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CATCHING UP: THE RISE OF THE CHINESE WIND TURBINE INDUSTRY

Lefevre-Marton, Nicolas

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CATCHING UP: THE RISE OF THE CHINESE WIND TURBINE INDUSTRY

Nicolas Lefevre-Marton

A DISSERTATION
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OF PRINCETON UNIVERSITY
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ABSTRACT

This thesis argues that Chinese firms can catch up with the technological frontier in the scope of new climate friendly energy technologies and provides a detailed study of the case of wind power.

Chapter 2 assesses the nature and extent of wind turbine technology catch-up. Firstly, it uses various wind turbine technology indicators to detail the convergence of trends of leading Chinese firms with firms at the technological frontier. Secondly, the chapter assesses the evolution of technological capabilities among leading Chinese turbine manufacturers. It shows that Chinese firms were progressively introducing turbine technologies similar to those produced by frontier firms and had rapidly improved their capabilities, allowing them to increasingly rely on independent technology development efforts.

Chapter 3 describes how the Chinese wind power technology development system, characterized by the presence of a powerful and proactive government, provided the necessary conditions for Chinese wind turbine manufacturers to make rapid technological progress. In particular, it highlights the policies introduced by the government to create a large and rapidly growing wind power market in China and the steps taken by the government to ensure that Chinese firms entered and progressively dominated the domestic turbine manufacturing market. The competition which ensued among domestic turbine manufacturers was arguably the main driver of technology development efforts. The most significant challenge to the continued progress of the industry was whether the Chinese system could transition from a model of technology development based on technology transfer to one based on its own innovation efforts.

Chapter 4 shows that due to limited government support over the years in both Europe and the United States, the wind power technology frontier has evolved relatively slowly, making it easier for Chinese firms to catch up. Firstly, using patenting rates as indicators of knowledge development, the chapter shows a strong correlation between changes in government wind power support policies and patenting activity. Secondly, using both technology penetration rates and patenting trends, the chapter shows that the evolution of the wind power frontier was slow compared to most other technology sectors globally.

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- Chapter 1 - Assessing Technological Catch-up in the Scope of Climate Friendly Energy Technologies: Introduction, Literature Review, and Methodology

1.1 WHAT ROLE WILL CHINA PLAY IN THE DEVELOPMENT OF NEW CLIMATE-FRIENDLY ENERGY TECHNOLOGIES?

1.1.1 The need for new climate friendly energy technologies

To stabilize rising atmospheric concentrations of greenhouse gases and limit the adverse socio-economic effects associated with temperature increases and other climate-related changes, global anthropogenic emissions of greenhouse gases eventually need to be reduced to a small fraction of current levels. Indeed, as long as global emissions are above the natural capacity of the earth to absorb greenhouse gases atmospheric concentrations will continue to increase (Sarmiento and Gruber, 2002).

The impact of different timings of emissions reductions on atmospheric concentrations is reflected in various efforts to model interactions between human activity and the climate system (e.g. Chesnay and Weyant, 2006; Clarke et al., 2009; IPCCC, 2007a, Ch.3). Clarke et al. (2009) present results from ten different integrated assessment models developed by research groups in various countries. Each model aimed to explore the feasibility and implications of achieving three distinct atmospheric concentration targets by 2100 for some of the main anthropogenic greenhouse gases.[1] The targets were set at 450 ppmv CO_2-e, 550 ppmv CO_2-e, and 650 ppmv

[1] The six gases considered in the models were: carbon dioxide (CO_2), nitrous oxide (N2O), methane (CH4), and three fluorinated gasses (HFC, PFC, SF6).

CO_2-e.[2] In contrast, the atmospheric concentration level in 2000 was approximately 420 ppmv CO_2-e. Each of the modeling teams also ran reference scenarios, where the world economy was assumed to continue along a business-as-usual trajectory, without efforts to curb emissions. Following these reference cases, atmospheric concentrations in 2100 ranged from 800 to 1500 ppmv CO_2-e depending on model characteristics.

In all reference cases, business-as-usual emissions resulted in concentrations exceeding 450 ppmv CO_2-e prior to 2020. Most models were therefore unable to meet this target by 2100 without temporarily overshooting it. For CO_2, the most important anthropogenic greenhouse gas, 2050 emissions reductions ranged from 20% to 90% below 2000 levels. In all cases, CO_2 emissions needed to be close to zero or negative by 2100. In contrast, the 650 ppmv CO_2-e target, the least stringent of the three considered in the study, was met by most models by first allowing CO_2 emissions to continue to rise until 2050 before subsequently being reduced towards zero to 2100.[3]

Whether efforts to reduce emissions are introduced immediately or delayed, the energy sector is bound to be heavily involved. The burning of fossil fuels in the scope of energy production and use accounts for approximately 70% of global anthropogenic greenhouse gas emissions (IEA, 2010a). Energy-related emissions can be reduced to some extent through changes to consumption habits and the deployment of existing climate friendly technologies, such as fuel

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[2] ppmv refers to 'parts per million by volume' and is a measure of the concentration of a gas in the atmosphere. CO_2-e refers to 'CO_2-equivalent' and is a conversion unit for greenhouse gases with different global warming potentials.

[3] The bulk of models produced 2050 CO_2 emissions in the range of 20% to 70% above 2000 levels.

switching from coal to gas, or the replacement of old equipment in household and industrial sectors by more energy efficient ones. Ultimately, however, new technologies which emit no or only limited amounts of greenhouse gases will need to be developed, brought to market, and deployed on a global scale. At present, such new climate friendly energy technologies consist primarily of various forms of renewable energy, such as wind, solar, or bio-energy, as well as carbon capture and storage (CCS).[4] The modeling results discussed above highlight that the greater the emissions reductions, the greater the need to increase the share of such new climate friendly technologies within the global fuel mix (Clarke et al., 2009). Much of the challenge of climate change mitigation therefore lies in the ability to develop and deploy these new technologies.

1.1.2 Climate change mitigation policies and the international institutional framework

From an economics perspective anthropogenic climate change results from failing to account for adverse socio-economic effects of climate change in transactions of goods and services linked to emissions of greenhouse gases (i.e. climate change is an externality). The fact that these effects are broadly diffused in society implies that governments need to introduce policies and other measures in order to reduce emissions and induce the deployment and development of new climate friendly energy technologies.[5]

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[4] The term 'new' is used here to refer to technologies which can potentially contribute to significantly reduce greenhouse gas emissions but which currently play a small part in the global fuel mix. However, it does not mean that these technologies have been discovered recently. Nuclear energy may therefore arguably also be considered to fall in this category.

[5] In some instances the climate benefits of a technology are a co-benefit of some other attribute for which the technology is being developed. For example some renewable energy technologies

Such policies can take a broad variety of forms. At one end of the spectrum are economic instruments which aim to internalize the climate change externality. These include placing a tax on greenhouse gas emissions or allocating a limited number of tradable emissions permits. At the other end of the spectrum are policies, sometimes referred to as command and control, which aim to support or discourage the use or development of specific technologies or practices. These include a broad variety of measures such as technology standards, mandates, and regulations. Economic instruments raise the price of greenhouse gas emitting activities, thereby generating incentives for firms to develop technological substitutes that emit comparatively fewer emissions. In contrast, command and control measures aim to more directly guide the direction and pace of technology development towards climate friendly alternatives (Newell et al., 1999; Jaff et al. 2002).

An important characteristic of climate change is that once emitted, greenhouse gases mix well in the atmosphere and, as a result, emissions in one location eventually affect the climate globally.[6] Unilateral efforts to reduce emissions by a government may therefore have little effects if at the same time other nations allow their emissions to continue to rise. This is particularly true if efforts to reduce emissions lead to the relocation of greenhouse gas intensive

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are particularly well suited to remote power generation, in which case government policies may not be necessary.

[6] However, climate models do predict important regional variations in climate change (see IPCC, 2007b, Ch. 11).

activities in countries without emissions reduction policies.[7] In sum, not only is climate change a governance issue, it is one that requires global and coordinated actions.

The 1992 United Nations Framework Convention on Climate Change (UNFCCC), its 1997 Kyoto Protocol, and other agreements negotiated under the auspices of the UNFCCC constitute the main international institution created to address climate change. The UNFCCC calls for global efforts to reduce greenhouse gas emissions and stabilize atmospheric concentrations at a level "which prevents dangerous interference with the climate system".[8] However the international institutional framework has failed to define a clear mechanism to distribute long-term emission reduction responsibilities among nations (Schmalensee, 1998; Aldy and Stavins, 2007b).

While many reasons have been put forth for this failure, two characteristics of the international climate institution stand out. The first is that no consensus has emerged concerning what constitutes dangerous interference with the climate system. Scientists are confident that rising concentrations of greenhouse gases will lead to a variety of potentially significant adverse impacts on society and the natural environment yet uncertainty surrounding the magnitude of these impacts remains high (IPCC, 2007c). The scientific literature also refers to potential greenhouse gas concentration thresholds above which climate change effects would increase rapidly yet these are difficult to identify with any precision (.e.g. O'Neill and Oppenheimer,

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[7] This spill-over effect is often referred to as carbon leakage, see IPCC (2007a, Ch. 11) for a review of the literature.

[8] See article 2 of the UNFCCC text. Available online at: http://unfccc.int. Since its adoption the convention has been widely endorsed by governments. As of September 2012, the UNFCCC had been ratified by 194 states.

2002; Lenton et al. 2008). Barrett and Dannenberg (2012) underscore why collective action on climate change can fail in light of uncertainty about such thresholds.[9]

The second characteristic is that the climate institution was built around the notion that developed countries and developing countries had different responsibilities. The UNFCCC underscores that "developed country Parties should take the lead in combating climate change and the adverse effects thereof".[10] The main rationale for this arrangement, as outlined in various agreements under the UNFCCC, is three-fold: first, the bulk of historical emissions have come from developed countries; second, per-capita emissions of developing countries remain low in comparison to developed countries; and third, developing countries must be allowed to emit greenhouse gases to meet more pressing social and developmental needs.[11]

Furthermore, core texts of the international climate regime emphasize that developed countries will finance any emission reduction efforts of developing countries. These texts also stress that developed countries are responsible for developing and transferring affordable climate friendly technologies to developing countries.[12]

These features of the international climate institution have led to a long lasting negotiation impasse. By and large, countries included in the list of developing country parties under the

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[9] The UNFCCC's Copenhagen Accord of 2010 introduced an objective of keeping global warming to below 2 °C. However projections based on policy efforts pledged by governments show this will almost certainly be exceeded (Rodelj, 2010).

[10] See article 3.1 of the UNFCCC text.

[11] See in particular the text of the Berlin Mandate, which resulted from the first UNFCCC Conference of the Parties, held in 1995. Available online at: http://unfccc.int.

[12] See for example articles 4.3, 4.5, 4.7 of the UNFCCC text, article 1 (d) of the Bali Action Plan, which resulted from the thirteenths UNFCCC Conference of the Parties, held in 2007.

UNFCCCC have kept to the main tenets of previously agreed texts while developed country parties have called for a more inclusive approach where developing countries would progressively adopt emission reduction responsibilities (Aldy and Stavins, 2012).

1.1.3 The prospects of new industries

There is little doubt that introducing a price on greenhouse gas emissions would increase the cost of the vast majority of industrial activities, which over time would affect economic output (Nordhaus and Boyer, 2000). Rising costs would only be dampened as climate friendly technologies become available at costs below those of incumbent technologies when a price on emissions is included. Furthermore, the trend may eventually be reversed if the costs of climate friendly technologies break even with those of incumbent technologies without inclusion of a price on emissions. However, technology development is a long-term endeavor and there are no guarantees that it will result in cost competitive alternatives. The task of mitigating climate change is therefore most often characterized as a burden on the economy.[13]

Nevertheless, the process of technological development associated with climate change mitigation will reward those who own successful new climate friendly technologies as they will benefit from the sale of the technologies (or of the emissions reductions resulting from their use) to those who face comparatively higher costs to meet their emissions reduction obligations. There are therefore potential industrial opportunities underlying the burden sharing process. This industrial perspective on climate change mitigation is often reflected in government planning

[13] The process of allocating emissions reductions responsibilities among countries is notably referred to as ‘burden sharing’.

documents. For example, the European Commission's European Strategic Energy Technology Plan (European Commission, 2007, p.4) warned:

> *If we fall behind in the intensifying global race to win low carbon technology markets, we may need to rely on imported technologies to meet our targets, missing out on huge commercial opportunities for EU businesses.*

Similarly, the Japanese Ministry of Economy, Trade, and Industry's Innovative Energy Technology Program (METI, 2008, p. 3) noted:

> *Since Japan has the world's top level technology in the field of energy, we need to strongly promote international cooperation and actively contribute to substantial global emissions reductions while reinforcing and maintaining our competitiveness. This can be done both by focusing our research and development resources on the technology fields where we can lead the world and by accelerating and promoting technology development with the recognition that technology is an important resource for Japan.*

Another example is the United States White House Blueprint for a Secure Energy Future (White House, 2011, p.4) which highlighted that "leading the world in clean energy is critical to strengthening the American economy and winning the future".

Such statements provide some indication of the perceived magnitude of the economic and industrial stakes involved in the development of new climate friendly technologies. The fact that such statements are made by governments of advanced economies is not surprising. They are among the group of countries which, in the scope of the UNFCCC, have agreed to take the lead in reducing emissions. In addition, the most significant technological advances of the last century have taken place in these countries and as a result they have accumulated strong technology and industrial capabilities.

This, however, is not the case of China. China is not bound to reduce emissions and is a designated recipient of climate friendly technology transfer and financial assistance under the

UNFCCC. In addition, over the last century China does to not have a proven track record of contributing to the advancement of technological development. Nevertheless, the Chinese government has also clearly outlined its ambitions to develop climate friendly technologies, further underscoring the perceived potential economic value of a strong industrial presence in such sectors. For example, Premier Wen Jiaoboa noted at a World Economic Forum meeting in 2009 that China "will accelerate the development of a low carbon economy and green economy so as to gain an advantageous position in the international industrial competition".[14]

1.1.4 Research question and hypothesis

Given the above mentioned ambitions of the Chinese government, this research aims to assess whether Chinese firms can catch up with firms at the technology frontier in the scope of new climate friendly energy technologies. In particular, it aims to determine the extent to which, and ways in which, Chinese firms and research institutions involved in technology development efforts are likely to make non trivial contributions to the development of new climate friendly energy technologies.

The central hypothesis of this thesis is that Chinese firms can catch up with the climate friendly energy technology frontier. The hypothesis rests on the combination of two complementary arguments. The first focuses on developments within China, while the second focuses on developments at the technology frontier.

[14] Chinese Premier Wen Jiabao at the opening plenary of the "Annual Meeting of the New Champions" of the World Economic Forum, Dalian, Liaoning Province, Sept. 10, 2009.

- *First hypothesis argument: Chinese firms can make rapid progress in the development of new climate friendly energy technologies because 1) the government can create relatively large domestic markets for these technologies, and 2) they are part of a system of technology development with a powerful and proactive government at its heart.*

  The first point of this argument rests on the fact that market opportunities are central to technology development. Thanks to its large size and rapidly rising energy demand, the Chinese government can create through policy a market for climate friendly energy technologies of significant size by international standards. This therefore provides an opportunity for Chinese firms and other entities to accumulate valuable experience, thereby accelerating technology development.

  The second point of the argument rests on the notion of systems of technology development - described in more details in the literature reviewed below - which consists of the interactions between firms, government, and research institutions underpinning the processes of technology development. China has competent industrial goods manufacturing firms as well as many technical research institutions. More importantly, however, the Chinese government can exert strong influence on both firms and research institutions to guide the direction and pace of technology development, and intervene in the market to foster technological development among Chinese firms.

- *Second hypothesis argument: The frontier of new climate friendly energy technologies has evolved relatively slowly because of limited government support for their development in advanced economies.*

  Whether due to the failure of the international climate institution discussed above or other reasons, government support policies in advanced economies, such as European countries

and the United States, for the development of new climate friendly energy technologies has been limited. As a result, the frontier of new climate friendly energy technologies has evolved slowly relative to other technologies.

Bringing these parameters together, the hypothesis states that Chinese firms can catch up with the climate friendly energy technology frontier because on the one hand they can make rapid progress with technology development and on the other, progress at the frontier has been relatively slow.

Answering the above research question and assessing the validity of the stated hypothesis are important for a number of reasons. One of these concerns the international climate change mitigation institution discussed above. It is worth stressing that much policy attention has focused on the notion, found in article 3 of the UNFCCC, of "common but differentiated responsibilities" among countries. In contrast, relatively little attention has been given to the notion of countries' "respective capabilities", found in the text of the same article. By investigating whether China can catch up with the development of new climate friendly energy technologies this research will therefore shed some light on the country's capabilities. The research may therefore contribute to shift the emphasis of the climate mitigation policy debate from determining how responsibilities among countries differ to questions of technology and industrial development.

Another important aspect of this research is that it may contribute to the literature on developmental strategies. Over the past half century, a small number of developing countries who started out with little technological sophistication developed strong capabilities in a number of fields. This phenomenon has led to a large body of scholarly work that highlights the

instrumental role of government in shaping competitive advantages in specific industrial sectors (e.g. Amsden, 2001; Kohli, 2004). The case of climate friendly energy technologies in China may therefore provide new insights to this important literature.

1.2 LITERATURE REVIEW

This section aims to anchor the research question and hypothesis to the literature, and lay the grounds for the methodological discussion to follow. The starting point is a definition of the term 'technology' at the heart of the research question. Though in every day parlance the term technology refers to artifacts or devices, the literature typically adopts a broader definition. There are numerous variations yet these almost invariably encompass both physical elements and knowledge. For example, Westphal et al. (1985, p. 170) define technology as follows:

> *Technology refers to a collection of physical processes which transform inputs into outputs, to the specifications of the inputs and outputs, and to the social arrangements that structure the activities involved in carrying out these transformations. Technology thus is the practical application of technological knowledge, which is what underlies and is given usable expression in technology. Such knowledge has technical and transactional elements, the former relating to product characteristics and physical processes, and the latter to social arrangements. These social arrangements include various kinds of market and contractual relationships among entities as well as organizational modes and procedural methods to regulate an entity's internal operations.*

Similarly, Dosi (1982, p.152) defines technology as:

> *[…] A set of pieces of knowledge, both directly 'practical' (related to concrete problems and devices) and 'theoretical' (but practically applicable though not necessarily applied), know-how, methods, procedures, experience of successes and failures and also, of course, physical devices and equipment. Existing physical devices embody – so to speak – the achievements in the development of a technology in a defined problem solving activity. At the same time, a 'disembodied' part of technology consists of particular expertise, experience of past attempts and past technological solutions, together with the knowledge and the achievements of the 'state of the art'.*

Other important terms which must be defined are the 'technological frontier' and 'technological catch-up'. Dosi (1982, p.152) defines the technological frontier "as the highest level reached upon a technological path with respect to the relevant technological and economic dimensions". Adopting similar terminology, technological catch-up can be defined as the processes by which an entity at lower levels along a technological path rises at a faster pace than the evolution of the technological frontier (i.e. the highest level along the path). Technological catch-up is therefore an intrinsically dynamic process which depends on the evolution of both the technological frontier and the entity catching up.

The literature review in this section focuses on highlighting important scholarly work on the development of new technologies at the frontier, and on the processes of technological catch-up. The literature on these topics is vast so I adopt a few restrictions in light of the nature of the above research question and hypothesis. Firstly, I focus on the literature most relevant to an analysis at the level of an industry or of a technology. The literature at higher levels of aggregation, for example on macroeconomic assessments of growth, catch-up, and the role of technology, is therefore not discussed here.[15] Secondly, I place particular emphasis on literature with sufficient granularity to account for the roles of various agents, including the government, in the processes of technology development. Thirdly, I focus on literature which addresses technological catch-up at the international level and in particular in the scope of industrial development in emerging economies.

[15] See for example Ruttan (2001), Fagerberg (1994), and Dosi et al. (1994) for a discussion of macroeconomic growth models and the challenges of integrating key elements from the empirical literature.

1.2.1 The development of new technologies

1.2.1.1 Conceptual frameworks

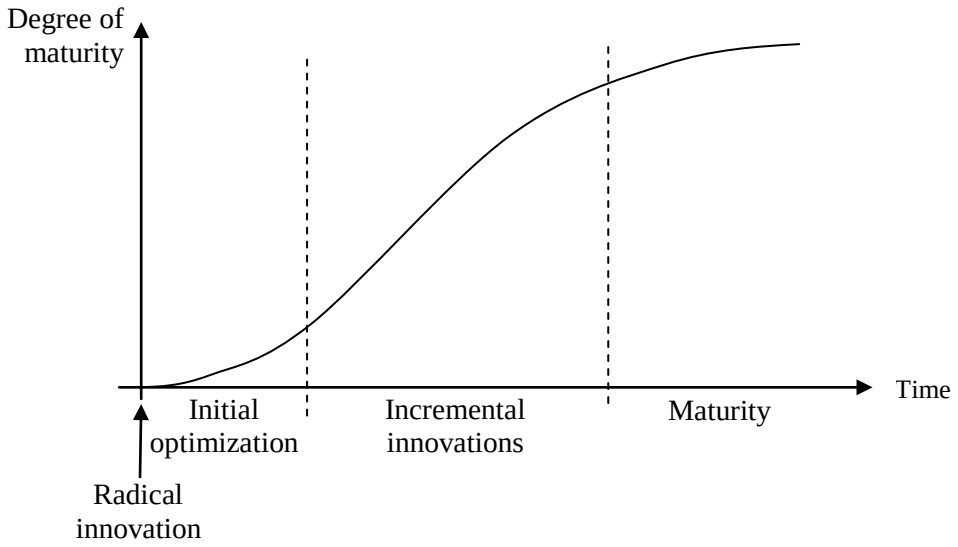
A widely adopted breakdown of technology development stems from the work of Schumpeter (1934) and consists of three basic stages: invention - the formulation of the idea at the origin of a new technology; innovation - the process of creating useful products and processes based on the invention; and diffusion - the fulfillment of the economic potential of the products or processes developed through markets.

More recent writings on technology development have moved away from a strict distinction between invention and innovation (Nelson and Winter, 1977). Still, the literature recognizes that certain innovations are more important than others and a distinction is commonly made between radical and incremental innovations. Radical innovations consist of the introduction of new products or processes which break from those prevailing at the time. In contrast, incremental innovations serve to improve existing products or processes. A successful radical innovation will therefore lead to a series of incremental innovations until the economic potential of the product or process developed is exhausted, or a new radical innovation introduces a new, superior product or process which eventually supplants it (Dosi, 1982; Perez, 2004). A technology's development is a cumulative process as incremental innovations build on the achievements of previous innovations.[16]

[16] In fact radical innovations are oftentimes cumulative as well as "major innovations constitute new building blocks which provide a basis for subsequent technologies" (Rosenberg, 1994, p 15).

This crude depiction gives a sense of technology determinism yet a central feature of technology development is that it is highly uncertain. Rosenberg (1996) notes that a technology's success is far from predictable at the time of its first introduction (i.e. the radical innovation in the above discussion) as it depends on a number of factors, each characterized by significant uncertainties. One such factor is the inability to foresee the multitude of incremental innovations which may follow. This is linked to the fact that radical innovations introduce technologies which are typically very crude. The variety of future uses is therefore impossible to predict. Furthermore, future uses may also depend on unforeseeable innovations occurring in other sectors.

Figure 1.1: Evolution of a technology
(A technological trajectory)



Source: Perez (2004)

Perez (2004) schematizes the links between radical and incremental innovations from the introduction of a new product or process to its maturity, as shown in figure 1.1. Following a radical innovation, the new product or process introduced undergoes some preliminary

optimization. As it secures market shares, incremental innovations are introduced to improve the product or process in terms of quality, efficiency, or other relevant technical criteria. Gradually, firms and other agents involved in the technology face diminishing returns to further innovation and a maturity plateau is reached.

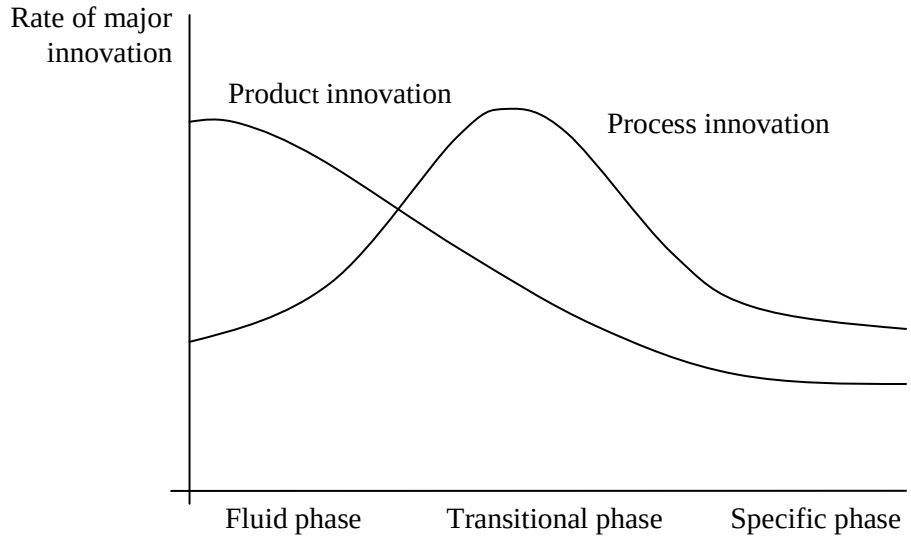
In their contribution to technology life cycle theory, Abernathy and Utterback (1978) place particular emphasis on the relation between product and process innovations.[17] They identify three phases in a technology's development, as depicted in figure 1.2. In the first phase, different product designs compete with one another. These are the result of independent radical innovations and often have distinct physical properties. This formative period of a technology is referred to as the 'fluid phase', as various competing products imply that production processes are not firmly established. Products at this early stage will typically be crude, expensive, and unreliable (Kim, 1999; Rosenberg 1996).

The fluid phase ends with the emergence of a dominant design, after which demands for various product attributes become increasingly well articulated in the marketplace. This progressively narrows the scope of new product innovations towards increasingly incremental innovations. Cost competition rather than product competition starts driving innovation and radical innovations are increasingly found in manufacturing processes. Abernathy and Utterback call this as the 'transition' phase. Utterback (1996) notes that an important trait of this phase is

[17] Product innovations relate to the development and market introduction of new products while process innovations relate to the development and market introduction of new production processes for a given product. As noted by Stoneman (1995b, p.3) while the distinction is useful, "one firm's new product innovation may be another firm's new process innovation".

that product manufacturing progressively shifts from relying on skilled labor and general purpose equipment to the introduction of specialized equipment operated by a less skilled workforce. Subsequently, as in the case with product innovation, process innovations become incremental in scope in what Abernathy and Utterback (1978) call the 'specific' phase. Utterback (1996) uses this conceptual framework to explain the historical development of a broad range of industrial technologies. He introduces some variations on this framework to distinguish between assembled (e.g. the automobile or the typewriter) and non-assembled products (e.g. electricity or chemicals), or to explain how the emergence of a new competing technology affects the various steps outlined above.

Figure 1.2: The dynamics of product and process innovation



Source: Abernathy and Utterback (1978)

The framework developed by Abernathy and Utterback (1978) highlights the role that demand for technology, articulated through markets, plays in guiding the technology development process. However, as noted by several scholars (e.g. Mowery and Rosenberg, 1979), 'demand-

pull' for technology cannot alone explain the entire technology development process. Nelson and Winter (1977) and Dosi (1982) help to conceptually answer this puzzle by linking the realms of science, technology, and production. They highlight the role of 'selection devices', or 'selection environments', through which scientific or technology objectives are formulated, priorities are established, and resources allocated in the pursuit of selected projects. In particular, they distinguish between market and non-market selection environments.

Market selection environments, where the 'demand-pull' for technology is the strongest, play a predominant role towards the end of the science-technology-production continuum. There, firms decide whether it is worthwhile to adopt an innovation based on whether they think they can generate profits. Profits, however, only materialize as a consequence of how consumers react once the innovation is introduced in the market place. The way in which consumer preferences are expressed in the market place and how well firms serve these preferences through technology innovation are therefore the central mechanisms of market selection environments.

The economic criterion of profitability becomes less useful as a guide to technology choices as one moves upstream along the science-technology-production continuum. Nelson and Winter (1977) note that away from the marketplace, established heuristics guide technology development efforts. Firms typically have their own technology development strategies based on their experience and capabilities. They may also follow established strategies, such as seeking the exploitation of scale economies or increasing mechanization as cost saving strategies. The more one moves upstream from the marketplace, the more significant non-market selection environments characterized by institutional and social factors become. In non-market selection environments, firms, universities, other research organizations, as well as government agencies,

are the main agents shaping technological development. In these environments long standing scientific and technological research agenda typically play an important role.

Many scholars have underscored that there are numerous feedbacks among the various selection environments help adapt to changing conditions, whether resulting from economic changes or new scientific/technological breakthroughs. Rosenberg (1982, ch.7; 1994, ch.8) notably stresses that the science-technology-production continuum is far from unidirectional, and there are often important feedbacks from technology to science as well as from production to science.

Dosi (1982) and Nelson and Winter (1978) also stress the role of government policy in both market and non-market selection environments. For example, the monitoring role of regulatory agencies in various sectors prior to the introduction of technologies or processes in the market place (.e.g. in pharmaceuticals, or aerospace), or more targeted policies aiming at achieving specific goals (e.g. national security, health care, or environmental protection), can strongly influence the nature and direction of technology development.

1.2.1.2 Research and development (R&D), learning from experience, and imitation

The above discussion outlines some of the main elements and drivers involved in the development of new technologies. However, it provides no information on technology development activities per se. Here the principal means available to firms and other agents to generate new technological knowledge are briefly discussed. I focus on technology innovation activities, which consist primarily of research and development (R&D) and various processes of learning from experience. I also discuss the role of technology imitation activities, which aim to

copy technologies and therefore to acquire knowledge developed by others. While imitation in itself does not generate new technological knowledge, the literature highlights that it is often an important contributor to innovation activities and also allows firms or other agents to keep up with technologies developed elsewhere.

R&D is often broken down between basic research and applied R&D. Basic research is typically associated with scientific inquiry and has no applied objectives. Applied R&D in contrast ultimately targets specific commercial uses. In general, most basic research efforts take place in universities and other research institutions and are funded by governments. In contrast, applied R&D is for the most part funded by firms.[18] Technology development also tends to be the dominant type of activity (Rosenberg, 1994, ch.1). Development activities include the iterative steps of testing and making improvements to new product or process designs - oftentimes relying on prototypes - prior to their eventual market introduction. However, most development activities aim to improve and modify existing products (Rosenberg, 1994; 1996).

As noted by Patel and Pavitt (1995) since the 1950s and 1960s governments and a number of other institutions have engaged in systematic efforts to collect quantitative data on R&D activities, such as levels and sources of funding as well as staff numbers and qualifications by sector.[19] This has contributed to the establishment of a large literature on R&D and its role in the

[18] These broad trends are well documented in statistics compiled by the Joint OECD-Eurostat international data collection on resources devoted to R&D and available online at: www.oecd.org/sti/rds

[19] For example in the case of the USA, the Business R&D and Innovation Survey (BRDIS) is conducted jointly by the U.S. Census Bureau and the National Science Foundation (NSF) and

economy. For example, a large body of econometric studies emphasizes the contribution of R&D to productivity and economic growth (Griliches, 1998). R&D data has also been extensively used to assess how the structure and organization of firms and markets affect technology development (for an overview see Cohen, 1995).

Learning from experience refers to the processes through which technological skills and knowledge are acquired by individuals and organizations by accumulating experience in undertaking certain tasks. The process which has received the most attention in the literature is learning-by-doing. Arrow (1962a) played an important role in formally introducing learning-by-doing in neo-classical economics thinking. The original formulation of the term focuses on the observed labor productivity gains resulting from the accumulation of experience in production within manufacturing plants.[20] A closely related process is learning-by-using, which consists of the gains resulting from experience accumulated with the utilization of a technology (Rosenberg, 1982, ch.6). As noted by Rosenberg, these gains can materialize as technology improvements resulting from feedback loops between users and the technology development process. Alternatively, learning-by-using can lead to enhanced productivity from either lengthening the life of the technology or reducing operation and maintenance costs. Other scholars have further broken down processes of learning from experience. For example, Bell (1984) draws from case studies of infant enterprises to distinguish between learning-by-operating, learning-by-changing, and learning-from-system performance feedback, among other sources of learning.

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replaces the Survey of Industrial Research and Development (SIRD), which was in place since the 1950s. For international guidelines on R&D data collection see OECD (2002).

[20] See Wright (1936) for one of the first references to learning-by-doing in the production of airplanes.

A rich literature, often referred to as the learning curve, or experience curve literature, attempts to quantitatively capture the effects of learning from experience. This literature typically uses cumulative production as an indicator of experience and correlates this with changes in the performance of production activities, such as through changes in man-hours per unit produced or, more generally, costs of production. Learning curves are often characterized by a learning rate which is a constant percentage improvement in performance for each doubling of accumulated experience (Conley, 1970). Learning curves have been extensively used at the level of the manufacturing plant (Argote and Epple, 1990). However, some studies have broadened the approach to the level of a technology. In such cases the analysis typically has some predefined geographic scope. For example, the learning curves literature applied to energy technologies reviewed by McDonald and Schrattenholzer (2000) highlights that some studies are limited to production in certain countries or regions while others consider production globally.[21]

The learning curve offers a powerful tool yet suffers from important limitations. In particular, it is difficult to link observed learning rates to actual learning processes. The literature highlights a high variability in observed learning rates across industries, and often for the same technology at different locations, yet provides limited explanations. Similarly, changes in learning rates over time have been observed for many technologies yet the literature again fails to provide satisfactory explanations (McDonald and Schrattenholzer, 2000; Argote and Epple, 1990). One important issue is that changes in performance observed may be due to a variety of factors other than learning (Bell, 1984). This is all the more true as learning curves are applied in broader

[21] See Jamsab and Kölher (2008) for a more general discussion on the use of learning curves in the scope of energy technologies.

contexts, away from labor productivity metrics at the plant level to more aggregated metrics (such as production costs) at the industry or technology level. Such factors may include changes in prices of raw materials, economies of scale in the production process, changes in the size of the products being manufactured,[22] or the effects of the other means of technology development – i.e. R&D and imitation.

Nemet (2006) attempts to distinguish some of these factors in the scope of the global learning curve for solar photovoltaic (PV) technology. He concludes that most of the reductions in PV module costs observed between 1980 and 2000 can be attributed to processes other than learning-by-doing. In particular, he identifies economies of scale in production, a drop in the price of the raw material (purified silicon) resulting from manufacturing improvements in the microprocessor industry, and module efficiency gains resulting from R&D. He notes that learning-by-doing may have only affected 10% of the observed reduction in costs.

An important characteristic of technology innovation is that once new technological knowledge has been created, it is hard to exclude others from using it, whether this knowledge is embodied in artifacts or not. Technological knowledge can therefore be used relatively easily by others as input to their own innovation efforts. This phenomenon is sometimes referred to as knowledge spillover. Such spillovers have long been recognized in the literature (Arrow, 1962b) and have been formally included in economic growth models with endogenous technological change (e.g. Grossman and Helpman, 1991). However, there have been few empirical

[22] See Wilson (2012) for a discussion of the relation between up-scaling and learning.

assessments of spillovers, in large part because such knowledge flows are elusive and not accounted for by market transactions.

In practice, knowledge spillovers are actively sought through imitation activities, such as reverse engineering of existing products or processes, the hiring of staff working for competing firms, drawing on new patent applications, the review of technical publications, or other means of information exchanges (e.g. via conferences and informal channels). The limited availability of data on imitation activities has led several scholars to survey firms to identify some of the salient features of their imitation efforts. Mansfield et al. (1981), for example, survey firms in chemicals, drugs, electronics, and machinery industries regarding the imitation of 48 product innovations. The study compares innovation and imitation timing and cost requirements. It also assesses the effect of holding patents for innovations on imitation costs, and the extent to which patenting encourages innovation in light of risks of being imitated. Based on a survey of firms, Mansfield (1985) compiles data on the time needed for information on product or process development decisions, or on technical details of new products and processes, to leak to competing firms.[23] Levine et al. (1987) and Cohen et al. (2000) survey hundreds of R&D staff in United States firms to draw information on the most important means adopted to protect innovations as well as how firms benefit from the innovations of others. Similarly, Cohen et al.

[23] In Mansfield (1985) the sample consisted of 100 firms in 13 different manufacturing sectors.

(2002) survey R&D staff in both United States and Japanese firms in a comparative study of R&D spillovers and the role of patents.[24]

Another branch of the literature uses patent citations contained in patent applications as an indicator of knowledge spillovers. In particular, several scholars have combined this with information on the location of inventors contained in patent applications to assess the geographic scope of spillovers (e.g. Jaffe et al. 1993; Jaffe and Trajtenberg, 1998; Maurseth and Verspagen, 2002).

The discussion above highlights some of the impediments in undertaking assessments of specific means of technology development. Data availability is a notable hurdle, particularly concerning learning from experience and imitation activities. In addition, the important overlaps and feedbacks among R&D, learning from experience processes, and imitation activities make separate assessments difficult. R&D and learning processes are most often undertaken concomitantly. Similarly, both R&D and learning efforts may result from imitation activities. An important literature on technology development has thus focused on documenting case studies of technology development in specific industries or technologies by combining both qualitative information and quantitative data. For example, the semiconductor industry has been the object of many studies (e.g. Irwin and Klenow, 1994; Langlois and Steinmueller, 1999), much like the computer industry (e.g. Bresnahan and Greenstein, 1999; Bresnahan and Malerba, 1999; Mowery, 1999), the aircraft industry (e.g. Mowery and Rosenberg, 1982), the chemicals industry

[24] Such surveys have provided a wealth of empirical data allowing others to continue work on this topic (e.g. Arora and Ceccagnoli, 2006).

(Arora et al., 1999), telecommunications equipment (e.g. Rosenberg, 1994, chap. 11), among others. These case studies provide a rich body of work on technology development dynamics. They highlight that though the basic technology development concepts and core mechanisms outlined above are always present, there is in fact a large variety in the underlying features of each technological trajectory (Mowery and Nelson, 1999b).

1.2.1.3 Systems of technology innovation

The case studies mentioned above also highlight a number of import systemic dimensions to technology development, such as government funded R&D, the role of domestic niche markets for new technologies (e.g. through the military), or research collaborations between industries and universities (Mowery and Nelson, 1999a). The 'systems of innovation' literature focuses on the study of such systemic dimensions, placing particular emphasis on the role of interactions between different types of agents in the technology development process. Three strands of the innovation systems are discussed here: 'national innovation systems', 'sectoral systems of innovation', and 'technological systems of innovation'.[25] Each is used to answer distinct questions yet they share the same basic approach.

National innovation systems assess how firms, research organizations, government agencies and other agents of technology development within a given nation can together shape innovation processes. One objective of this literature is to understand the role of national institutions in the scope of different technologies with naturally distinct development characteristics. Another is to

[25] For a review of the systems of innovation literature see Carlsson (2007) and Equist (1997).

assess the role of national institutions in light of technology development processes more or less international in scope (Nelson and Rosenberg, 1993). Many national innovation system studies have been undertaken. For example, Freeman (1987, 1988) and Odagiri and Goto (1993) describe some of the characteristics of the Japanese system of innovation, Nelson (1988) and Mowery and Rosenberg (1993) focus on the United States innovation system.[26]

In contrast, the sectoral innovation systems approach focuses on understanding the role and interactions of different agents in the scope of a set of technologies used in specific industrial sectors (Malerba, 2002). This more focused approach is often international in scope and not restricted to a single technology. This notably allows capturing technological substitutions and the co-evolution of different technologies within specific industries. Malerba (2004) compiles sectoral innovation systems studies on pharmaceuticals and biotechnology, chemicals, telecommunications, software, and machine tools, with a particular geographic emphasis on Europe.

Finally, the technological innovation systems literature focuses on the development of specific technologies (Carlsson and Stankiewicz, 1991). As for the sectoral approach, there are no geographic boundaries to the analysis of technological innovation systems. The geographic scope of the analysis therefore depends on the specificity of the technology and often combines international and national considerations. Unlike the sectoral approach, however, the emphasis of the technological innovation systems literature is on technology development pertaining to one

[26] See Nelson (1993) for other essays describing the main features of National Innovation Systems of European and other nations.

type of technology. This implies that such assessments may cut across several industrial sectors. Carlsson (1995; 1997; 2001) compiles a series of detailed studies of technological systems focusing on factory automation, electronics and computers (primarily radio and telecommunications, military electronics, and power electronics), the development of specific drugs in the pharmaceuticals industry (beta blockers and a gastrointestinal drug), powder technology, and biomaterials.

The three strands of the innovation systems literature mentioned above typically identify technologies, actors, institutions, and the information networks linking them, and combine qualitative and quantitative information to characterize the key system features. This literature underscores the high level of diversity in the key features of different cases, whether at the national, sectoral, or technology level.

Generally, the innovation systems literature does not provide much additional methodological structure. One exception, however, comes from the technological innovation systems literature. Hekkert et al. (2007) and Bergek et al. (2008) propose to complement the analysis of innovation system structural components - i.e. the actors, institutions, and networks – by an assessment of system functions. They underscore that a functional view of innovation systems allows moving beyond previously static assessments. The term ‘function’ refers to of the various ways in which system components contribute to the goal of the innovation system (Johnson, 2001), which is to develop, diffuse, and use innovations (Edquist, 2005).

Johnson (2001) surveys the innovation literature and finds that, though terminologies differ widely, a high level of cohesion exists on what the underlying functions of innovations systems are. Hekkert et al. (2007) and Bergek et al. (2008) both build on the work of Johnson (2001) and

others to identify the main system functions. Table 1.1 compiles the functions identified by both studies, highlighting the high level of agreement between them.

Table 1.1: Functions of technology innovation systems (TIS) in the literature

TIS Functions in Bergek et al. (2008)	TIS Functions in Hekkert et al. (2007)	Brief definition
Knowledge development and diffusion	Knowledge development	Technological knowledge generated through R&D, learning from experience, and imitation (see Section 1.2.1.2).
	Knowledge diffusion through networks	The exchange of information between the actors of the TIS.
Influence on the direction of search	Guidance of the search	Consists of the selection devices guiding the TIS' technological trajectory (see Section 1.2.1.1). These include "activities which positively affect the visibility and clarity of specific wants among technology users" (Hekkert et al., 2007) and contribute to the inducement of new agents in joining the TIS (Bergek et al., 2008).
Entrepreneurial experimentation	Entrepreneurial activities	The experimentation with new technological knowledge by TIS agents. A process of trial and error necessary to address the inherent uncertainty of technology development.
Market formation	Market formation	The process of finding commercial applications for the new technology and progressively expanding them through diffusion.
Legitimation	Creation of legitimacy/counteract resistance to change	The progressive social acceptance of the technology. This may involve managing resistance from agents of competing or incumbent TISs.
Resource mobilization	Resource mobilization	The mobilization of financial and human capital towards knowledge development and other functions of the TIS. Important TIS resources may also include complementary products, services, and infrastructures (Bergek et al., 2008).
Development of positive externalities	n/a	The strengthening of TIS functions due to externalities from new agents joining the TIS.

