore	Total	Onshore share	Offshore share
Denmark	3,241	921	4,162	78%	22%
Germany	31,027	280	31,307	99%	1%

Unit of measurement: MW

Source: EWEA 2013, 13

Box 5: Innovation case – Horns Rev II

In 2006, the Danish government published a key report, ‘Energy Strategy 2025’, and political agreements were signed between major political parties in parliament. Agreements were also signed between the Danish Parliament and energy companies, aimed at reducing Danish energy consumption and strengthening wind power. One of the elements of the agreement was to construct a 200MW offshore wind farm in Denmark.

Horns Reef is located 15 kilometres off the west coast of Denmark. It hosts two offshore wind power parks: the world’s first offshore park (Horns Rev I, using Vestas turbines) and the world’s largest offshore park (Horns Rev II, using Siemens turbines).

Horns Rev II consists of 91 SWP 2.3-93 (Siemens Wind Power) wind turbines generating a total capacity of 209MW, which is equivalent to the yearly power supply of 200,000 households or approximately 2% of the total Danish consumption of electricity.

Box 5 (cont.): Innovation case – Horns Rev II

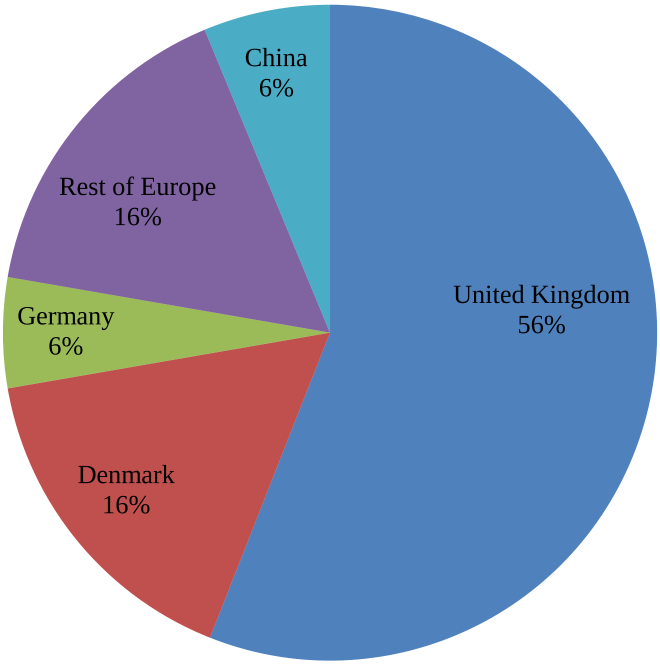
The case of Horns Rev II illustrates how wind power technology deployment has required the alignment of interests between a network of actors comprising (1) the state government: DEA, (2) electricity consumers: 18 large Danish firms and municipalities, (3) an energy company: DONG Energy, (4) a turbine provider: Siemens, and (5) project input providers: Energinet.dk (a Danish national transmission system operator), knowledge intensive business services, and specialised suppliers.

Through a round of public tendering, the Danish Energy Agency (DEA) allocated the contract to DONG Energy (previously Elsam), the largest energy company in Denmark. For the actual implementation DONG worked with a network of more than ten project suppliers. Danish/German Siemens Wind Power (formerly Bonus Energy A/S) was central in this network because of its expertise in the field of offshore wind power. The firm worked closely with partners in the network, including several specialised suppliers and providers of consultancy services.

As an element of the financial viability of the project, DONG has entered into partnership agreements with a group of 18 Danish energy consumers (firms and municipalities) where DONG works to identify possibilities for energy savings which reduced energy consumption by 10% on an average basis. In return, the consumers earmarked all financial savings for purchasing renewable energy from Horns Rev II. This provided DONG with a mechanism to finance the capital requirements of bringing additional renewable energy to the grid and expanding the commercial basis of renewable energy while providing the partners with a cost-neutral way of achieving significant reductions in carbon emissions. The pharmaceutical firm Novo Nordisk has been the first mover in this agreement. This firm has already received electricity from the project (and will be purchasing up to one-third of the total electricity produced at Horns Rev II) and is working towards the goal of fully powering its Danish facilities with green energy. In this way, the DEA facilitated the network formation and business model innovation for the implementation of offshore projects.

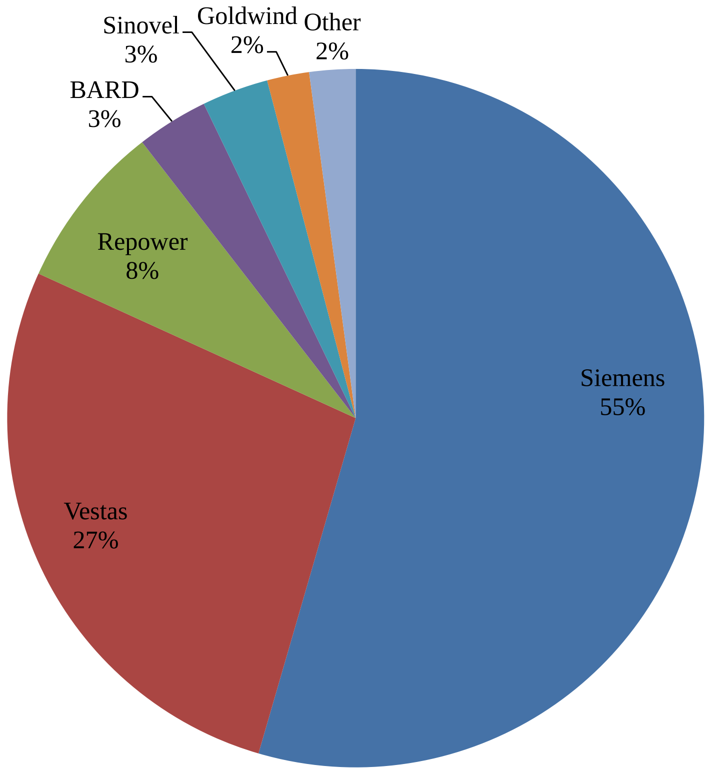
Sources: Interviews with company representatives, company documents and media reports

Figure 7: Accumulated offshore installation by country



Source: EWEA 2013, 10

Figure 8: Accumulated offshore installation by supplier company



Source: BTM Consult – a part of Navigant – 2013

Denmark can therefore be considered as dominant in the offshore segment: 90% of the world's offshore wind turbines are either Danish-produced or have Danish-developed foundations and components and have often relied on a range of Danish support services. Siemens and Vestas accounted for 57% and 27% of the market share of total accumulated installed offshore capacity respectively and in most recent years the offshore market has been dominated by Siemens. By contrast, the current offshore share of non-European firms is negligible. Sinovel (3%) and GE Wind Energy (1.7%) are the only non-European manufacturers who have already installed offshore wind turbines (own calculation based on BTM Consult (2010, 21).

Siemens Wind Power, through its subsidiary in Denmark, is the globally leading firm in offshore turbines. It has been a key supplier to Danish DONG energy, the world's largest offshore wind energy owner. It owns and operates offshore parks throughout Europe, not least in the United Kingdom.

The offshore base will be expanded substantially with new major offshore projects on the way. The Anholt Offshore Wind Farm is expected to be inaugurated in 2013 and will be the largest offshore wind farm in Denmark with an overall capacity of 400MW. It is likely to cover 4% of the Danish power consumption. Two new large-scale offshore wind farms are to be established: (1) Horns Rev III offshore wind farm with a capacity of 400MW in the North Sea and (2) Kriegers Flak offshore wind farm with a capacity of 600MW in the

Baltic Sea. Both of these offshore wind farms will be put up for tender in between 2013 and 2015 and are expected to be commissioned between 2017 and 2020.

At the end of 2011, Germany had an installed wind energy capacity of 30GW (BWE 2012; IEA 2013), of which 253MW (0.253GW) were installed offshore (IWES 2013). The overwhelming majority of Germany's wind energy capacity is therefore still onshore. Nevertheless, there is a current boom in the offshore sector as more and more firms recognise the opportunities the offshore sector provides.

Going offshore is a recent technological trend in Germany, which has been promoted by the positive learning-experience from the first German offshore test field Alpha Ventus.[12] Germany however follows a different approach than Denmark. While Denmark has tested smaller turbines offshore for many years, the German strategy is to catch up quickly and to go offshore immediately with larger turbines, albeit without the many years of experience. The need to build the offshore park far off the coast has led to technology that can withstand rougher winds, higher waves and more saltwater corrosion. However, the largest challenges for offshore wind energy are related to grid integration, particularly in Germany.

For Alpha Ventus there was a delay of two years before the grid operators Tennet enabled grid integration. Other challenges in the offshore sector are the choice of turbines and improving turbine design, maximising foundation design, installation of turbines and the fundaments, laying the sea cables, and grid integration. This has taken five years for Alpha Ventus, but is likely to take a shorter time of one to two years for second-generation offshore projects.

The EWE-led Riffgat close to Borkum used Siemens' Danish-produced 3.6MW turbines. This has led to a further increase in offshore parks such as the Vattenfall-owned Dan Tysk, which was intended to be operational by early 2014. The characteristics of the German offshore boom are partly comparable to how the onshore industry grew, but are more drastic because of shorter time frames: rapid up-scaling of turbine sizes, capacities, projects and investments. German offshore farms are therefore getting bigger and going further at a rapid pace. For example: Alpha Ventus was situated 45 kilometre (km) offshore, Dan Tysk is situated 75km off the shore line. The Vattenfall-owned Dan Tysk is an example of how investment of a foreign corporation drives risky and expensive off-shore development in Germany. Vattenfall is a multinational energy provider, which is owned by the Swedish state and it has acquired German and European suppliers to support these large-scale offshore projects.

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[12] In mid-2000, the regional power provider EWE started to become active in the offshore field together with Enercon, in a project which later became Germany's first offshore wind park: Alpha Ventus. Nevertheless, Enercon soon withdrew its activities offshore and decided to work onshore only. This is due to the fact that Enercon has expertise and is the market leader in the onshore sector, whereas high investments, different logistics, R&D and expertise would be needed for moving into the offshore sector. Nevertheless it was speculated by the interviewees that Enercon's E-126 7.58MW turbine – the world's largest wind turbine – might have been built and tested for the offshore market.

The onshore sector has remained the key market in Germany generating most profits, as it is significantly cheaper and more reliable than the offshore sector. The key reason for the move towards offshore and the scaling-up of wind turbines is the alleged lack of space. The move towards lower wind speed areas in southern Germany is also attributed to a lack of space as well as an over-capacity of turbines in the windy areas of northern Germany, which the outdated grid cannot handle.

However, the final jury is still out on the potential to further expand onshore wind energy in Germany. A recent study published by the Federal Environmental Office (Umweltbundesamt) claims that, throughout the country, significant space is still available for new wind energy farms. The same study even goes as far as calling for a discontinuation of political support (in terms of feed-in tariffs) for offshore wind facilities (Umweltbundesamt 2013).

2.5 Project size

Closely linked to the offshore trend, a second trend in deployment is the increasing size of individual projects. Individual projects are getting bigger, with more turbines in each project, particularly in new offshore projects, but also in onshore projects. In terms of trajectory, this is a break in the dominant trend, away from ‘Nordic’ Danish and German wind power models, which were based on private equity investment and popular participation. In stylised terms, it is a movement away from community-based deployment to big-business-based deployment. Large utilities and pension funds are now big players, as opposed to individual developers and cooperative finance. This creates entry barriers into the industry and new business models, which are linked to innovation in deployment. However, there is a diversity of paths. The main trend is an up-scaling to utility-sized projects (including offshore projects), but there is also a continuing sub-trend of smaller scale deployment, which might become more consolidated in the coming years, partly because of the repowering segment in which old turbines are being replaced. Such projects still tend to be rather small.

To recapitulate, there are now two main markets. One is the utility-scale market, which is for large projects, both onshore and offshore; large projects can have an individual impact in changing the energy mix. This is attractive to policymakers even if offshore wind is still more expensive. The big players are to be found in this market – such as Siemens Wind Power and GE Wind Energy. Some interviewees said that even Vestas may be too small to compete globally in this segment in the future.[13]

Figure 9 shows the changes in project size over time, demonstrating the trend in Europe in the period between 2001 and 2007. Projects smaller than 20MW were the predominant mode until the mid-2000s. However, as Figure 9 shows, onshore projects increased steadily in size while offshore projects contributed to the consolidation trend with most offshore projects being over 100MW. According to interviews, this trend continued after 2007.

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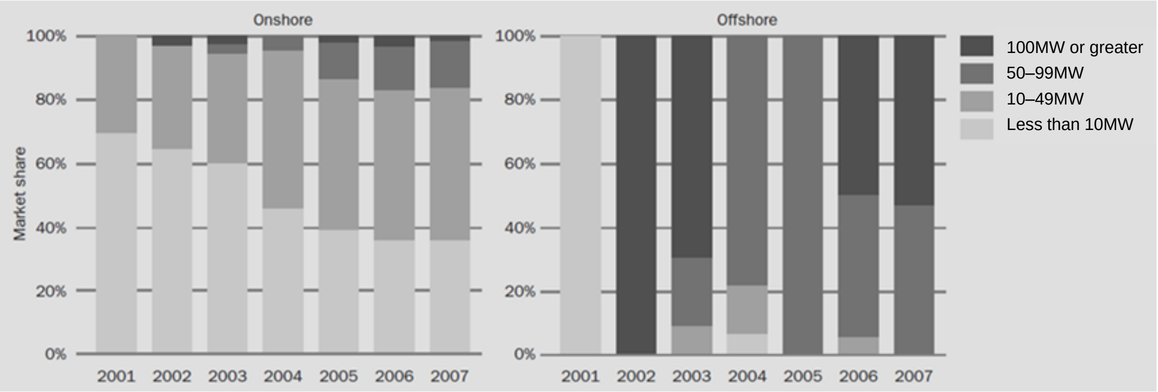
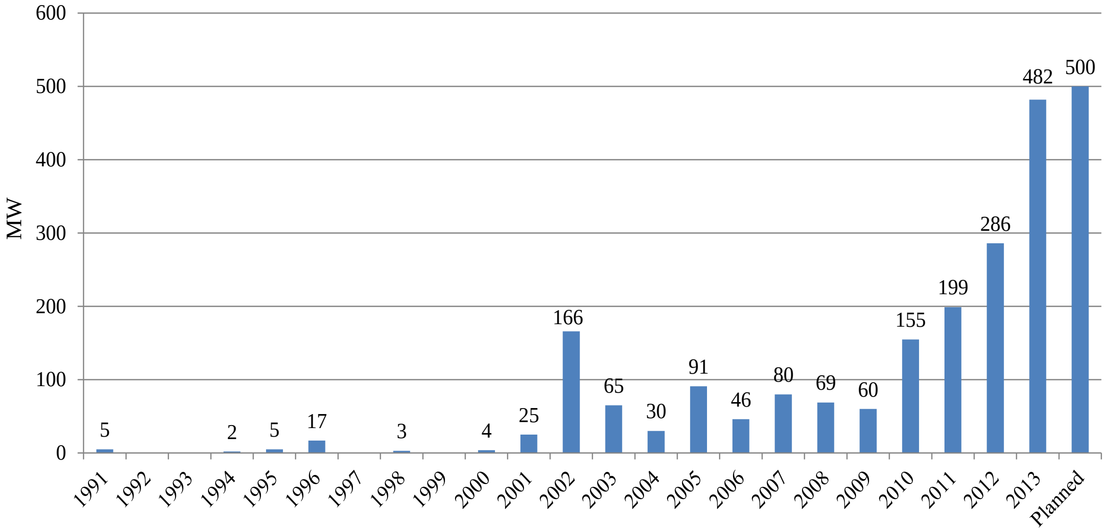
[13] This regards financial power rather than production power, since Vestas is the largest producer in the world.

Figure 9: Europe onshore/offshore project size overview



Source: EWEA 2009, 287

Figure 10: Average offshore wind farm size



Source: EWEA 2014

The second segment is the segment for ‘distributed generation’. These smaller projects are scattered and distributed more evenly in geographic terms. Some of the big players have phased out the segment. It is a growing segment (in absolute terms) within the overall growing wind market. One driver is energy policy-based on the recognition that there will be distribution/grid problems when all generation is centralised. The strategy is increasingly to go for both core utility-scale projects and facilities that are close to consumers and do not stress but relieve the central network. Some small companies focus exclusively on this segment. Rather than investing in big wind farms, they concentrate on small projects with 3 to 10 turbines.