1.2.2 Technological catch-up

1.2.2.1 Modes of international technology transfer

As outlined in the preamble to Section 1.2, technological catch-up occurs when an entity at lower levels along a technological path rises at a faster pace than that of entities at the highest levels, i.e. at the technological frontier. Information about the technological path is particularly valuable to entities behind the frontier as it is often times cheaper and faster to acquire technological knowledge than to attempt to develop it independently (Mascus, 2004). The international transfer of technology therefore plays an important role in providing firms and other agents in emerging economies with valuable technological information.

As highlighted by Bozeman (2000) and Zhao and Reisman (1992), there are many definitions of technology transfer in the literature and much depends on the disciplinary perspective adopted. Here I adopt a definition commonly used in the economics and policy literature, where technology transfer refers to "any process by which one party gains access to a second party's information and successfully learns and absorbs it into his production function" (Maskus, 2004, p.9).

Various modes of international technology transfer exist and are well documented in the literature. As noted by Radosevic (1999), these can be classified in numerous different ways. Here, similarly to Maskus (2004), I distinguish between formal and informal modes of international technology transfer. Formal modes of international technology transfer occur through market transactions, while informal modes are outside the scope of market transactions.

As noted below, there are many complementarities between formal and informal modes of transfers.

Formal modes of international technology transfers consist of trade in capital goods and professional services, foreign direct investment, joint ventures, and licensing. International trade in capital goods, such as machinery, equipment, or turn-key plants, or trade in professional services, such as engineering consulting services, or technical assistance, exposes the importer to the underlying technological knowledge. For example, the process of integrating imported machinery into production processes implies learning about its operation, adapting the supply chain upstream and downstream of it, etc (Radosevic, 1999). Such transfers of knowledge may be formally included in the purchase contracts e.g. via training or technical assistance.

Foreign direct investment, joint ventures and licensing, are among the channels available to firms in advanced economies seeking to diffuse their technology to foreign markets (Blomström and Kokko, 2003).[27] Foreign direct investment consists of establishing a subsidiary in a foreign market. A joint venture is a contract under which two or more firms agree to some level of collaboration, oftentimes by establishing a new company under co-ownership. Typically, the owner of the technology will make the technology available to foreign firms, which will use their knowledge of their local markets to enhance technology diffusion. Finally, the purchase of a license by a foreign firm gives production or distribution rights to some technology protected by

[27] Diffusion is used here in the Schumpeterian sense, discussed at the beginning of Section 1.1.

intellectual property, as well as the information and knowhow to make effective use of it (Maskus, 2004).[28]

Technology transfers via foreign direct investment, joint venture, or licensing therefore occur from the owner of the technology to the foreign firms involved, whether these are subsidiaries in the scope of foreign direct investment, partnering firms in the scope of joint ventures, or the firm licensing the technology. These foreign firms are provided with technical information and knowhow needed for producing and/or operating the imported technology. Often times this involves training of local staff and sharing of design documents.

These formal modes of technology transfer are complemented by informal modes, which notably allow technological knowledge to be further transferred to other firms and agents in the recipient countries. These informal modes are not market transacted and therefore fall under the umbrella of knowledge spillovers discussed previously. Assessing the role of such knowledge spillovers associated with trade and the operations of multinational corporations in foreign countries has been the focus of a large body of literature, reviewed by Saggi (2002) and Blomström and Kokko (1998). This literature focuses in particular on the role of reverse engineering and other ways of learning trade secrets;[29] labor turnover, where workers trained or

[28] Licensing is often used in both joint ventures and foreign direct investments as the legal tool to transfer the technologies among the firms involved (whether partners or subsidiaries).

[29] Reverse engineering efforts are sometimes referred to as demonstration effects, as local firms imitate the foreign technology once demonstrated to work in the local market.

previously employed by a multinational firm transfer important information to local firms; and vertical linkages, where technology is transferred to local suppliers or distributors.[30]

Informal modes of technology transfer can also play an important role without being linked to formal modes. Reverse engineering can target imported consumer goods; firms in emerging economies can study patent applications filed by foreign firms; temporary migration of students attending universities, scientists taking part in international collaborations, or engineers temporarily employed in firms in advanced economies may also contribute to technology transfer (Maskus, 2004).

1.2.2.2 Firm technological capabilities from technology transfer to innovation

Drawing on empirical studies of international technology transfer, a large body of literature highlights that once transferred technologies are oftentimes modified by the receiving firms (Pack and Wesphal, 1986; Bell and Pavitt, 1993; Fagerberg, 1994; Nelson, 2004; Bell, 2007). The need for such technology modifications and continued improvements stems from the fact that technology markets will typically be very different from region to region. For example, the characteristics of the demands from technologies will differ markedly from region to region and evolve at different paces. Similarly, different regions have different resource endowments and access to raw materials, which may affect the performance of the transferred technologies and call for modifications.

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[30] In their review of spillovers from multinational corporation activities in foreign countries, Blomstrom and Kakka (1998) include two other types of knowledge spillovers: the effect of increased competition resulting from foreign entry, and the creation of new export markets for local firms to enter.

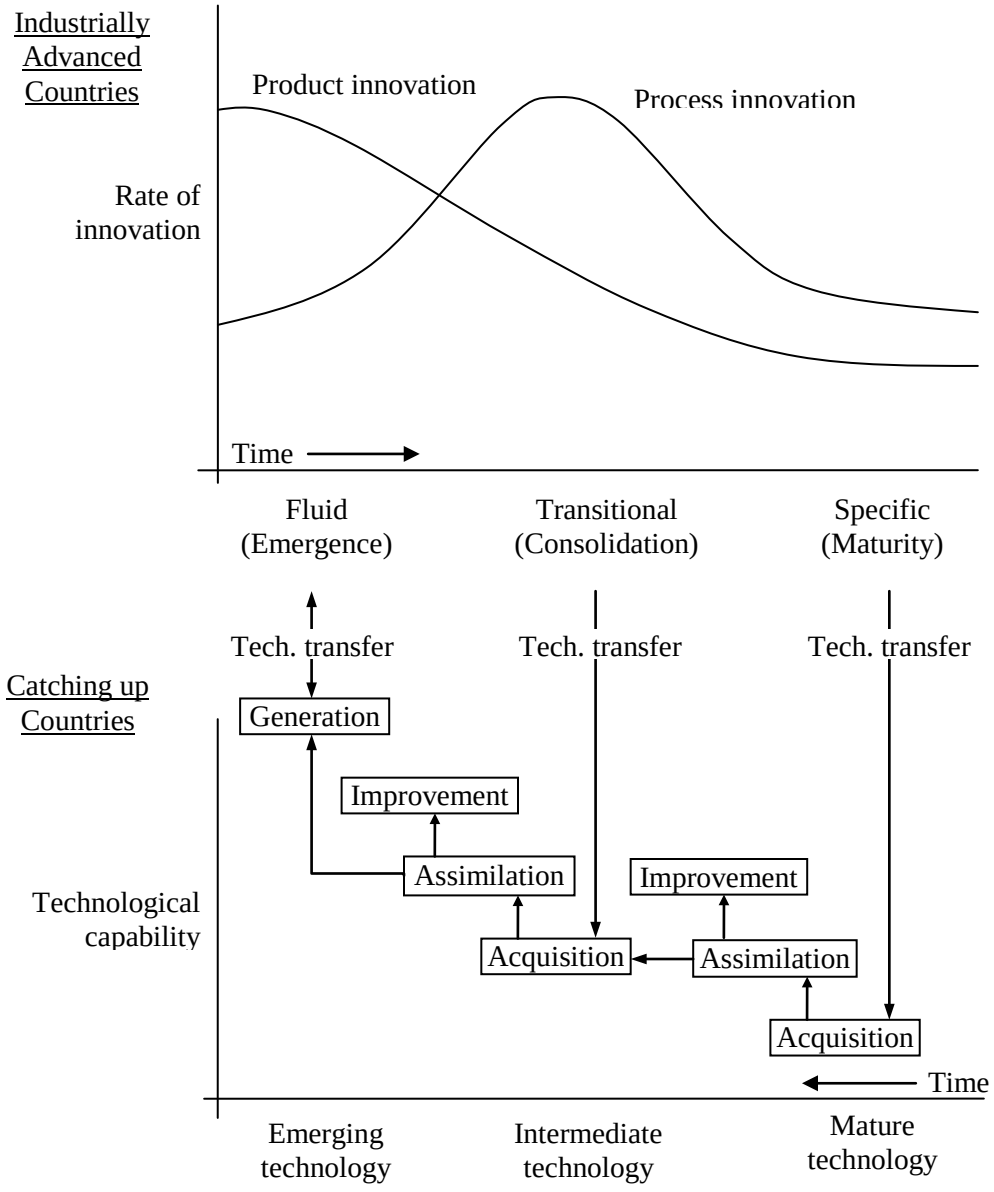
The literature refers to 'firm technological capabilities' to characterize the ability of firms in developing countries to seek out the most appropriate technologies through transfer and to improve and adapt them to the characteristics of their environment and in response to changing conditions (e.g. Bell and Pavitt, 1993; 1995; Bell, 2007; Lall, 1992; 1998; Kim, 1997; 1999). However, the taxonomies of firm technological capabilities also encompass capabilities linked to the development of new technologies (Radosevic, 1999).[31] As noted by Bell and Pavitt (1993, p.162), as firms accumulate technological capabilities they are progressively able to introduce more significant changes to the technologies being transferred and eventually "firms produce the kinds of technological change which are usually thought of as innovations".

Drawing on research on the evolution of several industries in Korea, Kim (1997; 1999) links the accumulation of technological capabilities in firms below the frontier in emerging economies to the dynamics of innovation in advanced economies outlined by Abernathy and Utterback (1978; Utterback, 1996) and reviewed in Section 1.2.1.1. Kim's model is schematized in figure 1.3 and has at its core a three step model of technology acquisition, assimilation, and improvement.When a technology in advanced economies has reached maturity (upper chart in figure 1.3), production processes typically become highly standardized and less reliant on skilled labor. The technology can be relocated to developing countries, where production costs are lower. Firms in emerging economies with limited technological capabilities can acquire the technology from advanced economies via technology transfer. Kim (1997; 1999) notes that once transferred from abroad, the technologies are further transferred to other firms within the

[31] See Section 1.2.1.2 for a discussion of activities linked to the development of new technologies.

country. Increased competition leads to efforts to assimilate the technology and introduce differentiated products. Firms with higher technological capabilities can introduce gradual improvements, often times driven by export opportunities.

Figure 1.3: Innovation processes and catching up



Source: Kim (1999)

Note: in the lower chart time flows in the opposite direction as in the upper chart.

Kim's model underscores that firms which have successfully acquired, assimilated, and possibly improved upon transferred technologies in the specific phase, may build on this experience and aim to repeat the process with technologies at an earlier stage of development. For technologies in the transition phase (upper chart in figure 1.3), however, firms in emerging economies must be able to engage in some basic forms of R&D activities to assimilate and improve on the transferred technology. Kim refers to the challenges as shifting from 'duplicative imitation' to 'creative imitation'. Some firms may accumulate sufficient technological capabilities to generate technologies in the fluid phase (upper chart in figure 1.3) and eventually compete with firms in industrially advanced countries.

Various authors have offered detailed breakdowns and descriptions of capabilities of firms in emerging economies.[32] Arguably the most complete classification was put forth by Lall (1992) and improved by Bell and Pavitt (1995). This classification, summarized in table 1.2, distinguishes between a firm's production capabilities and its technological capabilities.[33] As defined in Bell and Pavitt (1993, p.163):

> *The former incorporates the resources used to produce industrial goods at given levels of efficiency and given input combinations: equipment (capital-embodied technology), labor skills (operating and managerial know-how and experience), product and input specifications, and the organizational methods and systems used. Technological capabilities consist of the resources needed to generate and manage technical change, including skills, knowledge and experience, and institutional links and linkages.*

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[32] See Bell (2007) for a review of some of the most prominent classifications of firm level capabilities in the literature.

[33] Different authors have put forth different firm capabilities classifications with varying analytical scope. For example, Kim's (1999) 'technological capabilities' encompasses Bell and Pavitt's (1993; 1995) 'technological capabilities' as well as their 'production capabilities'.

Table 1.2: Firm technological capabilities

	Primary activities				Supporting activities	
	Investment		Production			
	Facility user's decision making and control	**Project preparation and implementation**	**Process and production organization**	**Product centered**	**Developing linkages**	**Capital goods supply**
BASIC PRODUCTION CAPABILITIES (Using existing production techniques)						
	Engaging primary contractor. Securing and disbursing finance.	Preparation of initial project outline. Construction of basic civil works. Simple plant erection.	Routine operation and basic maintenance of 'given' facilities. Efficiency improvements from experience in existing tasks.	Replication of fixed specification and designs. Routing quality control to maintain existing standards and specifications.	Procurement of available inputs from existing suppliers. Sale of 'given' products to existing and new customers.	Replication of unchanging items of plants and machinery.
TECHNOLOGICAL CAPABILITIES (Generating and managing technical change)						
Basic	Active monitoring and control of feasibility studies, technology choice/ sourcing, and project scheduling.	Feasibility studies. Outline planning. Standard equipment procurement. Simple ancillaries engineering.	Commissioning and debugging. Improved layout, scheduling, and maintenance. Minor adaptation.	Minor adaptation to market needs, and incremental improvements to product quality.	Searching and absorbing new information from suppliers, customers, and local institutions.	Copying new types of plants and machinery. Simple adaptation of existing designs and specifications.
Intermediate	Search, evaluation and selection of technology/ sources. Tenders/ negotiations. Overall project management.	Detailed engineering. Plant procurement. Environment assessment. Project scheduling and management. Commissioning. Training/ recruitment.	Process improvement. Licensing new technology. Introducing organizational changes.	Licensing new product technology and/or reverse engineering. Incremental new product design.	Technology transfer to suppliers and customers to raise efficiency, quality, and local sourcing.	Incrementally innovative reverse engineering and original design of plant and machinery.
Advanced	Developing new production systems and components.	Basic process design and related R&D	Process innovation and related R&D. Radical innovation and organization.	Product innovation and related R&D	Collaboration in technology development	R&D for specifications and designs of new plant and machinery.

Source: Bell and Pavitt (1995)

The classification also identifies three types of activities: investment, production and supporting activities; and distinguishes among three different depths of technological capabilities, highlighting the different levels of sophistication reached as capabilities accumulate. The 'advanced' level corresponds to frontier-like capabilities, while 'basic' and 'intermediate' correspond to sub-frontier levels of capabilities.

1.2.2.1 The role of government and the systemic nature of technological catch-up

Most scholars who have contributed to the literature on firm technological capabilities recognize that firms are only one element in a broader system of technological development. Kim (1999, p.119) notes that "firms develop their technological capability through in-house efforts, augmented by interactions with domestic and foreign institutions, constrained by regulations, and stimulated by government incentives in the dynamically changing global technology environment". In most cases, firm technological capabilities have been used to frame assessments of industrialization processes in developing countries at the industry level, and to underscore the central role of governments in inducing firms to acquire and upgrade their capabilities.

Lall (1992) combines his classification of firm level capabilities with an assessment of national technological capabilities, focusing on the interplay of capabilities linked to physical investments, human capital, and technological efforts; incentives for production and investment; and market and non-market institutions. He uses this national technological capabilities framework to discuss and compare a set of core indicators of industrial development in several

East Asian countries (Korea, Singapore, Taiwan, and Hong Kong), India, Thailand, and two Latin American countries (Brazil and Mexico).

In an earlier study, Lall (1987) develops a classification of firm capabilities to assess the performance of Indian firms from the early 1960s to the early 1980s in the cement, iron and steel, and textile industries, as well as in a number of case studies of firms in consumer goods, heavy electrical equipment, machine tools, and petroleum refining. The study provides a high level of detail at the firm level. However, it also carefully considers the role of policy-induced constraints on firms. In particular, Lall assesses the role of the government policy of protecting domestic firms from import competition and new foreign investments. The policy was notably complemented by mandatory use of domestic capital goods and local consultants. The study also highlights the role of government bias in favor of public sector ownership in iron and steel, as well as the effect of government support of small-scale enterprises through various subsidies. It also details how price controls, industrial licensing procedures, and the regulation of technology transfers were used in conjunction with government directed industrial planning and investments. Lall (1987, p.228) concludes that though the Indian firms studied have clearly expanded their technological capabilities, "the generally sluggish industrial growth created by the government's policies held back both the pace of learning and its deployment; and the anti-export bias and infrastructural constraints held back the exploitation of [technological capabilities] for foreign markets".

Amsden (2001) also develops a comprehensive classification of firm technological capabilities to compare and contrast how the governments of a group of developing countries during the second half of the 20th century induced the accumulation and enhancement of such capabilities

within firms.[34] Amsden (2001, p.8) argues that successful state driven late-industrialization was based on a principle of reciprocity whereby subsidies were allocated to domestic firms subject to meeting "monitorable performance standards that were redistributive in nature and results oriented". She explains how some governments succeeded in creating 'national leaders' in a variety of industries – i.e. successful domestic firms with their own knowledge based skills – while others failed. She also details the various government policies introduced and national institutions created in these countries as firms entered industries characterized by higher levels of technological complexity. Some of the most prominent types of government interventions included export promotion, the allocation of industrial licensing, performance standards, technology transfer controls, R&D subsidies, and the establishment of government research institutes.

The reciprocity principle outlined by Amdsen (2001) was arguably most effectively used in Korea. In her earlier account of that country's industrial development since the early 1960s, Amsden (1989) also uses firm technological capabilities as an analytical support and considers developments in a number of industries (e.g. cement, steel, automobiles, shipbuilding). However, she places far greater emphasis on a number of concurrent factors. In particular, she underscores the importance of a strong interventionist state, its interactions with large diversified business groups, as well as the existence of a cohort of competent engineers and an educated work force.

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[34] The developing countries considered in Amsden (2001), which she refers to as 'the rest', are those which had a minimum level of manufacturing experience following World War II, namely Argentina, Brazil, Chile, China, India, Indonesia, Korea, Malaysia, Mexico, Taiwan, Thailand, and Turkey. Countries with lower levels, 'the remainder', are not included.

Amsden (1989) details the cumulative nature of policies and measures introduced by the Korean government in support of industrialization. At their core were tariffs to protect infant industries, as well as a variety of incentives and subsidies for private investors. Price controls were also extensively used to tailor support to specific sectors and the government also closely monitored technology transfer. Amsden (1989; 1997) details the strong discipline exercised by the Korean government over private firms through a variety of performance-based incentives, and the role this played in spurring technological catch-up. She notes that the concentration of firm technological capabilities in a few large-scale diversified domestic companies notably made the enforcement of this discipline easier for the government. Of particular prominence to monitor firm performance was the use of export objectives, though various technology indicators, notably pertaining to technological transfer and R&D investments, were also used. Firms which performed poorly faced rationalization, seizure of assets, and, in the worst cases of failing firms, a refusal to bail them out. In contrast, well performing firms were provided with further subsidies as well as industrial licenses to operate in new markets.

Kim (1997; 1999) also uses his technological capabilities framework as a tool embedded in a broader narrative of industrial development in Korea. He builds on case studies of Korean industries since the 1960s (e.g. automobile, electronics, semiconductors) to identify the mechanisms which have allowed Korean firms to accumulate technological capabilities, first in mature technologies, followed by intermediate technologies, and ultimately emerging technologies (see figure 1.3).

Kim (1997; 1999) underscores in particular the role of the strict regulatory framework geared towards pushing domestic firms towards higher value industries, and the assimilation of foreign

technology. For example, the government's export promotion policies forced domestic firms to rapidly engage in the transfer and assimilation of foreign technology. Similarly, the government's strategic push towards heavy and chemical industries forced domestic firms to invest in another wave of technological learning based on foreign technology in industries where they had little prior experience.

Kim (1997, 1999) also highlights how the government adapted the regulatory framework over time. For example, in the early stage of industrialization during the 1960s and 1970s, the government restricted foreign direct investment as a means of technology transfer, accelerating technology assimilation and forcing firms to develop independent managerial capabilities. However, starting from the 1980s, as Korean firms engaged in more sophisticated industries and foreign technologies became more difficult to transfer, foreign direct investment and licensing were allowed to increase. Domestic R&D funding also started playing an important role within firms. Newly formed government research institutes and various reforms in the education system contributed to helping Korean firms move towards more research based technology development.

1.3 METHODOLOGY

1.3.1 General approach: case studies combining system and firm perspectives

The above literature review highlights the complex and dynamic nature of technology development and catch-up processes and how this has affected scholarly work on the topic. As technologies move from the realms of science to production and become commercially viable, the market becomes an important driver of technology development. Market opportunities allow firms to accumulate experience, which in turn feeds into technology learning processes.

Furthermore, market opportunities create incentives for firms to invest in other means of technology development, namely R&D and imitation. It is apparent from the literature, however, that these three principal means of technology development – R&D, learning from experience, and imitation – are heavily intertwined with important overlaps and feedbacks among them.

The literature emphasizes that the ability of firms below the frontier to engage in technological development goes hand in hand with their ability to accumulate technological capabilities. Furthermore, whether at or below the technology frontier, the literature underscores that technology development takes place in systems of agents. Firms play a central role, yet research organizations, government agencies, government policies, and other market and non-market institutions also have a strong influence on technology development. Below the frontier in emerging countries, government intervention through policies and other measures play a particularly central role in fostering technological progress. In this process, numerous modes of technology transfer from advanced economies are typically involved.

To capture these diverse characteristics, assessments of technology development and catch-up in the literature have relied heavily on case studies at the industry or technology level, combining both qualitative and quantitative data. Two approaches in the literature stand out in terms of the methodological structure they provide to case studies analysis. The first, 'technology innovation systems', has been used to assess innovation processes at the frontier. By combining assessments of a system's structural elements – i.e. actors, networks, and institutions – and of its functions, it offers a powerful tool to capture the systemic characteristics of technological development. In contrast, the second approach, 'firm technological capabilities', has been mainly used to assess technology development below the frontier in developing countries. It categorizes firm

technological capabilities along different types of activities and with various levels of depth, allowing for a detailed accounting of technology development.

Technology case studies therefore seem best suited to answer the research question outlined in Section 1.1.4 and I propose to combine the 'firm technological capabilities' and the 'technology innovation systems' approaches to form the methodology used to test the research hypothesis. The first approach provides the depth for a detailed assessment of technology development activities of firms below the frontier, which is necessary to assess the extent of technological catch-up and answer the research question. The second approach offers the breadth to systematically capture the role of various agents in technology development, including that of the government, which is central to the research hypothesis.

As noted above, the literature on technological catch-up in developing countries already combines firm technological capabilities with assessments of the systemic environment surrounding firms, notably the role of governments. However, these systemic assessments have remained relatively unstructured. By adopting the technology innovation systems approach I therefore hope to provide more structure to this part of the analysis.

The firm technological capabilities approach is designed to address questions of catch-up and is therefore well suited for this research. The main issue is whether the technological innovation system approach can be applied to assess technology development below the frontier. A similar issue has been raised in the scope of 'national systems of innovation', discussed in Section 1.2.1.3. Viotti (2002) argues that studies of national systems of innovation tend to focus on a country's scientific and technical institutions and that this is inappropriate for industrializing economies (i.e. below the frontier) where such institutions play a secondary role and possibly no

role at all in the process of technological development. Nelson (2004) agrees that some reorientation is needed for assessments of technological catch-up. However, he also notes that national innovation systems still provide a useful framework. He underscores that the ability to independently make incremental modifications to technologies, central to the process of catch-up, is conceptually close to innovation. In addition, Nelson (2004) argues that the focus on science and technology institutions is mandated in the scope of many modern industrial sectors as technological catch-up rapidly requires these.

The technological innovation systems approach provides a framework, articulated around structural elements and core system functions, that is sufficiently flexible to capture the role of a diverse set of agents. These may include science and technology institutions as well as many other types of agents depending on the nature of the case considered. Furthermore, with only minor modifications to the scope of the system functions identified in the literature and outlined in table 1.1, the approach can capture technology development dynamics more broadly, whether at the frontier or below it. As suggested by Nelson (2004) in the scope of national innovation systems, ‘technological innovation systems’ can therefore easily be recast into broader ’technology development systems’, suited for the needs of this research. These functional considerations at and below the frontier are detailed in table 1.3.

Table 1.3: functions of technology development systems

Name of function	Key function characteristics	Main distinction at and below the frontier
Market formation	Markets allow firms to accumulate experience, which is an essential input to knowledge development. Market competition and the prospects of securing profits also constitute one of the main incentives for firms to invest in knowledge development.	The ability of firms at the frontier to secure market shares for their product depends in large part on their technological capabilities. Firms below the frontier have lower technological capabilities yet may still gain access to markets if either: 1) Lower prices of factors of production combined with technology transfer make their products competitive with those of frontier firms, or; 2) Government creates a market through regulations only accessible to them.
Knowledge development and diffusion	Technological knowledge is developed through R&D, learning from experience, and imitation activities. Different agents are involved in these knowledge development activities. Collaborations and exchanges of information through networks are therefore central to this function.	The further below the frontier the more knowledge development is likely to be based on imitation activities, through some mode of technology transfer. However, as firms accumulate capabilities and get closer to the frontier learning from experience and R&D play increasingly important roles.
Entrepreneurial activity	Entrepreneurial activity consists of the ability of firms to take risks and probe new technologies, modify existing ones, or test new uses and applications. Many such actions will fail to produce useful technological progress, but some will succeed and prove profitable.	For firms below the frontier entrepreneurial activity also involves identifying and seeking the transfer of technologies new to their market. Much entrepreneurial activity is therefore also needed to successfully adapt transferred technologies to the specificities of local market conditions.
Guidance of search	Several factors influence the direction of technological development. These include, among others, assessments of technological opportunities, belief of actors in the growth potential, regulations and policy, and the articulation of demands by customers.	Below the frontier actors benefit from knowing the technological trajectory of the frontier. This prior knowledge may facilitate guidance and the direction of search.

Legitimation / counteracting resistance to chance	The legitimacy of a technology is a reflection of the extent to which the technology is deemed appropriate and desirable by various actors. Resistance to technological change can undermine the process of building legitimacy. Resistance may notably come from actors of incumbent technological systems who oppose the development of competing technologies.	Below the frontier, firms rely heavily on technologies previously developed by others (via technology transfer). To a large extent therefore, these technologies have already accrued legitimacy. This may facilitate the processes of legitimation and counteracting resistance to change below the frontier.
Resource mobilization	In order to grow, a technological development system requires the mobilization of qualified human capital and financial capital. In addition it often requires complementary assets such as access to existing knowledge, complementary services, or network infrastructure.	The central role of technology transfer in technology development below the frontier places particular emphasis on the need for access to existing knowledge.

Source: Based on Bergek et al. (2008) and Hekkert et al. (2007)

Note: The function 'development of positive externalities' in Bergek et al. (2008) is not included as it depends on other functions being successfully completed and therefore can be considered secondary to other functions.

1.3.2 Research method

As detailed in Section 1.1.4, the research question asks whether Chinese firms can catch up with the technology frontier in the scope of new climate friendly energy technologies, and if so, how and to what extent. The hypothesis that they can catch up is based on two arguments. The first argument is that Chinese firms can make rapid technological progress and consists of two elements: one, that the Chinese government creates a large domestic market for new climate friendly energy technologies relative to other countries; and two, that the Chinese government proactively supports technological development by Chinese firms. The second argument is that

the climate friendly energy technology frontier has been evolving relatively slowly due to limited policy support in advanced economies, thereby making catching up easier.

I propose to test the hypothesis through three separate assessments, each the focus of a subsequent chapter. I outline the main thrust of each assessment below, though further details are provided in the relevant chapters.

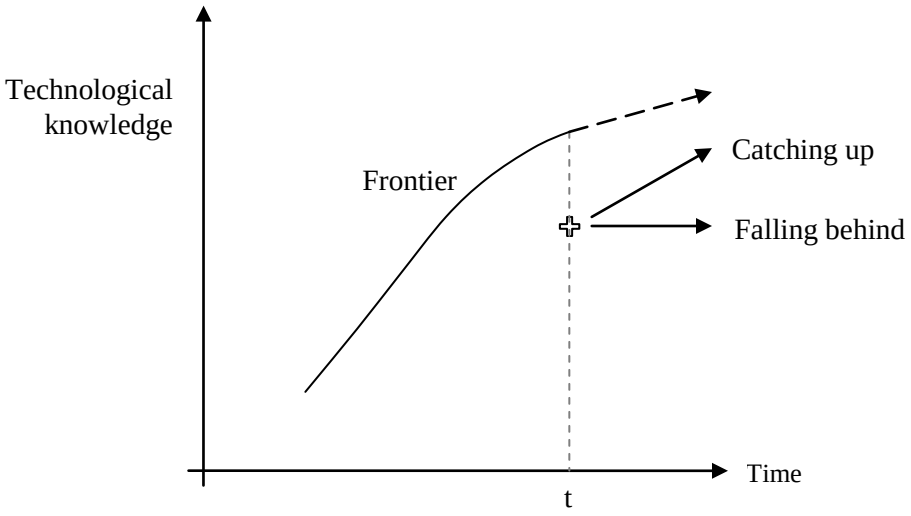
1.3.2.1 Assessing technological catch-up

The first assessment, presented in Chapter 2, addresses the core of the research question and focuses on determining whether China is catching up with the technology frontier in the scope of new climate friendly energy technologies. The definition of technological catch-up outlined above as 'entities at lower levels along a technological path rising at a faster pace than the evolution at the technological frontier' is conceptually appealing and I draw on Perez (2004, see figure 1.1) to depict the process over time schematically in figure 1.4. At the frontier, technological knowledge accumulates over time as a technology is developed. An entity below the frontier (the cross in figure 1.4) can catch up if it is able to accumulate technological knowledge at a faster pace than the evolution of the frontier, otherwise it will fall behind.[35,36] Catching up therefore consists of a convergence of technological knowledge over time.

[35] I borrow the term 'falling-behind' from Abramovitz (1986).

[36] The initial position of entities below the frontier (i.e. of the cross in figure 1.4) depends on the nature of technology transfers.

Figure 1.4: Technological catch-up or falling behind



The challenge, however, is to identify suitable metrics of technological knowledge to assess whether catch-up is indeed occurring. I propose to focus on technology specific metrics and compare their evolution at the frontier and in China. These consist of relevant indicators of technical progress in the new climate friendly energy technologies being considered.

However, focusing on technology specific metrics alone is insufficient. As highlighted in the above literature review, technological catch-up involves firms below the frontier acquiring the necessary technological capabilities to generate and manage technology development. I therefore also adopt the firm technological capabilities approach to assess the capabilities held by the leading Chinese firms involved in the development and manufacturing of the new climate friendly energy technologies considered.

1.3.2.2 Assessing the Chinese system of technology development

The second assessment, presented in Chapter 3, is concerned with the first argument of the research hypothesis. It aims to assess the Chinese system of technology development for new climate friendly energy technologies and, in particular, to determine the role of the Chinese government in inducing technological progress among Chinese firms. The analysis therefore follows the steps of the technology development systems approach outlined in Section 1.3.1. It identifies the structural elements of the system and assesses how and the extent to which each system function is fulfilled. Though all functions are investigated, I place particular emphasis on the functions of market formation and knowledge generation. In each, the role played by the Chinese government is assessed in details.

1.3.2.3 Assessing the evolution of the frontier

Finally, the third assessment, presented in Chapter 4, is concerned with the second argument of the research hypothesis and aims to assess the role of governments in determining the pace of the frontier of new climate friendly energy technologies.[37]

The assessment is broken down into two sub-components. The first sub-component aims to assess whether technology development at the frontier of new climate friendly energy technologies has been driven primarily by the support extended by governments through policies. I use patent applications as an indicator of knowledge development at the frontier,

[37] This third assessment focuses on the knowledge development function of technology development systems applied at the frontier (see table 1.3).

which I correlate with policy changes in countries which have historically provided strong support to climate friendly energy technology development.

The second sub-component aims to assess whether the frontier of new climate friendly energy technologies has progressed slowly relative to other technologies and industries. I use patent applications in combination with technology penetration rates as indicators of knowledge development at the frontier and compare trends of new climate friendly energy technologies to those related to other technologies and industries.

1.3.3 The case of wind power

1.3.3.1 Case selection

The research question and hypothesis consist of one dependent variable: technological catch-up, and three explanatory variables: first, the size of the domestic market relative to that of foreign markets; second, the level of activity of the Chinese government in supporting technology development among Chinese firms; and third, the pace of knowledge development at the technological frontier relative to other technologies. In theory, drawing conclusions on the generalized validity of the research hypothesis would require that the research method outlined above examine at least as many case studies as there are explanatory variables. Therefore at least two new case studies of new climate friendly energy technologies could be used to test the validity of the hypothesis, with emphasis on ensuring variation in the dependent variable. However, this thesis has focused solely on the case of wind power technology. While this single-case research design allows for only limited inference, it has explanatory value and furthermore puts forth a novel research method combining distinct approaches from the

literature. In future work, the findings presented in the following chapters need to be complemented by additional technology case studies. I discuss the selection of other potential technology case studies in chapter 5.

The focus on one technology case study reflects the level of detail required for each assessment and the difficult processes involved in securing access to industrial information in China. In particular, the three assessments outlined above require diverse data collection efforts, both quantitative and qualitative. Extensive interviews were notably conducted with officials from a sample of actors of the Chinese wind power technology development system, including wind turbine manufacturing firms, universities, research institutes, industry organizations, and government.

The choice of wind power was driven by a central feature of the research hypothesis: that China can create relatively large markets for climate friendly technologies. In this respect, wind power is an excellent case study. Indeed, as detailed in Chapter 2, by 2010 China had the largest national wind power market in the world in terms of installed capacity.

1.3.3.2 Introduction to wind power technology and cost drivers[38]

I introduce here some of the basic principles and key technological characteristics of wind power which have guided much of the technology development efforts described in subsequent sections. Though several types of wind turbines have been developed and tested over the years,

[38] This Section draws from Lynn (2012), Nelson (2009), and Manwell, McGowan, and Rogers (2009).

this thesis focuses on horizontal axis up-wind turbines as this technology is by far the most widespread across the world. The axis of the rotor on such turbines is parallel to the direction of the wind with the rotor turning perpendicular to it and in front of the tower on which it stands.[39]

Wind turbines convert kinetic energy in the wind into mechanical energy and ultimately electrical energy. The power contained in a steady airstream can be characterized by the equation $P = 0.5\rho AU^3$, where ρ is the density of the air, A is the cross-sectional area of the airstream, and U is the wind speed. This cubic relation implies that power increases disproportionately as wind speed increases. Wind turbines are therefore presented with much greater amounts of wind power during a period of high wind speed than during a comparable period of slow wind speed.[40] One consequence is that turbines will likely produce most power at speeds above the mean wind speed, even though these occur less frequently.

In addition to varying wind speeds, at any given site the direction of the wind will also vary over time. In order to capture the highest fraction of power in the wind, the rotor should be perpendicular to the wind direction as this increases the area A in the above equation.

Wind speeds tend to increase with height, particularly in the case of rough surfaces, such as forested areas or built environments. Installing turbines high above the ground or sea level allows capturing higher wind speeds, thereby increasing the power available in the wind. Conversely installing turbines in locations of low roughness, such as plains or the open sea, will

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[39] For details of other types of wind turbines see for example Nelson (2009)

[40] For example, assuming standard conditions of air density of 1.225 kg/m^3, the power contained in a meter square of airstream at 6 m/s is 132.3W. However, at double this wind speed, the power increases to 1058.4W, eight times the initial value.

increase the available power in the wind compared to an equivalent location with higher roughness. In addition, lower elevations are also linked to greater turbulence which can contribute to damage turbines.

Wind turbine rotors convert the kinetic energy in the wind into mechanical energy. According to Betz Limit, regardless of the turbine, the theoretical maximum power which can be extracted from the wind's energy is 59%. Assuming a given conversion efficiency, the equation above highlights that the rated power of a turbine increases with the swept area of the turbine.[41]

These basic principles have guided much of the technology development efforts discussed in this and subsequent chapters. These efforts have focused on bringing down the costs of electricity produced from wind power, whether by reducing the initial investment cost, reducing the annual operating and maintenance (O&M) costs, or by increasing the annual electricity production.[42] Though there are innumerable ways to improve wind power technology and reduce the cost of electricity, I highlight below some of the key areas of technology development.

One important area is blade design as this plays a central role in determining the conversion efficiency from kinetic energy in the wind to mechanical energy in the rotor shaft, and therefore affects total electrical output. Each location has a unique wind power distribution and the

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[41] For example, assuming standard conditions of air density of 1.225 kg/m^3, average wind speed of 12m/s, a turbine conversion efficiency of 50%, and a rotor diameter of 60m, the rated power of the turbine can be estimated using the above equation to be approximately 1.5MW. If the rotor diameter is increased to 70m, the rated power of the turbine increases to approximately 2MW.

[42] A calculation of the levelized cost of electricity production from wind power also includes the interest rate on capital and discount factors. These, however, are not directly related to technology and are therefore not included in this discussion.

selected rotor should capture as much power as is economically feasible over a broad spectrum of available wind speeds. One challenge is to balance the benefits of increasing production by capturing the power available at higher wind speeds, with the risks of damaging the turbines and thereby increasing O&M costs. All turbines have ways to avoid capturing wind power above certain wind speeds. The two most common approaches have been either to design airfoils which naturally stall above certain wind speeds, or to allow blades to be mechanically pitched away from the wind. In addition, the rotor may also be brought to a stop through various types of brakes. Larger swept areas allow capturing more wind power and therefore generating more electricity. A related area of technology development has therefore focused on blade materials and manufacturing methods to allow building increasingly long blades while maintaining essential properties.

However, a limiting factor in the trend towards larger turbines has been turbine weight. Heavier turbines are more expensive due to higher material costs and installation costs. Large turbines notably need specific cranes with heavy lifting capabilities which are costly to mobilize. Weight reduction has therefore been another important area of technology development which has concerned all aspects of the turbine, from the development of new lighter building materials to new drive train configurations and technologies.

A broad area of technology development concerns the conversion of mechanical power in the rotor shaft into electrical power through a generator, often in conjunction with a gearbox. The drive train (i.e. the combination of gearbox, shafts, and generator) can be coupled with a converter to ensure the power generated is compatible with the electricity grid specifications. Many different drive train and converter designs and technologies have been developed and

tested to enhance conversion efficiency and therefore increase power production. In this process, a number of other important criteria must also be taken into considerations, such as grid friendliness, or turbine weight.

Another central issue is turbine reliability. This is particularly important in remote locations where maintenance costs can be high and access can be difficult. The development of effective control and monitoring strategies for wind turbines therefore play a central role in maximizing power production and reducing O&M costs. In addition, simplifying turbine configurations to limit O&M requirements has been another important area of technology development.

Accurately mapping wind power resources to identify the best available locations for wind power is another essential task to ensure wind power projects maximize electricity production. Offshore locations have notably been highlighted as holding some of the best wind resources. This, however, raises important new technology challenges as technologies specific to offshore wind power conditions need to be developed. Turbine foundations and grid extensions notably account for a much larger share of total investment costs in the case of offshore projects and have therefore been the object of increased technology development efforts.

Finally, beyond the turbine itself, wind power is interconnected to regional power grids, governed by strict electricity quality standards. Compared to conventional power generation, the high level of intermittency of wind power production linked to the natural variability of the wind creates added costs to the overall system due to the need to provide more ancillary services, such as short-term load balancing. There are therefore important areas of technology development at the system level which contribute to reducing wind power generation costs.

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- Chapter 2 - The Nature and Extent of Technological Catch-up by Chinese Wind Turbine Manufacturing Firms

2.1 INTRODUCTION

2.1.1 Chapter objective and research approach

This chapter addresses the core of the research question outlined in Section 1.1.4. It aims to assess whether Chinese firms are catching up with the wind power technology frontier, and, if so, to what extent. As detailed in Chapter 1, the definition of technological catch-up as 'entities at lower levels along a technological path rising at a faster pace than entities at the technological frontier' can serve as the conceptual basis for an assessment of catch-up. One challenge, however, is to identify suitable metrics to assess whether such a convergence of trends over time is indeed occurring (see figure 1.4). In addition, one must assess the extent to which the firms catching up are responsible for the underlying technological development or whether they are simply benefiting from technologies developed by others (e.g. in the scope of technology diffusion from one nation to another).

The analysis in this chapter therefore consists of two parts. First, I consider the evolution of key technical indicators of wind power technology progress at the frontier and in China to assess whether a convergence of trends over time can be identified. Second, I draw on interviews conducted with officials from some of the largest Chinese wind turbine manufacturing firms to assess the evolution of firm technological capabilities.

Before turning to the assessment of technological catch-up, however, I first highlight the evolution of the Chinese wind power market compared to historical market leaders. As detailed

in Chapter 1, whether at the frontier or below it market opportunities underlie much of the technology development process. Differential market opportunities notably constitute a central feature of the research hypothesis outlined in Section 1.1.4.

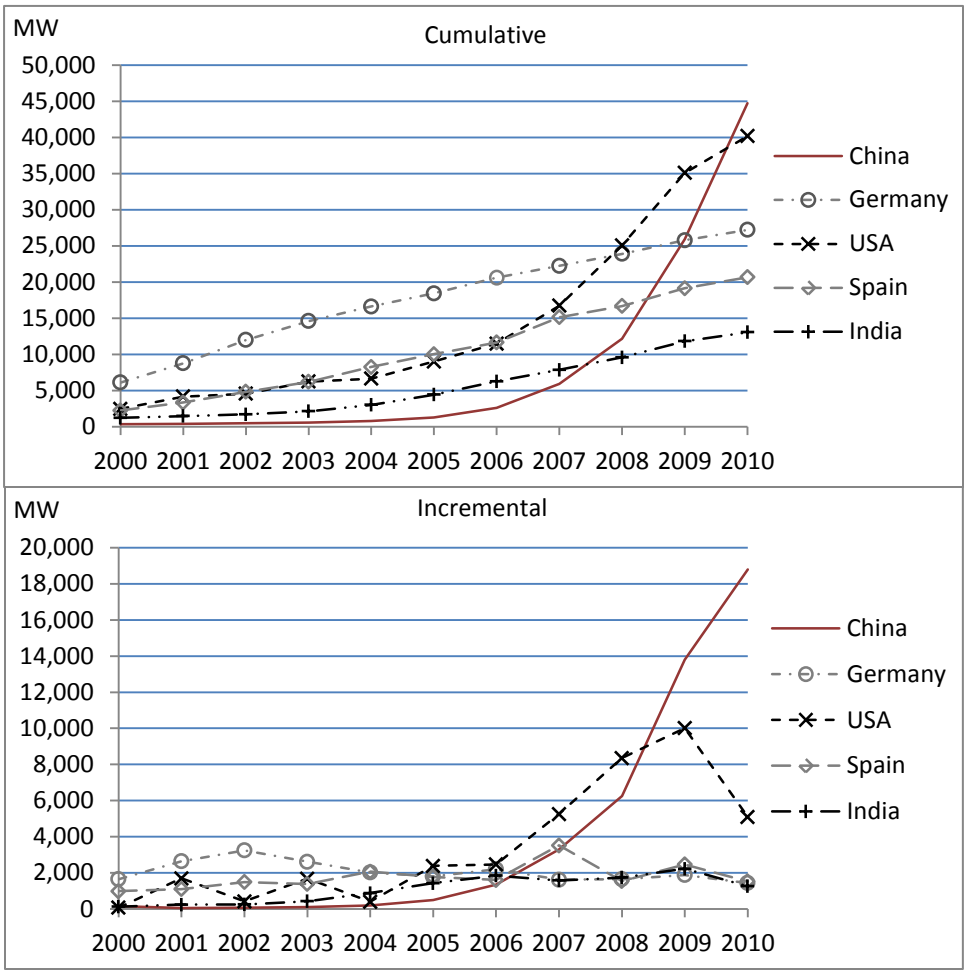
2.1.2 Wind turbine markets in China and other leading nations

Different metrics can be used to assess the evolution of wind power markets. I focus here on wind power capacity and numbers of turbines installed. Furthermore, I assess the evolution of markets at both the national and firm level.