Both Denmark and Germany had a decentralised structure during the 1980s and 1990s. In Denmark, during the 1980s, local wind cooperatives emerged as collectives of farmers or consumers investing in wind turbines on a collective basis. A tax-reduction scheme was in place on investments in wind turbines by cooperatives and private owners. This was a way of addressing the investment requirements that typically exceeded the capacity of individual actors. Generated electricity was consumed locally and excess generation was sold to the grid. By 2002, 80% of wind turbines were owned by wind energy cooperatives. Ownership was decentralised, sometimes with cooperatives of hundreds of investors owning three to five turbines (Moe 2012). During the 1990s, more than 2,000 cooperatives were created with the involvement of over 100,000 families and facilitated popular support (Krohn 2002). However, these projects were typically for small turbines (such as 55kW) and deployed in very small projects of only one or a small number of turbines.

In Denmark and Germany, a ‘replacement round’ in this segment is now taking place. Many turbines in the segment are 20 years old. This means that owners no longer get a subsidy – which is an incentive to replace them with new ones that do. In Germany, a scheme provides incentives for replacing old turbines with new ones. The Danish government has recently introduced a target for land-based turbines.

2.6 Services

This section examines the trend in deployment services, that is, the operation and maintenance (O&M) services content of new deployment projects. The increasing service component is a general trend across the manufacturer base in Europe.

Turbine suppliers are becoming more closely involved in deployment activities including planning, procurement, construction and O&M. Particularly the O&M element is attractive during the time of crisis when these service revenues can provide a steady income to manufacturers. An additional underlying reason has to do with changes in the value chain. Project owners – WTG customers – are increasingly large and powerful utilities leading to the reduced influence of small, independent power producers or cooperatives. These utility firms increasingly demand long-term full service contracts to reduce risks associated with wind power investments.

Vestas has developed an ‘Active Output Management’ service option which consists of both scheduled and unscheduled maintenance. According to Vestas it is ‘an energy-based guarantee’ that ensures the turbines are fully operational throughout the service agreement lifetime, so that a steady income is guaranteed (except if there is no wind).

Enercon is the firm that has gone the furthest in this regard and seeks to market itself as a full-package supplier by emphasising that it does not only sell wind turbines but also ‘the availability of energy’. Enercon operates its own wind parks, does the service, operation and maintenance, and sells the entire wind package. It does so mainly in the German market. It is heavily reliant on the local German market where it enjoys a market share of over 60%.

Some turbine manufacturers only produce parts of the turbines in-house (e.g. the blades), whereas other key components are outsourced and provided by suppliers (e.g. the direct drive or the gears). This enables the firms to be in a better position to provide lifetime warranty and full service contracts. Enercon also insures itself against damage and other business-related circumstances.

Selling ‘the availability of energy’ or the full package requires customers to sign a partner agreement with Enercon. 90% of Enercon’s customers in Germany and abroad sign these agreements. The payment for this extra service is dependent on the availability of wind. In years with higher wind speeds, the customers pay more; in years where the wind speeds are lower, the customer pays less. Usual operation and maintenance conditions are covered in the agreement. Additional insurance for *force majeure* and vandalism can be purchased in addition (Enercon 2012c). Some interviewees argued that the ‘German model’ of producing most components in-house and offering service, operation and maintenance for the entire life time of the wind turbine/park is a key innovation which, according to interviews, was pioneered by Enercon.

When it comes to the full service dimension, Siemens does not provide a lifetime warranty as Enercon does, but sticks to the three, five or seven years which is customary in the industry. Enercon is probably the company which has come furthest in the provision of ‘turnkey projects’ in which the firm integrates all elements of service provision related to installation in its contracts.

2.7 Summary

The overall aim of this section was to examine the following: What are key features of innovation paths in Denmark and Germany? To what extent do they differ? And, in particular, in which respects are they similar or do they differ respectively? An overview of the findings – based on both interviews and secondary data – is provided in Tables 5 and 6, while the remainder of the section elaborates on the main insights.

Table 5: Summary of the core technology paths

Trajectory (Key indicator)	**Key findings**
Size Turbine nameplate capacities	• Broadly similar paths in Denmark and Germany. • The key trend is one of dramatic up-scaling in both countries. • Some variation exists: the average size of turbines installed in Denmark is above 3.0MW while in Germany it was 2.5MW in 2009. • Producers from both countries are capable of supplying turbines bigger than 3.0MW. • Enercon has the world’s biggest turbine currently on offer (8.0MW) while Vestas has the highest market shares for multi-MW turbines (above 2.5MW). • All firms are conducting R&D for the next generation of giant turbines.
Reliability Capacity factor	• Broadly similar paths in Demark and Germany • The key trend in both countries is one of increasing the reliability of equipment. • Turbine reliability is difficult to isolate from other factors but contributes significantly to the increased capacity factor of each turbine and declining levelised cost of energy (LCOE) from wind. • Data from Denmark shows an increase in the capacity factors of turbines installed offshore. • There are high capacity factors in leading offshore parks in both countries (50% of nameplate capacity).

Table 5 (cont.): Summary of the core technology paths

Design Turbine architecture	• Variations exist between the two countries, with the dominant gear model as a distinctly Danish invention and the direct drive model distinctly German. • Gear-model wind turbines are prevalent amongst the wind turbines installed in Denmark, while direct drive models form the majority in Germany with more than 60%. In Denmark the direct drive market share is close to zero. Only one grid-connected direct drive turbine has been installed in Denmark (Envision prototype). • Co-existence between the gear and direct drive model is likely to continue. • There is no clear trend with regard to the future success of the newer direct drive model. Manufacturers are working in parallel on improving respective designs. • R&D on direct drive is now being conducted in Demark by Siemens and Envision

Source: Own compilation

Table 6: Summary of the deployment paths

Trajectory (Key indicator)	**Key findings**
Onshore/offshore installations Share of offshore installation	• Variations exist between the two countries, with the offshore segment most mature in Denmark. • Denmark has an offshore share of 22% of total installed capacity whereas in Germany it is 1% but is growing rapidly as a percentage of German wind power. • Service providers from both countries are capable of engaging in wind park construction; Danish actors are more engaged in park construction outside their country. • Both countries will increase offshore shares in coming years with substantial offshore capacity expansion in the pipeline.
Project size Number of turbines per project	• Broadly similar paths in Denmark and Germany. • Both countries are departing from ‘small-scale’ wind power, in favour of utility-scale deployment models. • New projects (not least offshore projects) now often have 50 to 100 turbines rather than 3 to 10 in the past. • Some variation exists: The community-based model has been historically stronger and continues to be a more important sub-trend in Denmark.
Services Service content of deployment contracts	• Full-package provision (turbine plus service) is a key feature of leading manufacturers in both countries. • In the onshore sector, this trend is particularly pronounced in Germany.

Source: Own compilation

As shown in Table 5 and Table 6 there are many commonalities between Germany and Denmark when it comes to pathways, both in core technology and deployment. In core technology the similarities were the up-scaling of turbine sizes and the efforts to increase the quality of turbines.

Both countries are involved in a race to build larger turbines. In Denmark, the average size of installed turbines has surpassed the 3MW mark, closely followed by the United Kingdom and Germany at around 2.5MW.[14] The vanguard status of Denmark and Germany in the up-scaling race is also manifest when looking at the supply side. In the multi-megawatt segment – i.e. the market for turbines above 2.5MW – the European lead firms are dominant with Vestas controlling more than 40% of the market and Siemens more than 20% in 2012. The other major players in that segment are GE, Enercon, and Sinovel, all with market shares of between 5 and 10%.

Informants also identified 'increasing turbine quality' as a key innovation path. On the income-generating side, increasing quality entails higher output due to more uptime and on the cost side, it entails a reduced need for O&M. Informants argued that the cost of wind energy was reduced as the quality of core turbine technology increased, for instance as the capacity factor of new turbines, such as those in Horns Rev II, moves above 50% of nameplate capacity.

There were also similarities between Denmark and Germany on the deployment side. Both countries have moved along similar paths when it comes to the organisation of deployment. In the early stage, projects were small with a significant local ownership. In this respect, the onshore market is more differentiated. Many first-generation turbines are at the end of their lifespan and are currently being phased out. Due to increasing turbine size, there are currently fewer turbines deployed than at any time in the past 10 to 20 years. However, these are concentrated in larger projects, and at the same time the production capacity and output have increased significantly.

Both countries are characterised by similar historical patterns of path evolution, starting with distributed deployment and then increasingly becoming concentrated in large-scale projects. However, distributed generation is currently being revitalised to a certain extent.

In core technology, the key difference is in the design of turbines. The 'Danish Design' (the doubly-fed induction generator with gears) remains the global standard and can be traced back to the initial experimentations of the pioneering engineers who started working on turbine design for electricity generation more than 100 years ago. The direct drive design emerged as a distinctly German design. It dominates the German installation base but is uncommon in Denmark.

Another key difference is in the role of the offshore segment. Denmark has been a pioneer, first spearheading offshore projects inside its borders and then as a leading supplier of offshore technology elsewhere.[15]. By contrast, the offshore segment has played a much smaller role in Germany so far. However, current plans for the offshore segment may put Germany in a leading role.

The horizontal integration of business functions is a further key trend, not least in Germany where Enercon is leading the way. Vertical integration refers to the in-house production of

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[14] European countries are clearly leaders in the up-scale race when compared to the China and India which are closer to the 1.5MW and 1.0MW mark respectively.

[15] Overall, Europe is a global leader in wind power. The United Kingdom is the leading offshore market in total numbers of MW installed, followed by Denmark and Germany.

components (the ‘core technology’ turbine production value chain) whereas horizontal integration refers to in-house provision of services (the deployment value chain). The increase in project size has meant that O&M contracts have become economically more interesting for the larger players. For example, the largest onshore project in Denmark – mentioned above – has a twenty-year service contract with Vestas, the supplier of the turbines. Full-package provision is more common in Germany in the onshore sector, whereas in the offshore sector Denmark has increasingly moved to full-package provision.

There are also some smaller variations noted in Table 5 and Table 6. These will not be repeated here but will be addressed in the next section where relevant.

Finally, the reader should keep in mind that we have focussed the European research on Denmark and Germany in the context of a larger project, which compares these countries with China and India. This chapter has given an outline of key ‘European’ innovation paths. There are many overlaps in the overarching technology trends. Some degree of similarity could be expected due to the deliberate selection of two leaders in the field which are also neighbouring countries. More variation would have been found if other countries in Europe had been included in the comparison.

Obviously, the innovation paths in Europe are not a closed chapter. While it is important to examine whether there are dominant trends, it is also important to recognise continuing diversity within and across countries. It is unclear whether the future will bring more convergence or divergence. For some of the trends it is possible to make an informed guess. The next section will examine the factors behind the similarities as well as the differences in order to do so.

3 The key determining factors

The previous chapter identified the key sectoral trends and innovation paths. The purpose of this section is to explain what shapes these innovation paths: What explains the similarities and the differences? Methodologically, this is difficult to answer due both to an attribution problem and to a time-lag problem. Most of the paths identified in Section 2 are explained by a combination of elements, such as government policy, factor conditions and innovation strategies firms adopt. No single determinant can explain wind energy innovation paths in Denmark and Germany. Where possible, we will therefore indicate the dynamics which lead to a concurrence of elements having a combined impact.

Initially, the various elements are described and discussed one at a time. However, it is important to note that the determining factors are also mutually interdependent. For example, the market for wind is highly dependent on government policies; firm strategies are highly dependent on the existence of related firms and networks – and *vice versa*. However, the purpose of the section is not to trace such interdependencies. The purpose is to lay out how different determining factors have influenced core technology and deployment innovation paths – both those that are similar in Denmark and Germany and those which are distinct in each country.

3.1 Government policies

Both Denmark and Germany have set ambitious targets for renewable energy. In Germany, the target is for renewables to reach 35% of final electricity consumption by 2020, mainly from wind and solar (BMU 2012; BMU 2011). In Denmark, the target share is 50% renewables by 2020. In both countries targets thus go beyond the EU targets of 20% of final electricity consumption from renewable energy by 2020 – which both countries have already met (IEA 2012).[16]

3.1.1 Policy context and evolution

The Danish story

It is widely accepted that government policies have played a key role in the establishment of a vibrant and globally competitive wind energy industry in Denmark. However, the government is now faced with important challenges and the ensuing need for policy renewal. This section examines the changing policy motives, priorities and measures. It distinguishes between the early period (inception and growth) and the more recent period (globalisation).

The Danish wind turbine industry started to develop in the 1970s and 1980s mainly because of an environmental grassroots movement (Karnøe 1999). Wind energy was developed as a response to the oil crises of the 1970s. At the same time, a key motivation was to build a globally competitive hub for creating innovative wind energy technology and highly paid jobs. The experimentation with wind energy received substantial support from politicians and business leaders concerned with energy security.

The priorities of Danish public policy have changed along with the evolution of the sector. In order to bring this out, it helps to distinguish between the inception and growth stage (1980–2000) and the globalisation stage (2000). Initially, the wind turbine industry in Denmark was not government-driven. Rather, the sector grew out of the anti-nuclear political movement, led by idealist entrepreneurs and supporters, who campaigned effectively to raise wider public support for renewable energy. This grassroots movement was primarily concerned with wind energy as an environmental public good. However, the mounting recognition of the need for alternative sources of renewable energy aligned with the interest of the then social democratic government, which was initially only concerned with reducing energy imports. The government introduced the Energy Package and the Energy Plan in 1979 and 1981, respectively. These packages created trust between public and private actors and were responsible for the commercial institutionalisation of the industry (Andersen / Drejer 2008). Government was thus pro-active in the early period and the initial priority was fairly narrow in focus: to circumvent dependence on energy imports by creating domestic energy sectors such as wind power and natural gas. A subsidy introduced for green energy was particularly important for the formation and growth of a professional wind turbine industry. During the 1990s, the Danish government had a

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[16] Nevertheless, the policy setting of the EU is still important for the national policy debate. It is therefore worthwhile to set out the EU policy landscape. This is done in the Appendix.

powerful and controversial social democratic Minister of the Environment who orchestrated support to wind power through a sub-department, the Danish Energy Authority (DEA).

However, after 2001, a new government, and new international political circumstances, placed the Danish wind-energy industry in a different setting. The new government advocated more market-based incentive mechanisms. As a result, Danish wind energy policy became more complex and driven by a broader spectrum of interests. The wind turbine sector expanded from the sphere of energy policy to the sphere of industrial policy as the sector became a significant employer and revenue earner. The priorities were influenced by regionalisation and globalisation in two main ways: First, a directive for the liberalisation of energy markets was implemented in the EU in 2001. This brought an end to green energy subsidies in Denmark and introduced new business models and new actors involved in wind power projects. The government had a more limited room to manoeuvre and a key priority was to find new ways to support the sector and the viability of projects in ways that were consistent with a liberal/conservative economic ideology. Second, inbound and outbound flows of foreign direct investment (FDI) became increasingly important. Market growth and the established wind energy competence cluster attracted inflows of multinational firms, thereby increasing competition in the domestic sector. However, the consolidation of the Danish turbine industry with several mergers and acquisitions also created new national champions. These competed not only at home, but also increasingly – and now predominantly – in export markets.

The 2001 election changed Danish policies drastically. Some of the changes resulted in a reduction in government funding for the development of wind technology and information dissemination. The new government also cancelled the obligations of the large utilities to build three further offshore wind farms totalling 500MW as a result of which the market ‘fell flat’. There was thus a ‘dry spell’ in the Danish wind market between 2004 and 2009 due to the changed policy priorities of the government. This led to increasing concerns in the wind industry that Denmark was falling behind in comparison to other European countries because of decreasing local market dynamism. This should be contrasted with the market expansion in countries such as Germany and Spain where long-term financial support mechanisms were in place.

More recently, Denmark has again become a country with strong policy support for wind. Several policy agreements have been adopted during the last few years, most notably the energy policy agreement of 2012. In this agreement, the Danish government received backing from parliament for various projects as described later in this paper.