Figure 2.1 shows cumulative and incremental installed wind power capacity from 2000 to 2010 for the five countries with the largest cumulative installed capacity in 2010. As of 2010, China had a cumulative capacity of 45 GW, making it the country with the largest total wind power capacity in the world. In contrast the United States, Germany, Spain and India respectively had installed capacities of 40GW, 27GW, 21GW, and 13GW. These results highlight the rapid growth of the Chinese wind power market since 2005, when it still lagged far behind the other countries.

Incremental installed capacity in China reached over 18GW in 2010, from 14GW in 2009, and 6GW in 2008. In contrast, the United States saw a drop in its incremental installed capacity from 10GW in 2009 to a little over 5GW in 2010. Germany, India, and Spain each had annual incremental installed capacity below 2GW from 2008 to 2010.

Figure 2.1: Cumulative and incremental installed wind power capacity by country



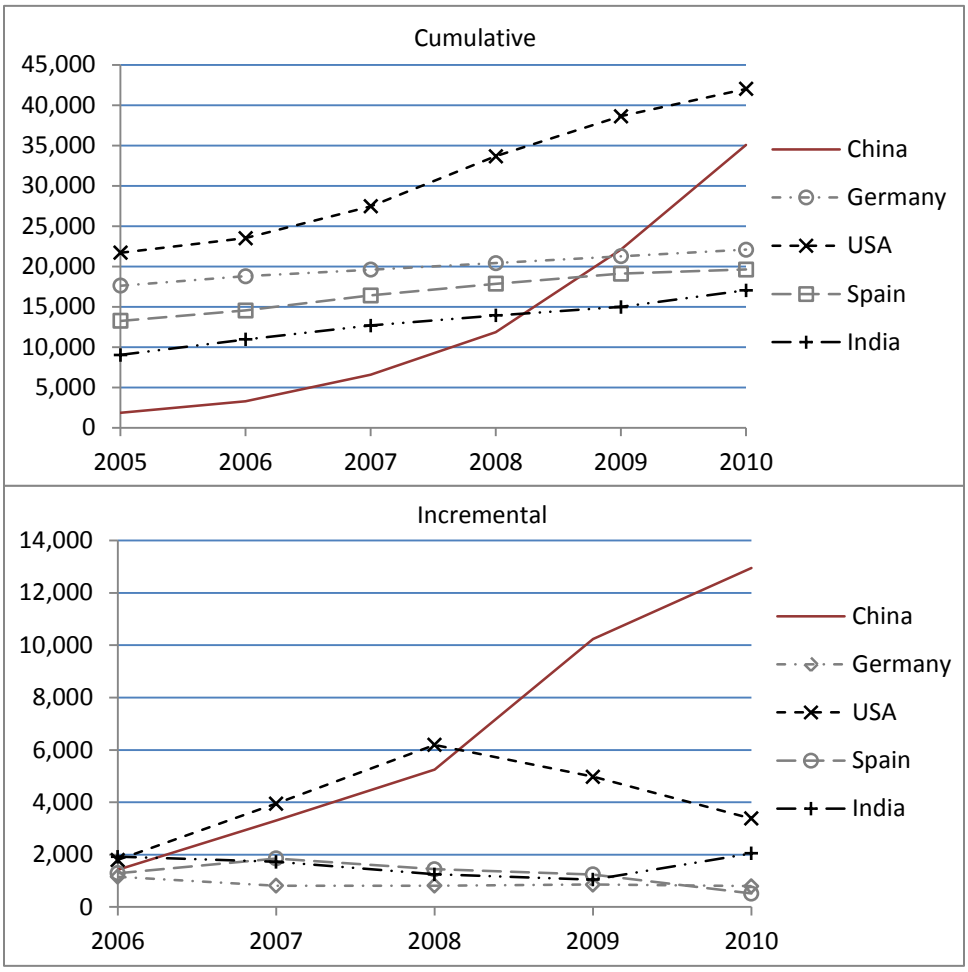
Note: Data from Alternative Energy e-Track[43]

Figure 2.2 shows the number of cumulative and incremental installed wind turbines in the same five countries. China had installed a total of approximately 35,000 turbines by the end of 2010, surpassing Germany, Spain, and India by the end of 2009. However, China still lagged behind the United States due to the fact that on a cumulative basis, the United States has a

[43] Data retrieved from http://www.alternativeenergyetrack.com/Index.aspx, November 2011.

smaller average turbine capacity compared to China. As a result, though the United States has a smaller cumulative capacity, it remains ahead in terms of number of turbines.

Figure 2.2: Number of cumulative and incremental installed wind turbines by country



Note: Data from BTM (2011)

In contrast, China experienced a rapid growth in the incremental number of turbines installed, reaching nearly 13,000 new units in 2010, while the United States saw a reduction in numbers in both 2009 and 2010 to below 3,400 units. In Spain, Germany, and India, the number of incremental installed turbines was of approximately 400, 800, and 2,100 respectively.

Figure 2.3 shows cumulative and incremental installed capacity for the five largest turbine manufacturers globally and for the five largest Chinese turbine manufacturers, ranked in terms of global cumulative installed capacity in 2010.[44] Trends of Chinese firms are indicated by dotted green or blue lines while those of leading frontier firms are indicated by solid black or grey lines. By 2010, Chinese firms were still far behind the group of frontier firms in terms of cumulative installed capacity. Sinovel, the leading Chinese turbine manufacturer had 10GW of cumulative installed capacity while the smallest of the five frontier firms, Suzlon Group, had 17.3GW. The leading frontier firm, Vestas, had accumulated a total of 45.5GW.

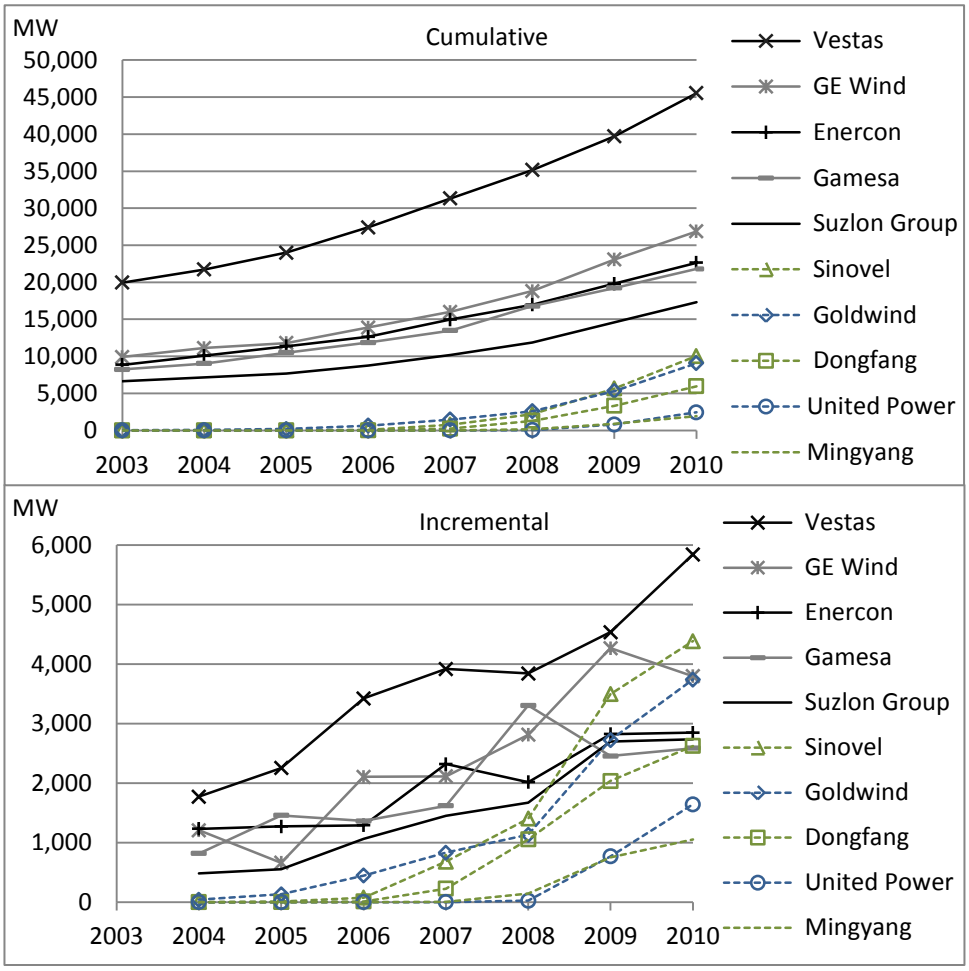
However, when looking at the evolution of annual incremental capacity installed, by 2010 four Chinese firms were ranked among the top 10 firms globally, with Sinovel and Goldwind ranked among the top five. In addition, apart from Vestas, which was ranked first, the rate of increase in incremental installed capacity towards the end of the decade appeared higher for Chinese firms than for frontier firms.

In sum, in the space of five years, China went from representing a small fraction of global installed wind power capacity to becoming the country with the largest cumulative installed capacity in the world. By 2010, over three times as much wind power capacity was installed in China than in the United States, the second largest market in the world, and over nine times more than in Germany or Spain. When looking at cumulative installed capacity at the firm level, Chinese firms lagged behind some of the leading firms. This is not surprising given the relative

[44] The five largest firms globally were Vestas, from Denmark, GEWind, from the USA, Enercon, from Germany, Gamesa, from Spain, and Suzlon, from India.

short history of the Chinese wind power market. However, incremental installations highlight the rapid growth of Chinese firms, which by 2010 were ranked among leading firms globally.

Figure 2.3: Cumulative and incremental installed wind power capacity by firm



Note: Data from Alternative Energy e-Track,[45] BTM (2011), and data provided to the author by the Chinese Wind Energy Association.

[45] Data retrieved from http://www.alternativeenergyetrack.com/Index.aspx, November 2011.

2.1 INDICATORS OF WIND POWER TECHNOLOGY PROGRESS

This section focuses on the first part of the chapter's analysis of technological catch-up and uses indicators of wind power technology progress to assess whether a convergence of trends over time can be identified between firms at the technological frontier and in China. In particular, I use indicators of some of the key characteristics of wind turbine technology as well as indicators of wind power plant performance.

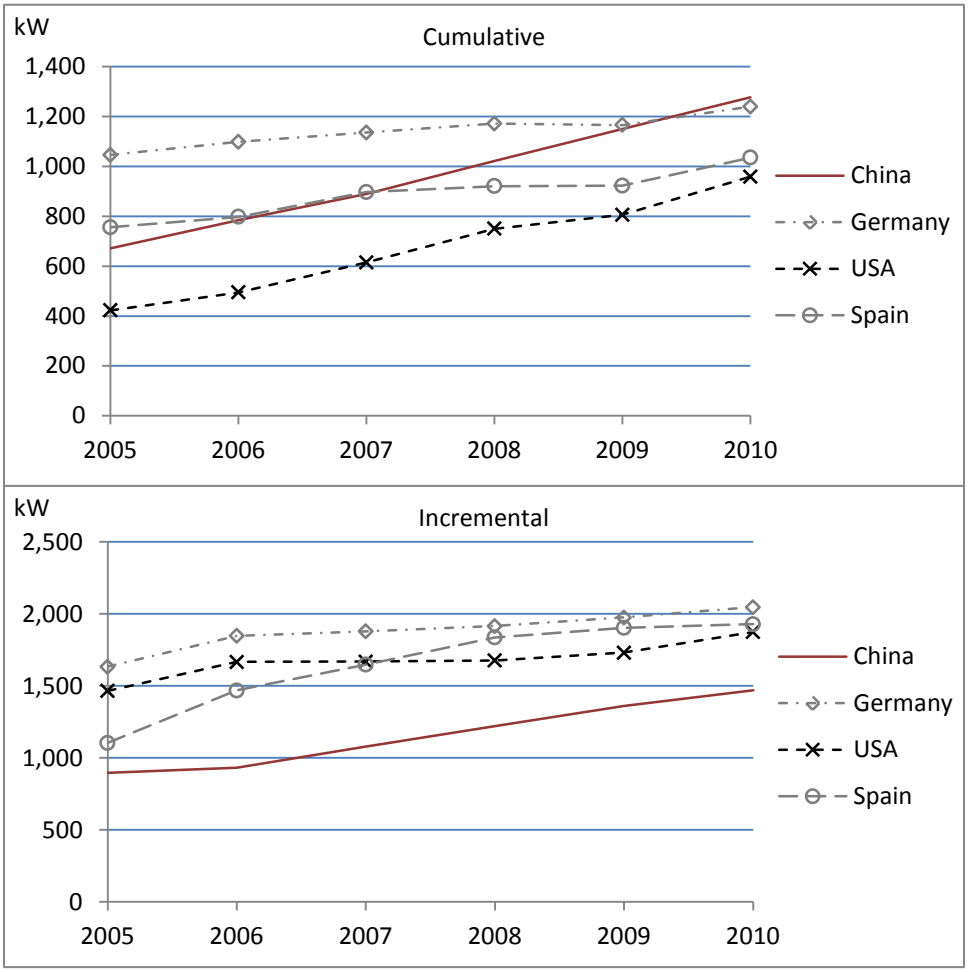
2.1.1 Wind turbine characteristics

A central feature of the evolution of wind turbine technology has been turbine size. Turbines have become increasingly large as firms have endeavored to continuously reduce electricity generation costs and optimize the use of limited geographic resources, first onshore and subsequently offshore.[46]

One simple metric of turbine size is the rated capacity of turbines. Figure 2.4 shows the evolution of average turbine rated capacity of the cumulative and incremental installed capacity in China and in the three main markets for wind power - the United States, Germany, and Spain. China experienced the fastest rise in average turbine size of its cumulative installed capacity and had the highest value in 2010. Yet when looking at the average turbine size of its annual incremental capacity, China remains behind other countries. Furthermore, the difference in average size with leading countries has only shrunk marginally between 2005 and 2010.

[46] See Section 1.3.3.2 for a discussion of the drivers of wind power technology and costs.

Figure 2.4: Average turbine capacity of cumulative and incremental wind power installed capacity by country



Note: Data from BTM (2011)

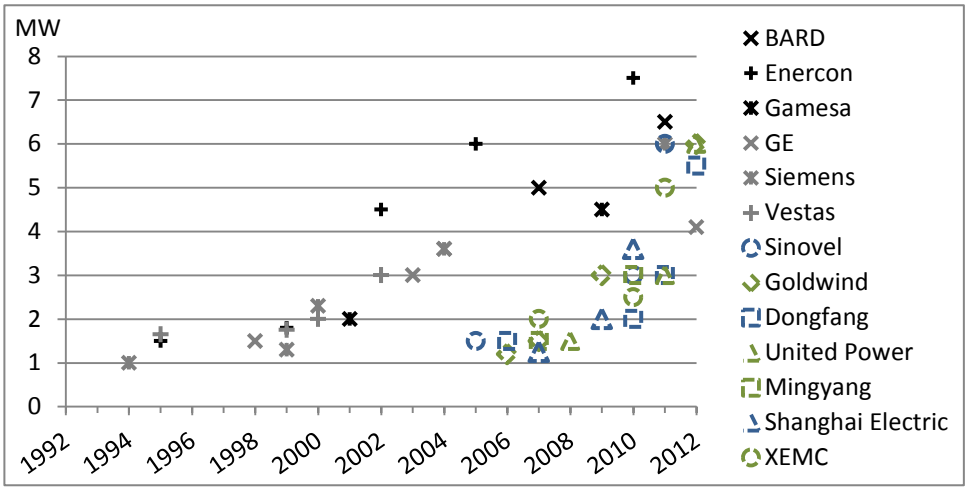
However, comparisons of average turbine capacity at the national level only provide limited insights on industrial trends. Such comparisons lump all firms involved in their respective national markets and therefore fail to discern technological leaders from laggards, or national firms from foreign firms. Focusing on leading firms at the frontier and in China provides a clearer picture of the potential for technological catch-up. Figure 2.5 shows the evolution of the

rated capacity of the prototypes of turbine series introduced by frontier firms and leading Chinese firms by year of first installation.[47] The firms considered include the main turbine producers in terms of capacity installed (shown in figures 2.3), as well as other prominent firms which introduced large capacity models. Frontier firms are represented by solid black or grey crosses while Chinese firms are represented by dotted blue or green shapes. The figure only shows turbines over 1MW in capacity, though several frontier companies started with much smaller models. Vestas' first commercial model introduced in 1979, for example, was a 30KW turbine. Among the leading Chinese firms, only Goldwind produced less than megawatt scale turbines, starting with a 600KW model in the late 1990s.

Frontier firms started producing megawatt scale turbines from the early 1990s and turbine size has since increased progressively, ranging from 4MW to 7.5MW by 2012. In contrast, most leading Chinese firms only entered the market between 2005 and 2008 with turbines ranging from 1.2MW to 2MW. After an initial phase of relatively slow increase in the capacity of new turbine series, the trend in turbine size rose rapidly with four of the six leading Chinese firms having prototypes ranging from 5MW to 6MW by 2012.

[47] Wind turbine manufacturers typically introduce new products within series of a given rated capacity, for example the '1.5MW' series. Within series are various turbine models. Each model has specific characteristics, usually according to the conditions in which it is designed to operate in, such as wind speeds, temperatures, etc.

Figure 2.5: Maximum capacity of turbine series introduced by frontier and leading Chinese firms

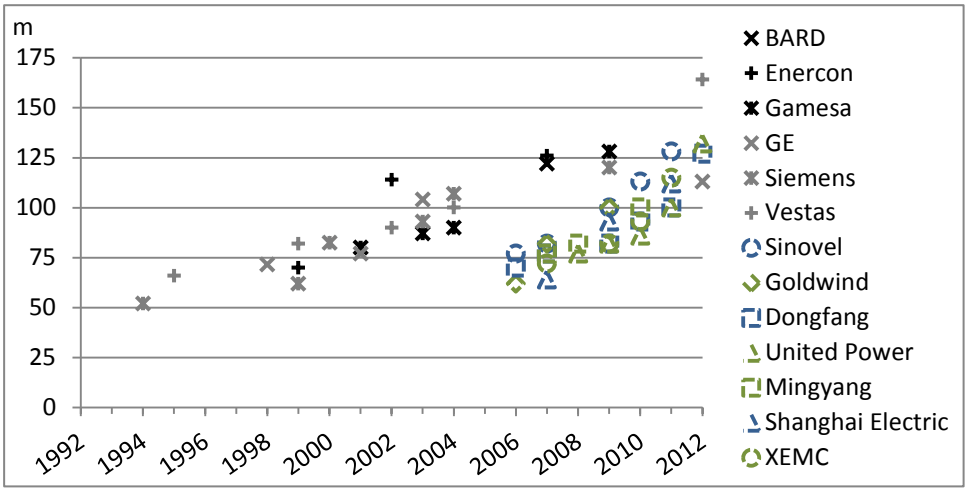


Note: Only includes series over 1MW in capacity.

The data include prototypes of commercial turbine series. I do not include here experimental or demonstration projects. Typically, commercial production of the series starts between one and two years after the installation of a prototype. If a series had more than one prototype installed the year of first installation was used.

A related feature of the evolution of wind turbine technology is blade length, as longer blades allow turbines to capture more of the wind's kinetic energy. Figure 2.6 shows the evolution of the maximum turbine rotor diameters of new models introduced by the same frontier and leading Chinese firms. The trend among frontier firms is of a progressive increase from rotor diameters in the 52m to 66m range in the mid 1990s to diameters in the 113m to 164m range in 2012. In contrast, the leading Chinese firms introduced models with maximum rotor diameters ranging from 62m to 77m in 2006. However, by 2012 new models had maximum rotor diameters in the range of 127m to132m.

Figure 2.6: Maximum rotor diameter of turbine models introduced by frontier and leading Chinese firms

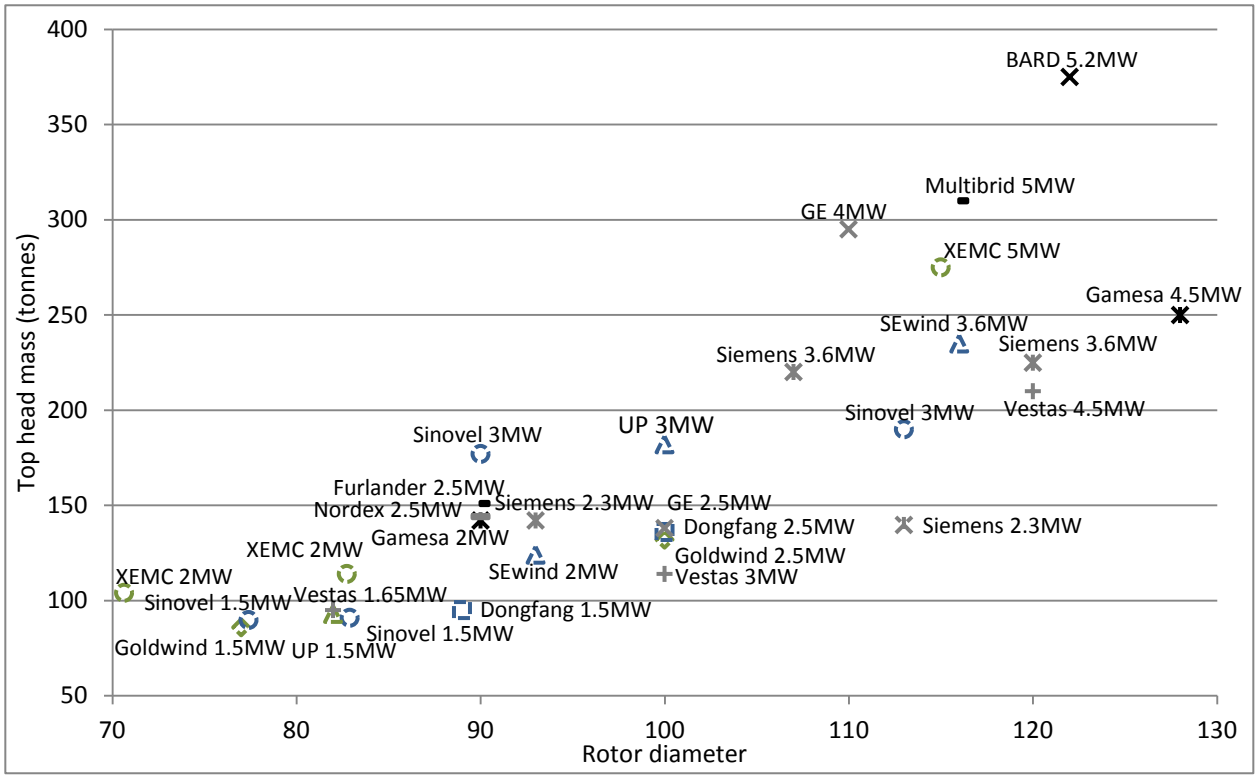


Note: the dates used are for the first installation of models.

Larger turbines are a challenge for onsite assembly of turbines as ever larger cranes are needed to raise the hub and rotor to the top of the towers.[48] Turbine top head mass (defined as the mass of rotor and hub) is therefore another key technological parameter as transport and turbine erection costs are linked to top head mass. Figure 2.7 highlights, however, that the top head mass of a sample of models manufactured by leading Chinese firms and commercially available by the end of 2011 were in the same range as that of models manufactured by frontier firms. Frontier firms are represented by solid black or grey crosses or dashes while Chinese firms are represented by dotted blue or green shapes.

[48] The hub sits at the top of the tower and contains various turbine components such as the nacelle, drive train, main shaft, bearings, among others. The main shaft connects the rotor to the hub.

Figure 2.7: Top-head mass of turbine models of frontier and leading Chinese firms

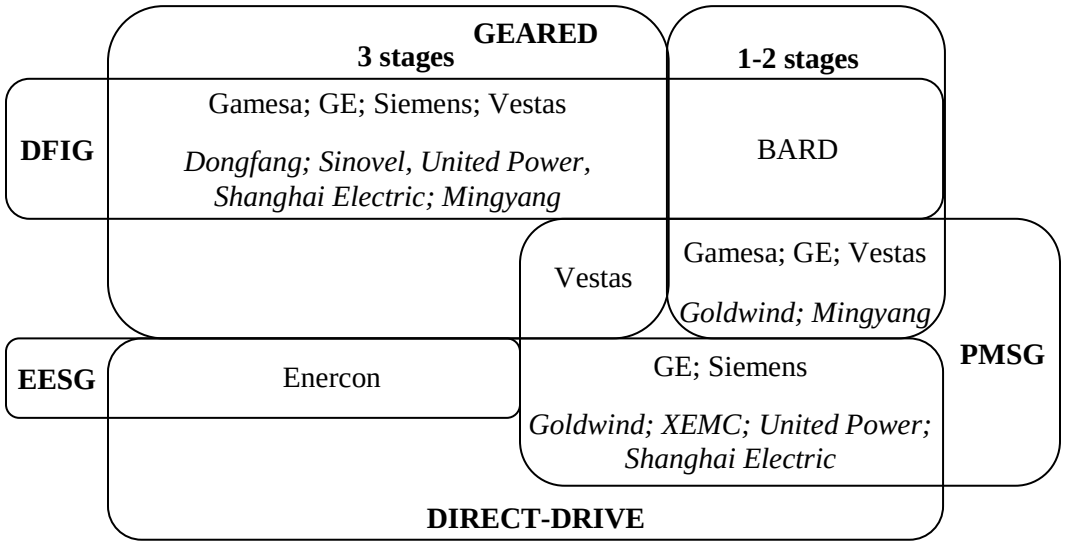


Note: Models commercially available in 2011.
UP: United Power; SEwind: Shanghai Electric.

Another important technological dimension to consider in the evolution of the wind turbine industry is the diversity of drive-train configurations. Trends over the past decades highlight the emergence of various drive-train configurations which co-exist in the marketplace, each characterized by specific advantages and limitations. One notable development was the emergence of direct-drive technology, where the rotor shaft is directly linked to the generator without the use of a gearbox. The choice of drive-train technology has widespread implications and is one of the fundamental choices made by manufacturers when designing new turbines. Different drive-trains have strong implications for control strategies, grid-friendliness, maintenance, overall turbine weight, which all affect the cost of electricity. The two components

of the drive-train which have been the object of most variety in design configurations are the gearbox and the generator type. Most turbines installed by 2010 globally used gearboxes but a number of manufacturers have adopted direct-drive configuration. One of the often stated advantages of direct-drive is that the absence of gearbox reduces maintenance costs. This is most valuable in remote locations and in particular for off-shore turbines. On the other hand, no gearbox means a slower rotating shaft which requires a large generator, thereby increasing the overall top-head mass. Figure 2.8 shows a matrix of the various combinations of gearboxes and generators adopted by the frontier and leading Chinese firms (in italics).

Figure 2.8: Drive-train configurations, frontier and leading Chinese manufacturers



Note: based on Fraunhofer IWES (2011)

Three types of generators are shown: the double-fed asynchronous induction generator (DFIG), the electrically excited synchronous generator (EESG), and the permanent magnet synchronous generator (PMSG). The three more common configurations adopted by both frontier and Chinese firms are DFIG with three-stage gearboxes; Direct-drive PMSG; and finally a hybrid configuration where a PMSG generator is combined with a one- or two-stage gearbox. The

matrix highlights that both frontier and Chinese firms offer comparable levels of diversity of drive-train configurations, and are therefore likely to tackle similar technological challenges, notably related to the development of the relatively newer direct-drive PMSG and hybrid configurations.

2.1.2 Wind turbine performance

The performance of wind turbines can be assessed using data on operation and maintenance (O&M) as well as electricity generation. Useful O&M data includes data on service and repair costs, types of failures, mean time between failures, or turbine availability rates. However, such data are difficult to compile in a systematic fashion as plant operators or turbine manufacturers in both China and other markets are reluctant to share this information. This section therefore draws exclusively on electricity generation data as a means to assess and compare turbine performance.

The indicator used to assess the performance of wind turbines is the capacity factor, which is the ratio of the actual electrical output over the maximum electrical output if turbines were running at their rated capacity all the time. Wind resource availability as well as turbine power generation performance are therefore central to determining the capacity factor of wind turbines. In theory, turbine design is another important determinant of the capacity factor. A hypothetically large rotor combined with a small generator would achieve an artificially high capacity factor, though at the price of limited electricity output and a high cost of electricity. In practice, however, project developers aim to select the best turbine designs for the location of the wind farm so as to optimize output and minimize cost of electricity. The capacity factor is therefore not a design criterion but rather an outcome of this decision-making process and can serve as a useful indicator of performance. Capacity factors can be calculated at various levels of

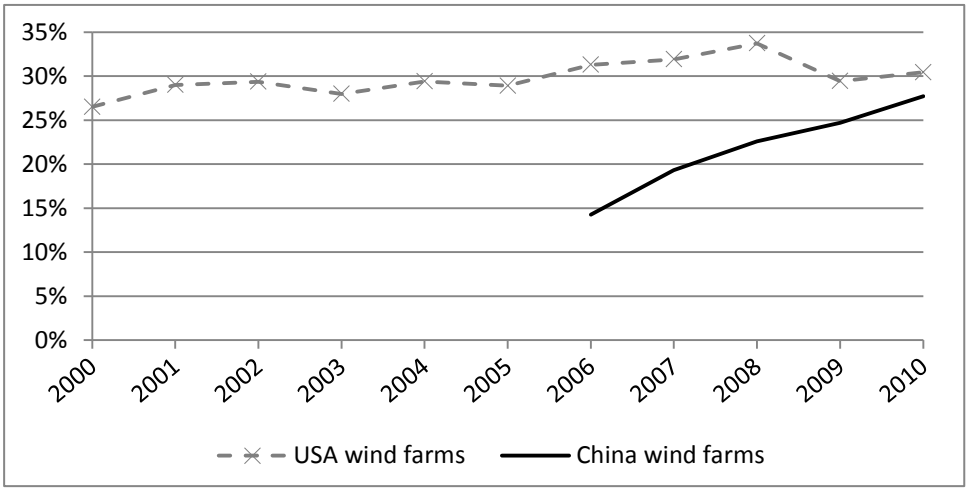
aggregation, from a single turbine, to a wind farm, and country. However, electrical output is typically monitored at the level of the wind farm and this is therefore the main unit of analysis adopted here.

Using capacity factors to assess how well turbines manufactured by Chinese firms are performing compared to those manufactured by frontier firms is challenging because wind resources vary greatly depending on location and time. There are also a number of important data limitations. Output data are not widely available at the wind farm level for all countries and information about the types of turbines used in each wind farm is seldom publicly available. In addition, electrical output data are typically only available with a delay due to sometimes lengthy monitoring, verification, and reporting periods. Output trends associated with much of the sharp rise in the size of Chinese turbines discussed above could not be compiled at the time of writing. Similarly, reporting on wind power curtailment (i.e. when electricity produced by wind farms is not fed to the grid because of oversupply or grid stability concerns) varies from location to location and may therefore affect results.

While a direct comparison of country-level capacity factors is particularly challenging for reasons mentioned above, it is instructive to assess and compare the change in performance in different countries over time. Figure 2.9 shows the evolution of capacity factors from a sample of United States and Chinese wind farms from 2000 to 2010. The United States trend is based on data collected by Wiser and Bolinger (2011) from a sample of 338 wind power projects built from 1983 to 2009. These projects represented 31,986MW at the end of 2009, accounting for 91% of the total installed wind power capacity in the United States at the time. Average sample-wide capacity factors for the United States has gradual increased over time, from 27% in 2000

(for 12 projects installed through 1999 and representing 1,005MW in capacity) to a peak of nearly 34% in 2008 (for 256 projects installed through 2007 and representing 15,686MW in capacity), before dropping to approximately 30% in 2010 (for all 338 projects installed through 2009). The authors explain that the drop in average capacity factors between 2008 and 2009-10 may be explained by annual variations in wind resources, as 2008 was considered a year with relatively high winds in the United States.

Figure 2.9: Average cumulative United States and Chinese sample-wide capacity factors by year



Note: United States wind farm data from Wiser and Bolinger (2011). Chinese wind farm data was provided to the author by the Chinese Wind Energy Association.

For China it was impossible to distinguish between projects installed prior to 2006 to those installed during 2006. To avoid accounting for projects under construction in 2006, I calculated the 2006 average sample wide capacity factor by excluding projects with capacity factors below 5%.

The trend for China is based on data from a sample of 268 projects installed through 2009, which represented 57% of total wind power installed capacity in China at the end of 2009. The average sample-wide capacity factor figures for China have increased rapidly from 2006 to 2010,

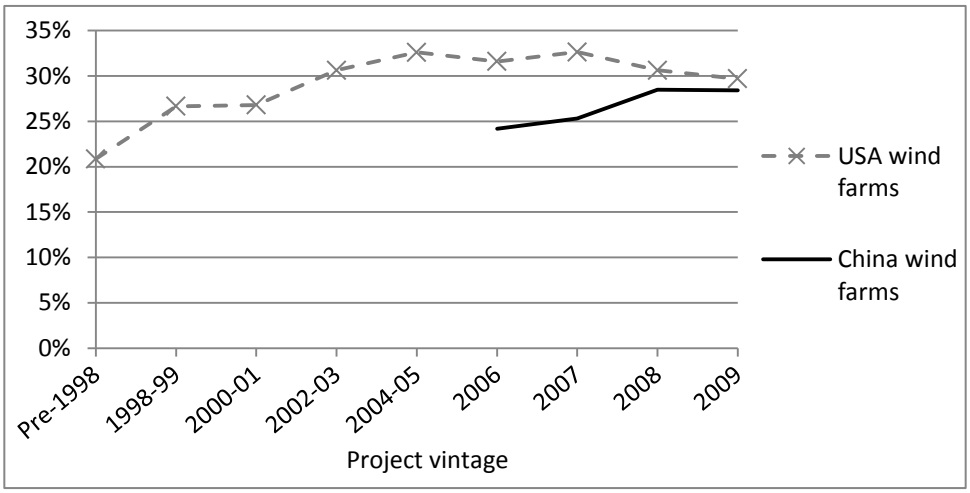
from 14% in 2006 (for 30 projects installed through 2006 representing 681MW in capacity) to 28% in 2010 (for all 268 projects installed through 2009).

Figure 2.10 shows capacity weighted average capacity factors in 2010 for wind farms of different vintages in both the United States and China. By focusing on capacity factors in a single year this approach avoids capturing yearly variations whether due to wind resources or curtailment. For the United States sample, the 2010 capacity weighted average capacity factors increased from 27% for projects installed in the 1998-2001 period (25 projects accounting for 1,553MW in capacity), to 33% for projects installed in the 2004-2007 period (84 projects accounting for 9,724MW in capacity), and then down to 30-31% for projects installed in 2008 and 2009 (163 projects accounting for 17,376MW in capacity). Wiser and Bolinger (2011) point to possible reasons for the drop in capacity factors for 2008-2009 turbine vintages, including increasingly limited project siting opportunities, a change in the policy incentives rewarding capacity rather than output,[49] and recent turbine reliability issues.

The 2010 capacity weighted average capacity factor for the Chinese sample of wind farms increased from 24% for projects installed in 2006 (29 projects representing 1426MW) to 28% for projects installed in the 2008-2009 period (2008 projects representing 11,997MW).

[49] See Section 2.1.3 for a discussion of the US government wind power deployment support policies.

Figure 2.10: Capacity-weighted average United States and Chinese 2010 capacity Factor by project vintage



Note: United States wind farm data from Wiser and Bolinger (2011). Chinese wind farm data provided to the author by the Chinese Wind Energy Association.

Project vintage corresponds to the period when projects were installed and connected to the grid.

For the Chinese sample the 2007 vintage data corresponds to projects installed between January and September 2007. 2008 vintage data corresponds to projects installed between October 2007 and December 2008.

The data for both the United States and Chinese samples shown in Figure 2.9 and 2.10 do not account for curtailment by grid operators. The trends therefore compound the performance of turbines and the ability of grid operators to accept wind power. Publicly available data on curtailment is sparse but some reports indicate that wind power not sold to the grid accounted for over 10% of total potential wind power generated in China, with much higher values for northern regions, where most wind power capacity is concentrated (Azur, 2011; CCBI, 2011). In contrast, Wiser and Bolinger (2011) provide curtailment information for six regions in the United States and shows that across these areas wind power curtailment reached a high of 10.4% of potential wind power generation in 2009 before dropping to 5.1% in 2010. The trend is primarily driven

by curtailment in the Electric Reliability Council of Texas (ERCOT) region, where the bulk of United States capacity is installed. Curtailment in ERCOT reached 17.7% of potential wind power generation in 2009 before dropping to 7.7% in 2010.

Curtailment issues further complicate any attempt to compare capacity factor trends at the national level. Nevertheless two points stand out from the above discussion of United States and Chinese wind farm samples. The first is that Chinese wind farms seem to have reached capacity factor levels in the same range as those found in the United States and Europe. As an indication, country level capacity factors for the United States, German, and Spain over 2009 and 2010 were estimated to be respectively approximately 28%, 17%, and 24% (WindStats, 2011). At the national level Azure (2011) reports a capacity factor averaging approximately 24% for China over the 2009-2010 period. The second point is that despite starting at very low levels, the overall rate of increase in capacity factors found from the sample of Chinese wind farms is significantly higher than that of the United States sample, reflecting sustained improvement in the performance of Chinese wind farms.

One way to more directly compare the performance of turbines manufactured by frontier and leading Chinese firms is to consider output by wind farms installed in China which use turbines from different manufacturers. Here a small sample of 47 wind farms was constructed based on data from the UNFCCC Clean Development Mechanism (CDM) project database.[50] The sample consists of projects which use turbines exclusively from either leading foreign or Chinese

[50] The UNFCCC CDM database can be accessed at http://cdm.unfccc.int/. In addition, I used data compiled by the Institute for Global Strategies in its IGES CDM Databases accessible at http://www.iges.or.jp/en/cdm/index.html

manufacturers.[51] Only projects for which data had been monitored and reported to the CDM for all of 2010 were included.[52] Finally, only projects using turbines over 1MW were considered (all projects in the sample use 1.5MW turbines except for nine projects, three of which use 1.25MW turbines and six of which use 2MW turbines).

Of the 47 wind farms in the sample 13 used turbines manufactured exclusively by leading foreign companies (primarily Vestas and GE) while the remaining wind farms used turbines manufactured exclusively by leading Chinese manufacturers (primarily Sinovel, Goldwind, and Dongfang). The capacity weighted average 2010 capacity factor for projects using turbines manufactured by foreign firms was 26% while that of projects using turbines manufactured by Chinese manufacturers was 24%.

To limit the effects of capturing different wind resources as well as different grid integration regimes, and therefore different curtailments rates, I cluster and compare the performance of a number of projects in the sample which are in relatively close proximity to one another and connected to the same regional grid (results are shown in table 2.1). The first cluster consists of six wind farms built in a region straddling North West Hebei Province and Inner Mongolia Autonomous Region. Half of the projects use leading foreign turbines and half use turbines manufactured by leading Chinese manufacturers. Four of the six projects are within a 15-mile radius from each other while the other two are respectively 54 and 83 miles away. The capacity

[51] Projects which use a mix of turbines were not included.

[52] For seven projects in the sample, electricity production data was not available for all of 2010. In such cases, a full year period starting late 2009 or beginning 2010 was used and therefore did not correspond exactly to 2010.

weighted average 2010 capacity factor of projects using Chinese turbine manufacturers was 30% while that of projects using foreign manufacturers was 25%.

Table 2.1: Capacity factor of wind farms by region and manufacturer type

Hebei Province / Inner Mongolia Autonomous Region Cluster	Foreign turbine manufacturers	Project # 1	29%
		Project # 2	27%
		Project # 3	21%
		Capacity weighted average	25%
	Chinese turbine manufacturers	Project # 4	28%
		Project # 5	26%
		Project # 6	35%
		Capacity weighted average	30%
Shandong Province Cluster	Foreign turbine manufacturers	Project # 1	24%
		Capacity weighted average	24%
	Chinese turbine manufacturers	Project # 2	24%
		Project # 3	23%
		Capacity weighted average	23%
Jiangsu province Cluster	Foreign turbine manufacturers	Project # 1	25%
		Project # 2	27%
		Capacity weighted average	26%
	Chinese turbine manufacturers	Project # 3	20%
		Project # 4	27%
		Capacity weighted average	22%
Inner Mongolia Autonomous Region Cluster	Foreign turbine manufacturers	Project # 1	24%
		Project # 2	23%
		Project # 3	15%
		Capacity weighted average	21%
	Chinese turbine manufacturers	Project # 4	26%
		Project # 5	25%
		Project # 6	18%
		Capacity weighted average	23%

The second cluster consists of three projects on the north western coast of Shangdong province. Two of these use turbines manufactured by Chinese manufacturers while the third uses turbines from a leading foreign manufacturer. The shortest and longest distances between projects in this cluster are 50 and 150 miles. The capacity weighted average 2010 capacity factor of the projects using Chinese turbine manufacturers was 23% while that of the project using a foreign manufacturer was 24%.

The third cluster consists of four projects located in Jiangsu province. Two use foreign turbine manufacturers while the other two use leading Chinese turbine manufacturers. Three projects in this cluster are within a 20 mile radius while the fourth is 70 miles away. The capacity weighted average 2010 capacity factor of projects using foreign manufacturers was 26% while that of projects using Chinese manufacturers was 22%.

The fourth cluster of projects consists of six projects in Inner Mongolia Autonomous Region. Three of these use foreign turbine manufacturers and three use leading Chinese turbine manufacturers. Four projects are within a 21 mile radius, while two others (only four mile apart from each other) are approximately 70 miles away. The capacity weighted 2010 capacity factor of the projects using foreign manufacturers was 21% while that of projects using Chinese manufacturers was 23%.

Though based on a small sample of Chinese wind farms, the above results do not show conclusively any significant difference between the performances of wind farms using Chinese turbine manufacturers and those using foreign manufacturers.

2.1.3 Summary

Technology indicators of turbine rated capacity and blade length show a convergence of trends, with Chinese firms progressively introducing new models in the same range of sizes as firms at the frontier. Turbine top head mass manufactured by Chinese firms also appears to be in the same range as turbines manufactured by frontier firms. In addition, the diversity of drive-train configurations found among frontier firms is also apparent among Chinese firms.

Comparisons of turbine performance are difficult due to limited data available and as a result, I was only able to compare capacity factors. Another limitation was that sufficient production data was not yet available at the time of writing to capture much of the recent rise in turbine size mentioned above. Nevertheless, data compiled on capacity factors for a sample of wind farms in China shows that the trend is rapidly increasing. In contrast, capacity factors of a sample of United States wind farms have evolved more gradually. By 2010 capacity factors in China were in the same range as those found in leading markets. Furthermore, data from a small sample of Chinese wind farms using either turbines manufactured by Chinese firms or frontier firms also suggests no significant differences in capacity factors. In sum, wind power technology indicators show that Chinese firms are indeed catching up with the wind power frontier.

2.2 TECHNOLOGICAL CAPABILITIES OF CHINESE WIND TURBINE MANUFACTURERS

2.2.1 Assessing firm technological capabilities associated with product technology

As indicated previously, technological catch-up implies that converging trends of technological indicators are combined with rising firm technological capabilities. This section therefore focuses on the second part of the chapter's analysis of technological catch-up and considers the technological capabilities of Chinese wind turbine manufacturing firms.

Firm technological capabilities refer to the ability of firms to manage technological development. Bell and Pavitt (1995) provide a general framework, discussed in Chapter 1, to help understand different levels of such capabilities. They break down firm technological capabilities along three types of activities: investment, production, and supporting activities (see table 1.2). In each case they distinguish between basic, intermediate, and advanced levels, with the latter being akin to capabilities of firms at the frontier. In this section I draw on Bell and Pavitt's framework to guide the assessment of technological capabilities of some of China's leading wind turbine manufacturers.

However, rather than consider capabilities of firms along every types of activity identified by Bell and Pavitt, I focus on only the subset of activities linked to product technology. Indeed as shown in table 2.2, Bell and Pavitt's framework can be reorganized to distinguish between capabilities associated with the firm's product technology and those associated with its manufacturing process technology, with in each case separate investment, production, and supporting activities.

Table 2.2: Firm level-technological capabilities by type of technology

	Product technology			Manufacturing process technology		
	Investment	**Production**	**Supporting**	**Investment**	**Production**	**Supporting**
Basic	Active monitoring and control of feasibility studies, technology choice/ sourcing, and project scheduling.	Minor adaptation to market needs, and incremental improvements to product quality.	Searching and absorbing new information from suppliers, customers, and local institutions.	Feasibility studies. Outline planning. Standard equipment procurement. Simple ancillaries engineering.	Commissioning and debugging. Improved layout, scheduling, and maintenance. Minor adaptation.	Copying new types of plants and machinery. Simple adaptation of existing designs and specifications.
Intermediate	Search, evaluation and selection of technology/ sources. Tenders/ negotiations. Overall project management.	Licensing new product technology and/or reverse engineering. Incremental new product design.	Technology transfer to suppliers and customers to raise efficiency, quality, and local sourcing.	Detailed engineering. Plant procurement. Environment assessment. Project scheduling and management. Commissioning. Training/ recruitment.	Process improvement. Licensing new technology. Introducing organizational changes.	Incrementally innovative reverse engineering and original design of plant and machinery.
Advanced	Developing new production systems and components.	Product innovation and related R&D	Collaboration in technology development	Basic process design and related R&D	Process innovation and related R&D. Radical innovation and organization.	R&D for specifications and designs of new plant and machinery.

Note: Based on Bell and Pavitt (1995).

Product technology (left pane of table 2.2) refers to the technological content of the products manufactured by the firm. In the case of wind turbine manufacturers, the technological content of wind turbines consists primarily of the turbine designs and blueprints and the turbine components. Investment activities (first column, table 2.2) refer to the decision-making process related to the choice of product technology and sourcing strategy. Production activities (second

column) consist of the means by which the product technology are produced or acquired by the firm. Supporting activities (third column) consist of the use of linkages with other entities such as the customers, component suppliers, and research institutions, which the firm uses to support its investment and production activities.

Manufacturing process technology (right pane of table 2.2) refers to the technological content associated with the manufacturing process. In the scope of turbine manufacturers, this consists of the plants where turbines are assembled, the machinery used to manufacture the various turbine components, as well as the supporting process organization put in place by the firm. Investment activities under this category (fourth column, table 2.2) consist of the decision-making process related to the choice of manufacturing process technologies. Production activities (fifth column) consist of the means by which manufacturing process technologies are expanded and improved. Finally, the supporting activities (sixth column) focus on how new manufacturing process technologies are obtained.

There are clearly important feedbacks involved in the technology development process between product technology and manufacturing process technology. Nevertheless, I focus here specifically on the capabilities of Chinese wind turbine manufacturers associated with their product technology, i.e. wind turbines (left pane of table 2.2). The reason is that the research question put forth in Section 1.1.4 focuses on the features of climate friendly energy technologies which are distinct from other energy technologies. Product technology is where such features lie and is therefore the natural focus of enquiry in the scope of this research. In contrast, capabilities associated with manufacturing process technology are common to industrial goods manufacturing activities in general, and are therefore secondary to this research.

Identifying a firm's capabilities associated with its product technology requires qualitative information on its organization and on some of its activities. In order to obtain this information, interviews were conducted between May and October 2011 with one or more high level officials from six leading Chinese wind turbine manufacturing firms: Sinovel, Goldwind, Dongfang, United Power, Shanghai Electric (SEwind), and XEMC Wind Power Company (XEMC). These firms represented over 70% of the Chinese turbine manufacturing market in 2010 (see table 2.3). The officials interviewed in each case had deep knowledge of their respective company's product technology history and strategy as well as a very strong understanding of the Chinese and international wind turbine market.[53]

For each firm, the interviews consisted of five parts. The first part focused on details of the turbine series and models manufactured and planned and how these had evolved over time. The second part focused on the means by which firms obtained turbine designs and blueprints. The third part focused on the supply and manufacturing of the main turbine components. The fourth part focused on the firm's R&D activities, while the fifth focused on interactions with government and the role of regulations.[54] Interviews were semi-structured: a pre-determined set of questions for each part were identified based on the firm capabilities framework outlined in table 2.2, yet ample room was left in each case for follow-up questions to allow for thorough discussions of important issues.

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[53] In each firm, the interviewees had different responsibilities (position titles included chief engineers, directors of R&D, and heads of strategy).

[54] Findings from the fifth part of the interviews are discussed in Chapter 4.

Below I first discuss in some details interview findings concerning turbine designs and blueprints, turbine components, and R&D activities. I then draw from this to assess using table 2.2 the evolution of technological capabilities of Chinese wind turbine manufacturers. First, however, it is useful to put into perspective the evolution of the role of Chinese turbine manufacturers firms in the Chinese market, and to briefly describe the industrial roots of the six firms which took part in this study.

Table 2.3: Main wind turbine manufacturers in China and firms taking part in study

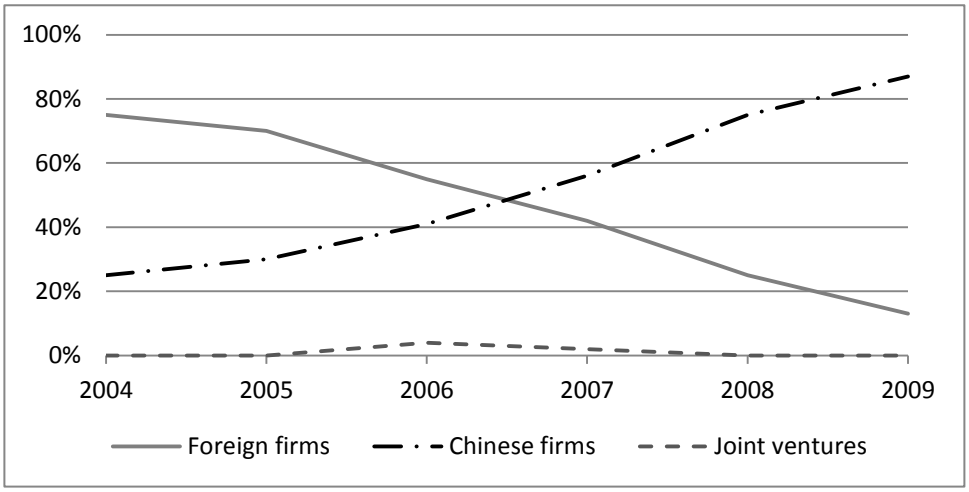
	2009 installed capacity in China		**2010 installed capacity in China**	
	%	MW	%	MW
China total:	100	13,750	100	18,928
Main Chinese companies included in the study				
Sinovel	25.12	3454	23.1	4372
Goldwind	19.51	2683	19.6	3710
Dongfang	17.73	2438	13.8	2612
United Power	5.5	756	8.6	1628
Sewind (Shanghai Electric)	2.07	285	3.1	587
XEMC	3.25	447	2.7	511
subtotal:	73.18	10062	70.9	13420
Main Chinese companies not included in the study				
Mingyang	4.06	558	5.5	1041
CCWE (Huachuang)	1.17	161	2.6	492
subtotal:	5.23	719	8.1	1533
Main foreign companies (not included in the study)				
Vestas	4.2	578	4.5	852
Gamesa	2.9	399	3.1	587
subtotal:	7.1	976	7.6	1439

Source: BTM (2011); BTM (2010).

2.2.2 Industrial actors of China's emerging wind power market

As highlighted in figure 2.1 the Chinese wind power market grew at a rapid rate from very low levels in 2004 to becoming the largest market in the world in terms of installed capacity by 2010. At the same time, the type of turbine manufacturer involved in the Chinese market changed radically. Figure 2.11 shows the shares of annual wind power installed capacity in China by type of firm. While initially dominated by foreign frontier firms, such as Vestas and Gamesa, the share of Chinese firms has progressively risen, accounting for the lion's share of the market by 2009.

Figure 2.11: Share of newly installed capacity by type of turbine manufacturer



Source: (Li et al. 2010)

Of the six Chinese manufacturers considered in the scope of this study, Goldwind is the only one that was not formed by an existing large-scale industrial firm. Goldwind was the second largest Chinese turbine manufacturer in 2010 and ranked fourth in the world in terms of installed

capacity.[55] Formed by Xinjiang Wind Energy Company in 2001, it has by far the longest history among Chinese manufacturers. The parent organization, Xinjiang Wind Energy Research Institute has been involved in the development of wind power in China since 1986, notably through support by a variety of foreign development organizations (Walz, 2010).

Sinovel was the largest Chinese turbine manufacturer in 2010 and ranked second in the world behind Vestas in terms of installed capacity. Sinovel was founded in 2004 as a spin-off of Dalian Heavy Industry, which is one of the main manufacturers of cranes and shipyard equipment in China, and also manufactures a variety of heavy duty equipment such as metallurgical machinery and tunnel boring machinery. Senior management staff of Sinovel came from the design institute of Dalian Heavy Industry. Dalian Heavy Industry remained one of the main shareholders of Sinovel.[56]

Dongfang was the third largest Chinese turbine manufacturer in 2010 and ranked seventh in the world. It was established in 2004 by Dongfang Electric Corporation, a state-owned enterprise and one of the world's largest manufacturers of power generation equipment. Dongfang Electric Corporation is involved in the manufacture of equipment in a broad variety of industries including power generation, electricity transmission and distribution, railways, water treatment, and heavy duty machinery.

United Power was established in 2007 by China Guodian Corporation, also a state-owned enterprise. Guodian is one of the five largest power producers in China, and is involved in the

[55] Firm ranking data used in this section comes from BTM (2011).
[56] Neither Goldwind or Sinovel are state-owned or state-controlled companies.

investment, construction and operation of power plants. One of Guodian's other subsidiaries, China Longyuan Power Group, was the leading wind farm operator in China and ranked third in the world in 2010 in terms of cumulative wind power installed capacity under management. United Power was the fourth largest turbine manufacturer and ranked 10th in the world in 2010.

In 2010, SEwind was the sixth largest Chinese turbine manufacturer and the 14th in the world. It was created in 2006 by Shanghai Electric, a state-controlled enterprise and another major power equipment manufacturer in China, also involved in a variety of manufacturing industries such as trains and other railway equipment, electrical machinery, and machine tools.

Finally, XEMC Windpower Company was ranked seventh in China and 15th in the world in terms of accumulated installed capacity in 2010. XEMC is a subsidiary of Xiangtan Electric Manufacturing Corporation, a state-owned enterprise which specializes in the manufacturing of electric equipment ranging from industrial motors and generators to elevators, as well as heavy trucks, rail equipment, ship propulsion systems, among others.

2.2.3 Turbine designs and blueprints

Designs and blueprints constitute the technological anatomy of the wind turbine. They codify the technological choices which make up its unique layout, and embody a broad spectrum of engineering calculations pertaining to a variety of fields ranging from fluid mechanics, material sciences, mechanical engineering, electrical engineering, and acoustics, among others. Designs and blueprints are therefore at the heart of wind power technology. In this section, I discuss how Chinese wind turbine manufacturers obtained and developed the designs and blueprints for the various turbine series and models produced since entering the market.

2.2.3.1 Licensing and joint-venture

Chinese firms wanting to enter the wind turbine manufacturing market lacked experience in turbine design and turned to foreign companies for the transfer of technologies. The first wave of such transfers was in the form of licensing agreements, which allowed Chinese firms to manufacture turbines in exchange of the payment of royalties. Goldwind, considered the pioneer of Chinese wind turbine manufacturers, entered the Chinese market through license agreements with Jacobs, a German firm.[57] The first such agreement, in 1996, concerned a 600KW turbine, while the second, in 2003, allowed Goldwind to manufacture a 750KW machine. Both of these machines used gearboxes and stall power regulation technology, then widespread in the industry.

Dongfang entered the market with a 1.5MW turbine based on a licensing agreement signed in 2004 with RE Power, of Germany, which had merged a few years earlier with Jacobs, the original licensor of Goldwind. The 1.5MW machine which Dongfang started producing in 2005 is a gearbox, variable-pitch, variable-speed, double-fed induction generator (DFIG) turbine; the work horse of the wind turbine industry. Sinovel entered the market the following year with a similar model which it started producing in 2006. It received the technology through a license agreement with Furlander, also from Germany. SEwind entered the market with a 1.25MW DFIG turbine, obtained through a license agreement with DeWind, from Holland. It too started production in 2006.

[57] By 2001 Jacobs had been acquired by RE Power, another German company, to form RE Power Systems AG. The licensing of the 750KW model is therefore most often attributed to RE Power though the core technology was from Jacobs.

XEMC adopted a slightly different route. It started a joint-venture with Harakosan of Japan, which had previously acquired a Dutch company called Zephyros, which had recently gone bankrupt. Zephyros was among the small group of firms which had developed direct-drive permanent magnet (DDPM) technology. Through this joint venture, in 2007 XEMC started manufacturing a 2MW direct-drive turbine based on Zephyros technology.

Interviewees from all firms underscored that following initial installation in China, many turbines did not perform as expected and required significant maintenance. Interviewees noted that in retrospect, these initial models were not very well suited for Chinese conditions, for example with respect to temperature variations or dust levels in the air. Soon after their initial deployment Chinese manufacturers started making small modifications to the turbine designs in order to better adapt them to the specificity of the Chinese environment. At the same time demand for wind power in China was growing rapidly and manufacturers responded by making further changes, offering models specifically suited to the diverse conditions found across the various wind rich regions of China. Aside from progressively introducing models that were able to accommodate different wind conditions through different blade lengths and tower heights, manufacturers offered models specifically tailored to the cold climates of the northern regions, where much of the initial growth in demand for wind turbines was concentrated, to high altitudes, to the desert condition of north-western regions, to different grid requirements, among others. These modifications were made by the Chinese manufacturers, sometimes in collaboration with specialized firms, but for the most part independently from the original European licensors.

For most firms, the turbine series which stemmed from these initial licensing agreements became core product lines and by 2011, Chinese manufacturers offered a broad variety of models to suit all possible market conditions. Sinovel installed in China over 6,600 turbines in its 1.5MW series between 2006 and 2010, bringing the firm to the forefront of global rankings based on installed capacity. Dongfang sold close to 4,000 units in its 1.5MW series, while SEwind and XEMC each installed approximately 550 units in their respective 1.25MW and 2MW series.

2.2.3.2 Joint-development

Following the first wave of licensing based technology transfers, Chinese firms began to cooperate directly with European companies to jointly design and develop new turbine models. Joint-development agreements provided a more flexible framework to tailor the transfer of technology from European firms to the specific needs of Chinese firms, as well as a more formalized way for Chinese engineers to get training and exposure to turbine design and development.[58] In addition, this allowed Chinese firms to have at least joint ownership of the associated intellectual property, if not sole ownership. Rather than pay royalties on turbines produced as in the case of licensing agreements, through joint-development agreements Chinese firms paid their foreign counterpart a fee for the latter's assistance in the 'joint-development' process.

[58] Training and technical assistance was also provided in the scope of licensing agreements. Furhlander, for example, provided technical assistance, quality control, and training to Sinovel as it installed the first licensed turbines in China. However in general it appears to have been more limited than in the scope of joint-development agreements.

One firm that made extensive use of joint-development agreements is United Power. It entered the Chinese wind turbine manufacturing market in 2007 through an agreement with Aerodyn, a German company, through which it obtained the designs and blueprints of a 1.5MW DFIG turbine. Aerodyn did the bulk of the design work and the agreement served as a vehicle for United Power engineers to get training from their German counterparts. Approximately 10 engineers went on several trips to Germany to get training and worked directly with Aerodyne staff on the turbine design. United Power also received turbine design software in the process.

Like in other technology transfers mentioned above, however, the turbine model United Power initially received from Aerodyn was not well suited to the specificities of Chinese conditions. United Power started introducing its own modifications to the initial turbine design, which aimed to better accommodate the turbines to the Chinese environment, and led to the same process of product diversification discussed above. But the firm also engaged in modifications targeting more central features of the design, for example aimed at achieving some weight reductions or improving control strategies. The 1.5MW series became the firm's main product line, with close to 1,600 units installed in China by the end of 2010.

Soon after the completion of this first agreement, United Power entered into another joint-development agreement, with Garrard Hassan, an international engineering firm specialized in renewable energy and headquartered in England. The focus of this agreement was to develop a 3MW DFIG turbine for both on-shore and off-shore wind farms. Once again engineers from each company were sent to work with their counterparts in England or China, and United Power engineers received training as well as exposure to new design software. But at the core was the transfer of the designs of a new, larger model, and this time United Power's contribution to the

design process was more significant. Garrard Hassan provided the basic turbine designs as well as technical assistance while United Power made most of the detailed designs. A prototype of this 3MW DFIG turbine was erected for testing in China in 2011.

Subsequently, United Power engaged in a third joint-development agreement with a Scottish firm specialized in direct-drive technology.[59] The purpose of the cooperative agreement was to develop of a 3MW DDPM turbine. Though the Scottish partner was responsible for the bulk of the designs pertaining to the generator, the collaboration was more balanced with respect to the rest of the turbine.[60] By the end of 2011 detailed designs of the turbine were completed and United Power was preparing to start manufacturing.

Companies which had previously entered the market through licensing agreements also embraced this new approach to technology transfer. In 2005 Goldwind signed a joint-development agreement with a German company called Vensys, another pioneering company in direct-drive technology, with roots in academia. Though by then it was already licensing direct-drive turbines to other companies in Europe, Vensys had no manufacturing experience. Goldwind and Vensys collaborated on the design of a 1.2MW direct-drive permanent magnet turbine and produced a prototype in 2006. Vensys did most of the design work, particularly concerning the drive train, generator, and rotor, while Goldwind took more responsibility for the control system. Following the erection of the prototype, Goldwind and Vensys increased the machine's capacity from 1.2MW to a 1.5MW and Goldwind started mass production in 2007.

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[59] The name of the firm was not provided at the time of the interview.

[60] Due to much larger generator size and the absence of gearbox the layout and load distribution in a direct-drive turbine are very different from DFIG turbines.

Goldwind offered a variety of models, with different rotor diameters, various tower heights, and the technical variety to accommodate the specific conditions of the different regions (cold climate, desert, high altitude, etc). By 2010 the 1.5MW direct-drive series had become Goldwind's main product line, with over 3,900 units installed.[61]

In 2008 Sinovel entered a joint-development agreement with Windtech, an Austrian firm which had recently been acquired by American Superconductor (AMSC), for the development of a 3MW DFIG model for both onshore and offshore projects. Sinovel had been accumulating experience with its 1.5MW DFIG series but had no exposure to off-shore designs. Windtech provided the basic designs for the new model as well as technical assistance while Sinovel engineers worked on the detailed design. The resulting 3MW DFIG turbine was an important landmark in the growing Chinese market as it was used in the Donghai Bridge wind farm, the first Chinese offshore demonstration project, which runs parallel to the Donghai Bridge, off the coast of Shanghai. By the end of 2010, all 34 turbines in the project had been tested and connected to the grid, and in total over 130 3MW turbines had been installed.

Similarly, SEwind collaborated with Aerodyn on the development of a 2MW DFIG turbine. Again, this involved both collaboration and training. Over 30 engineers from SEwind were involved in training with Aerodyn over a three to four months period. The 2MW SEwind turbines, for which the two companies share the associated intellectual property, became commercially available in 2009 and by the end of 2010 close to 390 units had been installed.

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[61] The 1.5MW series was Goldwind's main product in terms of installed capacity. In terms of cumulative units sold the 750KW gearbox series was still ahead.

Dongfang also entered in a joint-design agreement with Windtech for the development of a 3MW DFIG turbine and a 5.5MW DDPM turbine, expected to become commercially available from 2013.

2.2.3.3 Independent design

Following these joint development agreements, Chinese manufacturers continued to contract with foreign firms for the design of new turbines but with increasingly narrow scope. This was the case of SEwind, which for the most part independently developed its offshore 3.6MW DFIG turbine, a prototype of which was installed in 2010. The SEWind official interviewed noted that Aerodyn, which had previously collaborated with SEwind for the development of the 2MW DFIG turbine, was only responsible for about 20% of the work on the 3.6MW model, primarily to check the designs and make minor adjustments. Similarly Sinovel developed a 5MW model for the most part independently, turning to Windtech, its partner on the 3MW series, as well as other consulting firms, for assistance with the design of specific components, such as the control system. The first 5MW offshore turbine was erected in 2011, adjacent to the first Donghai wind farm. All intellectual property associated with these models is owned by SEwind and Sinovel respectively.

Typically, efforts by Chinese firms to independently design new models were at first based on relatively small up-scales of existing models. For example, following joint development work on its 1.5MW and 3MW DFIG turbines, United Power independently designed a 2MW DFIG turbine and started producing a small batch in 2010. Dongfang independently developed a 2MW model based on experience accumulated with its 1.5MW DFIG series, and installed a prototype in 2010. Aside from higher rated capacity these new models offered turbine manufacturers the

opportunity to make additional incremental changes to existing designs. For example following the successful launch of its 2MW series, XEMC independently designed a 2.5MW DDPM turbine, for which prototypes were erected in 2010. For this new model XEMC introduced a number of incremental changes to the 2MW design, for example concerning the ventilation system, the lubrication system, or nacelle design to better deal with typhoons. Similarly, Sinovel independently designed a 6MW DFIG turbine based on its 5MW model and first installed the new turbine also in 2011. For this model, Sinovel introduced a number of modifications, including the use of a full power converter to improve grid friendliness, a different gearbox layout from previous models, as well as a number of specific features to address offshore conditions, such as improved redundancy design to increase reliability.

Small steps towards independent designs were followed by more ambitious efforts. United Power independently developed a 6MW DFIG model, twice the rated capacity of its largest existing model, and produced a prototype in 2011. Goldwind, in an effort to mitigate financial risks related to spikes in the price of rare earth elements used in PMSG generators, drew on its experience with both gearboxes and DDPM technology to independently design a 3MW hybrid turbine, combining a gearbox and medium speed permanent magnet generator. This new design reduced the size of the generator, thereby reducing the overall weight and quantity of rare earth elements needed. A prototype was completed in 2009. Though originally intended as demonstration project, Goldwind indicated that it had started producing the hybrid turbine in small batches. Similarly SEwind is currently independently developing a 5MW DDPM offshore turbine, moving away from the DFIG technology it used in its previous models. While much of the design work on these turbines is done independently, most manufacturers indicated that they

still turn to foreign consultants for assistance with specific issues, for example with blade design, finite element analysis, drive train analysis, prototype testing, among others.

2.2.3.4 Acquisitions of foreign firm

Two Chinese manufacturers deepened bonds with European firms through acquisitions. Goldwind acquired a majority stake in Vensys in 2008. The two companies subsequently cooperated to develop a 2.5MW DDPM model for which a prototype was erected in 2009 followed by production in 2010. The general features of this turbine are similar to the 1.5MW model, but Goldwind and Vensys introduced a number of improvements to the design in order to optimize the structure and reduce turbine weight per unit capacity. They also completed the design of a scaled-up 3MW model which became commercially available in 2012. In addition, they designed a 6MW machine the first prototype of which is to be installed in 2013. One feature of the acquisition of Vensys by Goldwind is that Vensys continues to license its own turbine designs to firms outside of China under its own brand name.

In 2009 XEMC acquired Darwind, a Dutch wind turbine design firm. Darwind was another recipient of direct-drive turbine designs from Zephyros following the firm's bankruptcy, and had since been working on a 5MW direct-drive version (de Vries, 2011). Soon after the acquisition of Darwind, the new entity – XEMC-Darwind – completed the new 5MW turbine design and a first prototype was installed in Holland in 2011, while a second was being erected in China at the time of interview.

2.2.4 Wind turbine components

In this section I turn to some of the main components of wind turbines – the gearbox, the generator, the bearings, the control system, the converters, and the blades. In each case, I focus on the evolution of the Chinese supply chain and how Chinese turbine manufacturers have secured supplies and addressed product quality concerns given the rapid evolution of the market and the new turbine series being introduced.[62]

It is important to keep in mind, however, that these components are composed of many sub-components, which are themselves composed of further sub-components. While the main components may be designed and manufactured in China, the manufacturers of these components may still source some of the sub-components from abroad. For example, several turbine manufacturers indicated that certain important sub-components, such as hydraulic pumps or sensors, were imported because they were both cheaper and of higher quality than what could be found in China. Similarly, United Power purchased the epoxy resin used in the manufacture of its own turbine blades, discussed below, from Europe or the United States, as Chinese suppliers had little quality control and lacked adequate certification.[63]

2.2.4.1 Gearboxes

While wind turbines are a relatively new technology in China, Chinese firms have in fact extensive experience in manufacturing certain turbine components. The gearbox market was

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[62] Other main turbine components such as the tower, the nacelle, the framework, or the shaft, were not considered as they were identified by various interviewees as being of lesser economic and strategic importance.

[63] The issue of turbine and component certification is discussed in chapter 3.

notably dominated by Chinese firms with extensive experience in gearbox manufacturing accumulated in other industrial sectors such as shipbuilding. Often these are large state-owned heavy industry enterprises such as Nanjing High-speed and Accurate Gear Group, or Chongqing Gearbox Company, both of which have long been among the main manufacturers of wind turbine gearboxes in China (ERI, 2008).

Many Chinese turbine manufacturers purchased their turbine gearboxes exclusively from Chinese suppliers. In some cases gearbox manufacturers were associated with turbine manufacturers. For example, Dalian Heavy Industry, which founded Sinovel and was still one of its main shareholders, manufactured turbine gearboxes and was one of Sinovel's main suppliers.

Though Chinese gearbox manufacturers dominated the Chinese market, several firms indicated that they still worked with foreign gearbox suppliers, particularly for some of their newer models. Dongfang for example, purchased gearboxes for its existing 1.5MW models from Chinese firms, but also turned to foreign suppliers for its newer and larger models. Similarly, United Power turned to a German manufacturer for the gearboxes of its 6MW turbine. Among the turbine manufacturers interviewed, United Power is also the only one which had also started manufacturing some of its own gearboxes, though production was still small at the time of the interviews.

2.2.4.2 Generators

The Chinese wind turbine generator market was also dominated by Chinese, often state-owned, enterprises. Much like gearboxes, these companies were involved in the manufacturing of generators and motors for a broad variety of industries before the growth of wind power in

China. Generator manufacturers included large industrial groups such as Shanghai Electric, Dongfang, and Xiangtan Electric Manufacturing Corporation, also involved in wind turbine manufacturing. In such cases, however, components manufacturing was typically run as separate business entities from wind turbines. The component manufacturing businesses priced their products independently and often supplied a variety of turbine manufacturers. The main advantage of corporate linkages between turbine and component manufacturers was that they facilitated communication in the process of development of new models.

Dongfang and Shanghai Electric are only one of several suppliers of generators used by their wind turbine manufacturing businesses. In contrast, XEMC has relied entirely on its own supplies of direct-drive generators, the design of which were obtained through the joint venture with Harakosan. Similarly, Goldwind also designs its own generator for all its direct-drive models and assembles them in-house based on parts manufactured by sub-contractors. United power indicated that though it purchases generators from Chinese manufacturers it still purchases some generators from ABB, one of the leading multinational suppliers of electrical equipment, particularly for its larger models. In addition, the firm recently started manufacturing some generators in small batches.[64]

2.2.4.3 Bearings

Despite a number of large Chinese industrial bearings manufacturers, unlike for gearboxes or generators, foreign suppliers remained central to the supply chain for wind turbine bearings in

[64] United Power indicated that at the time of the interview their production of gearboxes and generators represents 10% to 20% of the firm's needs though they hoped to increase this share.

China. One reason is product reliability, as bearings are particularly costly to replace. This is particularly true of the main shaft bearings, located between the rotor and the gearbox and/or generator, which require dismantling of the drive-train to replace.

Turbine manufacturers explained that while there are several Chinese suppliers of main shaft bearings for the most established turbine models on the market, they still turned for a large part of their supplies to foreign suppliers, such as the SKF Group, Schaeffler Technologies, or Timken, despite being significantly more expensive than bearings sold by Chinese firms. However, several manufacturers indicated that Chinese bearings manufacturers, to which they were increasingly prepared to turn to, were progressively gaining market shares. When XEMC for example, started producing its 2MW turbines, it only used foreign suppliers of bearings. However, it progressively started working with Chinese bearing manufacturers, which at the time of interview supplied part of their bearings needs for these models. The official interviewed explained that a similar approach was likely to take place with their 5MW series. Similarly, Dongfang indicated that it used almost exclusively Chinese bearing manufacturers for its 1.5MW model though it purchased bearings from foreign suppliers of its larger models. Some Chinese bearings manufacturers were also associated with wind turbine manufacturers. This is notably the case of Shanghai Electric, which produced both main shaft bearings and pitch bearings, and is one of the suppliers of SEwind.

2.2.4.4 Power converters

The power converter is the interface between the wind turbine generator and the electricity grid. It notably enables a variable speed operation of the turbine – and therefore greater

extraction of energy from the wind – by maintaining voltage, frequency, and other variables of electricity production at standards compatible with electricity grid requirements.

Chinese turbine manufacturers have relied heavily on foreign suppliers of converters, most often with manufacturing bases in China, to ensure quality and product reliability. Some of the most important actors in this market are large multinational electrical equipment companies such as ABB, Emerson, and Siemens. Dongfang for example, cooperates extensively with Emerson for the supply of converters. United Power also has established a long-term collaboration with ABB to develop converters for its turbines. ABB was United Power's main supplier of converters accounting for approximately a third of its demand. Smaller foreign firms specialized in wind power technology are also active in the Chinese market, such as AMSC/Windtech and The Switch. Sinovel for example, had relied largely on the supply of converters from AMSC/Windtech.

But as with bearings, turbine manufacturers highlighted the growing role of some domestic manufacturers. Sinovel notably started developing and manufacturing its own converters and had a small production which it intended to expand in the future. SEwind indicated that while it had extensively used foreign suppliers, it also purchased some power converters from Chinese firms, including a Shanghai Electric subsidiary that manufactured converters for the wind power market. Similarly, another firm in the Guodian group, Longyuan Electric Company, started developing and manufacturing converters for 1.5MW turbines, becoming one of United Power's suppliers. The XEMC interviewee explained that it started manufacturing its 2MW models using converters exclusively manufactured by foreign companies but the firm had since worked with Chinese manufacturers to develop alternative suppliers. After having relied on foreign suppliers,

Goldwind explained that it had started manufacturing its own converters for all of its models but that it still purchased a share of its converters from foreign firms including The Switch.

2.2.4.5 Control systems

Compared to other components, control systems and blades, discussed below, are more unique to the wind turbine industry. The control system monitors various aspects of the turbine operation and automatically adjusts the turbine's running to optimize performance. Control systems therefore refer to a coordinated set of separate controls, and consist of a mix of software and hardware. Some of the key controls include pitch controls, which change the orientation of blades in response to changes in wind speeds, yaw control, which changes the orientation of the turbine as the direction of the wind changes, and converter controls, to optimize the quality of power delivered to the grid. The central control system also needs to communicate with the wind farm control system.

Given the complexity and importance of control systems, for the most part turbine manufacturers have relied on foreign suppliers of complete control systems such as Mita-Teknik, based in Denmark, AMSC/Windtech, and Simens. Sinovel for example has relied almost exclusively on AMSC/Windtech for the supply of control systems. Similarly Dongfang purchased all of its control systems from European suppliers.

However, given the central role of control systems in managing the performance of turbines, many turbine manufacturers indicated that they aimed to develop and produce their own control systems. The Sinovel official interviewed explained that the firm had started developing its own control systems in collaboration with Mita-Teknik. At the time of the interview, however, these

only represented a small fraction of the firm's needs. Similarly SEwind had started deploying control systems it had recently developed. The pitch-control was still being supplied by a specialized German firm but the interviewee explained that they were also working with Chinese firms on the development of this sub-component. United Power is another firm which started developing its own control systems. Similarly, Goldwind explained that it used its own control system in its turbines. XEMC obtained designs and software for the entire control system used in its 2MW direct-drive turbine through its joint venture agreement with Harakosan. This has allowed the firm to improve and up-scale the control system to suit its 2.5MW and 5MW models.

2.2.4.6 Blades

The sound design and manufacturing of blades is vital to capturing as much kinetic energy in the wind as possible. Though collaboration between component and turbine manufacturers was central to all the components discussed above, turbine manufacturers indicated that blades were an area where such collaborations were particularly important.

There are now many Chinese blade manufacturers but the majority collaborate with foreign firms through joint ventures or other contractual arrangements. Avic Huiteng, for example, was among China's three largest blade manufacturers in terms of capacity since the early 2000s, and was one of the largest independent blade manufacturers in the world. The company was created in 2001 as a joint-venture between a propeller factory and an aviation turbine company. It started manufacturing wind turbine blades in 2002 for 600KW turbines and 750KW turbines in the following year. From 2004 it manufactured blades for megawatt-scale machines. At the time of the interview the firm had a variety of blade models for 3MW machines and was developing blades for 6MW turbines. Avic Huiteng entered the wind turbine blade manufacturing sector

through license agreements with CTC, a Dutch composite material design firm, and subsequently cooperated with CTC on new blade designs through joint-development agreements before acquiring CTC in 2009.

Sinovel and SEwind indicated that they purchased all their blades from such Chinese suppliers. For its 2MW series XEMC's blade suppliers were also mostly Chinese. However, for larger models they also turned to LM Wind Power, from Denmark, which is the largest independent blade producer in the world and has a large manufacturing base in China. Goldwind also collaborated with both Chinese manufacturers and LM Wind Power. In addition it purchased two Chinese blade manufacturers in 2010. At the time of the interview, however, these accounted for a small percentage of the firm's supply of blades and integration of the acquired firms in the company's supply chain was still at an early stage.

Dongfang manufactured blades for its 1.5MW and 2MW models. The blade designs were obtained through collaboration with Aerodyn, which Dongfang contracted for the task. However, Dongfang indicated that it would turn to foreign suppliers for its 3 and 5MW models. United Power independently designed and manufactured some of its blades and produced sufficient numbers for all its 1.5MW models. It hoped to expand production to other models, and gradually sell blades to other manufacturers. The firm was also planning to manufacture the blades of its 6MW turbine.

2.2.4.7 Dynamics of components supply

The approach adopted by turbine manufacturers to secure supplies of the main turbine components discussed above varied greatly depending on the manufacturer, its industrial

linkages to other companies, and the nature of each component's market in China. Nevertheless some common dynamics can be identified and are summarized below.

When they first entered the market, Chinese turbine manufacturers turned extensively to foreign suppliers of components. Part of the reason was that supply chains in China were not yet sufficiently developed, but manufacturers also wanted to minimize product reliability risks of their first turbines.[65] However as the market for their initial turbine models grew and experience accumulated, turbine manufacturers increasingly turned to Chinese suppliers as a means to reduce production costs. This in turn required the creation of numerous collaborations between Chinese turbine and component manufacturers. Many turbine manufacturers highlighted that this process has led to a host of new challenges as numerous technical problems with components emerged.

As turbine manufacturers started developing new, larger models, they most turned again to foreign component suppliers for initial production. Once more it is only after an initial growth in the market for the new products that Chinese suppliers appear to have started entering the market to supply components for these larger models. One possible reason which emerged from the discussions with turbine manufacturers was that the rate of development of new turbine models had been higher than that of the Chinese supply chain. The United Power interviewee, for example, said that even though the gearbox market in China had many large and experienced

[65] Using foreign suppliers did not necessarily ensure product reliability. SEwind for example used a German supplier of blades for its first batch of 1.25MW turbines. Problems emerged rapidly with the blades and the company quickly turned to a Chinese supplier for further production.

Chinese suppliers, the firm still relied on a German gearbox manufacturer for the initial components of its latest 6MW model because the Chinese supply chain was not ready to deal with such larger models

There are signs, however, that the discrepancy between the pace of development of the component supply chain and new turbine models is shrinking. As an example the Sinovel interviewee explained that the firm initially turned solely to foreign suppliers to provide the main components of its 3MW turbines but in the case of the firms' latest models – the 5MW and 6MW turbines – the Chinese component suppliers were more involved in supply negotiations from the outset.

Yet another explanation may come from the unwillingness of component manufacturers to engage in technology development. Indeed, several turbine manufacturers noted that Chinese component manufacturers tended to be reluctant to collaborate on new larger turbine models as they preferred to extend production of existing components rather than invest in the development and manufacturing of new products with uncertain future markets. Lengthy negotiations between turbine and component manufacturers have notably been needed simply to agree on the nature, extent, and sharing of technology development costs. Chinese bearing manufacturers, for example, generally followed trends set by foreign suppliers. Several interviewees noted that Chinese bearings manufacturers were reluctant to get involved in the development of bearings for larger new models due to high development costs and market risks involved.

One implication is that this has created an impetus for turbine manufacturers to consider producing their own components as a means to accelerate turbine development efforts. This has notably been one of the main drivers of Sinovel's recent efforts to develop its own control

system and converters. Similarly, United Power explained that an important driver in the decision to develop their own component manufacturing capabilities, notably with respect to blades, gearboxes, and generators, was to avoid relying on an inadequate component supply chain, unable to engage in technology development efforts.

2.2.5 Research and development

The above discussions described how Chinese turbine manufacturers tackled obtaining turbine designs and blueprints and securing supplies of some of the main turbine components. Here, I adopt a different perspective and discuss a particular type of activity undertaken within the firm: research and development (R&D). R&D is often considered in the literature on technological development as an activity which characterizes firms at the technological frontier. Yet, as discussed in Chapter 1, the pursuit of R&D activities is also important below the frontier, and as illustrated in table 2.2, is central to activities of firms with advanced technological capabilities. Often the distinction between R&D at the frontier and below it comes from the relative importance of the research and the development components of R&D. At or close to the frontier, R&D will typically be characterized by a higher proportion of applied research while farther below the frontier development will play a more central role.

One difficulty in assessing R&D is that while many attempts have been made to clearly define what constitute R&D activities (e.g. OECD, 2002), in practice, it remains a loosely defined concept. Firms at or below the frontier may consider certain activities to fall under the category of R&D while others may not. For this reason this section is based on a part of the interviews with officials from Chinese turbine manufacturing firms in which they were asked about the organization, current activities, and recent achievements of their firm's R&D activities. R&D

was purposely not strictly defined so as to allow interviewees to discuss whatever activities their firm considers as R&D. In addition in order to alleviate any concerns about proprietary information, it was made clear to each interviewee at the onset that we expected them to only share information to a level of detail they felt comfortable with, and that we were more interested in broader trends than individual cases. For this reason the level of detail in what follows varies significantly and should only serve to assess trends in R&D activities. Before turning to the organization of R&D activities within firms and their interactions with research institutions, I first briefly provide some background information about R&D funding, location of R&D activities, and R&D staff and management.

2.2.5.1 Funding, location, staff and management

Turbine manufacturers were reluctant to share detailed figures on relating to their annual R&D funding. In some cases, such as Dongfang, the interviewee explained that this was due to the fact that the wind turbine manufacturing business was not a clearly distinct accounting unit within the rest of the company. Nevertheless, all pointed that R&D investments were between 3.5% and 5% of revenues, which was the legal minimum requirement for their industry.[66]

At Sinovel, most R&D activities had been undertaken in two office buildings in central Beijing – one of which being where the company was first established – as well as in its various manufacturing plants where components and full turbine test beds were located. However at the time of interview, Sinovel was completing a new R&D center in Jiangsu Province to consolidate and expand its R&D activities. The center consisted of a large building complex dedicated to

[66] See chapter 4 for a discussion of the Chinese government R&D policy.

wind turbine R&D, and included a complete turbine test bed of 15MW in capacity, making it the largest in the world. In addition, the firm was also considering establishing R&D centers outside of China to support their efforts to export turbines.

Goldwind's R&D activities were located in Beijing, in Urumqi, and Germany, where Vensys is headquartered.[67] In Beijing, Goldwind is responsible for the National Wind Power Engineering Technology Research Center of China, which is accredited by the government as a national key laboratory.

XEMC created an independent Wind Power Institute responsible for all turbine design and research activities in Shandong Province, where XEMC is located. In addition Darwind's team, based in Holland, complemented XEMC's R&D efforts. Separate from the wind turbine business, XEMC's generator business also undertakes R&D on wind turbine generators, and operates a back-to-back generator test bed used for testing XEMC's direct-drive turbine generators.

Dongfang's wind power R&D activities are concentrated in Deyang, Sichuan Province, where the firm is headquartered. Similarly SEwind's R&D facilities are all located outside Shanghai, where SEwind and Shanghai Electric are based.

United Power Technology's R&D activities are concentrated in Beijing. The firm is responsible for the national key laboratory on Wind Power Equipment and Control Technology

[67] Urumqi is the capital of Xinjiang Province in North-West China, where Goldwind was founded and headquartered before moving to Beijing.

and has also established an Institute of Wind Power Equipment. In addition, Guodian established a New Power Technology Academy, which has its own wind power institute. At the time of the interview staff from these three entities were located in the same location in Beijing and worked as a single R&D group.

More than 600 people were reported to work on R&D at Sinovel. Most had master's degrees in engineering with a few PhDs. The senior management staff for R&D came from the core group of people formerly from the Design Institute of Dalian Heavy Industry which started Sinovel.

Goldwind reported having 500 engineers working on R&D in China and another 100 in Germany. In China 7-8% hold PhDs, 30% master's degrees and the rest bachelor's degrees. Senior R&D staff consisted of long standing employees, university professors (the chief engineer at the time of the interview was a former professor at Xingjian Agricultural University), people with advanced degrees coming from other companies, or people with experience having worked for foreign companies.

Dongfang had an R&D staff of about 200 people, with the majority having master's degrees. For the most part these employees came straight out of university, with backgrounds in all strands of engineering. Training of new recruits was based on in-house training programs, as well as training programs with AMSC/Windtech, in the scope of their joint-development agreement, or through contracts with Garrard Hassan.

United Power had 80 people working in its R&D group at the time of the interview though the interviewee expected the group to be at least double that size by the end of 2012. United Power indicated that the staff working on R&D come from various branches of Guodian as well as other

Chinese wind turbine manufacturers. At the time of the interview 20% of the R&D group had bachelor's degree, 60% had masters, and 20% had PhDs. The senior staff was among those who took part in the training organized by Aerodyne and Garrard Hassan in the scope of the joint-development agreements discussed above.