The German story

The German wind energy sector has been highly dependent on the political decisions that started in the early 1990s to support a fast and ambitious expansion of wind energy. The goal was to increase the share of wind energy and other renewable sources of energy within the total energy supply. Key policies that triggered the development of the wind energy industry were the introduction of the feed-in-legislation in 1991 and the Renewable Energy Law in 2000 (*Stromeinspeisungsgesetz StrEG* 1990; *Erneuerbare Energien-Gesetz* 2000). Another favourable public policy measure was the modification of the Federal Building Code in 1997 (*Baugesetzbuch BauGB* 1960), which made rapid and uncomplicated development of wind energy possible. Since the building law was changed in 1997, wind turbines have been given a privileged status. Local authorities can ‘be forced to accept wind turbines on their territory'. However, the local authorities are responsible for designating *"zones for wind energy parks, concentrating them on one appropriate site"* (Jobert / Laborgne / Mimler 2007, 2753). The feed-in-legislation was updated and fine-tuned every few years. Over time, the incentives have become more and more linked to the larger political programme of the *Energiewende* (energy transition), which aims at phasing out nuclear energy by 2021 and boosting the development and deployment of renewable sources of energy (BMU 2012; BMU 2011).

The main national regulator for wind energy used to be the Ministry for the Environment (BMU) with a mandate covering the policies and financial regulations that promote wind energy, such as the *Erneuerbare Energien-Gesetz (EEG)* and the feed-in-tariff. Broader, cross-cutting responsibilities relating to incentives and policies to foster innovation, development of firms, and economic growth were vested in the Ministry for Economic Affairs and Energy (BMWi). As part of a government reshuffle in late 2013 (resulting from the electoral victory of the so-called Grand Coalition), the entire energy agenda was transferred to the Ministry of Economic Affairs and Energy. This includes overall energy policy, grid management, promotion of renewable sources of energy as well as energy-efficiency enhancement. Importantly, the management and reform of Germany's energy transition (*Energiewende*) is thus directly linked to a comprehensive agenda of economic growth, competitiveness and innovation.

It is often suggested by experts that the EU dimension only plays a minor role for the German wind energy market. From a historical perspective, the EU tended to be seen as a barrier that sought to restrict the development of the EEG in the first place because the law encouraged the preferential treatment of one member state over another and encouraged 'unfair competition' within the EU. The German policies of the EEG are much more ambitious than the EU policies (compare: the EU 2020 target is 20% renewable energy among installed electric capacity, whereas the German target is 35% and in 2011 almost 20% of renewable energy had been installed). Nevertheless, today the EU plays a more important role than in the past, as public support in Germany is gradually fading due to rising electricity prices. While this energy transition has attracted global attention from both admirers and sceptics, there are signs that the government elected in late 2013 will slow down its pace – mainly for cost reasons. The energy transition is high on the explicit agenda of the government; but the latter is also concerned with mitigating a current electricity 'price hike' as well as with reducing what are considered overly generous incentives (Lütkenhorst / Pegels 2014).

Another key public actor in Germany is civil society. The green movement actually started the trend towards wind energy back in the early 1980s. It was based on opposition towards both nuclear power and fossil fuel energy. The green movement also includes various environmental non-governmental organisations (NGOs), most notably Greenpeace, that have been opposing nuclear energy as well as fossil fuel energy for decades in Germany in benefit of renewable energy sources such as wind. Unlike in many other countries, the green movement is powerful in Germany and the Green party grew in significance in the late 1990s and the 2000s and even came to power in a coalition with the Social Democrats. Today, the Green Party forms part of government in federal states, such as in Baden-Württemberg and North Rhine-Westphalia and drives a strong political agenda which favours renewable energy, particularly wind energy.

A key difference to Denmark is that, in Germany, key concerns were related to the adverse effects of nuclear energy – for national health, safety and security. The anti-nuclear opposition that arose due to Chernobyl in the late 1980s played a key role in driving forward the wind energy agenda. In Denmark, on the other hand, the emphasis on wind as an alternative to nuclear energy came much earlier when there was a debate about whether to introduce nuclear energy power plants or not (and decided against it). The head start in Denmark can thus be explained by the initial circumstances of these two countries. During the founding 1970s, energy security issues were the key drivers of wind energy development. In Denmark there was a very strong resistance to nuclear energy. While there was some deliberation and some steps were taken (Risø was initially an atomic energy research institute), this power source never received serious traction. This meant that there was a need to look at other sources, which resulted in the prolonged support regime for wind energy. Germany on the other hand had endorsed nuclear energy and did not suffer as severely from the energy crisis. Hence the government in Germany did not address the wind power industry with the same urgency during the formative years, which explains why the German industry did not take off on a significant scale until the 1990s.

3.2 Policy measures: boosting demand and supply

Government policies have had a major direct and indirect influence on the national innovation paths in wind power. One can make a useful distinction between ‘demand-side’ and ‘supply-side’ policies, i.e. policy measures boosting demand through feed-in tariffs and related purchase guarantees as opposed to policy measures supporting the development and funding of technological development and innovation. Both types of policies have been applied in Denmark and in Germany with similarities in principle and variations in detail.

As mentioned, public acceptance of wind energy is high in both countries with a strong civil society driven by political and environmental motives. Thus, both countries benefited from a relatively high degree of community and civil society support, which facilitated deployment; although local resistance to particular projects was unavoidable, it did not significantly hinder wind energy development. Government concerns about energy security also contributed to these green policies as did the lobbying of firms in the wind energy supply chain.

3.2.1 Demand-side policy measures

In both countries, the stimulation of *demand* has been historically very important for the industrial development and deployment of wind energy. Anybody can build an onshore wind farm at a chosen site provided that it adheres to prevailing legislation and official approval. Connection to the grid is guaranteed.

In Denmark, the initial Energy Package stipulated that producers would receive a subsidised minimum price for renewable energy (feed-in tariff – the so-called Wind Turbine Guarantee). Producers were guaranteed access to the national energy grid and the largest and publicly controlled association of power producers (Elsam, now DONG energy) was mandated to purchase the output (a power purchase agreement). At present, the feed-in-tariff for onshore wind is no longer constructed as a traditional flat-rate tariff, but as a price premium model where a bonus is paid in addition to the prevailing market price (see Table 7). Although there is a premium add-on to the market price, there is no minimum price guarantee. The effective going rate is thus essentially determined by the market price at the Nordic Electricity Exchange (Nord Pool Spot). This allows for the integration of wind into the electricity market and creates more competition between developers, which in turn provides incentives for increasing the reliability of equipment and reducing O&M costs. In Europe, only Denmark and Cyprus have adopted premium price feed-in tariffs (Jenner / Groba / Indvik 2013).

Table 7: National wind policies in Denmark and Germany

Denmark	• Wind Energy guarantee. • Promotion of Renewable Energy Act - based on the 2008 Energy Policy Agreement. • Wind energy to make up 50% of final electricity consumption by 2020. • Danish feed-in tariff: o Onshore wind energy: Price premiums of 3.35 EUR cent/kWh for the first 22,000 full-load hours + 0.31 EUR cent/kWh for balancing costs. o Offshore wind energy: fixed payment which varies between different tenders. At Horns Rev II it is 6.95 EUR cent/kWh for the first 50,000 full-load hours.
Germany	• Renewable Energy Law EEG • Renewable energy to make up 35% of final electricity consumption by 2020, mainly from wind and solar (in 2011 almost 20% had already been achieved). • German feed-in tariff: o Onshore wind energy: 8.93 EUR ct/kWh for the first 5 years + 0.48 EUR ct/kWh bonus = 9.41 EUR ct/kWh for first 5 years, then 4.87 ct/kWh. o Offshore wind energy: 15 ct/kWh for the first 12 years, then 3.5 ct/kWh or alternatively 19 ct/kWh for the first 8 years.

Sources: DEA 2014; Egeberg-Gjelstrup 2011; BMU 2012

The demand-creation for offshore projects is managed differently (except near-shore projects and open-door offshore projects outside tenders).[17] For offshore wind installations, there is a tender process where demand requirements are specified. The tenders often specify both elements of turbine design and size of installed turbines, demanding above-average turbine sizes.

The feed-in tariff is specified in a tender procedure – through competitive bidding to ensure the lowest possible cost accruing to the government. The feed-in tariff (winning price) is given for a certain amount of generated electricity (a number of full-load hours). It differs from project to project because the result of a tender depends on the project location, wind conditions and the competitive situation in the market at the time. The government-owned Danish transmission system operator (TSO) constructs, owns and maintains underwater cables for grid connection as well as the transformer station (DEA 2014).

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[17] In the open-door procedure, the project developer takes the initiative to establish an offshore wind farm of a chosen size in a specific area. In an open-door project, the developer pays for the transmission of the produced electricity to land (DEA 2014).

Explicit incentives for up-scaling are given in the case of replenishing existing turbine parks in Denmark. Wind turbines that are from before 1995 and that enlarge their capacity at least threefold can benefit from a higher tariff level for a specific period of time, depending on the relationship of the turbines to the reference model. Denmark guaranteed an extra premium on larger turbine models when old turbines were decommissioned between 2004 and 2009.

The initiation of projects was at a standstill for a number of years during the 2000s, but new projects are under way with the new cross-party energy deal of 2012, which includes a model government pension fund co-financing of projects. These trends are likely to deepen existing trends, particularly a deepening of the offshore path.

In Germany, the feed-in-tariff for offshore is higher in the first years and lower in the later years than for onshore, however the long-term financial incentives are similar to onshore, namely around 9 cent per kWh. The investment costs for offshore however are currently twice as high as for onshore. Most of the interviewees argue that long-term stability for wind energy firms and energy providers is dependent on the EEG and there is concern that the EEG will be reformed in 2014, which is likely to lead to lower feed-in-tariffs (BEE 2014). There is an underlying fear in the industry that the EEG will be weakened in the long-term or in the worst-case scenario phased out completely.[18]

The key point is that government policies had a direct impact on the up-scaling of turbines through the feed-in-tariff that provides financial incentives per kWh. The German political path tends to favour larger turbines and the repowering of areas with older turbines. The ambitious targets for wind and associated tariffs create general incentives for up-scaling and increasing turbine quality. Furthermore, in Germany wind energy companies have a substantial local market presence and hence they are very strongly influenced by domestic demand-side policy measures.

In a comparative perspective, it can be observed that demand-creating policy incentives have actively created the offshore market in both countries – with a particularly pronounced impact in Denmark where a large number of tenders were put in place. In this case, government policies indirectly tend to favour large-scale offshore developments and utility-scale developments due to the feed-in-tariff that makes large-scale wind farms more economically viable when large amounts of electricity are generated.

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[18] The political ambition and also the political situation with regard to the feed-in-tariff are similar in Germany and Denmark. Both have ambitious renewable energy policies and feed-in tariffs for wind energy. While Germany and Denmark have favourable political and financial arrangements for wind energy, it is a different kind of support than in the Chinese case which has also been studied within the overall project. While the EEG and the feed-in-tariff are promoting wind energy in a liberal market economy, China’s planned economy, its state-financed wind firms, and its coordinated approach can be much more competitive than German firms. Some interviewees argue further that Germany lacks the political coordination that is necessary for an energy transition and a further expansion of the renewable energy sectors. Currently, there is no ministry in Germany purely dedicated to energy and these competences fall with the Ministry for the Environment (BMU) and to some extent the Ministry for Economic Affairs and Energy (BMWi), as well as the Ministry for Traffic and Digital Infrastructure (BMVi) for offshore wind farms.

Table 8 shows a typology of support policies which makes two distinctions: first, between targeting support for upfront investment (fixed costs) versus generation (variable costs and income generation); second, between quantities versus price-based mechanisms. Although the policy regimes have changed from early days, the current support regimes in both countries tend to emphasise generation (output) rather than investment, and price rather than quantity.

Table 8: Typology of support policies

	Quantity	**Price**
Investment	Tendering systems for investment grants	Investment subsidies Tax credits Low interest/soft loans
Generation	Renewable energy portfolio standards (i.e. quotas) Tendering systems for long term contracts	Fixed price feed-in tariffs Premium feed-in tariffs

Source: Modified from Jenner / Groba / Indvik 2013

3.2.2 Supply-side policy measures

On the supply side, science and technology policy as well as financial support facilities have been hugely important in both countries. Both core and deployment technology trends are facilitated by government investments in technological research projects.

In Denmark, many of these were facilitated by Megavind (a strategic public-private partnership to promote the Danish wind turbine industry) and saw the involvement of most large firms located in Denmark in cooperation with Risø, Aalborg University, and other technology development organisations.

The Danish government introduced financial incentives including loan guarantees, export credits and favourable customs duties that incentivised component imports rather than complete turbines. It also created an institutional support system comprised of a regulatory environment and the funding of R&D organisations. Specific support for offshore wind technology was important towards the end of the industry's growth period. Danish policies in this area have been characterised as 'proactive' as they were stable and supportive and anticipated barriers to collaboration in the Danish innovation system (1991-2001). DEA supported studies on the risk mitigation of suppliers' involvement in offshore development and project implementation; furthermore DEA established information-sharing requirements (with Risø institute) in the tendering process (Smit / Junginger / Smits 2007).

Two particular elements became particularly crucial at the globalisation stage. The first was standard setting. Denmark was the first country to introduce ambitious quality certification in wind energy technology and it is still the global leader in this area. According to some observers, quality certification was a *de facto* measure of infant industrial protection because very tight regulations on turbine installations in the countryside made it difficult for foreign manufacturers to enter the market (Lewis and Wiser 2007). The Risø National Laboratory for Sustainable Energy received funding for wind turbine design and this centre worked with local producers to meet the specified standards. It is widely regarded as the globally leading wind power research facility and has been central to the development of Danish wind power technology. The second element was the use of export credit assistance in the form of low interest loans. This was coupled with assistance through the development cooperation system, i.e. through the Danida private sector development programme. Danida provided grants and loans (in its countries of operation) for the use of Danish-produced turbines. The Danish export Credit Fund has provided guarantees for Danish wind turbine exports worldwide.

The Danish Wind Turbine Certification scheme ensures that design, manufacture and installation of wind turbines – both onshore and offshore – meet safety, energy and quality-related requirements.

Both demand-side policies (feed-in tariffs) and supply-side policies (science and technology (S&T)) have to some extent helped national champion firms, but at least in Denmark both type of support mechanisms have been open to both domestic and foreign firms. As illustrated by the Horns Rev II project, a foreign firm (Siemens) won the tender. While Siemens Wind has R&D facilities in Denmark and some production sites, its headquarters are in Germany. On the research side, several multinational corporations (MNCs) have participated in publicly funded collaborative research including Siemens, Suzlon, Gamesa, and Envision. Several Chinese firms that have no investments in Denmark have participated in joint research projects with Danish universities. Particular grants for wind energy research are earmarked for collaboration with Chinese firms and universities.

Also, in Germany a number of policy-related factors on the supply side have shaped the wind energy innovation paths. In essence, wind energy innovation developed as a means of energy security in response to the oil crises of the 1970s, as well as an alternative to nuclear energy.[19] More recently, wind energy innovation has developed as a way to become a global forerunner in green energy technology and thereby creates employment, competitive advantages and economic growth. Government support to wind energy (and, for that matter, to other renewable energy technologies) is reflected in a variety of dedicated loan programmes (mostly operated by the KfW Development Bank as, for instance, in the case of the Offshore Wind Energy Loan Programme started in 2011); federal and state-level funding of research programmes (largely through various specialised Fraunhofer and Helmholtz institutes); as well as support to demonstration projects and public-private innovation alliances. In 2005, the German Offshore Wind Energy Foundation (Stiftung Offshore Windernergie) was established with a focus on research funding, knowledge-sharing and advocacy for offshore wind. In terms of

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[19] At the moment, a challenge is that federal states of southern Germany want to become more independent and increase their own wind energy capacities. In southern Germany, turbines are being built in low wind speed areas which could decrease the need for wind energy from the north. The state could therefore be understood as the main determinant of the German wind energy path which means that growth of the industry is very much dependent on the political dimension of wind energy and how the energy transition will be financed. At the same time, however, the government is dependent on large-scale investments from private actors.

innovation clusters, the North Western Region Wind Power Cluster (comprising Lower Saxony, Schleswig-Holstein, Bremen and Hamburg) is of particular importance. It has expanded into a network of more than 300 partners including government institutions, research agencies, wind park operators, leading turbine manufacturers and specialised component suppliers (Lütkenhorst / Pegels 2014).

Denmark and Germany are likely to continue their strong support for wind energy. The new energy deal in Denmark has secured support until 2030 (UPI 2012). At the same time there has been some debate in Denmark about the preferential treatment of wind. The new energy deal is more broad-based and includes ambitious targets for biomass, a demand made by farming organisations. Nevertheless, wind continues to be the lead renewable energy (RE) sector in Denmark for the foreseeable future and along with other green industries it is gaining strong political support because it is seen as one strategic industry for the future.