SEwind indicated having approximately 130 engineers working on R&D, with the majority having bachelors or masters degrees, and only a few holding PhDs. XEMC had approximately 130 engineers working in its Wind Power Institute in China and another 60 at Darwind, in Holland. In addition XEMC's generator manufacturing branch had staff working on generator specific R&D. About 30% of the engineers in the institute had master's degrees, 5% PhDs, and the rest held bachelor's degrees. The majority joined from various branches of the XEMC group. In addition to receiving training upon joining the institute some were also sent to Darwind for further training.

2.2.5.2 Organization, priorities, and activities

The primary focus of Sinovel's R&D group was making existing turbine series more reliable. This consisted of making incremental improvements based the firm's experience and operational data obtained from existing turbines. A variety of projects fell in this category but one recent area highlighted by the Sinovel official (as well as by several other manufacturers) aimed to ensure that new electricity grid standards were met by both existing and new models. This involved introducing new technologies such as Low Voltage Ride Through and active/reactive power.

Another important area for Sinovel's R&D group is the development of new products. This included efforts to independently develop turbine control systems and converters, which, as mentioned previously, had recently been introduced to Sinovel's turbines. The interviewee also highlighted R&D work on larger capacity turbines beyond the firm's latest 6MW series. Sinovel was notably working on the design and development of a 10MW turbine and investigating different drive train configurations, such as using medium speed generators. The official also noted that a new direction for the firm was to offer services beyond turbine manufacturing and maintenance, such as the management of wind farms and the development of new meteorological tools, for example aimed at the micro-siting of turbines.

Goldwind's R&D staff was separated in three groups. The first focused on the overall design of turbines, the second worked on product and mechanical design, while the third worked on electronics and controls. In addition, a new entity, for which a new building was under construction at the time of the interview, would be focusing specifically on blades. The interviewee highlighted that blade design was a priority of the firm, notably in light of the recent acquisition of the two Chinese blade manufacturers. Another area of priority was enhancing component reliability. With respect to future models, the interviewee indicated that Goldwind was collaborating with Vensys on the feasibility of a 10MW model.

Dongfang's two main R&D focus areas were turbine designs and control systems. Concerning turbine design, the interviewee identified the independent design of the 2MW machine as one of their main achievements. Though they currently had no plans beyond the 3MW and 5MW models under development with AMSC, the official stated that Dongfang would likely continue to seek collaborations with foreign firms for the design of potential future models. With respect

to control systems the interviewee highlighted that their priority was to develop and implement their own control systems strategies.

United Power's R&D group was organized along three lines of work: load calculations, including overall turbine and blade designs, followed by drive train and generator, and finally control systems and strategies. As with other firms, a priority area was to improve the designs of existing products based on their growing experience, including work to enhance grid friendliness standards of their turbines. Another key area of the group was to finalize the various new models which United Power planed to commercialize (the 3MW DDPM and the 6MW DFIG). With respect to future models, United Power also indicated that it was undergoing the initial stage of research on a 12MW turbine based on a superconducting generator, a technology which no company anywhere in the world had yet adopted in a commercial wind turbine.

SEwind's R&D activities are organized around blade research, electronics, load calculations, systems design (e.g. lubrication system or cooling system), and mechanics (e.g. finite element analysis). Some of the R&D priorities highlighted were typhoon resilience, further development of SEwind's main control system, the development of a pitch control system, and the design of the permanent magnet generator which SEwind planned to use in its 5MW direct-drive machine. This came in addition to the monitoring of the 3.6MW model prototype, which had been operating for several month at the time of the interview. Some of the main recent achievements of SEwind's R&D group were the design and manufacture of increasingly long diameter blades, which they achieved in collaboration with their Chinese blade suppliers. Another important achievement was the development and implementation of their control systems. When asked about work on future models or alternative drive trains, the interviewees explained that they were

focusing on their 5MW product, and that for the time being they had no R&D projects on larger capacity models. One interviewee explained that beyond 5MW, turbine weight with existing drive-train configuration became a significant issue. He added that though alternative drive trains to the dominant DFIG or PPDM configurations existed, these were still too far from being commercially viable.

XEMC highlighted that the first priority of their R&D group was to keep improving the design and control strategy for their 2MW series based on operating data from wind farms in China. The second priority was the introduction of the 5MW model, for which a second prototype was being erected in China at the time of the interview. The interviewee notably highlighted efforts to improve nacelle and hub design to further reduce turbine top head mass, and work on improving control strategies. The group at Darwind, in Holland, took most responsibility for main turbine designs and verifications, while the institute staff in China was responsible for the detailed design process. As with other firms the XEMC official underscored recent work done to improve grid friendliness. With respect to larger models the interviewee noted that they had no further turbine development plans beyond their 5MW model, though he acknowledged the strong push in the Chinese market towards even bigger turbines.

2.2.5.3 Collaboration with universities and other research organizations

The Sinovel interviewee highlighted collaborations with various research institutions such as North China Electric Power University, the Electric Power Research Institute of the State Grid Company, and Tsinghua University. These collaborations in part aimed at longer-term technology development than the firm's own R&D work. For example, in the scope of its ambition to enter new segments of the wind power industry, Sinovel collaborated with the North

China Electric Power University on the development of tools to improve micro-siting of turbines in China. Nevertheless the interviewee noted that such collaborations were also used to address specific problems that their own research teams had not yet solved and to assist them in the development of new products. In addition, they served as a means to recruit future employees.

Goldwind highlighted a number of collaborations with universities, in particular South East University and Nanjing Aviation and Aeronautics University – both based in Nanjing – and Xinjiang University. Goldwind collaborated with the first on generator research, the second on blade research, and with the third on control systems. The primary objective of these collaborations was to give Goldwind some new ideas on the structure and design of each of these components.

The United Power interviewee mentioned recent collaboration projects with research groups at Tsinghua University and North China Electric Power University. He explained that through one such collaboration a research group at Tsinghua University ran calculations to improve the design of the generator of their 1.5MW turbine. The interviewee also highlighted that they expected university collaborations to play a prominent role in the scope of their new 12MW turbine project.

SEwind highlighted a range of research collaborations with universities as well as research institutions, such as the Shanghai Glass Fiber institute, with which it collaborated on blade materials and designs. Collaborations with universities have included work on grid integration and control systems. However interviewees noted that results were often not so useful, as they could not readily be integrated in the firm's products.

The XEMC official highlighted that most of their university collaborations were with local universities in Shandong Province. The interviewee noted that their R&D collaborations were typically aimed at assisting the firm with specific calculations in which the university research groups had particular strength, or which were needed at a time when the firm was understaffed. One example put forth by the interviewee was a project with a research group at Tsinghua University to assist them with design calculations for their 2MW turbine generator.

2.2.6 Evaluating firm technological capabilities

The above discussion of how Chinese wind turbine manufacturers obtained or developed designs and blueprints for their turbine models, managed the supply of components, and engaged in R&D activities, provides a basis to assess their firm technological capabilities associated with product technology. I use here the left pane of the modified Bell and Pavitt (1995) framework as shown in table 2.2.

2.2.6.1 Investment activities

A number of important points stand out with respect to the decision making processes surrounding the choice and source of product technology. Turbine manufacturers have managed the introduction of a vast number of new types of turbines in a relatively short time period. This involved the introduction of different turbine models tailored for specific environments as well as the introduction of new turbine series of increasingly large capacity. For Goldwind, United Power, and SEwind, this also involved introducing series with different drive train technologies (in particular DFIG and DDPM, though in the case of Goldwind, this also includd a hybrid drive train). Underlying this trend is a sequence of technology transfer agreements with foreign firms giving Chinese manufacturers access to designs and blueprints of turbines. These agreements

reflect an elaborate decision making process aimed at not only acquiring technology but also building the associated knowhow within the firms. Licensing agreements with one set of firms – Furlander, Jacobs/RE Power, and Dewind – were followed by joint-development agreements with a distinct set of firms – AMSC/Windtech, Aerodyn, Garrard Hassan, Vensys (before being acquired by Goldwind) – as well as an engineering firm working with United Power on its 3MW DDPM turbine. Turbine manufacturers explained that the choice of the foreign partners was a relatively straight forward process as there were few potential candidates. The decisions made by Chinese manufacturers were typically determined by opportunity, the reputation of the foreign firm, and the appeal of the financial terms. None mentioned any formal tender process. Nevertheless, managing a sequence of diverse technology transfer agreements with different foreign firms, including licensing and joint-development agreements , while monitoring the evolution of one's firm's production activities (discussed below) to decide when to introduce interdependently developed models, underscores an elaborate decision making process.

At the same time, turbine manufacturers developed their component sourcing strategies in an environment where the supply chain had shifted from being mainly based on imports to being increasingly localized and based on a rapidly growing presence of domestic suppliers. Turbine manufacturers therefore had to engage new Chinese suppliers which often had limited experience in the wind turbine sector. For some products this process has involved tenders and negotiations with various potential suppliers. For newer turbines, however, negotiations involved few suppliers and were often more complex as they involved production as well as technology development decisions. There are also clear indications that turbine manufacturers carefully monitored component markets to determine whether to develop their own component production.

These points indicate that the capabilities of Chinese wind turbine manufacturers with respect to investment activities fall in the 'advanced' category identified by Bell and Pavitt (1995) and shown in table 2.2. The experience of Chinese turbine manufacturers suggests that for both turbine blueprints and components they engaged in the search, evaluation, and selection of technologies and supply sources, which are central characteristics of intermediate capabilities. However, in addition to this Chinese manufacturers rapidly engaged in the independent development of new turbine models as well as of new components, which characterize advanced capabilities.

2.2.6.2 Production activities

The means by which Chinese manufacturers have produced wind turbines have evolved significantly. This is particularly true when considering the sequence of steps taken by manufacturers to acquire and develop turbine designs and blueprints. The first step was the licensing of relatively standard European turbine models as a means for manufacturers to enter the market. Turbine manufacturers then started introducing minor design changes to better adapt the turbines to the specificities of Chinese regions and to diversify their products. Next, manufacturers acquired further technological knowhow through joint-development agreements. To refer to the terminology used in table 2.2, these agreements can be considered as a form of assisted reverse engineering, where Chinese firms collaborated with, and received training from, foreign holders of technology on the development of a new wave of wind turbine models. Subsequently, Chinese manufacturers progressively introduced independent designs of incrementally larger capacity turbines. These were small up-scales of existing designs, though manufacturers also used these opportunities to introduce minor design modifications to improve

performance. Finally, several firms also independently developed models of even larger capacity, sometimes adopting different drive train technology.

With respect to turbine components, the most notable feature of production activities is that after relying on the supply of main components, all turbine manufacturers started to develop and manufacture some of their turbine components independently. This concerns primarily the control systems, yet various firms also embarked on the development and manufacturing of other components, such as converters, generators, or blades.

When looking at R&D efforts all firms gave priority to introducing incremental improvements to the designs of existing models, as well as to the completion of designs of turbine models in the pipeline. Similarly, R&D efforts targeting components aimed mainly at introducing incremental improvements to components already being manufactured, or at preparing for the introduction of components which had until then been purchased from outside suppliers.

Nevertheless, Sinovel, Goldwind and United Power, were also involved in larger and more long-term R&D projects. These aimed to development future turbine models with capacity between 10MW and 12MW, beyond what was commercially available anywhere in the world. Such large turbines necessarily imply important technical challenges, notably with respect to turbine weight. United Power was notably investigating novel drive train concepts based on a superconducting generator, which was not commercially available anywhere in the world.

With respect to the framework in table 2.2, since entering the turbine manufacturing market, firms' capabilities related to production activities appear to have rapidly evolved from 'basic' – where the focus was on introducing minor adaptations and incremental improvements to

transferred models – to ‘intermediate’ – where manufacturers shifted their emphasis to joint-development of turbine designs, the independent development of components, and the development and production of new turbines. There are also signs that some of the leading Chinese manufacturers are starting to engage in production activities associated with ‘advanced’ capabilities, where firms invest in product innovation and related R&D.

2.2.6.3 Supporting activities

Supporting activities consist of interactions with other entities which bolster investment and production activities. From the above discussion, three types of interactions stand out as having played a particularly important role. The first consists of the variety of interactions with foreign firms which either supplied turbine designs or provided technical assistance to Chinese firms. Whether through licensing, joint-development, or consulting work, such interactions played a central role in the establishment of a Chinese wind turbine industry. Most importantly, they gave Chinese firms access to technological knowledge in ways that allowed rapid assimilation.

Another important type of interactions consists of those between turbine manufacturers and component suppliers. Turbine manufacturers have collaborated extensively with component suppliers to improve the quality of existing components as well as to design and develop components for new turbine models. The growth in the number of Chinese component suppliers has led to an important learning process since in most cases they had little prior experience with wind power technologies. Chinese turbine manufacturers therefore had to share their knowledge and engage in a process of trial and error to identify suitable suppliers and improve their products.

Finally, the third type of interactions consists of collaborations with universities and other research organizations. All turbine manufacturers identified that the main emphasis of these collaborations was on providing them with assistance in solving specific technical problems associated with the development of their new turbines. In this respect, these collaborations appear similar in nature to the work done by the firm's own R&D staff.

Looking at table 2.2, these interactions correspond to all levels of capabilities for supporting activities. The search and absorption of technological knowledge from foreign firms is characteristic of 'basic' capabilities. Working with domestic component suppliers to help them improve their product quality while increasing local sourcing matches 'intermediate' capabilities. Finally, collaborating with universities and other research organizations on turbine development corresponds to 'advanced' capabilities.

2.3 CONCLUSION

The analysis presented in this chapter indicates that Chinese wind turbine manufacturers are indeed catching up with foreign frontier firms. Indicators of wind turbine technology progress showed converging trends in terms of both wind turbine characteristics and performance. There are, however, some important areas for which data could not be assembled. It was notably impossible to gather data on operation and maintenance trends either in China or other leading countries. Similarly, data used for the calculation of capacity factors in China do not consider much of the recent rise in turbine size. Future work should therefore aim to complement the data compiled in the scope of this research.

The evaluation of firm technological capabilities associated with product technology in six of China's leading wind turbine manufacturers showed that these had grown rapidly, being at the time of interviews at advanced or intermediate levels for the three types of activities identified by Bell and Pavitt (1995, see left pane of table 2.2). The firms held advanced capabilities with respect to investment and supporting activities. To some extent, this comes as no surprise given that all manufactures, with the exception of Goldwind, were formed by large industrial firms that already had extensive experience in large scale industrial product manufacturing and project management in a broad variety of industries.[68]

More striking however was the evolution of firm capabilities related to production activities. These rapidly evolved from basic to intermediate levels, and in some cases appeared to be reaching advanced levels. The evolution of the means of technology transfer adopted – from licensing, to joint development, acquisition, and targeted technical assistance contracts – played a critical role in the rapid growth of capabilities associated with production activities. Not only did these means of technology transfer provide the Chinese manufacturers with access to wind turbine technological knowledge, they also facilitated its assimilation through extensive and close collaboration with foreign firms.

By 2011 all firms had acquired sufficient knowhow to independently develop new turbine models. However the primary emphasis of their technology development efforts, both in house

[68] The one exception, Goldwind, has the longest experience in wind turbine manufacturing and used its position as first mover in the Chinese market to establish itself as one of the leading firms in the industry.

or in collaboration with research institutions was on introducing incremental, short-term technology improvements. Still, some firms engaged in more ambitious R&D projects with more long-term outlooks, akin to innovation efforts at the frontier.

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- Chapter 3 - The Role of Government in the Chinese Wind Turbine Technology Development System

3.1 INTRODUCTION

3.1.1 Chapter objective and research approach

This chapter focuses on the first argument of the research hypothesis which states that the rapid technological progress made by Chinese wind turbine manufacturers results from the fact that on the one hand, the government can create a relatively large market for wind power, and on the other, Chinese firms benefit from a strong system of technology development with a powerful and proactive government at its heart.

The comparative analysis of wind power market trends in China and other leading nations presented in Chapter 2 confirmed that China created a large wind power market relative to other countries. This chapter therefore focuses on investigating the role of government and assessing how the Chinese wind turbine technology development system contributed to the progress made by Chinese wind turbine manufacturers described in Chapter 2.

I draw on interviews carried out in China between May and October 2011 with some of the main actors of China's wind turbine technology development system. Interviews focused on three different groups of actors: wind turbine manufacturers; organizations involved in the policy making process; and universities and other research organizations.

Interviews were based on the technology development system approach detailed in Section 1.3. In particular, two types of interviews were conducted, each focusing on a set of technology

development system functions.[69] Interviews with people from the policy making group covered each of the six system functions, namely 'market formation', 'knowledge development and diffusion', 'entrepreneurial activity', 'guidance of search', 'legitimation', and 'resource mobilization'. Interviews with the turbine manufacturers and research organizations focused on two system functions: 'knowledge development and diffusion' and 'guidance of search'. For both types of interviews the approach was semi-structured: a core set of interview questions were identified for each system function, yet ample room was left for follow-up questions to allow for thorough discussions of recurring and salient themes.

Interviewees in the turbine manufacturers group consisted of the same high level officials from the six wind turbine manufacturers discussed in Chapter 2: namely Sinovel, Goldwind, Dongfang Electric, United Power, Shanghai Electric, and XEMC.[70]

Interviewees in the policy making group consisted of high-level officials from the Department of Renewable and New Energy of the National Energy Administration (NEA), the Department of High-Tech Development and Industrialization of the Ministry of Science and Technology (MOST), the Energy Research Institute (ERI) of the National Development and Reform Commission (NDRC), the Chinese Academy of Science and Technology for Development (CASTED) of MOST, the China General Certification Center (CGC), the Chinese Wind Energy Association (CWEA), the Chinese Renewable Energy Industry Association (CREIA), the

[69] See table 1.3 of Chapter 1 for a description of the six technology development system functions.

[70] Information used in this chapter was collected during the fifth part the interview process described in Chapter 2.

Chinese Renewable Energy Society (CRES), and the Chinese Wind Energy Equipment Association (CWEEA).

Interviewees in the research organizations group consisted of leading faculty involved in research groups with significant and long standing involvement in wind power research. Specifically, interviews were carried out with professors at the Chinese Academy of Sciences' (CAS) Institute of Electrical Engineering, the North China Electric Power University's (NCEPU) Renewable Energy School, and at Tsinghua University's Department of Electrical Engineering, Department of Thermal Engineering, and Department of Automation.

Section 3.2 introduces the main actors of the Chinese wind turbine technology development system. Sections 3.3 and 3.4 discuss some of the most important features of the Chinese system discussed during the interviews: Section 3.3 focuses on efforts to create a domestic wind turbine industry, while Section 3.4 focuses on support for wind power R&D. In both cases, interview findings were complemented by additional research. Section 3.5 summarizes the key findings for each technology development system function, while Section 3.6 concludes. First, however, I provide some context for the Chinese government's interest in wind power.[71]

3.1.2 The roots of the Chinese government's interest in wind power

To better understand the role of government in China's wind turbine technology development system, I outline here some important trends underlying government planning decisions related to wind power. Many different factors may explain the Chinese government's interest in wind

[71] Findings in this chapter are based on interviews and therefore only extend to the time when interviews were conducted, from May to October 2011.

power and it is beyond the scope of this section to try to exhaustively identify these. Rather, I focus on three factors that appear to have played an important role: energy security, greenhouse gas emissions, and industrial development.

3.1.2.1 Energy security and greenhouse gas emissions

China's rapid economic growth has been accompanied by a surge in energy demand. Figure 3.1 shows that China's total primary energy supply had more than doubled between 2000 and 2010, when it reached over 2,500 Mtoe.[72] Coal is by far the dominant fuel, representing 57% of the country's fuel mix in 2000 and rising to 67% in 2010. Total electricity generation more than tripled over the same period, with coal accounting for 77% of the total electricity generated in 2010.

In 2010, China held 19% of global coal reserves and had a reserve to production ratio of 59 years.[73] The country also benefits from vast coal resources.[74,75] If only a fraction of these became exploitable its reserve to production ratio would rise significantly. Nevertheless, in 2010 China accounted for over half of the world's coal consumption and virtually all projections indicate

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[72] One tonne of oil equivalent (toe) refers to the net heat content of 1 tonne of crude oil. It is a metric commonly used as a way to compare the consumption and use of different types of fuels. One tonne means one metric ton or 1000 kg.

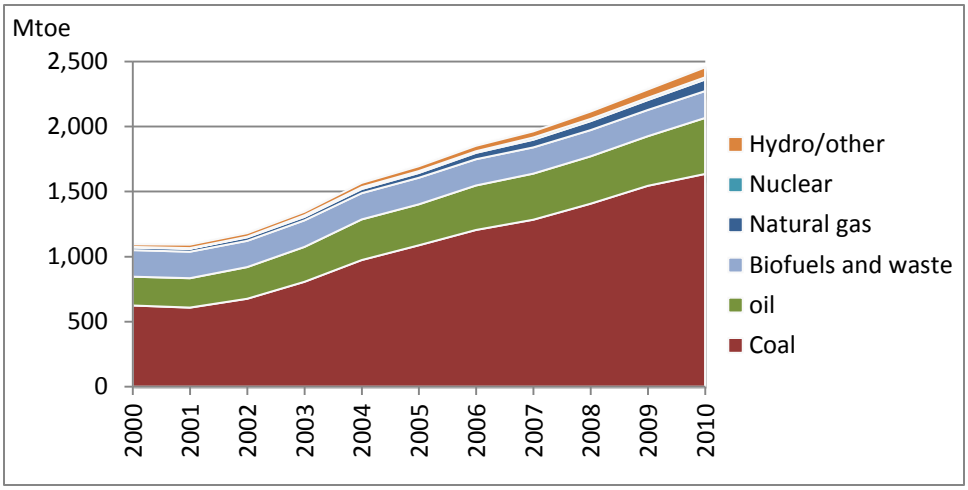
[73] Reserve to production ration based on 2010 levels.

[74] 2010 coal production, reserves, and resources data are from BGR (2012). Reserves are defined as proven volumes of energy resources that are economically exploitable at today's prices and using today's technology. In contrast resources refer to volumes that cannot currently be exploited for technical and/or economic reasons, as well as volumes that are unproven but geologically possible (BGR, 2012).

[75] China was ranked second after the United States in 2010 both in terms of reserves and resources.

continued growth. For example, the International Energy Agency forecasted in 2011 that coal demand in China would increase by 40% between 2009 and 2020 (IEA, 2011a).[76]

Figure 3.1: China's energy mix



Source: IEA (2012a)

Note: One tonne of oil equivalent (toe) is defined as 107 kilocalories (41.868 gigajoules). This quantity of energy is, within a few per cent, equal to the net heat content of 1 tonne of crude oil. One tonne means one metric ton or 1000 kg.

From an energy security perspective, the concern therefore appears to be less about long-term physical availability of domestic resources than about the potential inability of the domestic coal supply chain to meet the growing demand. In 2009, the country became for the first time a net importer of coal. Due to its sheer size, the country was already the second largest importer of coal in the world by 2010, following Japan. As a result, China is increasingly exposed to international coal price dynamics. The spot price of steam coal at Qinhuangdao, the country's largest port used for coal trade, has notably increased, doubling in value between September

[76] These figures are according the IEA's 'current policy scenario', which aims to include the effects of policies in force when projections were made.

2007 and September 2011.[77] Though understanding the causes of international coal price movements is a difficult task, it appears that part of the reason for the rise in Qinhuangdao spot prices is that international coal suppliers, such as Australia and Indonesia, were not able to keep up with China's rapid growth in import demand (IEA, 2011b).

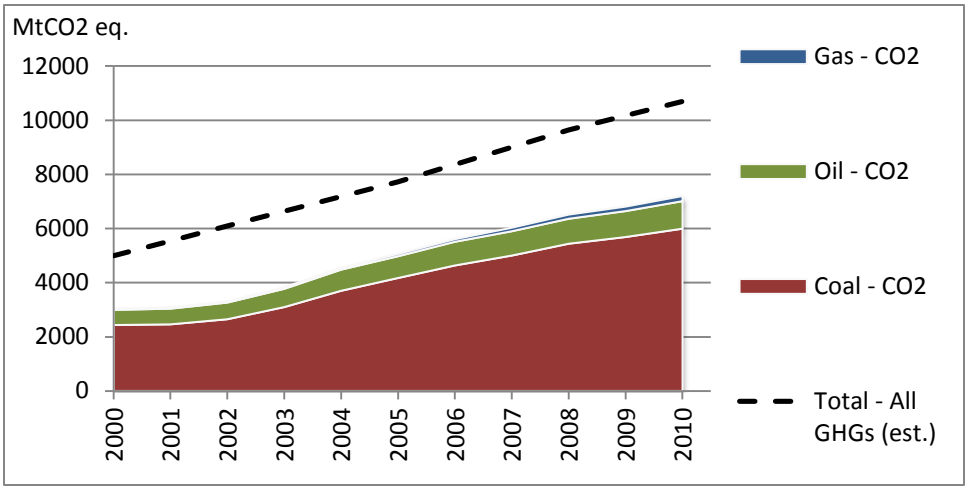
China's heavy reliance on coal to fuel its economic growth also has important implications in terms of greenhouse gas emissions. As shown in figure 3.2, China's total greenhouse gas emissions have increased from approximately 5,000 $MtCO_2$ in 2000 to close to 10,700 $MtCO_2$ in 2010. Around 2004 the country became the largest emitter of greenhouse gases in the world, ahead of the United States. By 2010 it accounted for 22% of global emissions, ahead of the United States and the European Union's 27 member countries, which respectively accounted for 13% and 10% of global emissions. The role of energy production and use in China's emissions has steadily increased, from 68% of total greenhouse gas emissions in 1990 to 76% in 2010. CO_2 emissions from coal combustion alone accounted for 56% of the country's total greenhouse gas emissions.

The Chinese government's response to the rapid rise in coal consumption and its implications for energy security and greenhouse gas emissions can be traced through objectives formulated in its five-year plans. A long-term objective has notably been to reduce the energy intensity of the country's economic activity. During the 10th five-year plan (2001-2005) the government aimed to reduce energy consumption per RMB 10,000 of GDP (in 1990 values) to 2.2 tons of standard coal. During the 11th five-year plan the government aimed to reduce energy consumption per unit

[77] Data retrieved from www.bloomberg.com

of GDP by 20% between 2006 and 2010 and achieved a reduction of 19.1%. Finally the 12th five-year plan aimed to achieve a further 16% reduction per unit of GDP by the end of 2015. Another objective concerns the use of non-fossil fuels. Under the 12th five-year plan, the government aimed to raise the share of non-fossil fuels to 11.4% and 15% of the total energy use by 2015 and 2020, respectively. The 12th five-year plan also introduced a greenhouse gas emissions intensity reduction objective, aiming to achieve a 17% reduction in CO_2 emissions per unit of GDP (Casey and Koleski, 2011).

Figure 3.2: China's greenhouse gas emissions and the role of energy related CO2



Source: IEA (2012b)

Note: One tonne of carbon dioxide equivalent (tCO2e) is a unit of measure used to compare the emissions from various greenhouse gases based on their global warming potential relative to carbon dioxide. One tonne means one metric ton or 1000 kg. Emissions trends are based on the IEA sectoral approach (see IEA, 2011c for details). All greenhouse gases consist of emissions of CO2, CH4, N2O, HFC, PFC, and SF6 from all sectors, excluding removals of greenhouse gases from land use or forestry sinks. The trend for all greenhouse gases is an extrapolation from data points in 2000, 2005, 2008, and 2010.

3.1.2.2 The quest for indigenous innovation

Value added from knowledge- and technology-intensive industries (KTI) in China has grown at a very rapid rate (figure 3.3).[78,79] From approximately USD 150 billion in 1995, China's KTI sector has grown to represent over USD 1.2 trillion in 2010, with 58% from commercial services, and the rest evenly split between government services and high-technology manufacturing industries.[80] As a result, China's share of global KTI value added has increased from 2% in 1995 to close to 7% in 2010. When looking at high-technology manufacturing industries alone, China's share of global value added has increased from under 3% in 1995 to close to 19% in 2010.

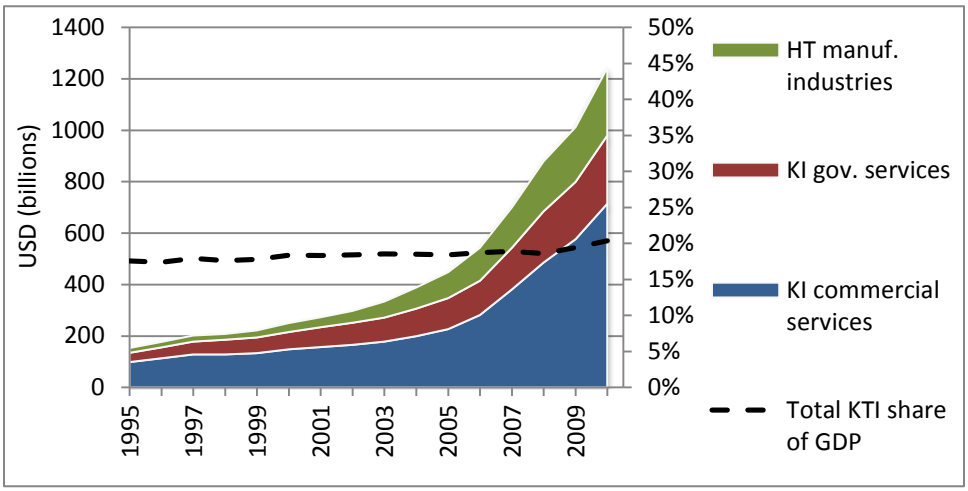
However, when expressed as a percentage of China's GDP, the share of KTI has only increased from approximately 18% of GDP in 1995 to 20% in 2010. This increase was primarily driven by growth in high-technology manufacturing, which rose from representing approximately 2% of GDP in 1995 to 4% in 2010, while the share of knowledge-intensive commercial and government services have remained approximately the same.

[78] KTI consists of knowledge-intensive services and high-technology manufacturing industries. Knowledge-intensive services are broken down into three types of commercial services (financial, business, and communications) and two types of government services (education and health). High-technology manufacturing consists of aircraft and aerospace, pharmaceuticals, computers and office machinery, semiconductors and communications equipment, and scientific instruments (NSB, 2012).

[79] Value added is as the measure of industry production that is the amount contributed to the value of a good or service. It excludes purchases of supplies and inputs (NSB, 2012).

[80] Unless otherwise noted, all data in this section is from NSB (2012).

Figure 3.3: Value added from knowledge- and technology-intensive industries in China



Source: NSB (2012)

Note: Primary y-axis is in billions current USD. KI: Knowledge intensive; HT: High technology. KTI: Knowledge- and technology-intensive industries. KTI consists of knowledge intensive sectors (commercial and government) and high technology manufacturing industries. See NSB (2012) for more details about the breakdown.

Looking at trade in high-technology goods provides some insights as to the origins of the rise in high technology manufacturing. China has gone from a trade deficit in high-technology goods of USD 6 billion in 1995 to a trade surplus of USD 157 billion in 2010, primarily driven by exports of communications goods, computers, and office machinery.[81] However, Xing (2010) finds that foreign invested firms accounted for 85% of China's total high-tech exports by 2008. Similarly, Liu and Daly (2011) find that in electric equipment and machinery, instruments, and electronic and telecommunications, foreign invested firms account for respectively 68%, 87%,

[81] Other high-technology goods presented either a trade deficit or only a slight surplus in 2010.

and 92% of China's total exports.[82] Xing (2010) underscores the important role played by Taiwanese companies, explaining that by 2007, these firms had relocated almost all of their production in laptop PC, digital camera, motherboard and liquid crystal display (LCD) monitor to mainland China. He attributes 82% of Chinese high-tech exports in 2008 to processing trade, which consists of the assembly of components imported from other countries. Though the majority of the value added of the end product was attributed to China and classified as high-technology, China's real contribution was most often limited to unskilled labor used in product assembly lines.

Concerns about China's ability to contribute to technology development reached the top of the government's agenda during the 11th five-year plan period with the release in 2006 of the National Medium- and Long-Term Plan for the Development of Science and Technology (2006-2020). The plan centered on the need to promote indigenous innovation and underscored that to close the gap with more advanced countries China could no longer simply import technology. It emphasized the need for technological "assimilation, absorption, and re-innovation" to strengthen the nation's indigenous R&D capability. The plan put forth a plethora of policy goals and large scale projects in a number of targeted sectors. Some of the broader goals included increasing China's gross expenditure on R&D to 2.5% of GDP by 2020 with a target for basic research to reach 15% of R&D spending. The plan also called for science and technology's contribution to the economy to reach 60% of GDP and for China's overall reliance on foreign

[82] The classification of high-technology goods adopted by Xing (2010) and Liu and Darley (2011) is slightly different from that adopted in NSB (2012).

technology to decline to below 30%.[83] Finally the plan also set as an objective that the number of annual patents granted to Chinese nationals and the number of citations of scientific papers be ranked among the top five countries in the world by 2020.

The 12th five-year plan, released in 2011, also emphasized the importance of indigenous innovation and placed scientific development at the core of the country's long-term economic development strategy. It set as an objective for the country to increase spending on R&D to 2.2% of GDP by 2015. In contrast the 11th five-year plan aimed for 2% of GDP by 2010.[84] The 12th five-year plan also introduced an objective to reach 3.3 patents per 10,000 people by 2015. The plan identified seven strategic emerging industries – which included alternative energy – as the drivers of China's future economic development and set as a goal for these industries to account for 8% of GDP by 2015 and 15% by 2020 (Casey and Koleski, 2011).

3.2 KEY ACTORS OF THE CHINESE WIND TURBINE TECHNOLOGY DEVELOPMENT SYSTEM

Actors of the Chinese wind turbine technology development system can be classified in six distinct groups: government, industry associations, research institutions, power generation and grid infrastructure firms, product manufacturing firms, and industry service providers. To different levels of intensity each group interacts with the others through various networks.

Chapter 2 described the role and capabilities of Chinese turbine manufacturers as well as the progressive establishment of domestic supply chains for the various key turbine components. It

[83] The plan did not detail how to measure science and technology's economic contribution or reliance on foreign technology.

[84] China's expenditure on R&D reached 1.5% of GDP in 2008 (Eurostat, 2012).

also discussed the role of research institutions from the perspective of turbine manufacturers. The emphasis of this section is therefore on introducing actors of other groups, which were highlighted during interviews as playing important roles in the wind turbine technology development system. In addition, given the central role of the government, I also discuss some of the networks used by the government.

3.2.1 Government actors

In 2010, the State Council established the National Energy Commission, a high level energy policy strategy group created to define the country's main energy goals and policy plans. The Commission was headed by the country's Premier and composed of various ministers and high level officials. Energy policy implementation authority, however, was mostly held by the National Development and Reform Commission (NDRC), which oversees the country's main industrial policies, including those concerned with energy. NDRC's office of price control was notably responsible for determining power generation prices from different energy sources, and therefore was involved in defining the incentive structure for wind power, which I detail in later sections of this chapter.

NDRC's National Energy Bureau was transformed in 2008 into the National Energy Administration (NEA) under the authority of the state council and the prime minister. The NEA was not a ministerial level organization, with the director of the NEA as the vice-minister of NDRC. A Chinese Wind Energy Association (CWEA) interviewee highlighted that, in practice, NEA was still part of NDRC, only somewhat more important than other departments within the organization. The interviewee underscored that the close relationship between NEA and NDRC gave NEA significant influence.

NEA was responsible for the supervision of energy markets and the implementation of specific policy measures. NEA coordinated the review of large wind farm projects and oversaw market rules, such as grid connection requirements. It also advised NDRC on price setting for wind power generation.

An NEA interviewee noted that approximately 15 people worked on renewable energy within NDRC while 12 people worked within the Department of Renewable and New Energy of NEA, of which four worked in the New Energy Division, which oversaw the wind power market. A CWEA interviewee highlighted that one implication of such a small cohort of government officials working on wind power was that it had established strong communication networks with other actors of the Chinese system.

Another NEA interviewee identified a small number of organizations which assisted them in industry data collection and analysis, as well as in the scope of specific projects. In particular he noted the central role of the Energy Research Institute (ERI) as well as China Hydropower Engineering Consulting group. The Chinese Wind Energy Association (CWEA), the Chinese Renewable Energy Industry Association (CREIA), and the Chinese Wind Energy Equipment Association (CWEEA) were also highlighted as contributing data and analysis to the policy making process.

The Energy Research Institute (ERI) is a government funded independent institute under NDRC. As highlighted by ERI interviewees, the main focus of the institute was energy policy formulation. ERI worked closely with NDRC, NEA and other government agencies and provided recommendations on policy issues such as legislation, five-year plans, and technical development strategy. The institute's involvement varied from advice to the drafting of

legislation. The institute was one of the lead authors of the 2005 renewable energy law, discussed in more details in subsequent sections.

The ERI interviewee also stressed the good communication channels between government, industry associations, and turbine manufacturers, whether state-owned or not. An interviewee from Sinovel explained, for example, that when the government drafts a new regulation or wants to implement a new policy, it organizes a series of workshops with turbine manufacturers and other actors, to collect comments and recommendation.

Other government ministries, such as the Ministry of Industry and Information Technology (MIIT), and the Ministry of Finance (MoF), played less important roles in the Chinese wind turbine technology development system. In theory the MIIT was responsible for formulating industry rules and policies but with respect to wind power its role and influence was limited. MoF played an important supporting role as it managed various clean energy funds and coordinated, in conjunction with NDRC and NEA, various subsidies and tax incentives.

The main actor with respect to government funding of research and development (R&D) was the Ministry of Science and Technology (MOST), which was responsible for coordinating various programs to support projects involving manufacturers, research institutes, and universities. MOST was supported by a variety of satellite organizations. The Chinese Academy of Science and Technology for Development (CASTED), for example, served to help R&D policy formulation in China. CASTED notably undertook field studies to assess the R&D needs of specific industries which fed into the MOST R&D planning process. The National Natural Science Foundation of China (NSFC), another important R&D entity in China, provides grants in support of basic research projects.

3.2.2 Industry associations

Three industry associations played a particularly prominent role in the Chinese wind turbine technology development system: the Chinese Wind Energy Association (CWEA), the Chinese Renewable Energy Industry Association (CREIA), and the Chinese Wind Energy Equipment Association (CWEEA), all of which are discussed in some details below. However, as highlighted by an interviewee from CWEEA there are a number of additional, more specialized industry organizations, such as the China Electrical Equipment Industry Association, which had a separate group bringing together manufacturers of wind turbines generators, converters, and control systems.

CWEA, CREIA, and CWEEA were part of a complex chain of organizations linked to various branches of the government. The CWEA was a part of the China Renewable Energy Society, which in turn belonged to the China Association for Science and Technology (CAST). The CWEA interviewee noted that though officially an association, CAST was like a government department, with its chairman having the equivalent of a ministerial post. The CREIA was officially registered under the authority of the State-owned Assets Supervision and Administration Commission (SASAC). Finally, the CWEEA was linked to the Chinese Academy of agricultural Mechanization Sciences, which until the late 1990s was affiliated to the then Ministry of Machinery Industry. Still, interviewees from each of the three associations indicated that in practice they had few, if any interactions with these affiliations.

The associations brought together various actors of the wind power industry. Members of the CWEA included turbine and component manufacturers, developers, research institutes and universities. Members of the CWEEA were mostly turbine and component manufacturers,

though they also included some research institutions. CREIA brought together firms from all renewable energy industries in China. Each served to facilitate exchanges among various actors. The associations could notably be used by firms as communication channels if they had concerns which they wanted to share with the government. For example CREIA coordinated the China Renewable Entrepreneur Club, which provided a closed door forum for the most prominent firms to get together and discuss issues affecting the industry, as well as to interact with the government to both try to influence policy direction and get a better understanding of the policy making process.

The associations also helped the government to assess wind power policies and monitor the state of the industry. The government often sought assistance from the CWEA to address specific industrial questions, typically to gather information from industry, identify the needs in the market, and formulate recommendations. One example was a confidential audit on turbine quality in the Chinese market undertaken by CWEA in 2011. However, the CWEA interviewee explained that they were also involved in the drafting of regulations and plans as well as in organizing the consultation of industrial actors to compile opinions for the government.

Each of the three associations was involved in the organization of conferences and large exhibitions. CWEA organized events including the largest annual exhibit on wind power in China. Similarly, the CWEEA organized an annual international wind turbine exhibition in Shanghai, as well as a smaller conference for its members and other guests.

Another important task of these associations was to collect of industry data. The CWEA annually collected a host of data from firms on the evolution of the industry. This data collection focused on capacity additions, though the CWEA interviewee noted that they had received the

endorsement of the NEA to expand their data collection efforts and cover performance and operation data as well. CREIA also compiled data from industry and put together technology road maps. The interviewee noted that NEA had approved an online data collection system which would give the association greater authority to collect and publish data.

3.2.3 Project developers and grid companies

There were numerous wind farm developers in China, including very large ones by international standards. In 2010, six Chinese firms, most of which state-owned or state-controlled, were among the leading 15 wind farm operators in the world in terms of cumulative installed capacity under management, with four in the top 10 (BTM, 2011). These six firms accounted for close to half of total installed capacity in China. Each of China's five main power generation groups, created as a result of power sector reforms carried out in 2002 (IEA, 2006), owned or held important stakes in some of these leading wind farm developers. Longyuan Power Group, for example, was China's largest wind farm developer and ranked third in the world in terms of installed capacity in 2010. It was affiliated to Guodian Corporation, one of China's largest power generation companies.

The 2002 power sector reforms also led to the creation of two large grid companies: State Grid Corporation of China, covering 26 provinces, and China Southern Power Grid Company Limited, covering five southern provinces. Because of the concentration of wind farms in northern regions, in 2010 State Grid Corporation oversaw over 95% of the grid connected wind power capacity in the country.

3.2.4 Industry service providers

The Chinese wind turbine technology development system involved a number of industry service providers, including foreign engineering consulting firms, which, as discussed in Chapter 2, played an important role in assisting Chinese turbine manufacturers develop new turbines. Here, however, I focus on two Chinese industry service providers: Hydro Engineering Consulting Group and the China General Certification Center.

China Hydropower Engineering Consulting Group, a state-owned enterprise, was one of four large power service companies created as a result of the 2002 power sector reform (IEA, 2006). It was the principal Chinese company responsible for providing a full range of technical services in the field of wind power development in China. As noted by a CREIA interviewee, the government relied on Hydropower Engineering Consulting Group's advice on the engineering planning and construction of wind farms. They also had the authority from NEA to collect information from wind farm developers concerning construction and operational data.

China General Certification Center (CGC) was the main Chinese turbine and turbine component certification organization, supported by the National Institute of Meteorology and the Certification and Accreditation Administration of the People's Republic of China

3.3 THE CREATION OF A DOMESTIC WIND POWER INDUSTRY

The Chinese government has endeavored to create a wind power market in China and to support the establishment of a domestic wind turbine manufacturing industry. In this section I

highlight the main regulatory features as well as some of the key issues of this process of industrial formation.[85]

3.3.1 Support to wind power deployment

The Wind Power Concessions Program, introduced by the central government in the early 2000s, marks the regulatory starting point of the emergence of a strong wind power market in China, discussed in Chapter 2.[86] Before the first round of concession projects, the average capacity of the 32 wind farms in China was 14.6MW (Li et al., 2006). From 2003 to 2007, five rounds of annual tenders were conducted under the concessions program which led to the allocation of 18 projects, ranging in capacity from 100MW to 300MW, and totaling 3.4GW in capacity.[87] The main features of the program managed by NDRC were the use of a competitive bidding process and a requirement for grid companies to purchase all power generated by wind power and to sign long-term purchasing power agreements with the selected project developers at the agreed bid price.[88]

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[85]Though provincial governments have also introduced regulation to support the wind power deployment, the discussion in this section only includes the regulatory framework introduced by the central government.

[86] A number of more limited efforts in support of wind power had been introduced prior to the concessions program. See Liu et al. (2002) for a discussion of these earlier efforts.

[87] See Ni (2008) and Li et al. (2010) for a complete list of concessions projects. Not all 18 projects allocated resulted from a tender. Depending on land availability, the winning bids of some projects were used to negotiate the construction of adjacent wind farms on similar terms.

[88] Developers bid for the price of electricity they would receive during the first 30,000 full load hours of cumulative electricity generated by the plant. After that, and until the end of the 25 years concession period, developers receive the average electricity price at that location. See Li et al. (2006) for a detailed account of the four first rounds of the concession bidding process.

The Renewable Energy Law enacted in 2005 and the host of regulations introduced subsequently to implement it firmly established the main features of the concessions program in the Chinese legal system. The use of competitive tenders was adopted to develop new wind farms and the law maintained the requirement that grid companies connect the selected wind farms to the grid and purchase all wind power generated. Under the law the extra costs to grid companies were financed by a surcharge on electricity prices for all power users.

The law also held power generation firms responsible for meeting renewable energy targets. In particular, NDRC's 2007 Medium and Long-Term Plan for Renewable Energy Development in China stated that power generation firms operating more than 5GW in total generation capacity had to have 3% of their total capacity by 2010 from non-hydro renewable energy sources, and 8% by 2020.

By the end of 2008 over 160 wind farms had been built through these regulatory means. Based on this experience, in 2009 NDRC changed the wind power project pricing system from a tender based system to a fixed feed-in tariff.[89] The new system distinguished four tariffs ranging from RMB 0.51 to 0.61/kWh depending on wind resources, with higher tariffs in lower wind power resource regions, and divided the country accordingly. The wind power tariffs were higher than the tariffs set for thermal power generation, which were at the time of approximately RMB 0.40/kWh.[90]

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[89] Notice No. 1906, "Regarding Grid-Connected Power Pricing for Wind Power", NDRC, 2009

[90] In practice, the grid company pays the wind farm the same tariff as for the thermal power generation and the difference with the wind power tariff is paid for by the Renewable Energy

The above evolution of wind power market incentives concerned only on-shore wind farms. In 2010 NDRC and the NEA introduced a concessions program to start off-shore wind power development and a first round of four projects totaling 1GW in capacity was approved. The allocation of a second round of projects totaling 2GW was scheduled for 2012 but was subsequently delayed due to project siting issues.

The government also introduced a variety of tax breaks for clean energy investments including wind power. Effective as of 2008, the new Enterprise Income Tax law included a reduction in income tax rates from 25% to 15% for high-technology firms, from which, depending on criteria discussed later in this chapter, wind turbine manufacturing firms could benefit. Wind power projects approved from 2008 onwards also benefited from a three-year exemption and three-year 50% reduction in corporate income taxes.[91] Finally the value added tax (VAT) rate for wind power generated electricity was reduced from 17% to 8.5%.[92]

Several interviewees underscored the pivotal role of the capacity requirements placed on large power generation companies in spurring the development of the Chinese wind power market. An interviewee from CREIA noted that the 2010 target had been achieved in advance and believed that the 2020 target would also be met. He explained that there was a dimension of prestige for

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Development Fund, created under the Renewable Energy Law, which is funded by the surcharge paid by end users.

[91] "Notice on Issues on Implementation of the Directory of Favorable Enterprise Income Tax for Public Infrastructure Projects", Ministry of Finance and the State Administration of Taxation, December 2007.

[92] "Notice Regarding Policy Issues for Comprehensive Utilization of Some Natural Resources and Value-Added Taxation of Other Goods", Ministry of Finance and the State Administration of Tax, 1 December 2001. "Catalog of Tax Preferences for Public Infrastructure Projects", Ministry of Finance, State Administration of Taxation, 2008.

large power companies in achieving the targets and embracing a green growth model. Most of the firms were state-owned and successfully meeting targets was seen favorably by the government. He highlighted that there was also some competition among large power generators, where the success of some pushed others to try to perform better.

However, the interviewee explained that there was also a financial rationale underlying the aggressive pursuit of wind power project development by power generation companies. While there have been many reports of poorly managed wind power projects in China, the most successful developers, such as Longyuan, were in fact achieving satisfactory rates of return from their wind farm operations, particularly in contrast to the rest of the power generation portfolios of their holding companies. Between 2004 and 2011, Chinese power generation companies experienced rapidly declining profit margins in large part due to financial losses on coal power generation operations, which in most cases constituted the bulk of their power generation portfolios (Recknagel, 2010; Azure, 2008). Coal prices in China have increased by approximately 200% between 2005 and 2010 while industrial power prices rose only by approximately 30% for the same period (DBS, 2011). Both coal prices and electricity prices were set by the government. However, as underscored by the CREIA interviewee, coal prices were harder to control as domestic prices were increasingly exposed to international market prices.

3.3.2 Support to domestic turbine manufacturers

In 2006, the state council identified large capacity wind power generation units as part of a group of key technologies that were “greatly related to the development of the national

economy".[93] The NDRC's 2007 Medium- and Long-Term Plan for Renewable Energy Development in China established the following goals:

> *By 2010 China will basically have achieved the ability to produce domestically the main renewable energy equipment it uses. By 2020, local manufacturing capability based mainly on home-grown Intellectual Property Right (IPR) will be achieved.*

The government implemented a number of measures which sought to establish a wind turbine manufacturing industry in China and support domestic firms. Local content requirements for government-supported wind power projects constituted the backbone of such efforts.[94] For the proposals submitted during the Concessions program the government set the local content requirement initially at 50% and increased it to 70% after the first round.[95] In addition, in response to concerns that these requirements were not being enforced, as of the fourth round of the concessions program, developers were asked to work with turbine manufacturers to submit details of their domestic manufacturing plans.[96] The 70% local content requirements were extended in 2005 to all wind farms built in China.[97] These were eventually removed by NDRC in 2009, at least partly in response to international complaints brought to the World Trade Organization (WTO). However, as detailed in Chapter 2, by that time a wind turbine component

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[93] "Several Opinions on Expediting the Rejuvenation of the Equipment Manufacturing Industry", State Council if the Chinese Republic of China, 13 February 2006.

[94] The first local content requirements related to wind power were introduced in the 9th Five Year Plan (1996-2000), which stated that turbine equipment purchased for projects approved by NDRC had to have a 40% local content. See Dewey & LeBoeuf (2010).

[95] Specifically, 70% of turbine components by purchase value must be manufactured in China and the turbines must be assembled in China.

[96] See Li et al. (2006) for a detailed account of the concessions program regulatory structure and details of the first four rounds of bidding and project allocations.

[97] "Notice on the Requirements for the Administration of Wind Power Construction", July 2005, National Development and Reform Commission (NDRC).

supply chain had been established in China and the market was dominated by Chinese firms that already exceeded these requirements.

Though as depicted in figure 2.11 the share of projects using turbines manufactured by foreign firms had dropped from 70% in 2005 to a little over 10% in 2009, it is difficult to establish whether NDRC favored domestic turbine manufacturers during the screening and selection of projects for the concessions program or after the enactment of the renewable energy law. Several criteria had been specifically identified for the approval of concessions projects, including bid price, local content requirements, technical plan, and technological track record, yet none concerned the nature of turbine manufacturers (Li et al., 2006; Baker & McKenzie et al., 2007). Similarly, all projects allocated in the first round of off-shore concessions used turbines from Chinese manufacturers (Zhang et al., 2011) though project allocation guidelines included no specific requirements to that effect.[98]

However, one indication that NDRC may have favored project proposals based on turbines manufactured by domestic firms was China's procurement law, effective since 2002, which mandated that government procurement target domestic suppliers when these were available.[99] It

[98] However, the off-shore project allocation guidelines state that the developer should be a "China-funded enterprise or Chinese-foreign enterprises where the Chinese party has a controlling stock interest". Interim Measure for the Management of the Development and Construction of Off-shore Wind Power, Article 14, National Energy Administration and the State Oceanic Administration, 22 January 2010.

[99] "The Government Procurement Law of the People's Republic of China", Order of the President No.68, 29 June 2002.

remained unclear however whether such procurement guidelines had applied to government investments in wind power.[100]

Still, the rapid dominance of the domestic market by Chinese turbine manufacturers may simply be due to financial reasons. Wind power deployment objectives for large power companies were set in terms of capacity installed rather than electricity generated. As highlighted by an interviewee from the CWEA the incentives were therefore primarily to buy the cheapest turbines rather than those which produced the cheapest electricity. This created an investment cost hurdle for foreign companies as their turbines were generally more expensive than Chinese turbines. Li et al. (2006), for example, note that project feasibility studies submitted in 2006 in the scope of the concessions program showed turbines from foreign manufacturers priced approximately 45% higher than turbines from domestic manufacturers.

One measure which favored domestic turbine manufacturers was a subsidy introduced in 2008 by the Ministry of Finance to encourage the development of increasingly large capacity turbines. [101] The subsidy was of a lump sum of RMB 600 per kW for the first 50 turbines produced of any new model with a capacity of 1.5MW or more. To qualify for the subsidy the wind turbine

[100] The clearest sign that the procurement law did apply to government investments in wind power came following a 2009 complaint from European manufacturers of wind power equipment about their exclusion from wind farm projects funded under the government economic stimulus plan. NDRC announced on its website that purchases for government investment projects counted as government procurement. See Asia Times, 11 June 2009, "Foreign Companies Blowing in the Wind". Still, it is unclear whether this comment concerned only stimulus funds or wind power investments more broadly.

[101] "Interim Measures for the Administration of the Special Fund for Industrialization of Wind Power Equipment", Ministry of Finance, Issued August 2008.

manufacturers had to be state-owned or under Chinese control.[102] The firms also had to own the intellectual property for their turbines. Furthermore, the blades, gearboxes, and generators used had to be manufactured by Chinese controlled companies, and turbines with Chinese-made converters and bearings were encouraged. In addition turbines had to be manufactured and tested in China. Recknagel (2010) estimates that the subsidy accounted for up to 10% of the development cost of a 1.5MW turbine. The program was ended in 2011 following a complaint by the United States to the WTO (USTR, 2011). However, as discussed in Chapter 2, by then the capabilities of Chinese turbine manufacturers were already relatively high and a complete domestic supply chain for turbine components had to a large extent been established.

The government measures detailed above were successful in creating a large domestic manufacturing market and in encouraging Chinese firms to enter it. Several measures were identified by interviewees as having been particularly instrumental in this respect. A CWEA interviewee underscored the pivotal role of the 100MW minimum project size of the concessions program in establishing a strong manufacturing base in China. An NEA interviewee credited the combined effects of creating a large market through the concessions program and the renewable energy law with the 70% local content requirement for spurring Chinese firms to enter the market.

[102] Firms under Chinese control are either Chinese firms or joint-ventures with Chinese firms owning a majority stake.

3.3.3 Addressing electricity grid integration issues

Grid integration had been one of the main stumbling blocks for the growth of the Chinese wind power market. Though the Renewable Energy Law discussed above stipulated that grid companies had to expand the grid to accommodate the growth in installed wind power capacity, in reality there was a growing lag in grid connections. By the end of 2010 the share of total installed wind power capacity in China not yet connected to the grid reached approximately 30% (Ni and Yang, 2012; Azure, 2011; National Energy Board, 2011; Schwartz, 2011). In addition, wind farms which were connected to the grid had experienced numerous large-scale disconnections, sometimes hundreds of turbines at a time, which had put significant strain on the electricity system (WPM, 2011e).

There appeared to be multiple reasons for these grid integration issues. First, on-shore wind farms were concentrated in the northern and north-western provinces of China, far from the large electricity demand centers in the central and eastern parts of the country. The growth in wind power in these regions exceeded the ability of the local grids to cope with all the wind power generated (Jiang et al., 2011). Grid connection therefore effectively implied building long distance transmissions lines, which were costly and demanding in terms of planning.

Second, the approval of wind farms by the government proved to be highly uncoordinated, making grid connection planning all the more difficult. NDRC had been responsible for the approval of projects over 50MW in capacity, while the approval of smaller wind farms had been left to provincial governments. This resulted in over 90% of Chinese wind farms being approved at the provincial level as developers sought to avoid the more stringent project review process of NDRC (WPM, 2011a).

Third, as underscored by Li et al. (2010) the renewable energy law and subsequent regulations concerning the power grid had failed to clearly define responsibilities, objectives, and incentives for grid companies to build adequate grid capacity.[103] Among other concerns Li et al. (2010) note that the regulatory framework had not included strict punishments when grid companies failed to build grid connections to wind farms, nor provisions for compensating wind farm developers for revenues shortfalls due to the lack of timely grid connection. In addition, the renewable energy surcharge proved insufficient to cover costs incurred by grid companies (CGI, 2012).

Finally, the rapid growth in installed wind power capacity had not been accompanied by the timely introduction of adequate standards concerning grid integration technology. There was notably no mandatory requirements concerning Low Voltage Ride Through (LVRT) technology, which allows turbines to stay connected to the grid in the event of a sudden drop in voltage at the point of connection. Most turbines in China were originally installed without LVRT or other grid integration functionalities and this had been highlighted as one of the main reasons behind the widespread disconnections.[104]

The government reiterated the obligation of grid companies to connect wind farms on numerous occasions.[105] It notably introduced amendments to the Renewable Energy Law in 2009

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[103] In particular "management Rules Related to Renewable Energy Power Generation", NDRC, 2006, and "Measures on the Supervision of Power-Grid Enterprise Purchase of the Full Amount of Renewable Energy Electricity", State Electricity Regulatory Commission, 2007.

[104] Standards were introduced in the early years of the Chinese industry, though these were of limited scope.

[105] See Li et al. 2010, Section 8.

which for the most part focused on addressing grid integration issues. The revised law raised the penalty to grid companies if they failed to comply with grid connection obligations, and called for setting quantitative targets linked to the obligations of grid companies.

In 2010 the government started introducing detailed measures to address grid integration issues. The NEA introduced regulations mandating the inclusion of specific grid technologies, both at the plant level and for individual turbines, including LVRT and other functionalities.[106] The Standardization Administration of the People´s Republic of China (SAC) also approved new technology requirements related to the grid connection of wind farms, which came into effect in 2012.[107]

Wind farms and wind turbines already in operation were required to be retrofitted with grid friendly technologies. The revised renewable energy law also emphasized the obligation of grid companies to purchase all electricity generated from projects "which conform to grid-connected technical standards".[108] In addition, the NEA introduced in 2010 a regulation which makes testing of grid connection and compliance with technical requirements mandatory for wind turbines used in newly approved wind farms (Jiang et al., 2011).[109]

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[106] "Design Regulations for Large-Scale Wind Power Connecting to the System", National Energy Administration, 2010.

[107] "Regulations for Wind Farm Connection to Power Grid Technology" (GB/T 19963-2011), Standardization Administration of China, December 2011.

[108] Article 14 of the amended Renewable Energy Law. The original text only contained the obligation to purchase all power generated.

[109] "Tentative Management Procedures for Grid-Connection Testing of Wind Turbines", NEA, December 2010

With respect to project planning, a new regulation introduced in 2011 set stricter project approval rules. Under the new rules construction of new wind farms could not begin before the approval process was completed or the projects would not receive feed in tariffs or grid access. Furthermore the new approval process required provincial governments to apply to the NEA for approval of wind farms under 50MW. In addition, all wind farms were required to have a formal evaluation one year after the start of operations (GWEC, 2011; Nomura, 2011).

In 2011, the government also raised the renewable energy surcharge on all electricity sales from RMB 0.004 per kWh to 0.008 per kWh to better support the mandatory purchase of power generated from renewable energy sources and the costs associated with grid extensions born by grid companies (CGI, 2012).[110]

Furthermore, to continue market formation while easing pressure on grid companies the NEA also introduced measures to accelerate the approval and building of wind farms in low wind resource areas, closer to electricity demand centers and therefore easier to connect to the grid (GWEC, 2011, WPM, 2011b; WPM, 2012). The first commercial low-wind speed project was completed in May 2011 and many new low-wind speed projects have since been approved.

Finally, in 2011, the State Grid Corporation, which by the end of 2010 accounted for over 96% of grid connected wind power capacity in China, released a white paper on the promotion of wind power (Schwartz, 2011; State Grid Corporation, 2011). The white paper was the first of its kind for the company and detailed plans for grid extensions associated with eight 10GW regional

[110] "Interim Measures of Development Fund for Renewable Energy Collection and Management", Ministry of Finance, NDRC, NEA, 29 November 2011.

wind power bases planned by the NEA. The white paper identified the wind power bases which would predominantly serve local demand and those which would serve load centers in central and coastal regions through new long distance high and ultra-high voltage transmissions lines (Ni and Yang, 2012). The whitepaper also outlined plans for the construction of extensive pumped storage capacity in order to help balance intermittent wind power and ensure grid stability (Schwartz, 2011).

Grid integration issues were highlighted by many interviewees as constituting a significant challenge to the progress of the Chinese wind power industry. With respect to the elaboration of the new grid standards, an ERI interviewee highlighted that these were primarily the result of lengthy negotiations between the large power generation companies and the state grid companies in response to the technical challenges created by growing wind power capacity. He explained that the government played primarily a facilitator role.

An NEA interviewee noted that there were now grid integration standards on three levels - the enterprise level, the industry level, and the national level – and that these concerned manufacturers, utility companies, and grid companies at the state and local level. A CWEEA interviewee explained that the new standards notably contributed to slowing down the pace of market development, at least temporarily, as wind farms and turbines which did not meet the new technical requirements would have to make improvements before being able to get approval. Similarly he explained that retrofitting existing turbines would take time and impose new costs on manufacturers and developers. The ERI interviewee was confident that these recent developments would lead to efficient grid infrastructures capable of integrating the foreseen growth in wind power capacity. He stressed that in light of the size of the Chinese wind market

and the pace at which it had grown, issues linked to such infrastructural adjustments were to be expected.

3.3.4 Addressing turbine technology issues

The evolution of wind turbine technology within the Chinese market was a central preoccupation for the government since the introduction of the concessions program in the early 2000s. The government had encouraged the development of increasingly large capacity turbines through a number of specific regulations. The government notably introduced minimum capacity requirements for turbines used in wind farms. In the scope of the concessions program, the government originally set a minimum turbine capacity of 600kW, which was increased from the fourth round of bidding in 2006 to 750kW. A further increase in 2009 of the minimum turbine capacity requirement to 1MW was also reported.[111] These measures were accompanied by clear goals concerning turbine size in planning documents. For example, in the 11th Five-year Renewable Energy Development Plan, released in 2008, NDRC called for achieving domestic production of 1.5MW onshore turbines by 2010.[112]

In 2008, to encourage the manufacturing of increasingly large turbines in China, the government introduced a rebate on VAT and border tariffs on the import of key components of turbines greater than 1.2MW in capacity. At the same time it also removed an import tax

[111] See New York Times, 13 July 2009, "China Builds High Wall to Guard Energy Industry".
[112] "Renewable Energy Development under the 11th Five-Year Plan", NDRC, March 2008.

exemption for turbines smaller than 2.5MW.[113] The rebates were updated in 2010 to include components of turbines greater than 1.5MW in capacity, and the threshold for the import tax exemption was raised to turbines above 3MW.[114] Similarly, as detailed in Section 3.3.2, the lump sum subsidy introduced in 2008 of RMB 600 per kW offered to Chinese manufacturers for the first 50 units of a new model also had a minimum capacity requirement of 1.5MW.

Another measure which aimed to encourage manufacturing of larger capacity turbines in China was to only include joint ventures for turbines larger than 1.5MW in the 'encouraged' section of the 2007 foreign investment catalogue.[115] In the 2011 edition, the threshold was raised to joint ventures for the manufacture of turbines above 3MW.[116]

However, the rapid growth of the Chinese wind power market also raised concerns among policy makers about the adverse effects of excessive competition on turbine quality. The wind power market attracted many new entrants to the Chinese turbine manufacturing sector, which by the end of 2009 consisted of approximately 80 firms (WPM, 2011d). As highlighted by a CWEA interviewee, the turbine market was characterized by intense price competition. Several interviewees from turbine manufacturers underscored that the shift towards Chinese suppliers of

[113] "Notice on Adjustments of Import Tariffs for Large-output Wind Power Generation Units, their Main Components and Raw Materials", Ministry of Finance, April 2008.

[114] "Notice on the List of the Interim Provisions on Import Tax Policies for Major Technology Equipment", Ministry of Finance and State Administration of Taxation, April 2010.

[115] "Catalogue for the Guidance of Foreign Investment Industries", State Council, Amended in 2007.

[116] "Catalogue for the Guidance of Foreign Investment Industries", State Council, Amended in 2011. This version also encourages foreign investment in specific components: various axletrees for turbines above 1.5MW and gear transmissions.

turbine components, detailed in Chapter 2, was one of the principal means employed to reduce turbine manufacturing costs. This in turn, resulted in growing competition among suppliers of turbine components, which further contributed to reduce costs.

Li et al. (2006) also highlight the unreasonably low project bids during the first rounds of the concessions program. Although alleviated by the introduction of fixed feed-in-tariffs for on-shore wind farms, excessively low bidding prices resurged in the scope of the first off-shore tender organized in 2010. The price range of RMB 0.62 to 0.74 per kWh for the four projects was only marginally above the range of RMB 0.51 to 0.61 per kWh for on-shore feed-in-tariffs, and was considered by experts to be significantly below the real costs of off-shore wind power (WMP, 2011c).

Turbine quality concerns peaked in 2010, when ten large wind turbines collapsed in quick succession in various Chinese wind farms. A CWEA interviewee explained that a CWEA investigation requested by the NEA highlighted important underlying systemic issues, combining component quality concerns to poor plant management. He gave an example of a combination of events that had caused a turbine to collapse. Not only had a key turbine component failed but the batteries of the failsafe system designed to stop the blades in such events were also not charged. Furthermore, though the turbine control system informed the operator of the battery discharge, the necessary maintenance was not provided. The turbine's rotor therefore span out of control in high winds leading to the turbine's eventual collapse.

Several turbine manufacturers explained that widespread turbine quality concerns have often led project developers to request that turbine manufacturers use particular component suppliers. For example, with respect to the main shaft bearing or the converters, two of the most important

components of the turbine in terms of potential down time and damage costs, developers have often requested that turbine manufacturers use foreign suppliers. This raised the price of the turbine yet offered developers some guarantees concerning future O&M costs.

To address turbine quality concerns, the government aimed to progressively reduce competition in the market by dissuading low-quality turbine manufacturers from remaining in the market. In a notice issued in 2009, NDRC and other government departments announced that they would seek to prevent overcapacity in the wind power equipment industry so as to encourage leading enterprises and limit excessive price competition.[117] In 2010, the Chinese Ministry of Industry and Information Technology (MIIT), in collaboration with NDRC and NEA, issued a draft regulation on admittance standards for the wind turbine manufacturing industry, which aimed to limit access to the wind turbine market to firms with a certain level of capabilities (Baker Botts, 2010; WPM, 2010). The standards included the requirements that manufacturers be able to produce turbines of at least 2.5MW in capacity, have total annual turbine manufacturing capacity greater than 1GW, and have a track record of having produced at least 200 megawatt-class turbines which have each undergone 240 hours of operations. The proposed standards also set requirements with respect to specific R&D capabilities, including the ability to design complete turbines and to hold expertise in such fields as aerodynamics, structural analysis and software development. Failure to meet these requirements would lead to the loss of government entitlements, including tax benefits, land access, and bank loans.

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[117] "Notice of the NDRC and other Departments of Certain Opinions in Relation to Curbing Overcapacity and Repeated Construction in Some Industries and Guiding the Healthy Development of Industries", NDRC, September 2009.

Measures aimed to address grid connection issues discussed in Section 3.4.3 were also deemed to have positive effects on turbine quality. The wind farm approval reforms introduced in 2011 notably gave greater oversight of project quality to the NEA. An NEA interviewee also explained that the new grid technology requirements implicitly required a certain level of technological capabilities and forced companies to invest more in R&D and other technological capabilities.

Several interviewees were cautious about the proposed manufacturer admittance standards. One interviewee from the CWEA acknowledged the turbine quality issues in the Chinese wind power market but believed that ultimately a shakeup of the industry should be driven by competition among firms. Another CWEA interviewee made a parallel to the beginning of the European wind power market, where the market consolidated naturally over time. The interviewee also downplayed concerns about the excessive number of manufacturers in China, noting that the majority had in fact produced very few turbines. He explained that at first, small firms that had secured orders could simply purchase components from suppliers and assemble them to produce turbines. However, he stressed this was unsustainable in the longer term as demands in terms of technology, logistics, and scale had increased significantly. He noted that at the time of the interview there were only 10 to 15 manufacturers in China capable of meeting these increasingly high demands. This view was echoed by a Chinese Wind Energy Equipment Association (CWEEA) interviewee, who thought competition was the only thing which would actually make existing firms leave the market. He stressed that the low turbine prices made it

difficult for turbine manufacturers without large production bases to remain in the market.[118] The standards, in his view, were therefore not necessary.

3.3.5 Structural and institutional issues undermining the quality of wind power projects

Interviews with various actors of the Chinese wind turbine technology development system highlighted a number of characteristics of the Chinese wind power market and its institutions which undermined the quality of wind power projects. Three of these are discussed below.

3.3.5.1 Misplaced incentives

As highlighted by a CWEA interviewee, the fact that the government set wind power deployment targets for power generation companies in terms of installed capacity rather than power generated had a profound impact on the quality of turbines selected in wind power projects. The interviewee explained that the main wind farm developers were owned by large state-owned enterprises whose main priority was to show the government the fast pace at which they were installing wind power capacity. He stressed that for a long time questions of turbine quality and wind farm operation and maintenance (O&M) were not a high priority. As a result, the wind turbine market became crowded with manufacturers that focused on producing turbines at low cost rather than based on their long-term performance.

However, an interviewee from North China Electric Power University (NCEPU) noted that the situation was changing. Part of the reason was because the warranties on turbines in a growing

[118] At the time of the interview, turbine prices in China were under 4,000 RMB/kW, with some as low as 3,800 RMB/kW.

share of existing wind farms were expiring. Under most wind farm contracts in China, wind turbines were covered by warranties for two or three years, during which time turbine manufacturers were responsible for O&M. After this initial period, O&M responsibilities were passed on to the wind farm owners.[119] A CREIA interviewee noted that as a result of this, developers had started to compare more carefully the merits of different turbines. He explained that this contributed to progressively rising technological demands placed on turbine manufacturers.

A CWEA interviewee also noted that bank lending in the scope of wind farm financing was not based on an evaluation of project quality but rather on what collaterals the firm taking the loan could provide. In contrast, he stressed that in Europe or the United States, banks paid close attention to the project itself, often asking independent auditors for due diligence work prior to agreeing to a loan, and thereby providing an additional quality based verification of projects.

3.3.5.2 Turbine certification issues

Interviews with wind turbine manufacturers highlighted that most wind turbine models they had produced had received design certification while only a few had received type certification.[120] The Chinese wind turbine manufacturing market began its rapid growth prior to

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[119] The interviewee explained that unlike in the US where O&M is often outsourced to specialized firms, in China the power companies have their own O&M teams.

[120] A design certification implies that the criteria listed in the turbine design documents were sound and the turbine will operate safely and according to the stated power generation information. The standard practice is for the certification organization to check all the calculations and procedures identified in the design documents by running its own calculations using the same input data to verify the robustness of the turbine designs provided by the

the establishment of Chinese wind turbine certification organizations and as a result much of the certification of Chinese turbines was undertaken by established foreign firms, which were quick to offer wind turbine certification services in China. These included Germanischer Lloyd (GL) and Technischer Überwachungs-Verein (TUV), both from Germany, as well as Det Norske Veritas (DNV) from Norway. Chinese certification organizations which were progressively increasing their involvement in the wind power sector included the China General Certification Center (CGC) and the China Classification Society.

A CGC interviewee noted that turbine design certifications used in China followed the same basic process as in Europe or the United States, and implicitly assumed that turbine production processes followed the specifications outlined in the design documents. However he highlighted that this was often not the case in China, and that this may explain some of the technology issues experienced by certified turbines in recent years. He explained that in a European or the United States context turbine design certification may be sufficient as factories and manufacturing plants had their own quality standards, such as ISO 9000, which could be relied upon. In addition, firms typically had teams responsible for quality control, often including dedicated testing laboratories. He noted that in China however, the manufacturing conditions most often did not meet such quality standards. For example he explained that the Euro Code 3 standard for steel structures were not used for turbine towers in China as welding methods commonly used in China did not correspond to welding standards identified in the Euro Code 3 standard.

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manufacturer. Firm audits may also be undertaken to check control systems. Type certification includes design evaluation, as well as the testing of machines, and manufacturing evaluation (RED, 2011).

The CGC interviewee therefore stressed the need for more extensive turbine certification procedures tailored to Chinese conditions. He explained that his organization had completed a new blade certification protocol specifically elaborated for China which he thought may help address these issues. The first steps were similar to that of international certification organization, and focused on the verification of design documents. Then a prototype of a blade manufactured using the design document should be tested according to all standard test procedures. A third step was a verification of the blade manufacturing process, for example to check that the plant was equipped with temperature and humidity control systems, as well as adequate blade material mixing machines. In addition, the procedure included personnel requirements with respect to training on how to use the machines. Finally the certification included unplanned audits of the manufacturing plants.

The interviewee explained that CGC was planning on developing certification protocols for other main turbine components, such as gearboxes and the generator. However he was concerned that more extensive turbine and component certification procedures would not easily be adopted. A CREIA interviewee underscored that there were no government policies in place which specifically required certification and that the certification of turbines was primarily a result of market forces.[121] The CGC interviewee noted that some Chinese turbine manufacturers failed to understand the role of certification and sometimes put pressure on them to provide certificates in a very short time, threatening to go to a competing organization if this could not be done.

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[121] One regulation which did require turbine certification was the lump sum subsidy, discussed above, given between 2008 and 2011 to manufacturers that introduce new, large capacity models. Furthermore, the wind turbine manufacturing standards proposed by MIIT, also discussed above, refer to the need for manufacturers to have quality certification.

3.3.5.3 Wind resource monitoring and modeling issues

Another hurdle to the development of quality wind power projects in China concerns the monitoring and modeling of wind power resources. An ERI interviewee noted that in the United States or Europe, wind farm developers relied on specialized consulting firms to undertake detailed assessments of wind resources at potential wind farm sites. He explained that in contrast, in China the pace of development was such that site selection had not been given a high priority by developers. Rather than do a complete assessment of wind resource availability, a common approach had been to copy others. For example, in Inner Mongolia, where many existing wind farms were located, wind farm siting decisions had often been based on the performance of neighboring wind farms rather than on the assessment of a site's specific wind resources.

A CWEA interviewee explained that an additional issue concerned the wind load models commonly used in the turbine manufacturing process. The models used were defined by the International Electrotechnical Commission (IEC), based primarily on experience accumulated in the United States and EU markets. However, the interviewee explained that these models were not well suited for Chinese wind conditions. Measurements of wind loads from various areas in China, such as Xingjian, showed distinctive functional forms. He explained that in such conditions, using turbine designs based on the IEC wind load model would be inefficient at best, and may have implications in terms of O&M. He concluded that much worked still needed to be done in terms of wind load modeling to better capture the wind profiles of different regions of China.

3.4 SUPPORT TO WIND POWER RESEARCH AND DEVELOPMENT (R&D)

R&D was an important theme in several interviews. This section describes some the main features of the Chinese wind turbine technology development system in support of R&D and discusses the most salient findings from the interviews. As for interviews with turbine manufacturers discussed in Chapter 2, R&D was not strictly defined to allow interviewees to discuss all activities they deemed to fall under the umbrella of R&D.

3.4.1 Firm incentives to invest in R&D

Effective since 2008, the Enterprise Income Tax Law shifted the emphasis of industry tax incentives from export-driven manufacturing and regional development, to new and high technology enterprises and the development of specific industries.[122] Wind power was among the encouraged sectors and as such wind turbine and other component manufacturers could benefit from these tax incentives. Firms, however, needed to qualify as new and high technology enterprises, which required owning core intellectual property and investing between 3 and 6% of revenues in R&D, with at least 60% incurred inside China.[123] In addition, firms were required to have 30% of their science and technology personnel with college or university degrees, and at least 10% involved in the R&D of high or new-technology products or services. The regulations also provided detailed definitions of what activities and projects qualified as R&D. They also established a system where firms had to reapply every three years to continue benefitting from

[122] As noted previously the law offered a reduction in income tax from 25% to 15% for high-technology firms.

[123] R&D investment rates ranged from 6% if revenues were below RMB 50 million to 3% if revenues were above RMB 200 million. R&D investments were to be maintained at these levels over three-year rolling periods.

the status of new or high technology enterprise (Deloitte, 2007; Orrick, 2010). The new Income Tax Law also reformulated a pre-existing 'super-deduction' of R&D expenses by new and high tech enterprises, allowing them to deduct 150% of their R&D expenses from their tax bill (Deloitte, 2009).

Furthermore, an interviewee from MOST added that because firms in the wind power sector were for the most part state-owned or state controlled, investing in R&D reduced the amount of the firm's profits which the government could claim, and this itself constituted an additional incentive for investing.

3.4.2 Government R&D funding

The two main actors involved in government funding of wind power R&D are the National Natural Science Foundation of China (NSFC), and the Ministry of Science and Technology (MOST). The NSFC supports basic science projects through research grants allocated through a yearly competitive project proposal selection process. These are relatively small scale projects that emphasize the publication of research findings in peer reviewed journals. An interviewee from MOST explained that support for wind power R&D from MOST was primarily articulated around the three national science and technology programs: the National Basic Research Program (973 Program), the State High Tech Development Program (or 863 Program), and the Science and Technology Support Program. These are structured along clearly identified project guidelines. The 973 Program focused on long-term applied research projects, and is deemed to lay the foundations for the next stage of technological development. The 863 Program focused on technological issues deemed of practical relevance to the industry in the next 5 to 10 years. Finally, the Support Program focused on key technical problems linked with mass production

and commercialization. The MOST interviewee stressed that unlike projects supported by the NSFC, MOST programs funded applied research and therefore emphasized concrete solutions and tangible outputs.

A key distinction among these distinct R&D project funding channels was the source of funding. Given its focus on basic science, the NSFC is entirely funded by the government. The MOST 973 Program target long-term research and as such projects were also almost entirely funded by the government. In contrast, because of its focus on technology development, the 863 Program had by design a high level of involvement from firms, notably through collaborations with university and research organizations. An estimate by the interviewee from MOST was that the government funded on average between 50-60% of the costs of projects supported in the scope of the 863 Program while firms funded the rest. Finally, projects under the Support Program were for the most part funded by firms. NEA and CWEA interviewees noted that most government funding for wind power R&D was funded through the 863 and Support Program. Only relatively small amounts of wind power research funding were channeled through the 973 Program or the NSFC.

NDRC and MOST established a network of state sponsored laboratories, so called National Laboratories and State Key Laboratories. As explained by the MOST interviewee, these could be set up within universities or firms which had a proven track record of excellence in a given field. When these were established within universities the government provided some limited yearly research funding. For example an interviewee from NCEPU explained the University received some core research funding from the government for its Key Laboratory for Alternative

Electrical Power Systems with Renewable Energy Sources, though this was a very small fraction of the lab's research funding needs.

When such laboratories were set-up within firms, they were expected to fund the entirety of the laboratory's R&D. Among the six leading Chinese wind turbine manufacturers interviewed, Sinovel's new National Energy Offshore Wind Power Technology and Equipment R&D Center, Goldwind's National Wind Power Engineering Technology Research Center of China, United Power's National Key Laboratory on Wind Power Equipment and Control Technology, and XEMC's National Key Laboratory of Wind Power Generation Technology were recognized by the central government as national or state key laboratories.[124]

A CWEA interviewee explained that prior to the rapid growth of the Chinese market MOST R&D funding was instrumental in supporting Chinese firms involved in wind turbine technology development. For example in the early 2000s Goldwind received government R&D funding to support industrial production of the its 600kW model as well as development of its 750kW model. However, the interviewee noted that as the Chinese wind market grew, the financial support from MOST became progressively small compared to the resources firms were independently investing in technology development. This view was echoed by an interviewee from ERI who thought R&D funded through MOST programs had, by the time of the interview, in fact very limited significance compared to the R&D efforts independently funded by firms.

[124] The Sinovel interviewee explained that the government funded approximately 10% of the total investment cost to build the firm's new R&D center. Funds came from a special fund created by article 24 the Renewable Energy Law.

This was further supported by interviewees from Chinese turbine manufacturers. An interviewee from Goldwind noted that the firm had received some government R&D support for every model they had developed. Other turbine manufacturers interviewed had also been involved in MOST R&D projects in the scope of their turbines developments. For example, Dongfang received project funding from the government for the development of its 2MW turbine. SEWind was involved in a project for the development of blades and control systems in the scope of the company's 3.6MW turbine. The company was also seeking MOST funding for its planned 5MW turbine. Similarly the United Power interviewee indicated that the firm was seeking 863 project funding to pursue the development of its planned 12MW turbine. However all manufacturers indicated that government R&D funding represented only a relatively small fraction of their total R&D investments. While the Goldwind interviewee estimated that approximately 10% of the firm's total R&D expenditures were supported by government funds, others noted to a much small contribution.[125] The Dongfang interviewee, for example, explained that the firm received approximately 3% of the cost of developing and erecting the prototype for their 2MW turbine from a MOST project.

An interviewee from United Power stressed that the main benefits of participation in MOST supported R&D efforts were not the financial support received, noting that large wind turbine manufacturers did not lack resources to invest in R&D. Rather, it was the honor the firm received and the recognition which came with it. He stressed that this honor from undertaking a MOST supported R&D project was the best advertisement a firm could receive for its products. The

[125] The Goldwind interviewee underscored that the firm received funds through MOST projects as well as NDRC or the ministry of Industry and Information.

interviewee from XEMC echoed this view, noting that though they received limited funds from the government, taking part in government-supported projects was excellent promotion as it reflected the firm's technological capabilities to develop new products. This point was also underscored by the CWEA interviewee, noting that though the relative value of the financial contribution received from MOST Programs had decreased as the industry had grown, taking part in MOST projects remained a prized honor for Chinese firms and they were therefore keen to continue playing an active part in such projects.

Nevertheless a CREIA interviewee questioned the organization of MOST Programs around specific projects, noting that these were typically narrow in scope and failed to provide continuity. He explained that such projects lasted no more than one or two years and typically brought people together from firms and various research organizations for this time period only. There were no incentives or mechanisms in place to follow up on the achievements of the project and really test whether findings were usable or not over time. This short-sightedness made accountability for project results difficult as it remained unclear which projects had been successful and which had not.

3.4.3 Government R&D planning

Interviewees from MOST, CWEA, Tsinghua, CAS, and NCEPU explained that two years before a five-year plan, MOST brought together a large group of experts which was tasked with identifying a detailed list of R&D issues that needed to be addressed in the next five-year period. An interviewee from Tsinghua estimated that for every subject area, such as wind power, dozens of experts were involved, often times through industry associations such as CWEA. An interviewee from Goldwind explained that the process brought together turbine manufacturers,

wind farm developers, experts from universities, as well as industry associations. Another interviewee from CWEA indicated that the process was also informed by international experience. An interviewee from CASTED indicated that his organization notably assisted MOST in this planning process, such as by conducting studies of best practices internationally.

This expert consultation process resulted in detailed guidelines on a list of projects which MOST sought to fund. These included strict technical parameters, with some focusing specifically on the research procedure and key outputs. The guidelines were then made public, after which research groups and firms were able to submit proposals to receive funding and undertake a given project. A MOST committee then evaluated the projects submitted and selected the proposals it would fund. This was also informed by the research credentials of applicants and track record of past collaborations. Interviewees explained that following project completion, an audit by a team of experts from MOST checked whether the project objectives laid out in the proposals had been met and whether funds allocated by the government had been used according to the plan.

For example, 863 Program projects undertaken during the 11th five-year plan (2006-2010) included projects focused on the development of new turbine models, specific components, software, or new applications. Table 3.1 provides titles of some projects in each of these categories.

Starting from the 12th five-year plan (2011-2016), however, the planning process changed. A CAS interviewee explained that instead of establishing a detailed list of project guidelines the new approach only provides broad directions. Firms and research institutions therefore had greater freedom to submit proposals based on these broader guidelines. A MOST committee then

selects the best projects and uses these to form the new five-year research plan. The MOST and the firms or institutions which had been selected then negotiate the work plan and the terms of the agreement. One example of a project supported in the scope of the 863 Program in 2012 was entitled "Very large off-shore wind turbines" and consists of a consortium of research institutions and firms. The project included United Power and the 12MW turbine discussed in Chapter 2. In contrast, a project supported in the scope of the Science and Technology Support Program in 2012 was entitled "7MW wind turbine and key component design and industry production technology", highlighting the strong emphasis of the Support Program on commercialization.

Table 3.1: Examples of wind power 863 projects funded during the 11th five-year plan (2006-2011)

Project area	Name of project
New turbine models	2 MW direct-drive wind turbine and the design and manufacturing of its key components
	1.5 MW wind turbine low wind speed and the whole development of key technology development
Components	Wind turbine bearing design and manufacturing technology
	Aerodynamic and structural design of wind turbine blades
	Low voltage ride through technology
Software	Short-term forecasting technology of wind power generation
	Comprehensive analysis of wind farm siting software development tools

Some interviewees questioned the value of the MOST R&D planning process. An interviewee from ERI explained that the process tended to lag behind developments within firms and therefore had limited influence on the direction of R&D. An interviewee from NCEPU explained that for new industries MOST played an important role in identifying future technology trajectories. However, as an industry grew, manufacturers' own investments in R&D became larger than government R&D funding, and firms made decisions independently.

Nevertheless, a CWEA interviewee thought that though MOST funding was now small relative to resources expended by firms on R&D, the MOST R&D project planning still served to guide technology development efforts within the industry. He also noted that when some firms took part in such MOST supported R&D projects, other firms noticed and this would typically influence their own technological development choices.

A CASTED interviewee highlighted another aspect of the project selection process. He explained that it naturally involved firms which had the technological capabilities to solve problems and therefore was a way to identify and invest in R&D driven firms rather than those more focused on production.

3.4.4 The lack of a public platform for wind power R&D

A critique voiced by many interviewees was that the organization of government support for wind power R&D failed to provide a public platform allowing for the pooling of R&D resources and the sharing of findings among various actors. As explained by NEA, MOST, and CWEEA interviewees, only recipients of government sponsored R&D projects benefit from the resulting technology, knowledge, and knowhow developed. Similarly, CREIA and ERI interviewees stressed that the existing national or key laboratories belonged to the hosting firm or university. The government had little practical involvement and there were no obligations to share findings. The CREIA interviewee noted that in the case of firm laboratories in particular, output was not shared with others in the industry aside from eventual commercial technology transactions. The ERI interviewee stressed that as a result, R&D remained concentrated within firms which had their own research groups serving their own interests. He viewed that not having national laboratories or companies which provided R&D services to the all industry actors was an

important institutional limitation to the establishment of high quality wind power R&D in China. He stressed however that this was not unique to the wind power industry and that solutions would therefore imply broad institutional reforms of the ways in which government funds and supports R&D in China.