It is clear that national policies have been central in fostering these vibrant wind energy industries. Historically, national policies, such as the wind turbine guarantee in Denmark and the renewable energy law EEG in Germany, have been the main policy drivers. These preceded and went beyond policies and targets specified at the EU-level. This is a key explanatory factor when it comes to Denmark’s and Germany’s leading role within Europe: effective policy packages implemented over the last thirty years have been crucial.

3.2.3 How policies influenced innovation paths: summary

This section provides a short summary of the role of policies with respect to how they have influenced innovation paths. It does so by distilling the key insights on their influence on core technology and deployment paths, respectively.

Core technologies: Since the cost of energy is reduced when turbine size and reliability increase, governments in both countries have put policies in place to support technological development. When it comes to demand-side policies, several policies have contributed to core technology trends directly and indirectly. The output-based policy packages for turbine deployment in both countries have created incentives for technological developments that reduce the cost of energy; this applies to increasing the size and reliability of turbines. The replenishing policies in both countries have also contributed, including the associated Danish ‘scrapping payment’ starting in 2001 for turbines producing less than 150kW. The offshore policies, particularly those in Denmark, have added to the demand pressures for larger turbines. Larger turbine sizes are being increasingly built into offshore tender specifications. These tenders have also contributed to specific design paths since Danish tender material has designated gear model design turbines for new projects. Supply-side policies, such as collaborative research programmes, have also influenced innovation paths in core technology. The same applies to standardisation schemes enforced by government authorities, such as the Danish Wind Turbine Certification Scheme. As demonstrated by the German North Western wind cluster, the promotion of broad, multi-dimensional alliances of public and private actors has served as a powerful tool to trigger innovation and commercialisation.

Deployment: The regulatory environment puts considerable pressure on actors in the deployment chain, notably in the case of utilities. Adaptation of regulatory environments – for instance the shift from a traditional feed-in tariff to a premium-price model – has added incentives for improving reliability and the performance of wind parks. Demand-side policies have contributed directly to specific deployment paths, not least the increase in offshore deployment. Feed-in tariffs for offshore wind were the most important factor in this regard. However, there are still targets for land-based turbines, and onshore wind is still subject to the wind guarantee in Denmark whereby any turbine erected is guaranteed access to the electricity grid. At the same time the government is letting the feed-in tariffs for small turbines run out so that there is an economic incentive to take these smaller ones down and erect larger turbines in their place. In the case of Germany, the feed-in tariff approach is currently being revisited and various options, such as the introduction of competitive auctioning elements or alternatively the fundamental switch to a quota system, are being considered. In both countries, supply-side polices have had a lesser effect on deployment although governments have supported technological development in deployment, such as in offshore logistics.

3.3 Business context

3.3.1 Corporate actors in Denmark

Until the mid-1980s, the structure of the industry was very much shaped by the many wind turbine producers that grew out of the grassroots movement, with more than twenty producers in the market. After the so-called ‘California gold rush’ in 1985 when many firms overinvested in an export surge, the industry started to consolidate with a smaller number of lead firms coordinating the value chains, and eventually only two: Vestas and Siemens Wind Power.

Denmark’s prominence in the wind turbine industry is largely due to Vestas.[20] The offshore operations of German Siemens Wind Power (formerly Bonus Energy) are located in Brande, Denmark and have become an important player in the global industry too. Although these firms compete to supply new projects in their home market, they predominantly compete in foreign markets. However, they also collaborate closely in Danish cross-organisational policy and research initiatives. Many of the Danish wind turbine firms have become global, serving an increasing number of markets across the world. Indeed, a notable feature of the Danish wind turbine industry is its internationalisation in terms of markets served and to some extent also ownership. This is due to a strong supply-side capacity combined with a limited domestic market. Vestas is the most globalised of all wind turbine manufactures in the world, in terms of sales, production facilities, and workforce (BTM Consult 2013).[21]

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[20] Vestas still maintains a market leader position even though competition has increased significantly. A clear sign of this came in 2012, the first year in which Vestas was not the Number 1 turbine firm in terms of market shares. In 2012, American GE sold more turbines than Vestas did.

[21] The Danish lead firms, most notably Vestas, have a high degree of vertical integration with many components being produced in-house. Around 50% or more of an average Vestas turbine is produced in-house (measured in relation to production costs). The value chain structure is a function of close

Denmark is also host to a large number of component suppliers. Suppliers often design components such as blades, gearboxes, generators and power electronics, typically to the specifications provided by the turbine firm. LM Wind Power is a Danish producer of blades for wind turbines. LM has been in operation since the beginning of the 1970s and still maintains a leading position in the global market. Over its long history, LM has supplied blades to leading European firms, has in recent years expanded its customer base, and is now a global supplier producing and selling to the leading companies all over the world. There are a range of other important suppliers that cater to the world market in all areas of wind power development including foundations, towers, blades, generators, gearboxes, mechanical components, control systems and consulting in areas of engineering and wind energy deployment.

The distinction between core technology and deployment mentioned and applied in Section 2 to examine innovation paths is also useful when considering value-chain actors and their coordination (Lema et al. 2011). The Danish utility DONG is a key actor. In Denmark, the coordination of the 'deployment chain' – consisting of the installation of turbines, operation and maintenance, ensuring grid connection, and finance – has shifted away from manufacturers to utilities, as power producers have come under pressure to incorporate renewable energy in their portfolios and investment requirements have increased. DONG is now operating across Europe and is the dominant firm in the offshore wind power segment. In most projects, DONG coordinates the various actors from the deployment and manufacturing chains, including consumers, transmission system operators, turbine manufacturers, logistics and construction firms, knowledge-intensive business services and specialised suppliers. The deployment service segment is arguably becoming more important as the sector drives towards offshore projects. While there are also variations in turbine technology, the big difference between the onshore and offshore markets lies in 'deployment functions' due to the immense technological and logistical challenges associated with the maritime installation of turbines (Poulsen / Rytter / Chen 2013).

3.3.2 Corporate actors in Germany

Overall, more than 200 companies are active in the German wind energy sector. In terms of value-chain segments, roughly one-third is to be found in manufacturing (from turbines to mechanical and electronic components) while two-thirds are engaged in various types of deployment services. The leading core technology companies are characterised by a sharp focus on either onshore or offshore markets: while Enercon is exclusively engaged onshore, BARD (of which some subsidiaries became insolvent in 2013) and Siemens Wind Power dominate the German offshore market (Lütkenhorst / Pegels 2014). Siemens Wind Power is also the global offshore market leader with a cumulative market share of 56% – even as high as 78% when looking at 2012 only (IWES 2013).

Enercon is Germany's largest wind energy firm and it dominates the German market with a 60%-market share. The market shares of German turbine producer firms by the end of

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attention to productivity and reliability of the turbine and of turbine designs that have been carefully developed over more than 30 years.

2011 were as follows: 60% Enercon, 20% Vestas, 10% REpower, 4% Nordex, 2% BARD, remaining 4%: others (BWE 2012; Urban et al. 2012).

Enercon was founded by Aloys Wobben who developed some of the earliest German wind turbines, first in the range of kilowatts, later in the multi-megawatt range. The firm started business as early as 1984 and its first commercial model was the E-15/16 with an installed capacity of 55kW.[22] While the E-15/16 was still gear-driven, Enercon developed the world's first commercial direct drive in 1992 with its E-40/500kW turbine. Since then, all of Enercon's turbines have an electromagnetic direct drive, which significantly reduces the amount of components in every unit compared to the gearbox. Proponents of the direct drive argue that this reduces the need for maintenance and repairs of the turbines. Secondly, Enercon created a business strategy which does not only sell wind turbines but also sells a 'full package' of access to wind energy: Enercon operates its own wind parks, carries out the service, operation and maintenance, provides insurance for its own turbines, and hence sells the entire wind package. Payments are related to the amount of windy days per year. As Enercon's service is rapid and is based on local in-house expertise, it can guarantee a much higher energy output than other wind manufacturers that do not service or repair their own turbines and who might often not even be aware who is in charge of these tasks. Enercon also claims that its rotor blade design is unique. In addition, it built the world's largest wind energy turbine in 2007, the E-126 with an installed capacity of 7.58 MW. Finally, Enercon is the only entirely German firm. Interestingly, and in contrast to other wind firms operating in Germany, it also started as a family business in the hands of Aloys Wobben. Wobben's ENERCON still remains a family business – albeit with a huge turnover – which has not been subject to mergers and acquisitions. It is heavily reliant on the local German market. Enercon has 2,500 employees worldwide working in its operation and maintenance sector to ensure fast and efficient care and service for its turbines (Enercon, 2012b).

While Enercon is the market leader in Germany, it is less successful in other countries and has not been able to expand in the same way as Vestas, Goldwind or Suzlon. Enercon is currently in a lawsuit with its Indian-based subsidiary Enercon India due to infringement of its intellectual property rights (IPRs). Partly as a result of this legal challenge, the company has taken a strategic decision to limit future expansion to OECD countries and a few other niche markets – implying also an exclusion of the Chinese market.

Smaller firm such as Jacobs Energie, BWU, pro + pro Energiesysteme became REpower due to mergers and acquisitions in 2001, while the German firm Multibrid was acquired by the French firm AREVA in 2007. In addition, Siemens entered the market by buying the Danish company Bonus AS in 2004. At the same time, smaller firms such as REpower and R&D firms such as Vensys have been attractive targets for takeovers by Asian wind energy players. REpower was bought by Indian Suzlon and Vensys by Chinese Goldwind. Apparently, German R&D firms and smaller manufacturing companies are attractive for acquisition and/or mergers with larger international corporations.

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[22] Enercon originated as a *mittelständischer Betrieb*, which is a typical German phenomenon that describes small- and medium-sized enterprises (SMEs) which were often family businesses owned by the middle class. Today, Enercon still retains the operating and management system of a *mittelständischer Betrieb*, but has the turnover of a multinational company.

3.4 Company strategies: integration and internationalisation

Company strategies are important factors that can transcend the firm level and influence national innovation paths. Clear innovation paths have emerged in both Denmark and Germany. In both cases, companies have made distinct and important technology choices, a fact that raises the question of whether the innovation paths are primarily nation- or company-specific. With regard to Denmark and Germany it is difficult to differentiate between a purely ‘national’ innovation path and a purely ‘firm-specific’ innovation path. Both Vestas and Enercon are market leaders and, without them, the Danish and German wind energy industry and the wind energy market would look very different. We therefore recognise that some of the ‘national’ determinants in this section are in fact closely interwoven with the ‘firm-specific’ determinants. This will be elaborated below with regard to factors affecting core technologies such as the direct drive versus the gear model as well as factors affecting deployment models such as the ‘full-package’ business model of Enercon and Vestas. Both companies see the wind services market as an opportunity to spread their business and secure a supplementary revenue stream in a highly competitive wind turbine market.

3.4.1 Vertical and horizontal integration strategies

Specific paths are sometimes created and shaped by firms and their strategies. The development of the direct drive was a key innovation by Enercon, which was the first company in the world to develop the direct drive two decades ago. This had an effect on other German and foreign firms, with other firms using the direct drive, such as Vensys and Siemens. Enercon has also changed the nature of production and relies mostly on itself when it comes to the production of components, the insurance of its turbines and its service, maintenance and operation.[23] According to some interviewees, the business model changes are related to the (anticipated) arrival on the German market of firms from rising powers such as China and India. Since the competition with rising powers from Asia, particularly China, is growing in the German wind energy sector, companies such as Enercon have started to use a different business model, which is employed to differentiate what is on offer. As mentioned above, demand for full-package provision exists in both Denmark and Germany, but the supply of full-package provision has gone furthest in Germany due to Enercon’s extensive market share.[24] Vestas is also a company that strives for both horizontal

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[23] This business model was emphasised far less by the Enercon interviewees themselves, but has been strongly emphasised by other competitors, including wind energy manufacturers, component suppliers and government officials.

[24] While this business model works very well for the German market, Enercon has problems in operating in large overseas markets such as the United States and India. Enercon was banned from the United States until 2010 because of a patent dispute. Its endeavour to enter the Indian market has also been problematic. First of all, its business in India has been in decline in recent years. “The Indian subsidiary of the German firm Enercon has lost a significant market share over the last few years (2003: 24%, 2008: less than 8.5%)” (Walz / Delgado 2012,101). Secondly, Enercon India is currently being sued by Enercon Germany due to IPR infringements and licensing problems. There are fears that the German company could lose its Indian subsidiary and the control of its patents. Moreover, the founder of Enercon is planning to shift his stock to a trust to block takeover bids from other corporations (as well as due to his deteriorating health and the lack of a potential leader for the future, according to one

and vertical integration. Compared to other firms, particularly Chinese firms, it produces most components in-house (Lema et al. 2011).

Turbine producers in Denmark and Germany had initially spearheaded turbine manufacturing as a commercial business. They started licensing out to new European entrants (often spin-offs of existing firms) in the 1980s. Firms such as Vestas (established 1981) and predecessors to REpower (established in 2001 as a merger between three German firms) began to open up new revenue streams from licensing out turbine design – in addition to their traditional manufacturing and installation business. These strategies emerged out of hyper-competition during the 1990s, which also resulted in a major process of industrial consolidation. The consolidation process is effectively illustrated by the case of Denmark: things started in the mid-1980s when there were around 20 turbine manufacturers in Denmark. Today, after 30 years, there are only two manufacturers left on the market: Vestas Wind Systems and Siemens Wind Power. This resulted from a process involving numerous mergers and acquisitions (M&As), industry exits (bankruptcies) and spin-offs (BTM Consult 2011, 150, 159).

Lead firm strategies are important but so are the strategies of smaller players. Providers of knowledge-intensive business services (KIBS), small engineering consultancy houses, do not have manufacturing capacity but adopt a business model focused on the licensing out of turbine design and related R&D and consultancy services. Windtech of Austria was among the first to sell licenses in the market, making business as a technology supplier to Germany's Fuhrländer and other European firms. Norwin of Denmark is another example of a company, which initially made a living by focusing on turbine design while entering an agreement with a German firm, Preussac, to manufacture turbines based on a licence agreement. It is a small KIBS provider that was started up by three key engineers from the R&D department of Danwind, a wind turbine firm which went out of business in 1991.

In this way, many new providers of KIBS emerged out of the consolidation/restructuring process. Most of the providers of KIBS which later played an important role in transferring technology to China – including Jacobs and Vensys – have emerged out of the lead firm base. This KIBS segment itself became a part of the consolidation process within the west, undergoing a range of mergers and acquisitions, such as the American Superconductor (AMSC) acquisition of Austrian Windtec in 2007. The KIBS segment presents an interesting entry point for tracing flows of knowledge and capabilities through various different organisations.[25]

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interviewee). Wobben said in a statement: "Securing the future of my company and its employees is something that is very near and dear to me" (*Bloomberg Businessweek* 2012, 1). The company's future development therefore seems to be uncertain to some extent. The same goes for Enercon's involvement in the offshore industry.

[25] For example, consider Jacobs Energie of Germany, a firm founded in Husum, Germany, in 1991 as an independent provider of operation and maintenance services. Alongside the provision of such services, the firm developed turbine prototypes, the first (a 500kW model) which was manufactured and marketed in 1994. After that point it began to spin-off a range of independent firms with different profiles, including BWU which manufactured turbines under license from Jacobs, and engineering consultancy pro + pro Energiesysteme which focused on turbine design. By 1998, a 1.5MW-turbine was designed by pro + pro and this was originally licensed to Jacobs, as well as to BWU and Führlander and Nordex. Jacobs, pro + pro and BWU were merged back together in one again in 2001 to become REpower. One of the owners, Hugo

New entrant manufacturers are also important. Many of these firms benefitted from the availability of technology on the market while having no proprietary technology themselves. This new breed of lead firms was able to use established technology to enter the industry. One of the most famous examples is the case of Gamesa of Spain that began in the late 1990s with the formation of a joint venture with Vestas (Elola / Parrilli / Rabellotti 2012). Gamesa drew on Danish technology through a licensing arrangement. However, Gamesa bought Vestas out in 2001 and combined the existing technology base with licensing agreements with REpower. It soon began to cater to the global market, thus competing with Vestas. Another example is German Führlander, which benefitted from this new environment, coming onto the market in 1996 with limited initial in-house R&D capacities, licensing designs from Windtec. A second way for new entrants to enter the industry was through the acquisition of faltering firms. Some giant multiproduct firms entered the industry in this way. Siemens Wind and GE Wind are examples of companies with little prior win experience who entered the markets by acquiring Bonus Energy (Denmark) and Enron Wind (formerly Zond, USA) respectively.[26]

Interviewees reveal that REpower started as a German small and medium-sized enterprise (SME) and has been active in the wind energy sector since 1980 through its predecessor. REpower in its present form exists since 2001. Since 2007, Suzlon started to take over 100% of REpower, a process that was to be fully finalised by late 2012. Nevertheless REpower is independent as there is no profit transfer; Suzlon does not have access to REpower’s technology nor its IPRs, but Suzlon has access to some of REpower’s components and access to the German market. REpower’s turbines have gears and its 6MW turbine is currently the world’s largest offshore turbine. There is an integration plan to integrate the two firms further although the technologies follow two different innovation paths and will continue to do so in the future. Thanks to the merger with Suzlon, REpower has emerged from being an SME from North Frisia with sales only in the German market to a global player, and today exports makes up 80% of REpower’s sales. It is highly likely that foreign companies will buy further SMEs in the wind energy sector.