Still, the NEA and CWEA interviewees explained that the issue was increasingly recognized and the idea of creating a public platform for wind power R&D was gaining traction within the government. The models for such a public platform most commonly cited by interviewees were the National Renewable Energy Laboratory (NREL), in the United States, and the Risø DTU National Laboratory for Sustainable Energy, in Denmark. However, several important questions remained about the role and organization such an institution would have in China.

One concerns the testing of components and turbines. As noted by the CWEA interviewee, public R&D platforms in the United States and Europe had revolved around offering state of the art, large scale testing equipment. For example, for a long time NREL operated the only complete turbine test bed – a 2.5MW dynamometer testing facility – which was the only place in the country where firms could bring complete drive trains to be tested and demonstrated. Such test laboratories were established more recently in Europe. For complete blade testing only few locations existed in the United States and Europe, again often located in shared R&D testing facilities. In contrast, the CWEA interviewee explained that in China, almost all the main manufacturers had their own large scale testing equipment for complete drive trains. Similarly, all blade manufacturers had their own blade test bed. The interviewee explained that given that most Chinese firms had their own testing equipment there was a risk that no one would use testing facilities offered by a possible public R&D organization in China.

Another question concerns the advantages of working within a public R&D platform compared to R&D centers within firms. The CWEA interviewee noted that NREL and RISO were established prior to the emergence of large wind turbine manufacturers and played an instrumental role in developing key technological knowledge at very early stages of the industry. In contrast, in China large turbine manufacturers developed prior to the establishment of such a public research platform, making the process of setting up such an organization very different. He explained that Chinese manufacturers had increasingly better capabilities to develop technologies, were often associated with very large industrial groups, had the financial resources to invest, and were able to hire qualified engineers.

One proposal put forth by the Institute of Electrical Engineering of the CAS in the scope of the 12th five-year plan was to establish a complete 15MW dynamometer test bed as a public platform dedicated to components and complete turbine systems R&D. The CAS interviewee stressed that the main focus of test beds operated by firms in China had been basic testing and quality control of products. In contrast the proposed public testing facility would be dedicated and fully equipped to undertake extensive testing and experimentation of components and turbines.

The NEA had also instructed ERI to work on a proposal to create a new R&D organization with a truly public outlook in China, following the model of RISO and NREL. ERI interviewees explained that their objective was to start by creating a new center, independent from existing universities, research organizations, or firms, yet which would be supported by a number of existing institutions, including existing key laboratories and national laboratories.

3.4.5 The role of research institutions

Chapter 2 discussed the role of Chinese universities and other research organizations from the perspective of turbine manufacturers. Here, I highlight some of the findings from interviews conducted with professors working on wind power technology development at three prominent Chinese universities or research organizations: Tsinghua University, considered by many as the leading science and engineering university in the country; North China Electric Power University (NCEPU), created by the then Ministry of Electricity and focused exclusively on engineering disciplines linked to the generation, transmission, and distribution of electricity; and finally, the Chinese Academy of Sciences, which focuses on natural sciences, engineering, and technology research. I highlight the type of research undertaken by each professor's research group and how this was linked to industry needs. The aim is to provide a complementary perspective on interactions between firms and research institutions to those discussed in Chapter 2. Furthermore, focusing on some of the leading research groups allows gauging the contribution of universities and research institutions to the Chinese wind power technology development system.

However, before discussing the work of these various research groups, it is worth noting that other actors of the Chinese wind turbine technology development system generally considered interactions between industry and research institutions as playing a secondary role in technology development efforts in China. An ERI interviewee stressed that such R&D collaborations accounted for only a small fraction of technology development efforts, noting that the bulk of activities took place within firms alone. A CWEA interviewee explained that though there were many research institutes and universities in China involved in wind power research only a small portion of what they produced was being used by firms. He thought Chinese research institutes

and universities placed too much emphasis on traditional academic metrics, such as the publication of research articles, rather than on the commercial application of their research.

This last critique was particularly telling of the conundrum faced by universities and other research institutions involved in wind power research in China. While these aspired to contribute to knowledge development, much of the needs of Chinese firms were geared toward technology support and problem solving. This was underscored by a Tsinghua professor who explained that in advanced economies, firms often had their own laboratories with skilled researchers and good experimental set-ups. Universities therefore tended to focus on basic or advanced applied research. In contrast, in China firms had less experience and lower capability levels. Universities therefore often focused on collaborating with firms to help them solve technical problem and develop their technologies. This view was complemented by an interviewee from NCEPU who explained that engineering research in China was closely linked to the short-term demands and needs of the industry.

3.4.5.1 Department of Electrical Engineering, Tsinghua University

The interviewee's research group consisted of five professors (three full professors, including the interviewee, and two associate professors), two postdoctoral students, ten doctoral students, and many Master students. The group was associated with the State Key Laboratory of Control and Simulation of Power System and Generation Equipments, established at Tsinghua University in 1995. The interviewee estimated that about a third of the group's funding came from MOST and the rest from firms.

During the 10th five-year plan period (2001-2005) the interviewee's group focused on Double Fed Induction Generator (DFIG) and converter technology. He explained that at the time, no manufacturer in China was familiar with DFIG and the group was awarded a MOST 863 project to develop DFIG generator designs as well as the technology needed for manufacturing, such as design software, etc. They worked on this project in collaboration with Guodian, one of the main power generating firms in the country. The group also received funding from the government for research on converter to be used with DFIG generators. It built the first mega-watt scale DFIG generator and converter in China and by the end of the 10th five-year plan they had developed essential knowhow to manufacture DFIG generators and converters. He stressed that this was not particularly advanced research, noting that very few universities in advanced economies worked on generators because such technology development efforts were mostly concentrated within firms. Nevertheless, he explained the group's efforts constituted an important foundation for the Chinese industry as they transferred the resulting generator technology to over 20 manufacturers in China, including Shanghai Electric and Lanzhou Electric Corporation, who were the first to develop DFIG generators in the country. They also transferred their converter technology to various firms, notably Leader Harvest Electric Technologies, which was the largest manufacturer of converters in China.[126]

During the 11th five-year plan, the group received funds to support the commercialization of generators and converters. They also started to work on wind turbine control systems. They developed software and a prototype of a turbine's main control system in collaboration with a

[126] In 2011the firm was acquired by Schneider Electric, a multinational energy management company headquartered in France.

manufacturer supported by one of the grid companies. The interviewee explained that they had since transferred their main control system technology to several others firms. In addition, the group worked on the development of pitch control systems, and eventually transferred the technology to Guodian. The interviewee explained that these projects were funded for the most part in the scope of the MOST Supporting Program.

The group also collaborated with Sinovel, for which they received some support funding from the Beijing Municipal Government. The collaboration focused on three technology development projects for wind turbines of 5MW capacity or above. The first was the development of Low Voltage Ride Through (LVRT) technology for large DFIG wind turbine systems. The second was the development of a mid voltage full power converter. Finally the third focused on the development of an electromagnetic coupler, which aimed to combine a variable speed rotor shaft with a constant speed generator. The objective of the latter was ultimately to restore the use of fixed speed synchronous generators, thereby avoiding the need for full power converters and facilitating grid integration.[127]

The interviewee explained that the third project was a particularly novel technology development effort. Though Sinovel did not pursue the idea beyond the research stage, Guodian had decided to move this from research to application and had established a project to develop a prototype of the coupling system for a 1.5MW turbine. At the time of interview the manufacturing had been completed and they were in the process of assembly. The group planned

[127] The idea was similar to a hydraulic coupling system developed by a Germany company called Voith, though the interviewee explained that he thought his group was the only known research group to work on an electromagnetic coupling system.

to pursue research on the electromagnetic coupler during the 12th five-year plan period. One direction was to develop further prototypes to test the new device, first developing a 3MW version and progressively applying the technology to even larger turbines. Another direction was to develop a new type of generator which would integrate the coupler and a generator into one product.[128]

3.4.5.2 Department of Automation, Tsinghua University

The interviewee's group consisted of one full professor, one assistant professor, five PhD students, and eleven master students. The group had been working on wind power since 2005. The interviewee estimated that approximately three quarters of the group's funding came from firms while the rest came from government research support funding.

The work of the group with respect to wind power could be divided into two types of activities. The first consisted of projects which focused on technological solutions beyond a ten year time horizon, while the second consisted of technology support projects undertaken with firms. Examples of projects which fell in the first category included research on torque vibration damping in very large direct-drive permanent magnet wind turbines, over 10MW in capacity. Another example was a project on how individual blade pitching strategies could contribute to stabilize very large floating offshore turbines. The interviewee explained that both these projects

[128] In this new device the 'stator' is rotating as well. There are therefore two rotors, an inner rotor, and an outer rotor, allowing for the adjustment of the relative speeds. The result is similar to a gearbox but because there is no contact between the inner and outer rotors there is no friction and no wear.

were funded by a National Natural Science Foundation research grant and the primary outputs were research papers published in specialized peer reviewed journals.

With respect to the second type of projects the interviewee explained that the group worked with firms on the development of converters and pitch control systems. One example was a project, completed shortly prior the interview, with Dongfang Electric. The objective was to help the firm develop the control system of a new converter for 1.5MW direct-drive wind turbines. This involved building experimental set-ups and running a series of tests in the firm's R&D facilities.

3.4.5.3 Department of Thermal Engineering, Tsinghua University

The interviewee explained that he had only worked on wind power research for five years and had one PhD student working with him on the topic. His area of expertise was non-linear dynamics applied to structural engineering.

He explained that his group first ventured in wind power R&D to provide technical assistance to firms. One early project consisted of assisting a Chinese turbine manufacturer with making modifications to turbine designs obtained through technology transfer and advising the firm on how to best collaborate with foreign firms. Another project involved technical advice to a manufacturer and a wind farm developer to try to understand why several turbines had collapsed.

The group's more recent research focused on wind turbine design. The interviewee explained that design procedures used in the industry did not appropriately account for dynamic and non-linear properties. He emphasized that in reality wind loads were constantly changing and therefore led to complex structural behaviors. Vibrations, for example, were addressed very

differently from a dynamic system perspective than from that of a conventional linear perspective. The group therefore aimed to build a more complete, dynamic mechanical model of the turbine structure and to develop a new turbine design program. In a first instance the objective was to publish results in peer reviewed journals. However if results obtained were positive the group would seek further funding from the National Natural Science Foundation and would consider approaching firms to collaborate on further development.

The interviewee explained that the size and scope of this project made it impossible to get funding from the three main MOST programs and had therefore used funding left from projects in coal combustion to support this research.[129]

3.4.5.4 School of Renewable Energy, North China Electric Power University

I interviewed two professors from the School of Renewable Energy who led groups almost entirely dedicated to wind power research. Both professors, however, stressed that a number of other professors in NCEPU's School of Electrical Engineering, School of Control and Computer Engineering, and School of Mechanical Engineering worked on various wind power technology projects. One of the professors interviewed led a group consisting of himself, one assistant professor, one lecturer, six PhD students, and a number of master students. The interviewee explained that approximately 30% of his group's research funding came from participation in MOST projects, primarily through the 863 Program, while 70% came from collaborations with firms. He underscored that the focus of his group's research was first and foremost on the

[129] The interviewee had also already been awarded the maximum of two National Natural Science Foundation projects allowed per person and per year.

production of technologies aimed to solve specific industry problems and which were readily usable.

During the 11th five-year plan period, the group led a MOST 863 project on the development of a wind power prediction model at the wind farm level. The project was a collaboration with the China Meteorological Bureau and a wind turbine manufacturer. The interviewee explained that the project resulted in software that the group was hoping to commercialize. The group also worked with a wind farm developer on the optimization of wind farm designs, specifically focusing on the siting of turbines in complex terrain. Though data availability was limited for China, they were able to use European data collected by RISO for very specific terrains to test and validate their models. Finally the group also worked on a project with Siemens, on the development of a wind turbine remote condition monitoring system. This project was based on the combination of various methods to continually assess the conditions of turbines and evaluate maintenance needs. These included the collection and analysis of data in real time from sensors placed within the turbines. With respect to the 12th five-year plan period the interviewee explained that to the group would shift some of its focus to offshore applications.

The second professor interviewed led a group consisting of himself, an assistant professor, five PhD students, and several master students. He explained that during the 11th five-year planning period MOST funding represented about a quarter of his group's total research funding, with the rest coming from industry collaborations.

His group focused on the development and design of wind turbines, noting that this was similar to R&D teams within turbine manufacturers. The interviewee explained that since 2008 his group had embarked on three large projects and were also involved in a number of smaller

projects. The first of the large projects was a MOST Supporting Program project on the development and demonstration of a 5MW offshore wind turbine. The project was led by two Chinese turbine manufacturing firms and his research group played a supporting role. The second project consisted of designing a 3MW offshore gearless DDPM wind turbine for a Korean company and also involved providing training to the firm's engineers. The third project was in collaboration with another Chinese manufacturer on the design and development of a 1.5MW onshore wind turbine. He noted that in many cases the firms with which his group collaborated did not have much expertise in wind power and had limited R&D capabilities.

3.4.5.5 Institute for Electrical Engineering, Chinese Academy of Sciences

About 10 people worked on wind power at the CAS Institute for Electrical Engineering, which included professors, post docs, and PhD students. The interviewee explained that the institute first got involved in wind turbine technology R&D in the late 1990s, in response to growing concerns within the government that all turbines installed in China were imported. The institute started work on the development of turbine converters and control systems. The interviewee explained that during the 10th five-year plan (2001-2005), his institute was the main research group in China to receive funding from MOST for wind turbine converter and control system research.

To commercialize the technologies developed by the institute, a startup company was established in 2001 called Beijing Corona Science and Technology. The interviewee explained that at the time of the interview Corona had approximately 50 R&D staff, of which 20% held PhDs, 50% master's degrees, and the rest bachelor's degrees. He stressed however that in

practice it was often difficult to distinguish the institute from Corona as they collaborated very closely on R&D and product development.

The first converters and control systems produced by Corona were for 600kW turbines, followed by converters and control systems for 750kW, 1MW, and eventually 1.5MW turbines. The growing use of pitched blades for turbines over 1MW also led the institute and Corona to develop pitch control technology and integrate this in the control systems produced.

During the 11th five-year plan the institute in collaboration with Corona received funding to develop 3MW turbine converters and control systems. The interviewee explained that the institute had focused on developing new control system functions (e.g. LVRT technology), running simulations and laboratory tests, while Corona had focused on detailed product development and full power testing.

The interviewee noted that during the 11th five-year plan, though the institute remained the largest recipient of MOST R&D funds on converter and control system, several other research groups also received funding (including the research group at Tsinghua University mentioned above). He explained that it was getting harder and harder for the institute to get financial support from the government as the emphasis was increasingly shifting to production, and therefore funding was increasingly targeting firms. The interviewee explained that during the 11th five-year plan MOST funding represented approximately 20% of the combined R&D funding of the institute and Corona, with Corona financing the rest.

The interviewee indicated that Corona had started work on 5MW products. He also highlighted an ongoing joint venture with Guodian Longyuan on the production of its 1.5MW converters.

Corona was also involved in a new joint-venture with Datang, a large state-owned power generation company, which had acquired a small wind turbine manufacturer.

3.5 TECHNOLOGY DEVELOPMENT SYSTEM FUNCTIONS

I return here to the six technology development system functions outlined in table 1.3 of Chapter 1. I summarize some of the key findings from the interviews to assess how each function has been fulfilled and what role the Chinese government has played.

3.5.1 Market formation function

The market formation function underpins the ability of firms to accumulate technological experience. In addition, competition in the market and the prospects of securing profits constitute an important incentive for firms to invest in technology development.

The discussion in Section 3.3 detailed how the Chinese government created a domestic market for wind power through a variety of policies. At the heart of these were minimum wind power capacity targets placed on power generation companies and a preferential price for electricity generated by wind power. The government also introduced a number of measures to support the establishment of a domestic wind turbine industry and to ensure the active participation of Chinese firms. These included local content requirements and a turbine technology development subsidy only available to Chinese wind turbine manufacturers. There were also some indications that the government had given preferential treatment in the allocation of wind farms to projects using Chinese turbine manufacturers. Furthermore, the formulation of wind power deployment objectives in terms of installed capacity favored domestic turbine manufacturers as they priced their turbines lower than their foreign competitors.

The market formation process was facilitated by the fact that the main state-owned power generation companies were under pressure from peers and the government to meet their capacity targets. In addition, the relatively negative financial conditions surrounding coal power generation investments also contributed to investments in wind power projects.

The government, however, also faced a number of challenges in its efforts to create a domestic wind power market. One of these was that the expansion of the electricity grid to connect wind farms had lagged behind project approvals and construction. In response, the government actively sought to address the various issues at stake through specific regulations. These involved reforming the wind farm approval process, revising the grid code, working with the national grid companies to plan future grid extensions, and increasing the surcharge on power prices to better account for wind power integration costs. Though it was too early to tell whether these measures would be successful, several interviewees were confident that the main issues had been addressed.

The interviews also highlighted a number of important underlying structural and institutional hurdles which undermined the quality of wind power projects. These notably concerned the nature of incentives for power generation firms, turbine certification, as well as wind resource and modeling issues. Several interviewees noted that these were institutionally complex to resolve, underscoring the challenges of the market formation processes.

The market which formed as a result of government policies was characterized by intense price competition among manufacturers as well as among project developers. Several interviewees stressed that this competitive market environment put Chinese manufacturers under pressure to develop competitive advantages. An ERI interviewee noted that the emergence of a diverse set of

wind turbine technologies in China, including direct-drive turbines, hybrid drive turbines, as well as two blade turbines, was a consequence of such market forces. He noted that though risky, adopting a different technological approach from competitors allowed firms to differentiate themselves as well as demonstrate their technological capabilities. This view was echoed by a CWEA interviewee who explained that the level of competition in the wind turbine market made it difficult for a new entrant to succeed based on a technology which was already well established. Another CWEA interviewee gave the example of Ming Yang, a Chinese wind turbine manufacturer that adopted a two blade turbine technology that was not well established either in the European or United States markets.[130] The interviewee explained that while the turbine design had been developed by Aerodyn, the firm had not been able to commercialize the technology in Europe and therefore partnered with Ming Yang, which was willing to introduce the technology in China.

Similarly, the ERI interviewee explained that once manufacturers had entered the Chinese market, the competitive pressure to develop new and larger models was very strong. He noted that firms that failed to introduce new products had difficulties holding on to their market share, even if their technology benefited from a good reputation. He gave the example of Vestas and Gamesa, both considered as frontier firms, who for three years at the beginning of the rapid growth of the Chinese wind power market only offered turbines of a maximum of 850kW in capacity. These smaller models were eventually phased out of the Chinese market after Chinese firms entered the market offering bigger capacity models. Similarly, a CWEA interviewee

[130] The design presents important technical challenges. For example, because of the unique load profile associated with using two blades, the blades have to be pitched every rotation.

stressed that a firm which only produces a 1.5MW turbine, the dominant model at the time of the interview, was sure to go out of business given that competitors were developing larger turbines.

3.5.2 Knowledge development and diffusion function

Knowledge development results from a mix of learning from experience, R&D, and imitation activities. Much of the incentives for firms to invest in knowledge development resulted from the market formation efforts discussed above and, in particular, the competitive market environment created. However as mentioned in earlier sections of this chapter, the government introduced a variety of additional measures to encourage wind turbine technological development. A number of these aimed specifically for turbine manufacturers to produce increasingly large turbine models. Furthermore, a significant reduction in the income tax rate was offered to firms which invested in R&D and owned their core intellectual property.

As detailed in Chapter 2, imitation activities in the form of technology transfers from foreign firms, combined with the accumulation of market experience, played a central role in allowing leading Chinese firms to accumulate technological knowledge. A CWEA interviewee underscored that joint-development agreements with foreign companies were particularly important in this process. He stressed that these gave Chinese firms the intellectual property, in the form of designs and blueprints, which allowed them to start experimenting with, and truly understanding the underlying technology.[131]

[131] The interviewee stressed that technology transfers such as licensing and joint-development were not the only models of technology development in China. Some smaller Chinese firms entered the market based on their own designs, such as Windy and Huanly, and turned to foreign

Linking the income tax system to the need to own intellectual property most likely played an important role in spurring the transition from technology transfer based on licensing to transfer based on joint-development agreements. However, interviewees from MOST and CWEEA also noted that turbine manufacturers naturally aimed to eventually develop their technologies independently from foreign firms. The transition may therefore also have been a consequence of firms' growing capabilities as they accumulated experience. Similarly, government measures to encourage the production of increasingly large turbines likely played some role in the trends observed, though as noted earlier, market forces were also leading to such technology development efforts. It is thus difficult to determine whether knowledge development resulted from government incentives or market forces alone.

Though Chinese manufacturers were accumulating technological capabilities rapidly, the CWEA interviewee thought developing new turbine models required design capabilities which many manufacturers still lacked. Similarly, the CREIA interviewee noted that, at the time of the interview, Chinese manufacturers still relied on joint-development with foreign companies and had some progress to make before being able to independently develop their own technology.

Nevertheless, other interviewees viewed the model of knowledge development through collaboration and joint-development with foreign firms as reaching its limits. An NEA interviewee acknowledged that Chinese manufacturers still faced important technological

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firms only for verification and monitoring. Similarly the Wind Turbine Energy Institute of Shenyang Polytechnic Institute developed its own blueprints which it sold to several firms, such as Jiangsu Xinyu Wind Power Equipment.

hurdles, ranging from the development of blade materials to a lack of experience with respect to control systems. However, he explained that Chinese manufacturers were reaching a stage where they were competing with foreign firms to build similar turbine models. Chinese firms could therefore no longer depend on what he referred to as a follower strategy, and needed to increasingly rely on their own technology development capabilities. This was echoed by an interviewee from CAS who described the Chinese industry as having been focused on following the footsteps of European turbine manufacturers. He explained that this had been a relatively low risk approach but that Chinese firms were reaching a point where even European firms were not sure how to proceed with technological development. In effect, these views considered Chinese firms to be on the verge of catching up with the frontier, and that future steps would require them to rely on their own ability to innovate.

Several interviewees raised concerns about the ability of firms to shift their technology development emphasis from technology transfer to R&D. In particular, technological collaboration and joint-development had allowed Chinese firms to focus much of their attention on production. A CAS interviewee explained that firms had become accustomed to being able to start mass production of new models within two years. Similarly, the CREIA interviewee stressed that firms were reluctant to invest in technologies which could not be commercialized within two or three years. This was echoed by a Tsinghua professor, who explained that he would not approach turbine manufacturers about his research findings until he had developed something close to being ready to use, noting that the emphasis of turbine manufacturers was on immediate technology adoption. Both CAS and CREIA interviewees were therefore concerned

that Chinese firms were not geared towards investing in more uncertain and lengthy R&D processes.

The CAS interviewee highlighted that one indication of the limited willingness of firms to invest in long-term R&D was that several known issues underlying technology development had failed to attract the necessary R&D attention. One example concerned the issue of wind load modeling, discussed above. The CAS interviewee explained that Chinese firms had adopted European standards of design even though wind load profiles in China showed unique features. He stressed that the performance of turbines would likely be improved significantly if these were more specifically designed to Chinese conditions. This called for R&D efforts to better characterize and understand Chinese wind resources and integrate them in new design procedures yet relatively little had been done on this topic.

The discussion in Chapter 2 on the nature of R&D efforts undertaken by some of the leading Chinese wind turbine manufacturers confirmed that their emphasis had primarily been on making incremental improvements to existing technologies. Nevertheless some firms had started investing in more significant, long-term R&D efforts, similar in scope to innovation efforts at the frontier. Interviews with professors working in prominent Chinese research institutions reflected a similar mix of R&D priorities. Their work had for the most part been oriented towards collaborations with firms to address short-term problems or to assist them in the development of improved technologies. However, some research groups were also engaged in more significant R&D work, tackling longer-term problems at the forefront of the industry. There were therefore clear signs that the capabilities to engage in advanced R&D were present in the Chinese wind

turbine technology development system, even though such activities played a relatively small role.

Concerning the diffusion of technological knowledge two main issues emerged from interviews. The first was that wind power technology R&D funding provided by the government through MOST only served its participants and therefore failed to benefits others in the industry. Many interviewees notably highlighted the lack of a public platform which allowed pooling of R&D resources and findings. The second issue concerned the nature of interactions between firms and research institutions. Several interviewees noted that research institutions played a small role in the technology development process relative to that of firms' own efforts. In addition, many interviews underscored that the bulk of work undertaken by research institutions focused on assisting firms with their immediate technology needs.

Taken together, these two issues highlighted that both government R&D funding and research institutions served to enhance existing R&D efforts by firms rather than be complementary to them. In particular, there was a clear lack of emphasis on efforts targeting common industry wide R&D themes adopting a longer-term technology outlook than that of firms, and which were less firm-centric by encouraging more collaboration among research institutions.

3.5.3 Guidance of search function

Arguably the most important factor guiding wind turbine technology development efforts in China was the technological direction and experience of frontier firms in Europe and the United States. This permeated the Chinese wind turbine technology development system through various forms of technology transfer, among which are those discussed in Chapter 2.

However several features of the Chinese wind turbine technology development system also provided strong guidance on the direction of search. The first was government regulation. One example was the Chinese government's support for wind power deployment in low wind speed areas. This notably led Chinese manufacturers to invest in the development of turbine models with comparatively longer blades than similar models in European or United States markets. Similarly, the government's emphasis on grid integration and the quality of power generated by wind farms led to the development and adoption of grid friendly technologies.

The second feature which provided guidance to the technology development process was the coherence and consistency of long-term government policy planning. While specific regulations, such as those mentioned above, had direct effects on firms, the combination of planning documents such as five-year plans, and overarching laws such as the Renewable Energy Law, provided strong signals to the industry about the long-term direction of government policy. All interviewees notably spoke with great confidence about the continued long-term growth of the industry noting that wind power was a sector the government wanted to develop. A CWEA interviewee highlighted that there was strong consensus in the industry about the commercial viability of designing larger machines given the strength of the regulatory environment.

Finally, a third feature of the Chinese system which helped guide technology development efforts was the formulation of MOST R&D funding priorities before each five-year plan. The process brought together a large group of experts from industry, research institutions, and government, which was tasked to identify the most pressing issues faced by the industry and list the research priorities for the next five years. Several interviewees noted that the resulting R&D project guidelines played a particularly important role in the early stages of the industry, when

R&D funding was scarce. However, with the rapid growth of the wind power market, government R&D funding became relatively small compared to R&D investments made by firms. Some interviewees therefore doubted whether the process sill provided much guidance.

3.5.4 Countering resistance to change function

As highlighted by an interviewee from CWEA, the nature of interactions between government and industry in China was such that, generally, firms did not express their potential opposition to a given policy course and tended to follow government guidance. Nevertheless, a CREIA interviewee underscored that large firms in China, such as the power generation firms or the state grid companies, had a strong influence on the decision making process. The State Council, the highest level of policy making, was therefore exposed to different opinions concerning wind power and other renewable energy sources, including strong objections.

All interviewees agreed that there was in fact very little resistance to wind power from actors involved with coal power generation – the main incumbent power generation technology in China. Two main reasons were put forth. First, several interviewees underscored that the rate of growth of energy demand in China was such that the contribution of all energy sources was needed. As noted by CASTED and CWEEA interviewees, this had been clearly recognized by the government who's goal of non-fossil fuel energy meeting 15% of the country's energy demand by 2020 overshadowed possible resistance to wind power. In addition, the ERI and CREIA interviewees noted that energy demand was growing at such a rate that the growth of traditional power sources was still very large.

Second, as explained by interviewees from CWEA, CWEEA, ERI, and NEA, the limited resistance to wind power was also due to the fact that coal plans and wind farms were owned by the same large power generation companies. The NEA interviewee notably underscored that wind power assets represented an increasingly important part of their profits.

Several interviewees identified grid companies as having been the only significant source of resistance to wind power development in China. A CWEA interviewee explained that the emergence of wind power had challenged the way grid management had traditionally been conducted in China. NEA and ERI interviewees both stressed that Grid companies were concerned that wind variability may lead to excessive power supply fluctuations which they were ill equipped to manage. However, the NEA interviewee was confident that measures implemented to address the issue, discussed previously, would ease these concerns and allow the sound development of the industry to continue. ERI and CWEEA interviewees stressed that ultimately grid companies had to comply with the government's direction.

3.5.1 Other system functions

The two remaining functions, 'entrepreneurial activity' and 'resource mobilization', were not discussed at length by any interviewee. These are therefore only mentioned in brief below.

3.5.1.1 Entrepreneurial activity

As mentioned above, an important sign of entrepreneurial activity in the Chinese wind turbine technology development system consisted of the willingness of Chinese firms to enter the market by adopting diverse turbine technologies, including some not well established in any other market.

The search by Chinese turbine manufacturers for technology transfer opportunities and the ability to seek multiple associations with foreign firms, detailed in Chapter 2, also underscore an important entrepreneurial spirit. Similarly, the role played by Chinese turbine manufacturers in working with potential Chinese component manufacturers to engage them in the market marks a willingness to engage in trial and error.

Finally, though as mentioned earlier much R&D efforts have focused on relatively short-term technology development some firms and research institutes had engaged in more substantial long-term R&D where the risks of failures were higher.

3.5.1.2 Resource mobilization

Several interviewees underscored that overall the wind power industry had ample access to capital. Even during the global financial crisis of 2008, interviewees noted that the wind sector remained more favorable than most other sectors. In addition state-owned enterprises often benefited from preferential access to capital and therefore project funding had not suffered from excessive capital constraints.

Similarly, no concerns were raised about the availability of qualified engineers to work in the growing wind power industry. Aside from the traditional engineering training offered by most universities in the country several universities also offered specialized academic curriculums. For example, NCEPU's School of Renewable Energy offered an undergraduate program dedicated to wind power engineering, which by 2011 was accepting 90 new students a year.

Probably the most significant issue with respect to the availability of resources concerned qualified research staff within universities. The issue was not a lack of highly educated and

qualified engineers. Rather, as noted by an ERI interviewee, the challenge was to attract people to work on long-term R&D. A CREIA interviewee explained that people had limited incentives to do continued, high-level academic research. In contrast, there were strong incentives to focus on industry issues as successful research may be followed by commercialization.

3.6 CONCLUSION

This chapter described some of the most salient features of the Chinese wind turbine technology development system. It highlighted how the system created the conditions for Chinese wind turbine manufacturers to make rapid progress in their technology development efforts. The government was at the heart of this process. It introduced the policies that created a rapidly growing wind power market in China. More importantly, however, through a variety of steps the government encouraged domestic firms to enter the market and therefore gain valuable experience. The government was also heavily engaged in addressing various issues in the domestic wind power market. In particular, it sought to resolve growing bottlenecks in the grid connection of wind farms, which led to a variety of steps involving turbine manufacturers, grid companies, and regulators. Though this chapter highlighted a number of other outstanding structural and institutional issues within the Chinese system, most seemed manageable in light of the apparent determination of the government to maintain industrial momentum.

As the overall market grew so did the role of domestic firms and a vibrant and competitive market environment rapidly developed. This involved competition among turbine manufacturers to secure turbine orders, among project developers to develop the best wind farm locations, as

well among power generation companies to add wind power capacity to their books and meet government targets.

The competitive nature of the Chinese wind power market provided a strong incentive for Chinese turbine manufacturers to seek competitive advantages through wind turbine technology development. This led to diverse turbine technologies being introduced in the market as well as a continuous drive to develop larger turbines. The government also introduced a host of measures to encourage technology development among domestic firms. A number of these supported the development of incrementally larger turbines. The government also encouraged the ownership of intellectual property through tax incentives. Similarly, it proposed stringent industry standards to address growing concerns about turbine quality. Whether such measures played a role in wind turbine technology development beyond what was already occurring in the market is unclear though they signaled to domestic firms the industrial trajectory the government wished to promote.

The government exerted its influence on firms, both state-owned and otherwise, through regulatory means and various networks. In particular, the government extensively used industry associations to keep track of industry developments, coordinate new regulatory steps, and facilitate the exchange of information with firms.

The chapter suggests that the hypothesis that technological progress made by wind turbine manufacturers was driven by the combination of exposure to large market opportunities and the active involvement of the government within a wind power technology development system is correct. Nevertheless, undoubtedly the biggest challenge facing the Chinese wind turbine technology development system was whether it would be able to transition from a model of

technology development based on technology transfer to one based on technology innovation. At the time of this research, the R&D agendas of both firms and research institutions were still dominated by short-term, incremental, problem-solving oriented technology development. In addition, the government R&D apparatus was primarily structured to support such R&D efforts within firms rather than to complement them, for example, by focusing on common, industry wide technology issues or longer term technology development efforts.

Still, some firms and leading research institutions were involved in frontier-like R&D projects, tackling technology challenges at the forefront of the industry. Though clearly a small part of the Chinese wind turbine technology development system, this indicates that innovation capabilities were present. Similarly, the government also appeared to be aware of the limitations of the current R&D support model and willing to consider possible reforms to its R&D support institutions.

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- Chapter 4 - The role of Government in the Evolution of the Wind Power Technology Frontier

4.1 INTRODUCTION

4.1.1 Chapter objective and research approach

While previous chapters focused on wind turbine technology developments in China, the emphasis of this chapter is on the wind power technology frontier. The analysis aims to assess the validity of the second argument of the research hypothesis, which states that the wind power technology frontier has evolved relatively slowly due to limited government support to technology development.[132]

The analysis in this chapter consists of two parts. The first aims to determine the role of government policy in technology development at the wind power technology frontier. The hypothesis for this first part is that government policy has been the main driver of technology development at the frontier. For this first part of the analysis I focus on three countries which have historically played an important role in advancing the wind power technology frontier – Denmark, Germany, and the United States. I focus specifically on 'knowledge development', which, as detailed in chapter 1, is one of the central functions of technology development systems. I use patents as indicators of knowledge development as, by definition, they embody new technological features. For each country, I assess the extent to which changes in government

[132] See Section 1.1.4 for more details on the research question and hypothesis.

wind power support policies are correlated with changes in the rate of patent applications associated with wind power technology.

The second part of the analysis aims to compare the pace of technology development at the wind power technology frontier to that of other technologies. The hypothesis for this second part is that the pace of technology development at the wind power technology frontier has been slow relative to other technologies. For this part of the analysis, I focus on both 'knowledge development' and 'market formation', which, as detailed in chapter 1, is another central function of technology development systems. I again use patenting activity as an indicator of knowledge development and I use technology penetration rates as indicators of market formation. For both, I compare trends for wind power to those of other technologies.

If the hypotheses of both parts of the analysis prove correct we can conclude that, in all likelihood, the relatively slow evolution of the wind power technology frontier is due to the limited government support.

The importance of the three countries considered in the first part of the analysis is reflected in the composition of the wind turbine manufacturing industry: Denmark is home to Vestas and Siemens,[133] which in 2010 were respectively the first and ninth largest manufacturers globally and together accounted for 20.7% of global capacity installed that year; Germany is home to Enercon, which in 2010 was the fifth largest turbine manufacturer, accounting for 7.2% of the global market; and finally the United States is home to General Electric, which in 2010 was the

[133] Siemens entered the wind turbine manufacturing market by acquiring Bonus Energy, the oldest manufacturer in Denmark (BTM, 2011).

third largest manufacturer of wind turbines and accounted for 9.6% of global installed capacity that year. The United States and Germany were also respectively the second and third largest markets in the world in terms of cumulative installed capacity (BTM, 2011). In addition, while a much smaller country, Denmark has the largest share of electricity consumption coming from wind power.

The focus of this chapter is on wind power technology development since the 1970s. However, to give some context to this analysis, I first highlight some of the earlier efforts to use wind energy for electricity generation.

4.1.2 Precursors to the modern wind turbine

Until the industrial revolution, large tower wind mills, used for various mechanical tasks such as grinding grain and pumping water, were ubiquitous throughout Europe. Similarly, during the 19th century, small stand-alone windmills used for pumping water were a common feature on United States farmlands. From a purely technological perspective, aside from a shift to electricity generation, there is no clear discontinuity between these antiquated wind-based technologies and the recent efforts discussed in this research. Instead, what distinguishes the modern period is the role of government, which, following the global oil shocks of the 1970s, was instrumental in supporting a technology which in all likelihood would otherwise have been limited to niche applications. Before turning to a detailed discussion of such policies, it is therefore first useful to provide further technological context. I discuss here some of the early efforts to develop wind turbines for electricity generation, prior to the 1970s.

One of the first efforts to use wind energy for electricity generation was a horizontal axis wind turbine built in 1888 on the property of a wealthy industrialist named Charles Brush in Cleveland, Ohio. The wind turbine was a wooden structure consisting of an 18 m high tower and a rotor 17 m in diameter made of 144 blades. The turbine had a 12kW capacity and was used to power the many incandescent lights in his house (Lynn, 2012; Shepherd, 1990). Though the turbine operated successfully for 20 years, the advent of electrification of cities across the United States and the expansion of centralized power generation led to its eventual abandonment (Righter, 2011).

Around the same time in Denmark, Poul La Cour, with funding from the Danish government, developed several experimental wind turbines which drew on many of the features of the old tower wind mills and incorporated rudimentary airfoil structures. As a result of these efforts, by 1918 some 120 Danish rural power stations used wind turbines rated 20-35kW in capacity. However, the rapid spread of fossil fuel-based power generation following the end of World War I quickly made these wind turbines obsolete (Shepherd, 1990; Andersen, 2007).

By the early 20th century, rural areas that were not connected to the power grid presented one of the last settings where wind power generation had a potential economic advantage over fossil fuel alternatives. This period was characterized by several efforts to develop small scale wind turbines for electricity generation in remote locations. In the United States, an important contribution was that of Marcellus Jacobs and his brother. Following the First World War, they developed on their parent's ranch in Montana a turbine with a three-blade rotor aimed to generate enough electricity to charge small batteries used for lighting and powering radios. Originally based on a modified airplane propeller to drive generators, these machines were

progressively refined to improve efficiency and in the early 1930s the Jacobs Wind Electric Company was created. Aside from their small size (turbines were typically around 2-3kW in capacity), the Jacobs turbine had some of the basic features of the turbines which would come to dominate the industry several decades later.[134] Though renowned for reliability, the Jacobs' enterprise became obsolete along with other small wind turbines manufacturers as rural electrification efforts in the United States intensified, and by the mid 1950s all had disappeared (Righter 2011; Manwell, McGowan, and Rogers, 2009).[135]

The first effort to develop a large scale, grid-connected wind turbine was an experimental two blade turbine with a 30 m diameter rotor and rated capacity of 100kW, installed in 1931 on the coast of the Black Sea in the former USSR (Sectorov, 1934). The experiment ran successfully for several years but led to no subsequent development efforts. In the United States, the most notable effort was the construction in 1941 of a two blade turbine with a 53 m diameter rotor and rated capacity of 1.25MW.[136] This was the largest wind turbine ever built and remained so for almost 40 years. The turbine was installed in Vermont and connected to the local grid. It ran successfully for 16 months before several technical failures led the project to be abandoned in 1945 (Righter, 2011). Following the Second World War, several other prototypes of grid connected wind turbines ranging in capacity from 100kW to 1000kW were built in England, France, Germany, and Denmark (Nelson, 2009; NASA, 1981). In the case of Denmark, efforts to

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[134] In particular, these had three blade rotors and were horizontal axis, up-wind turbines.

[135] Shepherd (1990) also discusses efforts to develop small scale wind turbines in the former Soviet Union around the same period (for more details see also Fateyev, 1959).

[136] The turbine is known as the Smith-Putnam, named after the man who designed it, Palmer Putnam, and the company which financed its construction, the S. Morgan Smith Company.

manufacture relatively small machines (ranging from 30 to 70kW in capacity) resumed prior to and during World War II. The most notable development led to the erection in 1957 of an experimental 200kW three blade turbine at Gedser, on the southern coast of Denmark. Though the machine did not immediately lead to commercial ventures, the turbine operated successfully for eight years (Lynn, 2012; Andersen, 2007, Neslon, 2009).

4.2 THE ROLE OF GOVERNMENT POLICY IN WIND POWER TECHNOLOGY DEVELOPMENT: THE CASE OF DENMARK, GERMANY, AND THE UNITED STATES

This section aims to determine the role of government policy in technology development at the wind power technology frontier. I focus on two primary means of government support to wind power technology development in Denmark, Germany, and the United States: technology deployment subsidies and R&D policies. Technology deployment subsidies underpin the establishment of wind power markets, thereby allowing firms and other agents to accumulate experience and creating incentives for firms to invest in various means of technology development. R&D policies support technology development activities undertaken by firms and research organizations.

In Section 4.2.1 I describe for each country the evolution of wind power technology deployment subsidies and assess the extent to which changes in subsidies explain fluctuations in the growth of the respective domestic wind power markets. In Section 4.2.2 I describe for each country the evolution of R&D policies. In Section 4.2.3 I use patent application rates as indicators of 'knowledge development', one of the central functions of technology development systems, and assess for each country the extent to which changes in government policies may be correlated with changes in wind power patenting rates.

The emphasis here is therefore solely on the role of government policies. In practice, however, many other factors may affect both wind power deployment and wind power patenting rates. For example, changes in fossil fuel prices affect the cost differential of power generation using wind power relative to incumbent fossil fuel based technologies and may therefore affect the rate of wind power deployment as well as the incentives to invest in technology development as reflected by patent data. A more complete assessment would therefore require accounting for a broader set of factors in each country. However, the objective here is to highlight the central of role of government support policies given the externality nature of climate change described in Chapter 1. The approach outlined above therefore allows for a sound preliminary assessment.

4.2.1 Wind power deployment policies

Governments wishing to encourage the deployment of wind power can implement a variety of policies. Usually a core set of quantity or price policies drive most of the technology deployment. A quantity policy sets quantity targets, typically in terms of installed capacity or power generated, which must be met by a specific group of actors (usually power companies). In contrast, price policies, whether in the form of taxes or subsidies, directly affect the revenues linked to specific technologies, thereby altering the investment incentive structure.

In this section, I describe the evolution of the main quantity and price policies supporting wind power deployment in each of the three countries considered, and assess the effects of changes in these support policies on the evolution of wind power deployment. In case of weak correlation with market trends, I provide further information about secondary policies and other contextual information which may explain the trends observed. In each case I start by outlining some of the

specific goals affecting wind power which have been issued by the government through national energy plans and other framework documents.[137]

4.2.1.1 Denmark

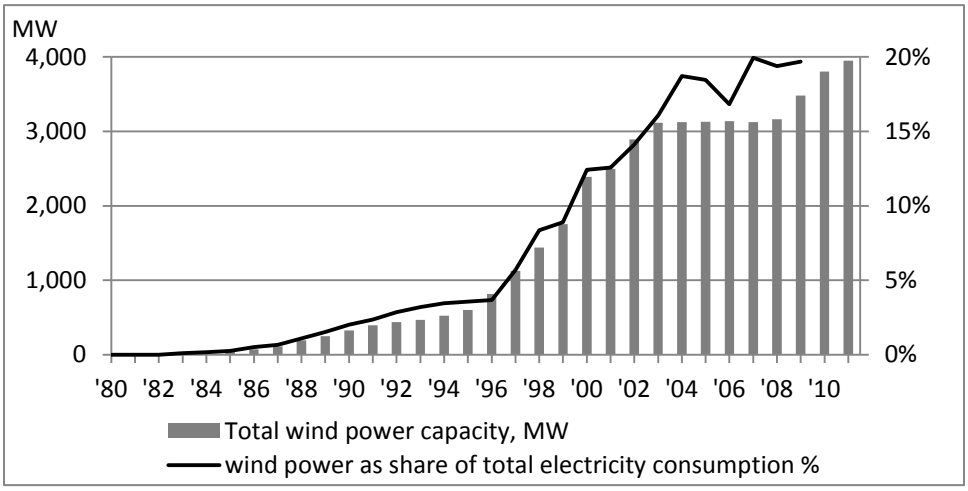
As of the mid-1970s, the Danish government began issuing long-term energy plans to guide the country's policy making. The emphasis at first was on reducing the country's dependence on oil imports, which in the mid-1970s, accounted for almost all of national consumption. The first plan, formulated in 1981, set a target equivalent to installing 1,000MW of wind power capacity by 1995. By the time of the next energy plan, issued in 1990, the emphasis had shifted towards addressing the environmental challenges associated with conventional energy production and use. The plan outlined a goal of reaching a total of 1,500MW of installed wind power capacity and meeting 10% of the country's electricity consumption by 2005 (Sawin, 2001). A 1996 plan placed strong emphasis on the need to reduce the country's greenhouse gas emissions and set a target of reaching 5,500MW of total installed wind power capacity by 2030, of which 4,000MW were to be installed offshore (IEA, 2001). In 2011, the Danish government released a new energy policy which aims for the country's energy and transport system to be entirely based on renewable energy by 2050. The plan sets a strategic milestone for wind power to account for 50% of electricity consumption by 2020 (IEA, 2012a).