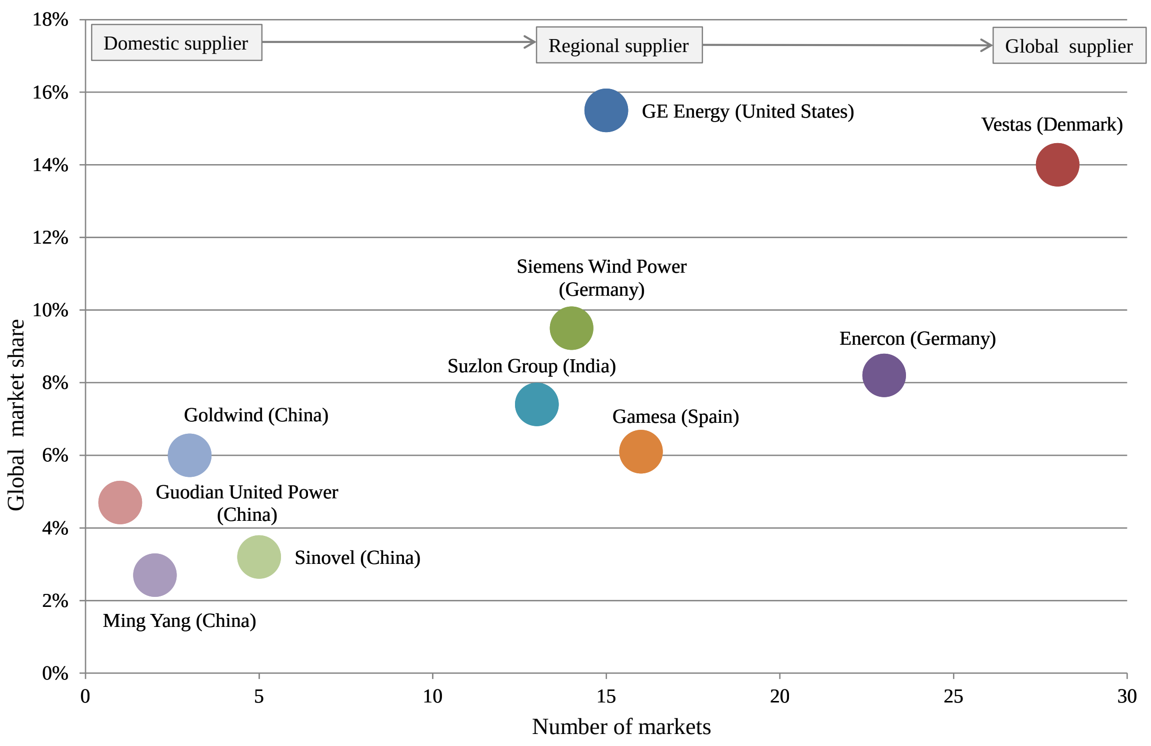
3.4.2 Domestic versus export market focus

As shown in Figure 11, Vestas is also a firm with a distinctly global strategy. To certain observers in fact, Vestas is no longer a ‘Danish Firm’ but rather a global firm that only sells a small fraction of its wind turbines to Denmark. Growth comes from the United States and China and other external markets and R&D is globally organised although firmly coordinated from Denmark. Even though Vestas is a globally organised firm which is inserted into multiple local innovation systems, the linkage within and back to the ‘mother cluster’ is thus likely to remain significant.

Denker, also owned Vensys Energiesysteme, a 1990 turbine design spin-off from the University of Applied Sciences in Saarbrücken. Both Jacobs and Vensys later became important to the flows of technology from Germany to China.

[26] Such strategies are also important for emerging market firms. Examples of these investments are Suzlon that bought Repower, and Goldwind that bought Vensys. This could be seen as a way for these Indian and Chinese corporations to buy themselves into the European innovation systems (Lema et al. 2011).

Figure 11: Global market shares and number of markets served by lead firms



Source: Adapted from BTM Consult – a part of Navigant – 2013

3.4.3 How company strategies influence the innovation paths: summary

For innovation paths in Germany and Denmark, company strategies have always been closely interwoven with national development. This section provides a brief sum-up of how core technology and deployment innovation paths have been influenced by the company strategies discussed above.

Core technology: The German and Danish wind energy sectors would not be as large and influential as they are today without their flagship lead firms and their efforts in developing core technology. Enercon and Vestas have shaped the national innovation paths by developing cutting-edge technology. Vestas has developed the world's largest testing facility to push the reliability frontier further forward. Enercon's strategy of betting on direct drive technology is another clear example. The vertical value chain foci are similar for most Danish and German wind turbine lead firms, particularly Enercon and Vestas but also Siemens. These firms produced more components in-house than do most firms, e.g. in China.

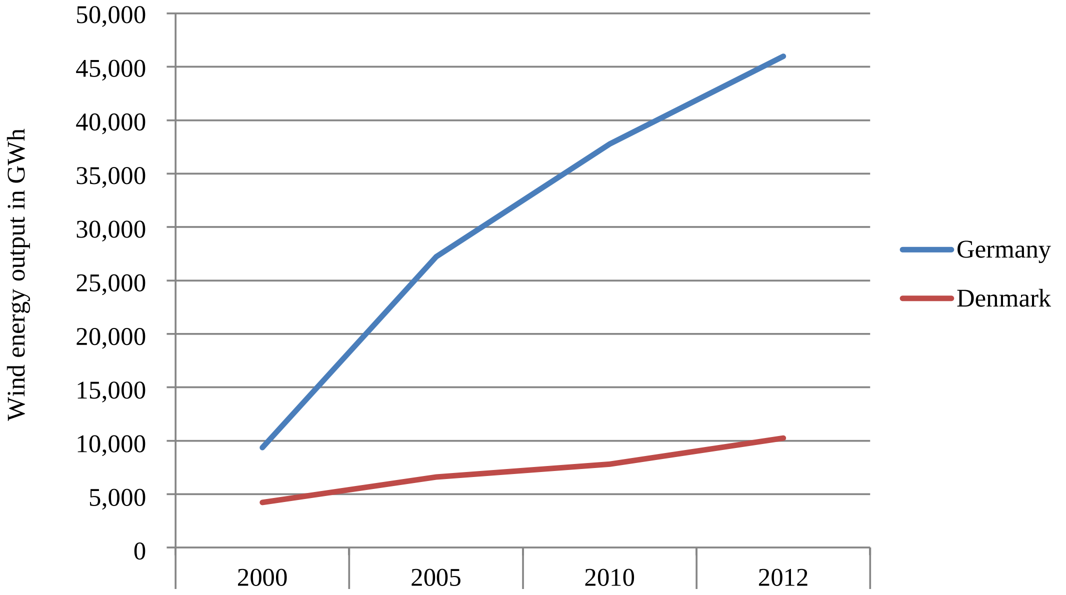
Deployment: When it comes to horizontal integration, these firms are also selling a 'full-package' deal rather than only hardware – hence they are driving a service trend. Seen in combination with investment in core technology development and production, the service component may be seen as taking advantage of labour-replacing technological advances produced by the firms themselves. For example, the technological advances reduce O&M costs that are included in the full package. Deployment trends are also influenced significantly by other firms in the value chains. Utilities in particular have pushed the offshore trend. In Denmark, Dong Energy has become the world's leading offshore wind operator. It has been driving development of new business models where pension funds have become partners in new projects that would not otherwise have been financeable. In Germany, the entry of multinational utilities (and the multinationalisation of domestic utilities) has been key to the increasing offshore paths.[27]

3.5 Demand conditions

3.5.1 Volume of demand

In Denmark, more than 20% of the electricity came from wind energy in 2010. In 2012, this figure had risen to almost 34%. In Germany, 6% of the electricity was derived from wind energy in 2010 and 7.5% in 2012 (IEA 2013). Nevertheless, Germany produced a total of 46,000GWh of electricity from wind in 2012, compared to 10,255GWh in Denmark. Figure 12 shows wind energy output in GWh in Germany and Denmark in 2000, 2005, 2010 and 2012, while Figure 13 shows the share of electricity generated from wind energy.

Figure 12: Wind energy output 2000–2012



Source: IEA 2013 (IEA Statistics)

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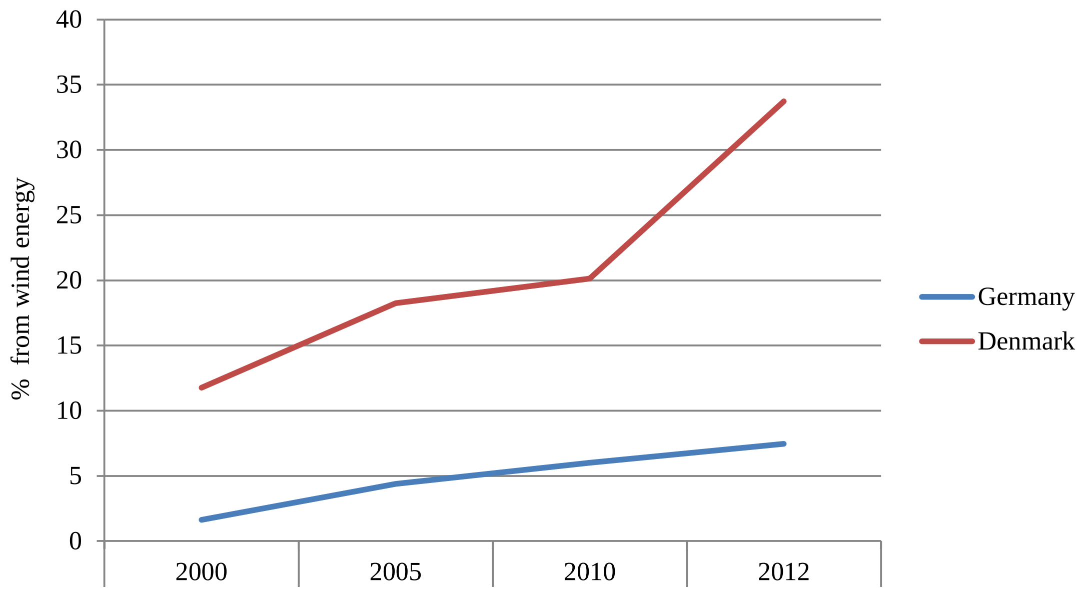
[27] Another important factor is that the German and Danish wind turbine industries are well organised and have significant lobbying power. In Germany, most wind energy firms have an office in the proximity of the *Bundestag* and the political parties in Berlin, whereas their headquarters and production facilities are mostly in the wind-swept areas of northern Germany. Having an office in Berlin ensures political representation and lobbying opportunities with regards to the government. The Danish wind industry is also well organised and has significant lobbying power, particularly the market leader Vestas.

Figure 13: Share of electricity generated from wind energy 2000–2012



Source: IEA 2013 (IEA Statistics)

In Denmark, a significant increase in installed capacity was first seen from 1995 to 2003 when 2,700MW were installed. Very few wind turbines were erected in the period from 2004 to 2008; this trend was reversed between 2009 and 2010 with a total of 700MW of new installations of which 450MW were accounted for by offshore turbines. Despite its tiny size, Denmark was among the Top 10 leading wind energy markets in the world until 2012. It had a cumulated installed capacity of 3,871MW. Denmark is a small country, with a fairly equal distribution of wind power plants throughout its entire territory although the cradle of wind power in Demark was in Jutland (western Denmark) as is most of a current expansion of offshore wind power. This expansion is reflected in Figure 13 which shows how wind power became a significant share of the electricity mix after 2010.

As indicated in Figure 12, the output of wind energy in Germany has been rising rapidly since 2000, but the production of wind energy is unequally distributed. Most of the installed capacity is in the north, close to the coast, where the wind is strongest. The following Federal States accounted for the highest share of installed capacity at the end of 2011: Lower Saxony (7,039MW), Berlin/Brandenburg (4,600MW), Saxony-Anhalt (3,642MW), Schleswig-Holstein (3,271MW) and North Rhine-Westphalia (3,070MW) (BWE 2012). Lower Saxony, the home of Enercon, has by far the highest installed wind energy capacity. Installed wind energy capacity in the southern federal states is small but has been on the increase in recent years, particularly in Baden-Württemberg and Bavaria, often in areas with low mountain ranges. Southern Germany has lower wind speeds, hence less wind turbines have been installed there (BWE 2012).

Even though the German market is flourishing, it is still very dependent on state support in the form of feed-in tariffs. There has been an overall volatility in the market since some politicians indicated that they wished to reform, or even abolish, the feed-in tariff.[28]

3.5.2 Nature of demand

Specific demand conditions factors also influence national innovation paths. One aspect mentioned by many informants is the ‘nature’ of demand because demand is highly specified beyond price. Wind energy tenders always come with detailed specifications and standards ranging from noise levels, height, colour, performance measures, etc. Some of these are easy to deal with through standardised variations or additions. A firm such as Vestas offers ‘add ons’ to all of its models, e.g. aviation lighting. Other variations may require a higher degree of customisation, e.g. durability in very high or low temperatures, or height adjustment. Many of the standards are continuously built into the core designs of turbines. The demands originating from policy regulations and augmented by utilities transpire down through the value chain to turbine manufacturers and suppliers.

The interviews suggested that another key aspect related to the nature of demand for Danish and German models concerns payments being made exclusively on the basis of electricity generation, not installed capacity. In Denmark, the market dynamics have been enhanced with a feed-in tariff for the onshore market that is a ‘premium price’ model where the price fluctuates with the overall electricity price.

These market-based models create added incentives for optimisation throughout the deployment and core technology value chains, ranging from a careful siting of wind turbines by the firm to increasing reliability and the reduction of O&M costs.

Dominants players in Denmark and Germany have been shaped by demanding policy regimes at home. The interviews suggest that in many overseas markets these firms now seek to ‘educate the market’ by emphasising the importance of the cost of energy (including lifetime costs of turbines and parks) as opposed to upfront investments.

The industry in Denmark and Germany changed significantly after 2008. It has gradually developed from being a turbine seller’s market into a buyer’s market. Policy-induced specifications imply *inter alia*: stricter expectations on height, noise and the look of the turbine are increasingly being demanded by local authorities.

The findings of the interviews suggest that in Germany one demand condition in particular drives the current innovation path: Enercon has been targeting the low- to medium-speed wind market; in southern Germany wind speeds are low, hence wind turbine innovation needs to focus on hub heights so as to generate as much electricity as possible in low wind speed areas. Interestingly, this has led to a situation whereby average energy yields per turbine are higher in the south than in the climatically favoured north (Lütkenhorst / Pegels 2014).

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[28] Some critics complain that utility firms make large profits from subsidised renewable energy while at the same time the price for renewable energy is rising.

Several wind energy firms, including German market leader Enercon, have developed new wind turbine models for low wind speed areas to meet the new demand in southern Germany. When it comes to addressing low-wind markets outside Germany, Enercon has the advantage of being the main player in Germany, one of the main low-wind markets. It has more than 50% of the market share in Germany. Bavaria, in particular is regarded as a main zone for the development of low-wind sites, not least because the *Energiewende* implies a large shift from nuclear power to renewables. Low-wind turbines require longer blades and taller towers, which Enercon has a comparative advantage in.

The services market in Europe has historically been the domain of manufacturers who have provided services within the warranty periods (they have typically signed contracts covering two to five years). But an increasing number of projects have recently ended their O&M warranty. This means that the market for post-warranty services has increased allowing independent service providers to enter the market. But to help increase and keep market shares, WTGs are now seeking to engage in and sign full service and long-term contracts. An additional factor is the influence of project owners seeking performance guarantees and predictable maintenance costs and funders who are demanding long-term service contracts to lower cash-flow volatility, and wind farm owners.

3.5.3 How demand conditions influence the innovation paths: summary

Demand conditions have influenced innovation paths in pivotal ways. The domestic markets in Denmark and Germany have functioned as largely government-induced ‘lead markets’ for creation and deepening of core technology and deployment paths.

Core technology: When it comes to the volume of demand, the absolute size of the Danish market is negligible in comparison with major markets such as in the United States or China. Nevertheless, the market has continuously functioned as a test-bed for increasingly advanced turbines – as is witnessed, for instance, in the globally highest average size of installed turbines. The nature of demand has been important. As mentioned above, the ‘premium price’ feed-in tariff model for onshore turbines has put extra emphasis on output generation capacity and reliability while leaving the specific technology choice to project owners. While the tender specifications for offshore projects have left less choice to project owners, they have also driven technological development. The value chain power shift from suppliers to project owners (utilities) has also meant that highly professional and sophisticated buyers, particularly Dong Energy, have created one of the most demanding markets globally. The combination of low volume and high sophistication of domestic market demand have helped to create highly technological advanced and export-oriented firms that have deepened their core technology paths. The German market is five times larger than the Danish market. Although a firm like Enercon operates in a number of markets, the German market has remained the main one. As such, the technology development in Enercon is significantly driven by domestic demand. As an example, the low wind speeds in southern Germany have led Enercon to focus on designs suited for such conditions. There is however, little evidence to suggest that direct drive technology is a result of specific German demand.

Deployment: Demand conditions have also influenced deployment trajectories. When it comes to the onshore/offshore distribution, market demand has been highly influential – but partly as direct result of geographical conditions (mentioned below) and political conditions (indicated above). When it comes to project size, the political conditions are also highly influential – both in driving up the average project size by funding giant projects, as well as in reserving a space for decentralised offshore projects. The increasing service content is also influenced significantly by market demand. The installed capacities are continuously on the increase – and so is the demand for operation and maintenance services. In other words, market demand is changing, with a need for performance guarantees and more predictable long-run variable costs over the lifetime of a wind project.

3.6 Factor conditions

3.6.1 Factor costs

National factor conditions are important for determining the national innovation paths, both with regard to core-technology and deployment. Wind energy resources are large in both countries. Hence there is a high geographical and technical potential for exploiting wind energy.

The interview findings suggest that, while labour costs in Denmark and Germany matter, they do so less than in most other industries because of high transportation costs. It is generally not economically viable to produce components in areas with low labour costs and ship them to the European market, although this varies from component to component. Hence there is a large degree of localisation in production. This localisation is also prevalent in deployment where the production and consumption of electricity needs to take place in proximity, using existing infrastructure. On the other hand, innovation is much more globalised, and Denmark and Germany are host to R&D activities of many leading firms due to the specialised base of human resources with skills and capabilities accumulated over the last 30 years.

Interview-based evidence suggests that German and European turbines are between 30% (in the case of Nordex or Vestas) and 60% (in the case of Enercon) more expensive than turbines from China. At the same time, many interviewees argue that the quality of Chinese products is not on par with European products and that Chinese firms do not offer expertise in relation to operation and maintenance. Chinese manufacturers have cheap factor costs, such as cheap labour, cheaper steel, are state subsidised, and are often state-owned enterprises (SOEs). However, despite this, there is still a fear among interviewees in Denmark and Germany that the low prices of Chinese turbines will put pressure on European producers to reduce costs.[29]

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[29] However, in Germany, many interviewees also highlight the problems of the divide between the southern German Federal States which have low wind resources, but a high need for energy compared to northern German federal states such as Lower Saxony and Schleswig-Holstein which have strong winds and an overcapacity in wind energy production. At the moment, the federal states of the north want the grid infrastructure from the north to the south to be expanded to facilitate the transport of electricity. The southern federal states, on the other hand would prefer to build more wind energy turbines in the south instead of importing wind energy from the north.

3.6.2 Geographical endowments

Geographical conditions are highly influential. Clearly, Denmark and Germany exhibit significant differences in both size and geography.

Germany is a country of over 80 million people, large power stations, and a comparatively large grid infrastructure. The country has generally deep offshore waters and a relatively short coastline. The onshore sector has therefore remained the key market in Germany, and the one with which most profits are made, as it is significantly more cost-effective and more reliable than the offshore sector. In recent years, there has been a strong growth in the offshore market though, partly due to the entry of multinational utility firms such as Vattenfall and E.ON. However, German firms such as RWE energy also operate in the offshore market.

While Germany has a relatively short coastline – and the coast of the Baltic Sea was completely excluded from wind energy developments in the 1980s and early 1990s due to the existence of the German Democratic Republic – its northwestern coastal areas have favourable onshore wind conditions. In addition, the waters of the coastal areas of Germany are fairly deep and difficult to access in terms of offshore logistics. Second generation offshore projects, such as Vattenfall's Dan Tysk and EWE's Riffgat are based on the experiences from Alpha Ventus, but are larger and more expensive.[30] Dan Tysk operates in even deeper waters (70km offshore) and with even rougher weather conditions. In total, seven more offshore wind parks are being planned and licensed in Germany in 2013.[31]

However, for a few years now the windy areas in northern Germany have been becoming increasingly saturated with wind energy farms, whereas there is still significant space for wind turbine developments in southern Germany. Grid integration and grid expansion are therefore key issues for the Germany wind energy sector as a large share of the energy from wind has to be transported from the north to the south, which requires thousands of kilometres of grid extension and upgrading (BWE 2012).

Another geographic challenge for the offshore wind industry is the fact that Germany's western and northern coasts are protected areas under the National Park Wadden Sea, hence the sea cables can only be built in very limited 'dedicated' areas (*Trassen*). Research is ongoing to monitor the impact of the offshore parks on aquatic fauna and flora. These areas are far out in the North Sea and at deep water levels. This means that the political process must govern and regulate the building process very tightly so as not to endanger large parts of the UNESCO-protected North Sea coast (BMU 2013). A BMU report shows that the first

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[30] At the commercial second generation offshore project Riffgat (close to Borkum), EWE has learned lessons from Alpha Ventus and has changed and optimised many operations, for example the logistics of transporting material offshore (shipping, etc.), the sea-cabling, the electric power transformation sub-station, operation and maintenance, fundaments (mono-piles rather than jackets or tripods) and choice of turbines. Riffgat has also contracted Siemens and their 3.6MW turbine. The project was expected to start generating electricity in May 2013.

[31] Second generation offshore projects, such as Vattenfall's Dan Tysk, operate in even deeper waters (70km offshore) and with even rougher weather conditions. For Dan Tysk, there was a competitive bidding process which was won by Siemens. The Siemens 3.6MW turbines are being used. It is an established technology but with a new, larger rotor, larger blades and high reliability (up-scaling). The electric output will therefore be similar to the electric output of 5MW turbines.

German offshore wind farm, Alpha Ventus, paved the way for several biological science research initiatives that analyse how the offshore wind farm impacts on aquatic life, particularly birds, whales, seals and fish. This has led to innovative engineering practices that aim at protecting marine life, particularly during the construction process of the offshore wind farms, such as by using sound-proofing techniques to protect wales from undersea noise that could be detrimental them (BMU 2013).

In comparison to Germany, Denmark is a small country of 6 million people with shallow waters and a long coastline, which is favourable for offshore developments; moreover it has a lower absolute demand for energy, more decentralised renewable energy, more combined heat and power (CHP), more decentralised storage, more coastline and significantly greater opportunities for trading electricity with its neighbours. Obviously, the exceedingly long Danish coastline has provided an advantage for offshore development (CIA 1981; Statistics Denmark 2014).

However, in Denmark also the onshore market accounts for the bulk of installed capacity whereas growth in demand is primarily driven by offshore installations. Dong energy is the primary utility firm for offshore installation but non-Danish firms (Vattenfall) also operate in the market. With regard to the offshore innovation path, Dong energy and its supply chain has benefited substantially from growth in demand from the United Kingdom and other markets with offshore strategies.

Table 9: Key geographical differences between Denmark and Germany

	Denmark	**Germany**
Coastline (m)	7,314,000	2,389,000
Landmass (km^2)	42,434	348,672
Population	5,608,784	80,523,700
Coastline/area ratio (m/km^2)	172.4	6.85
Coastline *per capita* (m)	1.30	0.03

Sources: Own calculations based on CIA 1981; Statistics Denmark 2014; Statistisches Bundesamt 2013

The scarcity of space in Europe has not only led to a constant up-scaling of turbines but also to the need for reliable products where service is included. The interviewees suggest that German and European companies offer full maintenance, service and logistics, rather than only hardware, particularly in the case of Enercon. Hence turbine quality and the ‘full-package’ business model have at least partially developed due to specific national geographical endowments.

3.6.3 How factor conditions influence the innovation paths: summary

As emphasised in this section, factor conditions have influenced trajectories in certain vital ways.

Core technology: Geographical conditions have shaped the development of particular core technology solutions, with turbines designed for offshore installation developed first by Danish firms. Also, the design of turbines for low wind speeds has been a core competence, not least for German firms. Factor costs have influenced the reliability path. In this regard, it is important to keep in mind that many turbine elements have high transportation costs. Danish and German firms tend to be vertically integrated with less outsourcing compared to certain foreign competitors and components are largely sourced from the European market, with relatively high labour costs embedded in high-quality solutions.

Deployment: Geographical endowments influence deployment paths, not least the onshore/offshore distribution. The Germany technology development is also very much linked to a perceived lack of land. There is a trend towards larger turbines, larger tower heights and larger rotors, particularly for onshore use. Denmark has a higher coastline *per capita* ratio than Germany and many ports and marine industries from which an offshore segment could grow. Germany has faced somewhat different starting conditions with a small coastline and deep waters. As German wind farms are built further from the coast, construction is more cumbersome. Another key factor condition is related to the grid infrastructure. The grid is relatively underdeveloped in Germany, whereas in Denmark the main transmission system operator (TSO) EnergyNet has been closely involved in expanding grids and connecting offshore projects.

Box 6: Innovation case – Alpha Ventus

Alpha Ventus is the first German offshore wind park. It is essentially a test field which was built to gain experience for the German offshore wind industry. It started in 2006 as Germany’s first offshore test field/pilot study. Alpha Ventus has delivered a steep learning curve with regard to offshore wind in Germany, including for the logistics of setting up the turbines, the fundaments, the sensors (*Sensorik*) and the turbines operation and maintenance.

Built in the North Sea in the proximity of the East Frisian island Borkum, Alpha Ventus has a combined installed capacity of 60MW and uses 12 large wind turbines from AREVA and REpower. The turbines each have an installed capacity of 5MW. The AREVA turbines have tripod-fundaments, whereas the REpower turbines have jacket fundaments. The wind farm is run by a consortium of utility companies – EWE, Vattenfall and E.ON – which have formed the consortium DOTI (Deutsche Offshore-Testfeld und Infrastruktur GmbH & Co KG). 250 million euros were invested in the project and 30 million were paid in subsidies by the then German Ministry for the Environment, BMU. Alpha Ventus first started its operations in 2010. It operates about 45km offshore and in water depth of 30m. Since the start of its operation, Alpha Ventus has delivered 15% more electricity than expected. This is due to high average wind speeds, which are in the range of 10m/s; wave heights can be in the range of 10m.

The turbine manufacturers were chosen by a competitive bidding process for multi-MW turbines. This resulted in two bidders being successful, namely AREVA Wind and REpower, which both built 5MW turbines. The interviewees report that at that time Siemens, GE and Enercon were not interested.

AREVA delivers complete offshore turbines which include a tripod fundament while REpower delivers only the turbine, not the fundament. Hence other suppliers added the fundament, which was a jacket fundament. The jacket fundament has the advantage that it weighs less and that less steel is needed.

There have been a lot of new innovations, steep learning curves and many milestones (e.g. the laying of the fundaments, the operation in deep water, the first time that 5MW turbines were used etc.). The consortium worked with operations used in the offshore oil and gas industry, for example, specific shipping operations. The project also faced challenges due to regulations and legislation for the environment and project certification that had never been used in Germany before.

The largest challenge for offshore wind energy in Germany is integration into the grid and grid expansion. For Alpha Ventus there was a delay of 2 years before the grid operators Tennet made grid integration possible. The interviewees argue that government authorities need to regulate this and force grid operators to invest in expanding the grid and making it compatible with offshore wind energy. This is however likely to result in an increase in electricity prices as grid operators are likely to force some of these costs onto customers.

Sources: Interviews with company representatives, company documents and media reports

3.7 Related firms, networks and clusters

Related firms and networks are factors that co-determine the national innovation paths, particularly with regard to core technology. Wind energy has a narrow and a broad value chain. The ‘narrow value chain’ produces and assembles the components of a wind turbine. This includes firms such as Vestas, Siemens, Enercon, Nordex etc. Specialised suppliers feed into this chain. Many of these are now operating globally. Examples from Denmark include firms such as Svendborg Brakes, which began to focus on brake systems in the late 1980s, primarily through its early relationship with Vestas. It is now a leading supplier in this field. C.C. Jensen develops oil filter systems that reduce the wear and tear on components. LM Glasfiber is the world’s largest manufacturer of rotor blades. Beyond Denmark, LM has three production facilities in India and China and is also supplier to Goldwind, among others.

There is also a ‘broad value chain’ (beyond component manufacturing), which includes tasks such as project feasibility analysis and planning. Ramboll offers engineering and planning services, including structural design, to the offshore wind industry. COWI consulting is another major engineering services company engaged in the industry.

The availability of the entire value chain with multiple specialised companies at each step is important for locating innovation activities in Denmark and Germany. At the same time, it is a critical determinant behind the foreign investment in the German and Danish wind sector.

According to the interviewees, these investments generally do not cater to the local market. One exception is Titan Energy, which acquired a tower factory from Vestas, which it will operate to supply the European market. As already mentioned, one key problem with the international trade in wind turbines is related to expensive transport and logistics that complicate business operations and increase prices. Thus, a more profitable way of accessing European markets is for foreign firms to invest directly in green field facilities or to buy European wind firms. Goldwind is such an example, which relies heavily on German technology from Vensys; another example is Suzlon, which acquired access to the German market by buying REpower.[32]

In general, the European wind sector has become more and more lucrative for investment from abroad. The constant up-scaling and the move offshore have increased the need for larger investments into both offshore wind parks and grids.

Utility firms such as Vattenfall, E.ON and hardware producers such as GE Wind Energy and Siemens Wind Power have become an integral part of the German wind sector. These large corporations are changing the scale and pace of the German wind sector, particularly offshore. Large corporations, their financial resources and their experience have become more and more vital in the growing offshore wind sector. This is a major element behind the large-scale nature of projects.

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[32] At the moment the cost of transport and the lack of experience will make it difficult for overseas wind firms, such as Chinese and Indian firms, to enter the German market with their products. This has led to an increased Chinese and Indian investment in German technology and wind firms. The competition from overseas markets is therefore a concern for wind firms in Germany; however the technological advantage and the business model advantage of German firms is considered very high, which remedies some of these concerns.

Companies that have experience of offshore markets in Denmark and the United Kingdom have been able to build on their earlier expertise in new offshore projects in Germany, particularly in the North Sea. In a sense, Germany has become a financial and technological laboratory for offshore wind energy: this is due to the rapid development offshore using larger turbines, which have often not been tested or installed elsewhere, and installations further out in the sea.

Testing is a particularly important element of R&D in the wind turbine business. The large European producers have invested in their own test sites for prototypes and some have invested in laboratories for testing modules. However, there are also significant external testing facilities. In Denmark, commercial testing laboratories exist with the Lindoe Offshore Renewables Center (LORC) located at the former Lindoe shipyard. Siemens, Vestas, Dong Energy, Vattenfall Risø/DTU are all among the investors in LORC. As an example, GE Wind signed an agreement to use the nacelle test (up to 10MW nacelles) facility of LORC. In terms of public facilities, Risø has facilities and the nautical test centre at Osterild is centrally important. In Germany, the Fraunhofer Institute often works with manufacturers on reliability tests. External testing facilities are key as they increase the impartiality of generated data.

Both Denmark and Germany have developed national innovation clusters based on high-quality engineering and technical skills. Both countries were home to leading wind energy firms that were relatively dispersed and situated in rural areas, before subsequently some clustering took place in areas around Aarhus in Denmark and Niedersachsen and Schleswig-Holstein in Germany. In Denmark, key players such as Vestas, Bonus/Siemens and LM became global players with very high exports shares (almost 100% during the dry spell of the mid-2000s). The German market has been dominated by Enercon, which by comparison is more national in focus. It also became home to a large number of engineering bureaux, which supported the industry.

Furthermore, industry clusters for the offshore industry have emerged, not least around ports facing the North Sea, such as Esbjerg in the case of Denmark.

3.7.1 How related firms and network influenced the innovation paths: summary

Core technology: Universities played a key role in developing the German gearless design. Experimental deployment was brought closer to dedicated R&D, which ultimately created viable results and led to the direct drive model. Germany's emphasis on funding a diversity of designs and firms in early deployment programmes was particularly important in the development of the industry in Germany (McDowall et al. 2013). Key alternatives to the dominant designs were introduced by new manufacturers that were typically offspring of, or had close connections to, research groups or engineering consultants. The University of Applied Sciences in Saarbrücken is the key source of the development of the permanent magnet direct-drive rotor, which was adopted by Vensys. In Germany, R&D for wind power was greatly supported by the government, peaked in the mid-1990s and was reduced when the industry took off. The direct drive in Enercon dates back to 1995 and further development over the years is a process Enercon describes as 'continuous technological development'. Enercon developed the electromagnetic direct drive, which is more costly, but also more long-lasting and less resource-intensive (e.g. with regards to rare earths) than the permanent magnetic direct drive. The dominant gear-model design emerged in Denmark and the evolution can be traced back more than 100 years (Pedersen, 2010). The literature has shown that Denmark successfully undertook incremental innovation as the engineers focused on scaling-up the dominant design in small turbines in manageable and safe steps. Each increment tended to be commercially viable. It was more successful than the early state-funded projects in other European countries – Germany, Sweden, the Netherlands – that were focused on developing large multi-MW turbines from the outset (Jacobsson and Johnson 2000). Similarly, Garud and Karnøe (2003) showed that the Danish programme relied on close networking between innovation system actors (firms, universities and users) using proven designs and could be improved and scaled up slowly.

Deployment: Utilities now play a key role in projects that are typically above 10MW and sometimes above 50MW, such as RWE energy in Germany and Vattenfall in Denmark. The entrance of multinational corporations such as E.ON and Vattenfall and local energy providers such as EWE has made it possible to develop the first large-scale offshore wind energy parks in Germany. Other actors are independent power producers and there is still some room for cooperatives and individual owners in small projects. The decrease in cooperatives and increase in turbine sizes means that popular support is decreasing for onshore turbines. A trait, which may be more unique to Europe, is the tendency of pension funds to become co-owners of offshore projects. These developments are the results of policy changes as well as the company-level strategies of utilities and investment funds (who are now more comfortable with placing investment in projects sponsored by large utilities than with smaller independent power producers). The utilities themselves have come under pressure to include more and more renewable energy in their portfolios as specified by the 20% renewables EU legislation and the specified national action plans. Part of this trend has undoubtedly also been spurred on by the financial crisis. Utilities are able to invest with their own cash reserves (sometimes in combination with pension funds) rather than entering the financial market for projects. Also, Germany has privatised the transmission systems and most observers agree that underinvestment in the grid by northern grid owners has hampered the integration of wind and increased uncertainties. Alpha Ventus was delayed for more than 2 years due to grid connection issues. There were delays in getting the offshore parks connected to the grid. Transmission system operators (TSOs) work with a backlog which means that current projects will not get grid connected before 2017.

3.8 Summary

This section has sought to unravel to what extent, how and why the innovation paths are different or similar in the Danish and German wind industry. In this summarising section, we present the key findings by pulling together the insights on shared and distinct elements of innovation paths, respectively.

The main similarities between the two countries were: up-scaling quality improvement in core technology, and the shift towards utility-scale projects. The differences were mainly seen in the importance and role of the direct drive technology and in the speed with which the deployment paths shift to the offshore segment and the extent of new full-package business models in deployment.

Table 10 provides an overview of the above analyses regarding the main determinants and influencing factors behind shared paths, while Table 11 summarises the factors that supported distinct innovation paths.

Table 10: Summary of key determinants: shared paths

Shared trajectory element	**Key reasons (determinants)**
Upscaling Turbine size	• Output-focused demand-side policies (feed-in tariff (FIT) structures). • Turbine-size requirements in government tenders. • End of FITs for smaller turbines installed in the past – incentives for replacement for larger turbines. • Firm investments in R&D for larger turbines. • Collaborative R&D in firm networks and with supporting institutions.
Increasing reliability	• Output-focused demand side policies (FIT structures). • Government funded R&D programmes. • Government involvement in setting quality standards. • Firm investments in testing facilities and design improvements. • Market changes with the increasing role of demanding buyers. • Local and in-house components/value chain collaboration. • Strong involvement of non-firm value chain actors (R&D institutes, KIBS).
Increasing project size	• Government policies driving up project size (particularly through offshore support), but also designating space for smaller land-based turbines. • Replenishing/re-powering policies. • Entry of utilities into wind energy market – large multinational utilities (in Germany in particular). • New models of finance (Denmark in particular).

Note: The tables summarises the insights derived from Section 3, building on interviews and secondary data.

Source: Own compilation

Table 11: Summary of key determinants: distinct paths

Distinct trajectory elements	**Key reasons (determinants)**
Turbine architecture (gear versus direct drive)	• Historical reliance on incremental improvements to gear model (Denmark). • R&D focused on direct drive within supporting institutions (Germany). • Lead firm strategies/investments betting on different technologies (e.g. Vestas vs. Enercon). • Architectures influenced by geographical conditions (e.g. low wind speed). • Tender material emphasising dominant design (Denmark).
Offshore segment	• Offshore policies adopted earlier in Denmark than in Germany. • Natural conditions more favourable in Denmark than in Germany. • New business models for financing large-scale projects (Denmark.) • Different role of TSOs in Denmark (public) and Germany (private) leading to different degrees of investment in infrastructure. • Reliance on domestic firms in Denmark (Dong Energy) with more reliance on foreign utilities for offshore projects in Germany. • Historically strong support industry from related maritime industries for offshore logistics (Denmark).
Services	• O&M services specific to turbine technology (Enercon). • Expanding services market – company strategy to secure revenue stream (both countries). • Capturing labour saving technological advances (both countries).

Note: The tables summarises the insights derived from Section 3, building on interviews and secondary data.

Source: Own compilation

Innovation paths common to both countries have roots in a confluence of determining factors, which are mainly due to social and political priorities, preferences and decisions at national level. However, the sub-trajectories, which create variations between Denmark and Germany differ in this regard. They tend to have roots in ‘given’ geographical conditions and in firm-level technology choices. In other words, many of the similarities in innovation paths between Denmark and Germany have common national causes, while firm-specific strategies also influence the innovation paths in significant ways.

4 Conclusions and outlook

This paper has examined the innovation paths of Denmark and Germany in the wind energy industry. These two countries have historically been the global forerunners in this industry. It is therefore pertinent to explore how their innovation paths have developed in the face of domestic challenges and global interaction with new and powerful wind energy actors from India and China. This concluding section seeks to bring together the key insights and raise questions for a future research agenda.

4.1 Innovation paths in Denmark and Germany

Section 3 of the paper showed that distinct long-term trends are discernible in the Danish and German wind energy sector, including the up-scaling trend (increasing turbine nameplate capacity), the significant advancements in quality (increasing capacity factors) and the shift to utility-scale deployment (increasing size of new projects). In both countries, turbine technology is following a trend of gradual increase in the size and electricity-generating capacity and an increasing emphasis on reliability of turbines. In both countries there is a trend in which the price of wind-generated electricity is decreasing, with an outlook to reaching parity with fossil fuel prices in the near future.[33]

Despite the common traits there is also variety between the two countries. While there is continued prevalence of the ‘dominant design’ (turbines with gears), the alternative direct drive design is now a major challenging technology being advanced by German firms in particular. Direct drive technology (gearless turbines) has emerged as a distinct German technology. Although there is an increasing shift to offshore wind in both countries, this is much more pronounced in Denmark than in Germany.

One immediate observation is worth noting: The innovation paths of today – as observed in this paper – have gone through important inflection points and differ from the trends of the past. Most notably, the distinct Danish-German community-based and small-scale deployment model discussed in Section 2 is now losing in overall importance despite a reinvigoration of land-based and distributed generation. As noted by Ely et al. (2013, 1072), *“the origins of this successful industry rest in grassroots innovation approaches, specifically*

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[33] Although wind-generated electricity has become cheaper in Denmark and Germany and other developed countries, they are not as cheap as in China. *“The installed cost of wind power projects is currently in the range of USD 1 700/kW to USD 2 150/kW for onshore wind farms in developed countries ... However, in China, where around half of recent new wind was added, installed costs are just USD 1 300/kW”* (IRENA 2012, 19).

in Denmark”. But the grassroots element is much less pronounced today as project ownership structures and financing models are shifting in favour of big business. The same applies to the innovation process itself, i.e. to the formerly community-based and collaborative innovation mode in core technology. It has changed from being a predominately informal process to a much more organised process where formal R&D plays a more important role. The increasing maturity of the technology means that experience-based learning in the early stages has been replaced by more formal learning methods (Hendry / Harborne 2011).

It is still too early to predict the future trajectories of the innovation paths, i.e. how pronounced and successful the identified trends will be in the future. Ultimately, the evolving trajectory will depend on the how the specific determinants unfold and interact.

4.2 Explaining the similarities and differences

Section 3 dealt with specific determinants of innovation paths: government policies and interventions, demand conditions (the size and nature of home markets), factor conditions (geography), related firms and networks, and firm strategies.

A driving hypothesis of the research was that national public policy is key to innovation in this industry. There is ample evidence to support this hypothesis: national policies and institutions were pivotal to the creation of the pathways. As Section 3 showed, public policies help explain the many similarities that exist between the two countries: the drive to reduce prices and improve quality and reliability as well as changes in deployment patterns. We also identified specific interventions that contributed in this respect.

Policy frameworks in Denmark and Germany have enabled domestic firms to become incubators of wind power technology and innovation. The national policy frameworks and indeed the constellation of national-level factors are likely to reinforce the national or European character of future paths. For instance, offshore technology is likely to be a key technology domain for north European firms with few outside rivals in the immediate future. This path is driven by EU and national policies and depends crucially on nationally/regionally accumulated competencies in related firms and industries.

Government policy is also important as an indirect contributor shaping pathways through other specific determinants. For example, both Denmark and Germany have hitherto had the advantage of being ‘early movers’, i.e. path shapers, in wind power due to persistent government support for demand and supply of wind power throughout the years. The main vehicle was market creation. For a long time, Denmark and Germany were the main markets for deployment. As will be discussed below, this is now changing to a certain extent, but the main focus here is the historical observation of how market demand has shaped the trajectory. This is clear, for example, in the shift to offshore markets. Denmark and Germany were pioneers in offshore market creation. While offshore growth has come from the United Kingdom in the most recent years, major new offshore projects are now under way in Denmark and Germany.

The essential point here is that there is a complex interplay of specific determinants and that this helps to explain the differences between Denmark and Germany. As argued above, the role of governments is particularly important in giving direction to the pathways within this multi-causal complex. It is important to emphasise multi-causality because, even though the government is the key coordinating actor, it is itself influenced by pre-existing conditions and endowments. In Denmark, the government provided R&D support to turbine development, which had already taken direction by initial ‘spontaneous’ innovations in turbine design. It provided particularly influential support for the shift to offshore deployment, but was in turn influenced by the great potential provided by 1.3 metres of coastline *per capita*. In Germany the design trajectory was shaped by specific research conducted by a team at the University of Saarbrücken while deployment policies were influenced, *inter alia*, by Germany’s meagre 0.03 metres of coastline *per capita*. Thus, the constellations of determinants are country-specific and it is the way in which they reinforce each other that helps to explain both similarities and differences in innovation paths.

While the remainder of this section builds on these conclusions, it also goes beyond them to discuss and explore the knowledge gaps, uncertainties and possible areas for future research. We first ask how national the pathways are – raising the question whether pathways are indeed more national than either company-specific or international. In other words, is the national lens appropriate for examining pathways? We then zoom in further on the international dimensions to discuss whether determinants at the global level are becoming more important than those at the national level. Finally, we argue that these questions can only be understood through international comparison which goes beyond Europe.

4.3 Pathways and national specificity

In this paper and the project that underlies it we have assumed – mainly implicitly, but reflected in the research design as well as in the initial positioning (see Section 1) – that national determinants would lead to distinct national innovation paths and that these would differ from country to country. However, during the course of the research it has become 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 emerge about national paths versus company-specific and international paths.

It is clear that the 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 in Denmark and Germany as well as the country-specific variations. But there are also cases where the suitability of a national lens can be questioned.

The paper has shown that pathways have a distinct *company-specific element*. Most notably, the difference between gear models and direct drive models reflects firm-level choices of the key players. It seems in this case that public policies have been key to ensuring a high level of innovative activity, but have had less influence on the specific nature of innovation. For example, governments in Denmark and Germany have not provided R&D support to particular technologies, but to research conducted in a variety of fields. The subsequent decisions on further development and commercialisation seem to have been made primarily at the firm level. Corporate strategy thus appears to be important and this prompts the question to what extent innovation paths are also company-specific. The contrasting cases of Vestas (Denmark: gear model), Enercon (Germany: direct drive) and Siemens (German and Danish: both gears and direct drive) suggest that they are, but this issue can only be fully explored through further dedicated research. Such research would need to develop ‘design genealogies' backtracking them though successions of different firm ownership. Only such detailed historical work, which includes the national and company-specific imprint on technological models can provide a robust answer to the question of whether pathways are national or company-specific.

The paper has also shown that some pathways have a *distinct international element*. Like the company-specific element, this issue could not be ignored. It appeared on the research radar, even though it was not captured by our initial research questions for this paper. To grasp this element it is useful to adopt a dynamic perspective and distinguish between 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 / Rennings 2005). In other words, European technologies have become global technologies over time and hence gradually lost their national distinctiveness.

Our study of key lead firms has shown this clearly. The dominant design epitomised 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 Demark. Similarly the Vensys case shows how the direct drive technology has been diffused outside Germany. Vensys has been bought by the Chinese corporation Goldwind and plays an integral part in research and development of Goldwind's international products. Vensys is most famous for developing turbines with permanent magnetic direct drive (PMDD), which are now used in China.

Boxes 7 and 8 juxtapose two cases of cross-country technology diffusion. While Box 7 describes the case of the Chinese company Envision entering the Danish market with its R&D operations, Box 8 illustrates how Vensys (as part of Chinese Goldwind) is gearing its activities increasingly towards the Chinese market.

Box 7: Innovation case – Envision 128/3.6 PP 2B

Envision is the biggest privately held wind turbine company in China and is currently Number 12 on the global wind turbine market. The firm was established in July 2006 and the first turbine prototype was already developed in 2006. Envision Energy has recently established an R&D centre in the greater Aarhus area in Denmark with the objective of developing larger turbines for the global market. This is a strategic asset seeking investment aimed at tapping into the capabilities of the European clusters in wind power.

The major goal for Envision Denmark was to design 'the future wind turbine'. Envision was the first company to develop a modern vertical two-blade rotor. The interview findings suggest that the new design – the two bladed rotor with partial pitch combined with direct drive technology – create savings on towers, foundations, nacelle, rotor, blades and transportation. The two-bladed turbine has significant advantages in high-wind tests.

According to informants, the EN 182-3.6 is on par with other turbines, but not cheaper when it comes to production costs. Nevertheless it still gives a reduction of approximately 8 to 10% in cost of energy. The reason is that the turbine is more modular and has fewer large components which makes it easier and cheaper to install the turbine. For example, the two wings can be transported in two pieces each. Maintenance cost reductions are also important. Envision has installed most of the electrical components in a 'box' outside/beside the turbine near the base. This enables Envision to reduce the cost of replacing a component by approximately 75%.

All components for the two-bladed turbine are standard and proven technology, except from the innovation of the wings and the rotor. No components are produced in-house. The firm has thus used standardised components for almost all elements of the turbine, while concentrating its innovation on one distinct element: the rotor consisting of two partial pitch blades. One informant stated that the fine-tuning, detailed engineering and developing new designs and modules for the wind turbines that major European lead firms do is a place where Envision is not trying to compete. In this way Envision can benefit from being second movers and use proven ideas and components.

Box 7 (cont.): Innovation case – Envision 128/3.6 PP 2B

Almost all components are sourced from suppliers and the complete model is one of open innovation. The development of the innovative rotor blade took place in cooperation with LM Wind Power. LM made calculations on restraints etc. and the aerodynamic profile and Envision made all of the structural design. Envision has furthermore developed models that are able to calculate different variables on a two-bladed turbine. The software for the turbine was developed in cooperation with DTU Risø. The aerodynamics and the software were hereafter optimised by Envision to ensure the best result. The testing of the EN 128-3.6 at the testing site in Thyborøn (Denmark) is planned to end in September 2015.

Sources: Interviews with company representatives, company documents and media reports

Box 8: Innovation case – Vensys 2.5

Vensys is a German wind turbine manufacturer that has been acquired by the Chinese company Goldwind. It started as a small engineering bureau that emerged from an R&D centre at the University of Saarbrücken. Vensys has been operating commercially in Germany since 2000, whereas the R&D activities at the university started about 10 years earlier. It conducts R&D in the fields of Direct Drive, energy efficiency, rotor design, larger wind turbines, low-wind speed areas, extreme climatic conditions such as extreme heat, cold, winds and grid stability. Its business model involves licensing to partners. Other innovations at Vensys are its drive belt (*Zahnriemen*) for the pitch mechanism and using capacitors rather than batteries for storage facilities (capacitors are used by Enercon too and this was a joint innovation between the two firms).

The permanent magnet direct drive (PMDD) is seen as Vensys most important innovation. The PMDD is a direct drive which uses a magnet to power the drive. The PMDD was researched and developed when Vensys was a small R&D bureau embedded in a university environment with no commercial pressures. Policies, regulatory frameworks and funding seem to have played only a very marginal role, whereas the key driving factors of the R&D activities at Vensys were initially the Germany innovation clusters, the engineering expertise, the clear and straight-forward R&D, and licensing processes in Germany (e.g. licensing new technology with the Germanic Lloyd). The PMDD is more expensive than gears due to its higher technical complexity and because rare earths are needed for its construction. Vensys tries to optimise the design of the PMDD by including as little magnetic material as possible and thereby using as little rare earths as possible.

Vensys first started out as a small engineering bureau which conducted R&D in wind turbines. It then started licensing its technology. However licensing poses risks of IPR infringements, provides only limited financial benefit and offers only limited contacts and networks. In relation to Goldwind, it gave Vensys access to the Chinese market and contacts. Selling the PMDD technology to the Chinese firm Goldwind is strategically sensible as China is one of the few countries that has access to rare earths resources, whereas other countries – such as Germany – struggle to access rare earths.

While the development of the PMDD constituted a major innovation ‘revolution’, the technological development and innovation of Goldwind/Vensys in recent years has become more evolutionary rather than revolutionary. Vensys calls this innovation process ‘progressive evolution’. Innovation is fairly incremental at this point, for example by improving the PMDD and Vensys’ earlier turbines. Today, Vensys’ technology seems to be more geared towards the requirements of the Chinese market (e.g. 1.5–2.5MW turbines) rather than the European market (e.g. up-scaling of turbines, offshore turbines). Vensys’ R&D therefore focuses on modifying existing turbines particularly relating to the energy efficiency and climatic conditions.

While Vensys’ current flagship turbines are the 1.5MW and 2.5MW turbines – due to the assumption that these are the best sizes for the Chinese market – it is known that Vensys and Goldwind jointly conduct R&D in larger turbines (3MW) and are developing prototypes in the range of 5 and 6MW. As mentioned before, the offshore 6MW Goldwind turbine is based on Vensys 2.5MW turbine, which is being up-scaled and improved by Goldwind.

Sources: Interviews with company representatives, company documents and media reports

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, which require to be taken into account. This clearly emerges when we expand our focus to view the ‘determinants’ in a global perspective.

4.4 Pathways and globalisation

The broader question for further research is whether processes that shape the pathways are becoming truly global. This is a question which extends beyond what has been addressed empirically in this paper, but already at this stage it is possible to provide insights for framing 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 and overlapping but it is useful to separate them analytically. This helps to address the issue of global convergence and the divergence of pathways.

In terms of policies and regulation, the European leaders are truly global firms embedded into 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. National policy frameworks differ markedly between countries in certain respects, but there is also a certain degree of imitation and adoption of ‘best practice’ (Narain / Chaudhary / Krishna forthcoming; Dai et al. forthcoming). For example, as shown by Menzel and Adrian (2013) the publication of international wind energy standards by the IEC (International Electrotechnical Commission) has increased rapidly over the last ten years. They have been adopted by national governments or have been used as a basis for defining national standards.[34] 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.

When it comes to demand conditions, the globalisation of wind power markets is central to the discussion about innovation paths in the European context on the one hand and global convergence on the other hand. There are signs that, while the local lead markets in Denmark and Germany have been historically important, their relevance is now decreasing with a shift in demand to the United States and to China (Lema / Berger / Schmitz 2013). This shift in demand means that firms are not necessarily or primarily innovative for the home market. For Vestas, the national market is only one (small) market among many, while for Enercon the German market is more important. So for Vestas the home market advantage has disappeared as local markets have become less important in recent years (less so for Enercon). In sum, Vestas had to go for the export market because the internal market is small. Enercon is in a different situation because the internal market is much bigger. In other words, national demand conditions may decrease in importance but the phasing depends on the size of the internal market. Overall, global markets have become more

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[34] 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 which facilitates the integration of turbines. Similarly, firms such as Gerrad Hassan have specialised in certification drawing on global experiences and intensive knowledge about standards.

important than local markets. However, while the volume is decreasing, it is not just about the volume of demand but also about the quality of demand.[35]

As an extension of the globalisation of demand, innovation paths are shaped by local geographical factors in emerging markets. Interviews in lead firms in the course of this research showed how innovation processes were significantly shaped by the drive to meet local conditions such as wind speeds, temperature, altitude, etc.

It is not just lead firms that go global, but Danish and German related firms and supplier networks are going global as well, based on principles of ‘follow sourcing’. However, the paths are also shaped by the fact that lead firms combine national supplier networks with the tapping of overseas suppliers (Lema et al. 2011). Vestas is currently seeking to shed a number of in-house manufacturing facilities to become a leaner organisation. It remains to be seen how this will influence supplier relationships at the global level.

The lead firms in Denmark and Germany are highly globalised. Compared to international competitors, they are the only real global suppliers, whereas lead firms from other countries are focused mainly on national or regional markets. Vestas is the 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.[36] Enercon differs because this firm produces most of its products in-house and since the key market is the German home market itself. But although the vast majority of sales are in Germany, Enercon still sells in more than 20 markets across the globe.

It was discussed above how Danish and German innovations paths are becoming globally diffused. These global paths may be understood as the globalisation of *innovation processes nested mainly in Denmark and Germany.* At the same time it is also clear from interviews that the wind power industry is witnessing a globalisation of the preceding *innovation process* itself (Lema 2012).[37] Take the case of Vestas: the majority of R&D is conducted in Denmark but the firm has globalised R&D with important functions undertaken outside Denmark (e.g. blade development in the United Kingdom).

4.5 The need for international comparison

The aim of this paper was to (a) identify the key features, similarities and differences in innovation paths in Denmark and Germany and (b) explore the reasons for the similarities and differences in these paths. This has led to further reflections (above) about how national these innovations paths really are. However, this issue can only really be tackled via comparative international research.

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[35] Local markets in Denmark and Germany continue to be highly demanding in terms of standards. Interviewees argued that Germany has the toughest standards in the world, followed by Denmark.

[36] Moreover, the ownership structure of Vestas is such that it is majority-owned by investors located outside Denmark.

[37] This distinction between innovation process and innovation outcome was made by Lall 1993.

In the wider European context, these two countries are exceptions and do not represent a dominant European innovation path, but perhaps a ‘vanguard path’ nested in western/northern Europe. Future research needs to unpack the diversity of paths within Europe.

In the wider global context it would be particularly important to compare this vanguard European path with China and India in order to identify how it differs from emerging paths in ‘Rising Asia’. Indeed, this is the next step in this research. Drawing on comparable research by Narain / Chaudhary / Krishna (forthcoming) on India and Dai et al. (forthcoming) on China, we intend to explore in a series of articles the question of how and why wind power innovation paths differ between Europe (Denmark and Germany), China and India. Using the type of analysis conducted above and drawing on this wider material will help to address more thoroughly the question of specificity – to which we could give only a partial answer in this paper. Moreover it will allow us to examine whether the paths are converging or diverging. Answering these questions is important because it can shed light on future climate change mitigation trajectories and because they have immense implications for global competition and collaboration in this important green industry.

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Annex

Annex 1: Wind and other renewable energy policies in the European Union

The EU is a global forerunner in wind energy. The EU 27 (number of member states up to and including June 2013) had a total installed capacity of about 106GW at the end of 2011 (GWEC 2012). Germany currently has the largest installed wind capacity, namely 33.2% of the EU's total, followed by Spain with 24.2% and the United Kingdom, Italy, France, Portugal and Denmark (ranked according to the size of their wind markets). Today wind energy accounts for 7% of the EU's electricity consumption (GWEC 2012). Table A1 provides a summary of the key EU policies in wind energy and supporting policy areas. This list does not attempt to be complete but offers an overview of key policies.

Table A1: Climate energy and wind policies in the European Union

Climate policy	• EU 20-20-20 targets (2007): o Reduction of at least 20% of GHG emissions below 1990-levels by 2020. o Emission Trading Scheme (ETS).
Energy policy	• EU 20-20-20 targets (2007): o 20% of energy consumption to come from renewable energy by 2020, including wind, biomass, hydro, and solar power. o 20% reduction in primary energy use through improving energy efficiency by 2020. o Legal framework for carbon capture and storage (CCS). • European Strategic Energy Technology Plan (SET-Plan, 2007): o EU to become carbon neutral by 2050 or as soon as possible thereafter. Focus on large wind turbines – particularly offshore, large-scale photovoltaics (PV) and concentrated solar power (CSP), second generation biofuels, CCS, smart grids, energy-efficient energy technology, nuclear fission technology. o 2009 SET-Plan Roadmap on Low Carbon Energy Technologies. • Renewable Energy Directive (2009): o 20% of energy consumption to come from renewable energy by 2020, 10% of mandatory biofuel blending.
Wind policy	• EU 20-20-20 targets (2007). • 2009 SET-Plan Roadmap on Low Carbon Energy Technologies: o Wind energy to make up 20% of final electricity consumption by 2020. • 2008 Offshore Wind Initiative.

Sources: Bhasin 2011; European Commission 2007; 2009a, b; 2010a, b, c; Urban 2010; Urban et al. 2012

When it comes to climate change mitigation, the EU is one of the most active players. The EU and individual member states have ratified the Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC) and agreed to jointly reduce their greenhouse gas emissions by 8% from 1990-levels by 2008–2012 (UNFCCC 1997). Since then, the EU has gradually stepped up its commitment to mitigate emissions. Fostering renewable energy is seen as central to achieving this objective (European Commission, 2010a, b, c). Key features of the *EU's climate change mitigation policies* include the 2009 European Emission Trading Scheme (EU-ETS) and the 20-20-20 targets for emission reduction, energy consumption and renewable energy, which are known as the EU

"Climate and Energy Package". The 2007 "Climate and Energy Package" aims to achieve the following:

- *"A reduction in EU greenhouse gas emissions of at least 20% below 1990 levels*
- *20% of EU energy consumption to come from renewable resources*
- *A 20% reduction in primary energy use compared with projected levels, to be achieved by improving energy efficiency"* (European Commission 2010a, 1).

The EU further aims to increase the EU's emission reduction to 30%, *"on condition that other major emitting countries in the developed and developing worlds commit to do their fair share under a global climate agreement"* endorsed by the UN climate change negotiations (European Commission 2010a, 1; Urban 2010; Urban et al. 2012).

Milestones of European *renewable energy policy* are the 2009 Renewable Energy Directive under which EU member states have national targets for renewable energy depending on national potentials; the 2007 Energy Policy for Europe; the 2007 European Strategy Energy Technology Plan (SET-Plan); and the 2009 SET-Plan Roadmap on Low Carbon Energy Technologies. The 2007 Strategy Energy Technology Plan (SET-Plan) is aimed at providing a policy direction for a transition towards a low-carbon economy. The final aim is for the EU to become carbon-neutral by 2050 or as soon as possible thereafter. The plan focuses on large wind turbines – particularly offshore, large-scale PV and CSP, second generation biofuels, CCS, smart grids to improve the integration of decentralised renewables into the grid, energy-efficient energy technology and nuclear fission technology (EC 2007; Urban 2010).

The 2009 SET-Plan's Roadmap on Low Carbon Energy Technologies includes the aim *"to enable wind energy to take a 20% share of the final EU electricity consumption by 2020"* (European Commission 2009a, 8). It focuses on improving the competitiveness of the technology, grid connectivity, as well as the exploitation of offshore wind power generation capacity. The initiative provides a EUR 6 billion funding scheme to promote wind energy in Europe over the next ten years. The scheme includes a more accurate mapping of wind resources in Europe, building *"5–10 new testing facilities for new turbine systems; up to 10 demonstration projects of next generation turbines including a 10-20 MW prototype; at least 4 prototypes of new offshore structures tested in different environments"*, as well as demonstration of new grid integration and manufacturing techniques (European Commission 2009a, 8–9). In line with this, the European Energy Programme for Recovery has set aside EUR 565 million to develop offshore wind energy projects (European Commission 2009a).

Nevertheless, these energy and climate policies have been criticised. Many countries in the EU are still heavily dependent on fossil fuel energy; hence the actual share of electricity generated from renewable energy is small. At the same time, some of the EU policies, such as the ETS, have been mismanaged and are far less effective than anticipated. Costs for carbon emissions are at an all-time low (IEA 2013) and methods such as grand-fathering[38] and exemptions for polluting industries have led to market distortions (Helm 2012). While the EU is an important level for policy, the wind energy sector has been driven mainly by national policy.

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[38] A grandfather clause is a provision in which an old rule continues to apply to some existing situations, while a new rule will apply to all future cases.

Annex 2: Examples of key wind energy actors in Denmark and Germany

Table A2: Key actors in Denmark

Government agencies	Danish Energy Agency
Business associations	Danish Wind Industry Association Danish Energy Association
Research centres	Risø Research Centre on Renewable Energy, LORC (Lindoe Offshore Renewable Center) Aalborg University Technical University of Denmark
Utilities/infrastructure	DONG Energy (utility, Denmark) Vattenfall (utility, Sweden) E.ON (utility, Germany) HOFOR (utility, Denmark) Neas Energy (electricity trade) Energinet.dk (TSO, state-owned)
Wind turbine generators	Vestas (Denmark) Siemens Wind Power (Denmark and Germany) Envision (China) Suzlon (India) GE Wind Energy (United States) Gamesa (Spain)
Component suppliers	Hundreds of suppliers including: ABB A/S (generators) Fritz Schur Technical Group (hydraulics) Hydratech Industries Wind Power (hydraulics) LM Wind Power (blades) Niebuhr Gears (gears) Mita-Teknik (control systems) KK-Electronic (control systems)
Service suppliers	A2Sea (Offshore installation vessels, JV between Dong Energy and Siemens). MT Højgaard (construction services) Danish Wind Design (turbine design) Norwin (turbine design and consultancy)

Source: Own compilation

Table A3: Key actors in Germany

Government agencies	BMU / renamed BMUB as of 2014 (Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety; ministry with the main responsibility for wind energy until 2013) BMWi (Federal Ministry for Economic Affairs and Energy; in charge of energy policy since 2014)
Business associations	BWE (German Wind Energy Association) VDMA Power Systems (German Engineering Foundation)
Research centres	Wide range of research centres including: CEwind ForWind
Utilities/infrastructure	E.ON (utility, German) EWE (utility, German) RWE (utility, German) Tennet (grid operator, Netherlands) Vattenfall (utility, Sweden)
Wind turbine generators	AREVA (wind energy firm, France) BARD (wind energy firm, Germany) Enercon (wind energy firm, Germany) Fuhrländer (wind energy firm, Germany) GE (wind energy firm, United States) Nordex (wind energy firm, Germany) REpower (wind energy firm, India and Germany), Siemens (wind energy firm, Germany and Denmark) Vensys (wind energy firm, China and Germany) Vestas (wind energy firm, Denmark)
Component suppliers	Hundreds of component suppliers including: Bosch Rexroth (wide range of drive and control technologies)
Service suppliers	Wide range of service suppliers including: DOTI (German Offshore-Testfield and Infrastructure company) (offshore wind developer)

Source: Own compilation

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