[137] Though changes in wind power support policies may be due to changes in governments and other political factors, these are not discussed in any depth in this chapter. Rather the primary objective is to compare and contrast support policies and assess their impact on deployment.

Figure 4.1 shows the evolution of total cumulative wind power capacity in Denmark as well as power generation from wind expressed as a share of total electricity consumption. The target set in 1981 of 1,000MW to be installed by 1995 was not met. In contrast, the next target, issued in 1990, was easily met. Installed capacity in 2005 was over 3,000MW, twice the target value, and wind power represented over 18% of total electricity demand compared to the 10% target. Though it is too early to tell, it seems that achieving the 1996 target of 5,500MW in total wind power capacity by 2030, including 4,000MW to be installed offshore, is well within reach. With close to 4,000MW in total installed capacity in 2011, of which 870MW was offshore, approximately 73% and 22% of the overall and offshore targets had already been met.

One of the first government measures to support the deployment of wind power was a capital grant program introduced in 1979, equivalent to 30% of the investments costs incurred by individuals to install small wind turbines on their properties. This subsidy gradually decreased to 10% of investment costs by 1989 before being phased out by the end of that year (Sawin, 2001). At the time, cooperatives and individuals wishing to erect small wind turbines on their properties had to negotiate with power companies to connect their turbines to the electricity grid and be paid reasonable rates on the sale of the electricity generated. Utility companies also agreed to pay a third of grid connection costs. However these negotiated agreements were established on a case by case basis and in practice led to slow developments and often difficult implementation (Bolinger, 2001; Sawin, 2001).

Figure 4.1: wind power cumulative installed capacity and generation as percentage of total electricity consumption, Denmark, 1980-2010



Note: Compiled from ENS (2011), IEA (2012b), and EIA (2012)

In 1992 the government passed a regulation introducing a feed-in tariff for wind power as well as a power purchase obligation for utility companies. The tariff for cooperatives and individual owners of single turbines less than 150kW in capacity was set at 85% of the average utility cost of production and distribution.[138] From the mid 1990s cooperatives and individual owners of turbines also benefited from two additional subsidies. The first was a reimbursement of the newly instituted 0.10 DKK/kWh CO_2 tax as well as a direct subsidy of 0.17 DKK/kWh from the proceeds of the electricity tax. The total feed-in tariff paid to cooperatives and private owners of wind turbines was therefore approximately 0.60 DKK/kWh of electricity generated (IEA, 2001; Krohn, 1998; and ENS, 1999). The turbine size limit was increased in the mid 1990s to 250kW before being abandoned (Sawin, 2001). In addition, restrictions on the eligibility for participation

[138] The resulting tariff varied depending on location but was between 0.37 and 0.45 DKK/kWh in 1998 (IEA, 2001)

in cooperatives, particularly concerning geographic proximity to the turbines owned and the extent of financial involvement, were progressively removed over the years (Bolinger, 2001). To further stimulate private wind power installation the government also offered favorable tax schemes on wind turbine investments. However, these were removed by the late 1990s, after which income from wind power generation was taxed as any other income (IEA, 2001).

By 1998 close to 84% of the Danish wind power market was privately owned by cooperatives or individuals (ENS, 1999). This may in part be explained by the fact that Danish utility companies believed nuclear power would play a central role in meeting the country's new environmental objectives. However, in 1985 the Danish Parliament decided that nuclear power would no longer be considered as a power generation alternative for the country (Sewin, 2001). The same year the government negotiated an agreement with power utility companies to install 100MW of wind power capacity over the coming five years. A second agreement to install another 100MW of wind power capacity was signed in 1990 while a third was signed in 1996 to install an additional 200MW by 2000 (ENS, 1999). Pursuant to these agreements, utility companies received the same feed-in tariff for wind power generation as cooperatives and individuals (Krohn, 1998).[139] Utility companies also completed two 5MW offshore demonstration projects in 1991 and 1995. The success of these projects led to an agreement signed with the government in 1997 to develop 750MW of offshore wind power by 2008 (ENS, 1999; Sewin, 2001).

[139] However, utilities did not benefit from the 0.17 DKK/kWh subsidy linked to electricity tax proceeds as they were already exempt from this tax.

In 1999, broad electricity sector reforms were launched and subsidies for wind power were adjusted in the process. For turbines installed prior to 2000, once an assigned number of full load hours were met, the feed-in-tariff was reduced from a total of 0.60 DKK/kWh to 0.43 DKK/kWh.[140] For turbines installed from 2000 onwards, the tariff was reduced to a fixed value of 0.43 DKK/kWh for the first 22,000 full load hours (approximately equivalent to 10 years of operation), after which turbines receive the electricity market price plus a 0.10 DKK/kWh premium until the end of their 20 year life (IEA, 2001). The government also introduced a subsidy of 0.17 DKK/kWh in addition to the 0.43 DKK/kWh tariff for turbines installed in conjunction to the decommissioning of old turbines less than 150 kW in capacity. For offshore wind farms, the government introduced a feed-in tariff of 0.453 DKK/kWh for the first 42,000 full load hours, after which the same 0.10 DKK/kWh premium on top of market rates was offered until the end of the turbine's 20 year life (IEA, 2004).[141]

In 2002, following a compromise reached among various political factions, the government introduced further reforms that lowered the subsidies for onshore wind power. For turbines installed prior to 2000, from 2003 the 0.43 DKK/kWh tariff was only offered until the turbine reached 10 years of operation. Subsequently and until they reach 20 years of operation turbines received the market price for electricity plus 0.10 DKK/kWh (IEA, 2003). Similarly, for turbines installed between 2000 and 2002, the government introduced a cap of 0.36 DKK/kWh for the

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[140] Full load hours are the hours when a turbine generates electricity at its rated capacity.

[141] Private investors were involved in two early offshore projects in 2000 (50MW) and 2003 (17MW), yet subsequent projects were larger and solely owned by the country's power companies. The offshore feed in-tariff mentioned above targeted utility owned projects (IEA, 2004).

market price plus premium offered once turbines had reached their initial full-load hours allocation. For turbines installed from 2003 the only government subsidy offered was the market price plus 0.10 DKK/kWh with a total cap of 0.36 DKK/kWh (IEA, 2003). When turbines were installed in the scope of the decommissioning of old turbines less than 150 kW in capacity an additional 0.17 DKK/kWh was offered for the first 12,000 full load hours on top of the electricity price plus 0.10 DKK/kWh with a total cap of 0.60 DKK/kWh (IEA, 2005).

In 2004, a broad political agreement was reached among political factions concerning the continued support for wind power. For turbines installed onshore from 2005, the feed-in tariff continued to consist of the electricity market price plus the 0.10 DKK/kWh subsidy received throughout the 20 year life of the turbines. For turbines installed in the scope of the replacement of old turbines under 450kW in capacity, a further 0.12 DKK/kWh for the first 12,000 full load hours was offered with a total cap of 0.48 DKK/kWh (IEA, 2004).[142]

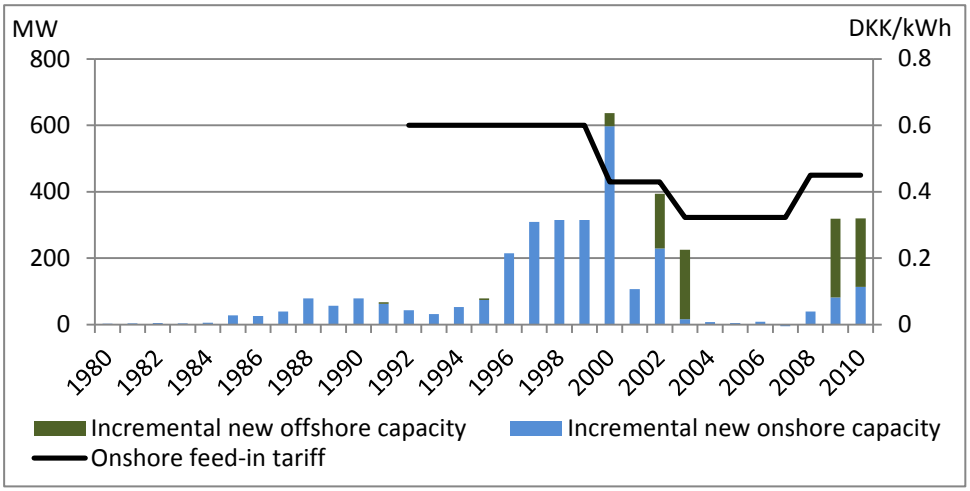
Concerning offshore developments, the 2004 agreement required construction of two large wind farms, each with a capacity of 200MW for which the subsidy was to be determined by a tender process (IEA, 2004). The first 200MW offshore project at Horns Rev II was awarded in 2005 at a feed-in price of 0.518 DKK/kWh for the first 50,000 hours (IEA, 2005). The second 200MW offshore project at Roedsand II was attributed in 2008 at a feed-in price of 0.629 DKK/kWh (IEA, 2008).

[142] An additional 0.023 DKK/kWh was introduced as part of the 2004 agreement to compensate for balancing costs.

A new 2008 policy raised the premium for new onshore wind turbines to 0.25 DKK/kWh above the market price for 22,000 full load hours. Turbines installed in the scope of the decommissioning of old turbines were given an extra 0.08 DKK/kWh subsidy for the first 12,000 full load hours. The 2008 policy also called for a tender for two additional 200MW offshore wind farms to come into operation by 2012 (IEA, 2008). The project located at Anholt was finally awarded in 2010 as one 400MW project at a feed in tariff of 1.05 DKK/kWh for the first 20 TWh (IEA, 2010).

When looking at the evolution of incremental installed capacity in the country (figure 4.2), various periods of market growth and contraction can be identified. The first period of growth, though limited compared to later ones, took place in the second half of the 1980s. Sarwin (2001) links this to the fact that the government investment credit was declining and would soon be phased out and people therefore took advantage of this while they still could. The period of contraction which followed can be linked to the relative policy vacuum in the first years of the 1990s. Sarwin (2001) also notes that complications related to the granting of turbine siting permits were not resolved by the government until 1994, which may also explain the low growth of the early 1990s.

Figure 4.2: Incremental wind power deployment and main support mechanism, Denmark, 1980-2010



Note: Capacity data compiled from ENS (2011) and IEA (2012b)

Onshore feed-in tariffs shown are those which were given during the initial period for projects built in the year indicated. Additional subsidies for turbine retrofitting are not included. Tariffs shown are based on electricity market price of 0.20 DKK/kWh.

This later point may also explain why the second growth period, which took place from 1994 to 1997 did not start earlier. Indeed, by far the main driver of this second and more significant growth period was the introduction starting in 1992 of a guaranteed minimum feed-in-tariff for wind power, also shown in figure 4.2, and the mandatory grid connection and purchase of power generated.

The spike in wind turbine installation in 2000, which surpassed 600MW, or twice the previous highest level, suggests a rush to secure funding before electricity sector reforms launched in 1999 lowered the feed-in tariffs (Sawin, 2001). Similarly, after falling to close to 100MW in installations in 2001, there was another relative spike in onshore installations in 2002, which can again be explained as a rush to secure funding prior to further feed-in tariff reductions introduced in 2002. The near zero onshore market between 2004 and 2008 is a result of insufficient support

resulting from the 2002 and 2004 reforms discussed above. The market only started picking up again in response to the introduction of more advantageous tariffs from 2008. Finally, the large offshore projects undertaken by utility companies are reflected in the offshore spikes of 2002-2003 and 2009-2010.

4.2.1.2 Germany

Much as in the case of Denmark, the first energy plans introduced by the German government during the late 1970s and early 1980s were focused on minimizing risks associated with oil import disruptions. These emphasized the use of domestic fossil fuel resources as well as nuclear energy and made little space for the deployment of renewable energy technologies. In a 1977 energy plan, for example, support to renewable energy was limited to R&D funding (Sawin, 2001).

Since the reunification of the country, energy plans started placing more emphasis on environmental concerns. A 1990 energy policy document stated that renewable energy would play a significant role in the country's future energy supply (Sawin, 2001). While the federal government did not identify specific targets for wind power development, the state government of Lower Saxony, a region known to have particularly good wind resources due to its coastal location, set a goal of installing 1,000MW of capacity by 2000, later increased to 1,700MW by 2005. Schleswig-Holstein, another coastal state, followed suit by establishing a goal to install 1,200MW by 2010 (IEA, 2001; Sawin, 2001).

In 1995, the government adopted a national target to reduce CO_2 emissions to 25% below 1990 levels by 2005. An energy plan released in 2001 strongly emphasized the need to ensure the

sustainability of the country's energy system and give equal importance to supply security, economic efficiency, and environmental protection. It included a target of generating 12.5% of the country's electricity from renewable energy, including large hydro energy projects, by 2010 (IEA, 2002b).

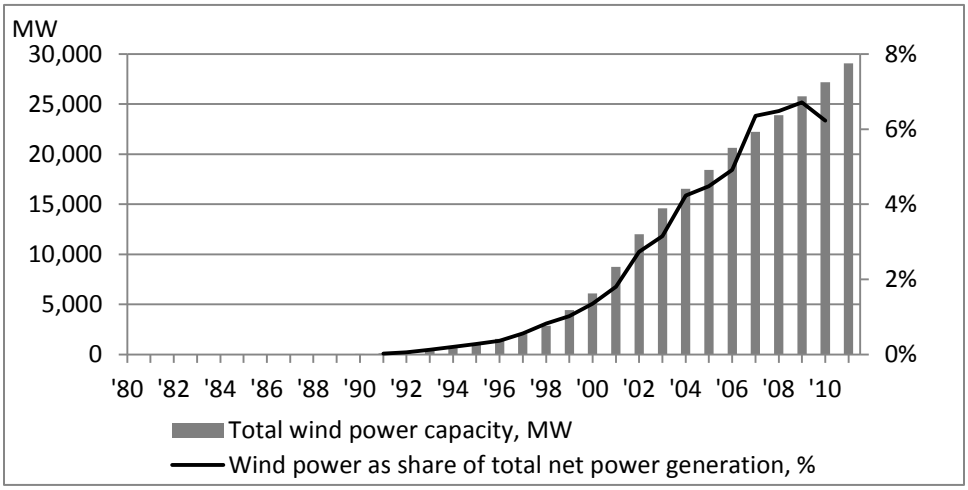
In 2002, the government introduced longer-term goals whereby renewable energy would account for 20% of electricity generation by 2020 and over 50% by 2050 (IEA, 2005). The same year a parliamentary decision was reached to phase out nuclear power by 2025, at the latest (IEA, 2002b). Though the government's renewable energy goals had not provided specified targets for wind power, this decision clearly indicated that wind power would play a prominent role in the country's electricity mix. The federal government announced plans to erect 500MW of offshore wind power by 2006, 3,000MW by 2010, as well as a long-term target of 25,000MW by 2030 (IEA, 2003; 2002a).

The target set in 2002 was increased in 2008 to 30% of electricity production by 2020 (IEA, 2008). In 2010 the government formulated long-term targets for the share of renewables in electricity production to represent 50% by 2030, 65% by 2040 and 80% by 2050 (IEA, 2010).

Though the government has refrained from identifying specific goals for wind power other than for offshore wind, it is nevertheless instructive to look at the overall evolution of wind power cumulative capacity and the share of overall electricity consumption it represents (figure 4.3). In 2011, installed capacity surpassed 29GW and wind power accounted for 6.2% of total net power generation in the country. As early as 2007, Germany had exceeded its target of generating 12.5% of its electricity from renewable energy sources by 2010, with wind accounting for 6.4% of total net power generation that year (BMU, 2008a). However, the

government's offshore targets have fallen short with the first offshore-wind project only erected in 2009. In terms of state level targets, Sarwin (2001) notes that the Lower Saxony and Schleswig-Holstein targets were exceeded.

Figure 4.3: wind power cumulative installed capacity and power generation as percentage of total net power generation, Germany, 1980-2010



Note: Compiled based on IEA (2001; 2002a; 2002b; 2003; 2004; 2005; 2006a; 2006b; 2008; 2009; 2010; 2011; 2012a, 2012b) and EIA (2012).

The first notable government policy in support of wind power deployment was the 100MW Demonstration Program, which started in 1989. The policy's primary objective, discussed in more details below, was to encourage technology development by providing support for the demonstration of new turbines. However it also played an important role in supporting technology deployment. For turbines selected under the program a choice was offered between receiving up to 60% of investment costs (with a cap on the total possible amount received), or a production subsidy for a 10 year period of 0.08 DM/kWh above the price wind turbines received from utility companies for power fed into the grid (Langniss, 2006).

In 1991, the government passed the Electricity Feed-in Law (EFL), under which utility companies were required to purchase electricity generated by wind turbines at 90% of the average electricity retail price two years prior. The resulting feed-in tariff oscillated between 0.1661 and 0.1728 DM/kWh from 1991 and 1999 (Bolinger, 2001). Under the EFL, grid connection costs were paid for by project investors while grid reinforcement costs were shared with utility companies.[143] In 1991, the government expanded the 100MW program to 250MW, though in light of the EFL the additional subsidy offered to turbines installed in the scope of the program was lowered to 0.06 DM/kWh (Sawin, 2001). Smaller measures were also introduced during the 1990s to further encourage wind power deployment, including low interest loans for wind power investments as well as favorable tax treatment linked to the depreciation of wind power assets (Bolinger, 2001; Sawin, 2001; IEA, 2001). During the early 1990s, a number of states also offered generous investment subsidies to wind power developers (Sawin, 2001).

The EFL and other incentives led to a rapid growth in wind power developments. However, most efforts were concentrated in the northern coastal regions of the country as these regions had the best wind resources. This placed a disproportionately large cost burden on the Northern utility companies and their consumer base, and contributed to generate opposition to the EFL. In response, an amendment to the EFL was introduced in 1998 which placed a cap of 5% of the total electricity which can be generated from wind turbines in any given region. In 2000, however, the government adopted the Renewable Energy Act (EEG), which aimed to expand and

[143] Grid connection consists of connecting the wind power project to the closest available grid. Grid reinforcement aims to improve the local grid to allow electricity generated by wind power projects to effectively meet demand.

improve support policies for renewable energy sources as well as ensure that they complied with European Union directives concerning the liberalization of the electricity market. The EEG abolished the 5% electricity generation cap introduced in 1998 and addressed the costs issues by mandating that the additional costs incurred from wind power development would shared among all electricity users in the country (Bolinger, 2001).

The main feature of the EEG was to no longer link the feed-in tariff to the electricity retail price and offer instead a fixed feed-in tariff based on the real costs of production, guaranteed for 20 years. To encourage technological progress, the EEG also planned to lower the feed-in tariff offered to new projects by 1.5% per year starting in 2002. The feed-in tariff was raised relative to the EFL to 0.178 DM/kWh for the first five years of the 20-year period. At the end of this period, plants generating at least 150% of a reference yield (based on a reference turbine size in specific wind conditions) received a basic feed-in tariff of 0.121 DM/kWh until the end of the 20-year period. For plants that did not achieve the 150% reference yield, the EEG introduced a formula to extend the higher rate period, after which they received the basic rate until the turbine operated for 20 years.[144] This approach was introduced to encourage the development of wind power projects in regions with less favorable wind conditions. In the case of offshore wind farms the EEG offered the same 0.178 DM/kWh tariff for the first nine years of a 20-year period for projects installed before the end of 2006 (Bolinger, 2001; IEA, 2001).[145] Under the EEG, the

[144] Following this formula, turbines received the higher tariff for an extra 2 months for every three quarter of a percentage point below the 150% threshold (IEA, 2001).

[145] The offshore tariff was adjusted according to distance from the shore and water depth.

costs of grid extension or reinforcement were borne entirely by the grid operator who could pass these through to end costumers via a surcharge on electricity prices (Sawin, 2001).

The Renewable Energy Act was revised in 2004. The amended EEG reinforced the requirement for grid operators to connect renewable energy projects to the grid and give priority to the electricity they generated. The amended EEG also accelerated the yearly feed-in tariff reduction for new plants from 1.5% to 2% a year, adopted a broader variety of reference yields based on different locations, and no longer provided support for projects where less than 60% of the reference yield was expected at the end of the five year period. To encourage decommissioning of old turbines, the amended EEG extended the initial high tariff period when a turbine with a over three times the capacity of the turbine it replaced was installed (BMU, 2007a).[146] From 2004, the initial high tariff for onshore plants was set at 0.087 euro/kWh, in conformity with the trends set by the 2000 EEG. The basic value was reduced slightly to 0.055 euro/kWh.

For offshore wind power, the amended EEG raised the initial high tariff to 0.091 euro/kWh and extended the period during which projects received this to 12 years, after which the basic tariff was set to 0.062 euro/kWh for the remaining eight years. The 2% decline in tariffs was also scheduled to only start in 2008 for offshore projects (BMU, 2007a; IEA, 2005).

By 2006, no offshore wind power projects had been built due to various bottlenecks in the permit granting process and grid access concerns. The government therefore introduced the

[146] For repowering, the period during which turbines receive the higher tariff is extended for two months for every 0.6% of a percentage point below the 150% threshold (BMU, 2007a).

Infrastructure Acceleration Act which forced transmission system operators to pay for and build the grid connections from offshore project sites to the onshore grid (IEA, 2006a).

In 2008 a new amendment to the Renewable Energy Act was adopted to compensate for the rise in steel and other raw material prices and to provide further support to the lagging offshore wind power market. For onshore projects, the higher tariff was increased starting in 2009 to 0.092 euro/kWh while the basic tariff was increased to 0.0502 euro/kWh. The yearly reduction in tariff was lowered from 2% to 1% starting from 2010. The amendment also offered an extra payment of 0.005 euro/kWh for projects linked to the decommissioning of old turbines and for turbines meeting specific technical standards for grid integration. For offshore turbines in operation before the end of 2015, the initial tariff was set at 0.15 euro/kWh for the first 12 years of operation. The subsequent basic tariff was set at 0.035 euro/kWh for the following eight years. For turbines installed after 2015, the initial tariff was set at 0.13 euro/kWh. A 5% annual reduction in the initial tariff was set for turbines installed as of 2015(IEA, 2009).

To facilitate the development of offshore wind projects, particularly in light of increasing difficulties to secure debt capital due to the financial crisis, the government launched in 2010 a EURO5 billion credit program through a government-owned bank to ensure readily available funds at market rates for the construction of 10 of the first wind farm projects in the planning pipeline (BMU and BMWI, 2010; IEA, 2011).

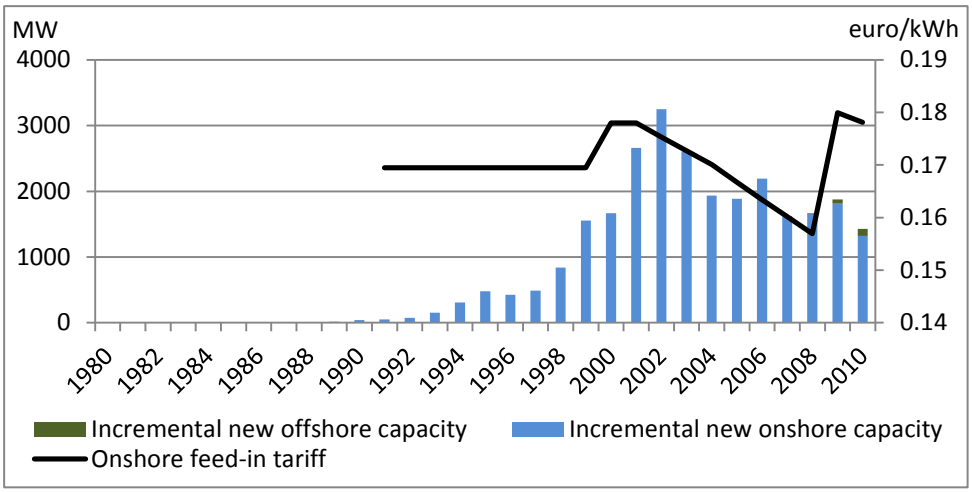
In 2012, a new amendment to the EEG was enacted. While the basic tariff structure for onshore wind and the added subsidy for repowering plants and meeting technical standards for grid integration remained unchanged, the annual tariff reduction rate increased from 1% to 1.5% for new projects. For offshore projects, the initial 0.15 euro/kWh was extended for projects installed

until 2018. However the annual reduction in tariffs increased from 5% to 7%. The amendment also offered the possibility for offshore projects to receive 0.19 euro/kWh for eight years rather than 0.15 euro/kWh for 12 years before dropping to 0.035 euro/kWh (IEA, 2011).

The effect of changes in government subsidies on the evolution of the wind power market in Germany can be identified in figure 4.4. The first growth period, from 1992 to 1995, which saw annual installed capacity rise from about 70MW to a little below 500MW, is likely a consequence of the introduction of the first feed-in law in 1991. The removal of state level investment grants may have contributed to the relative stagnation observed in 1996 and 1997, however, Sawin (2001) notes that the more likely cause was a challenge in court in 1994 to the legality of wind turbine siting laws. This created significant uncertainty until a new law was passed in 1997, streamlining the planning and approval process.

The sharp increase which took place between 1998 and 1999, surpassing 1,500MW installed per year, likely resulted from a combination of the enactment of the new siting law and a rush to install new plants in light of growing opposition to the feed-in-law, which eventually led to its amendment in 1998. Similarly, the stagnation of 2000 is likely a consequence of the capacity cap introduced in the amendment of 1998. The boom of 2001 and 2002, when installed capacity reached 3,250MW per year, the highest level in the thirty year time frame, can be attributed to the higher tariffs offered by the Renewable Energy Act of 2000.

Figure 4.4: Incremental wind power deployment and main support mechanism, Germany, 1980-2010



Note: Capacity data compiled from IEA (2001; 2002a; 2002b; 2003; 2004; 2005; 2006a; 2006b; 2008; 2009; 2010; 2011; 2012a; 2012b).

For purposes of clarity all onshore feed-in tariffs expressed in euros (conversion rate of 1.96 Deutschmarks to the euro). Tariffs shown are those which were given during the initial period for projects built in the year indicated. From 1991 to 1999 the average feed-in tariff value is used. Additional subsidies for turbine retrofitting are not included.

The peak in annual installation of 2002 was followed by an overall decline in incremental wind power installations. The reduction in annual installations was most significant between 2002 and 2004, when annual installations totaled a little over 1900MW. As shown in figure 4.4, the overall trend between 2002 and 2008 matches the progressive drop in feed-in tariffs. However, as highlighted by Fischedick (2004), the slowdown was most likely due to a combination of factors, including the gradual exhaustion of available high wind resource locations, growing resistance to wind power expansion among various groups of stakeholders, and uncertainties with respect to grid connection and cost sharing obligations. The latter was notably at the heart of the 2004 amendment to the renewable energy law, which aimed to reinforce grid connection obligations and further detail balancing cost sharing rules (WPM, 2004). The introduction of higher tariffs in

2008 appeared to have had only limited effects on the rate of installations in 2009 and 2010, further supporting the possibility that other factors were at play.

Though offshore wind power was clearly identified as an area of priority, the financial incentives offered to offshore projects through feed-in-tariffs were alone insufficient to spur deployment. Though 29 projects had reportedly been approved by government authorities between 2001 and 2010 the first project was only commissioned in 2009 and consisted of an R&D and demonstration project. In addition to issues pertaining to permits and grid connections discussed above, another challenge to offshore development was access to debt financing, particularly during the financial crisis of 2008 (IEA, 2011; 2012a).

4.2.1.3 United States

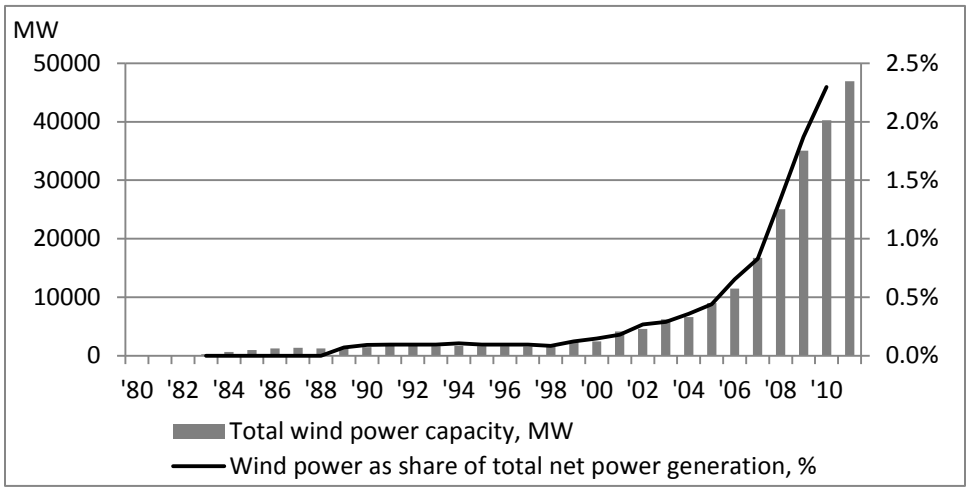
In 1973, the United States government released an energy plan which aimed to reduce the country's dependence on oil imports to zero by the end of the 1970s. However, it was not until 1979 and the second oil shock that the government announced targets of renewable energy production, including a goal to produce 500TWh of wind power per year by 2000. Furthermore, the Wind Energy Systems Act of 1980 set a target to install 800MW in capacity by the end of 1988. However, these goals were abandoned by the subsequent administration, which placed much of its energy policy emphasis on enhancing domestic fossil fuel production (Sawin, 2001).

In 1997, the government formulated a target under the Federal Wind Energy Program that aimed to achieve a cumulative wind power capacity of 6,700MW by 2000 (Sawin, 2001). The Department of Energy's Wind Powering America initiative introduced in 1999 contained goals for at least 5% of national electricity generation coming from wind power by 2020, and for total

installed capacity to reach 5,000MW by 2005, 10,000MW by 2010, and 80,000MW by 2020 (Sawin, 2001; IEA, 2001).

Figure 4.5 shows the evolution of wind power cumulative installed capacity and wind power generation as a share of total net power generation in the United States. Though goals set in the late 1970s and early 1980s were eventually abandoned, in 2000 only about 1% of the target set in 1979 was met while in 1988 the target set in 1980 was exceeded by over 50%. The 2000 capacity target set in 1997 was not met until 2005. However, the 1999 capacity targets for 2005 was exceeded by over 80%, while the target for 2010 was exceeded by over 300%.

Figure 4.5: wind power cumulative installed capacity and power generation as percentage of total net power generation, United States, 1980-2010



Note: Compiled from Sawin (2001), Wiser and Bolinger (2012), and EIA (2012).

In 1976, renewable energy facilities were categorized by the government as pollution control facilities, making them eligible for a 10% investment tax credit. The 1978 Energy Tax Act introduced an additional 10% investment tax credit for qualified renewable energy projects installed before the end of 1982. The Crude Oil Windfall Tax Act of 1980 raised this tax credit to

15% from 1980 and extended its availability to the end of 1985. These tax credits were however not extended beyond 1985 (Sawin, 2001).

The National Energy Act of 1978 introduced the Public Utilities Regulatory Policies Act (PURPA) which aimed to created competition by requiring utility companies to purchase electricity from 'qualifying facilities', defined as either cogeneration facilities or small renewable energy plants no greater than 80MW in capacity. However, the legality of PURPA was challenged in court by utility companies and the Act did not come into force until 1981 (Gielecki, Mayes, and Pete, 2000). PURPA required utility companies to connect qualifying facilities to the grid, provide ancillary services, and purchase excess electricity generated based on the notion of 'avoided costs' (Sawin, 2001; Gielecki, Mayes, and Pete, 2000).[147,148] In 1990, PURPA was temporarily amended to remove the 80MW size limitations on power generation facilities registered before the end of 1994 and for which construction started prior to 2000 (Sawin, 2001; Gielecki et al., 2000).

The government introduced several minor tax incentives in favor of wind power during the 1980s (Sawin, 2001; Gielecki, Mayes, and Pete, 2000). However, by far the most important wind power deployment support policy was an inflation adjusted production tax credit (PTC) introduced by the Energy Policy Act of 1992. The PTC was initially set at 0.015 USD/kWh for qualified wind power projects installed between 1994 and 1999 and selling power generated to to

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[147] 'Avoided costs' refer to the costs the utility companies would have to pay for the same amount of electricity (Sawin, 2001).

[148] In 1980 the Federal Energy Regulatory Commission (FERC) made connection to the grid mandatory as well as the need for utilities to purchase all electricity produced by small renewable energy plants, irrespective of the utilities' needs.

utility companies. The PTC could be claimed for power produced during the first ten years of a plant's operation. The government also introduced a Renewable Energy Production Incentive (REPI) at the same rate as the PTC for wind power plants in operation before the end of 2001 and owned by municipal utility companies or non-profit cooperatives that did not pay taxes to the government (Gielecki, Mayes, and Pete, 2000; Sawin, 2001; IEA, 2001).

The PTC expired in June 1999 but was extended retroactively at the end of 1999 to include plants in operation by the end of 2001. From 1999 the tax credit was raised to 0.017 USD/kWh (Sawin, 2001). The PTC expired again at the end of 2001 but was once more extended retroactively in March 2002 through the end of 2003 at a rate of 0.018 USD/kWh. Similarly the REPI was extended for plants in operation by the end of 2003 at a rate of 0.018 USD/kWh (IEA, 2003).

The PTC was again extended in October 2004 for wind power plants installed before the end of 2007 at a rate of 0.019 USD/kWh. The REPI was also extended over the same time frame (IEA, 2006b). In December 2006, the government extended the PTC through 2008 at a rate of 0.020 USD/kWh (IEA, 2008; 2009).The Emergency Economic Stabilization Act of 2008 renewed the PTC for wind energy for one year, until the end of 2009, at a rate of 0.021 USD/kWh. However, the American Recovery and Reinvestment Act of 2009 further extended the PCT until the end of 2012. The latter also introduced an Investment Tax Credit (ITC) available until the end of 2012, which wind power plant developers could choose instead of the PTC. The ITC allows 30% of the investment in a wind power plant to be refunded in the form of reduced income taxes or an upfront grant (IEA, 2009). The Recovery Act also made loan guaranties available for wind projects and provided funding for the construction of new transmission lines (IEA, 2010; 2011).

In 2007, the Federal Energy Regulatory Commission (FERC) introduced a new regulation to give greater access to transmission lines for all power generation plants, including wind power. In addition, the new law exempted intermittent power generation plants, such as wind power, from incurring excessive 'imbalance' costs when the amount of electricity delivered differed from the amount scheduled to be delivered (IEA, 2008).

Figure 4.6 shows the evolution of incremental installed capacity in the United States. The early period of market growth during the 1980s and early 1990s was almost entirely based in California.[149] The state government introduced some of the earliest and at the time most ambitious policies in support of wind power deployment. At the heart of these were a series of standard power purchase agreements detailing the provisions under which state utility companies were required to purchase power generated by qualifying facilities under PURPA. The first three of these 'standard offers' were short-term contracts that became available in 1982. The fourth and last standard offer was introduced in 1983. This allowed qualifying facilities to sign long-term contracts with utility companies for up to 30 years and receive a guaranteed fixed price during the first 10 years.[150] However, in response to concerns over the oversupply of electricity and high prices to consumers, the state government eventually suspended the fourth standard offer in 1985. While plans to define a final standard offer contract were subsequently devised, the process collapsed in 1995 in light of the complex methodological and procedural issues

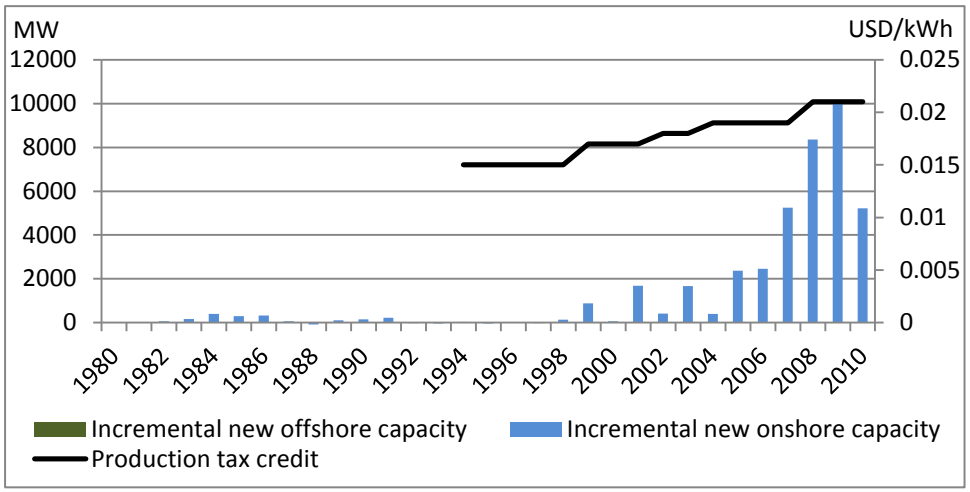
[149] Between 1983 and 1997 California accounted on average for 97% of incremental wind power capacity installed in the country (based on data from Sawin, 2001).

[150] Under the fourth standard offer contract, during the first 10 years qualifying facilities would receive a price for electricity based on the avoided long-term costs for utilities, as stipulated under PURPA. After the initial 10 years they would receive a price based on estimates of avoided short-run costs for utilities.

raised. As a result long-term contracts were abandoned and utility companies were no longer required to purchase power from qualifying facilities (Sawin, 2001).

The first period of growth in annual incremental wind power installation during the 1980s started almost immediately after the California state government introduced its standard offers. In fact, Sawin (2001) notes that almost all wind power projects in California between 1983 and the mid-1990s were in the scope of fourth standard offer contracts. She also attributes the decline in annual incremental installations between 1985 and 1987 to the expiration of both a federal tax credit at the end of 1985 and a California tax credit at the end of 1986. Finally, she associates the rise in annual installed capacity between 1989 and 1991 to a rush by developers to install projects before the expiration of the fourth standard offer contract (Sawin, 2001).

Figure 4.6: Incremental wind power deployment and main support mechanism, United States, 1980-2010



Note: Capacity data based on Sawin (2001) and Wiser and Bolinger (2012).

Following this early California experience, despite the introduction in 1994 of the PTC at the federal level, limited deployment took place nationally until 1999. The sharp increase in wind power installations in 1999 may be associated to a rush by project developers to secure contracts under PTC terms before its planned expiration in 1999. Similarly, the effects of subsequent short-term extensions and expirations of the PTC are apparent in years with high wind power capacity installed followed by years with much lower capacity installed. It is only following the 2004 extension of the PTC that more stable growth in the market was introduced. Part of the reason is that unlike in previous years, the PTC was not allowed to expire before being extended, thereby providing better financial stability to project developers. Installation peaked in 2009 to the historical level of 10 GW per year, which was likely due to a rush by developers to get projects approved before the planned expiration of the one year PTC extension introduced in 2008. The longer-term support offered by the government from 2009 has generated a more stable market in 2010 and 2011, represented by approximately 6,000 MW per year in new installations.

4.2.1.4 Summary

For each of the three countries, the above discussion underscores a high level of correlation between changes in government support policies and the level of wind power deployment. This suggests that markets for wind power have relied on government policies as they would have not been economically feasible otherwise.

The policy timelines in each case highlight the frequency with which the level of government support for wind power deployment has been altered. This has had a clear effect on the rate of deployment. As discussed in the literature review in Section 1.2, this is relevant as market opportunities drive firm investments in long-term technological development efforts. Such

frequent changes to government support policies may be linked to a number of factors. One of these, though beyond the scope of the above discussion, is politics. Extending government funding on a large scale and over several decades to a specific technology such as wind power is likely to be a politically taxing process. As governments change, so do political priorities, which in turn affect the willingness of governments to support deployment. In addition, as discussed in Chapter 1, one function of technology development systems is the process of legitimization of a new technology. This is a difficult process which involves counteracting resistance from stakeholders, including incumbent technology systems. It is not surprising therefore that over the years, political compromises have led to changes in the level of government deployment support in each of the three countries. For example, in the case of Denmark, a 2002 political compromise led to a reduction in wind power subsidies which can clearly be linked to a prolonged period of limited deployment. Similarly, in the case of the United States, on several occasions the government allowed support for wind power to expire, bringing domestic technology deployment to a halt.

The political decision to not pursue nuclear power as an alternative power generation technology in both Denmark and Germany likely had a number of positive effects on wind power deployment. Nuclear power is a low greenhouse gas emitting technology and given the climate mitigation ambitions of both countries, the decision likely led to more pronounced government support for wind power in addition to providing firms with more certainty with respect to the long-term prospects of wind power.

Another important factor which may explain the numerous changes in deployment support policies is the pervasive uncertainty faced by policy makers concerning the effectiveness of the

policies introduced. This is clearly apparent in the case of California during the 1980s, where the policies to support wind power deployment led to a rush of installations far beyond what the government expected. Such uncertainties are further fueled by changes in external factors, such as in the price of steel used in wind turbine manufacturing, the prices of fossil fuels, as well as the progress made in wind power technology and turbine manufacturing. Changes in such external factors alter the power generation cost differences between wind power and incumbent technologies thereby changing the effects of government policies. These factors continually evolve and though governments may try to tailor their support to technology deployment accordingly, this is likely to be an imperfect process as an information lag will necessarily persist.

A common feature in all three countries is the apparent ability of project developers to preemptively increase deployment to secure certain support levels prior to the time governments introduce changes. This is highlighted by the spikes in deployment prior to policy changes witnessed in each country. This phenomenon is not surprising given the bureaucratic process involved in policy change and the frequent interactions between government and firms. However, it further contributes to accentuating market fluctuations.

The case of offshore wind power development is also instructive as it highlights the difficulties faced by policy makers in creating new market opportunities for wind power. Of the three countries considered, only Denmark has succeeded in launching offshore wind power projects during the time frame considered. However, this involved large projects requiring lengthy approval processes. Offshore development is notably complicated as it requires costly and

technically sophisticated grid connections. This was one of the reasons behind the numerous delays faced by offshore projects in Germany, despite several increases in feed-in tariffs.

4.2.2 Research and development (R&D) support

Incentives for firms to invest in wind power technology R&D evolve as markets are created through technology deployment policies. Before such policies are introduced, firms have little commercial incentives to invest in technology development activities. As wind power markets are created, the prospects of capturing market shares and eventually making profits lead firms to start investing in wind power technology R&D. However, in these early stages private R&D funding may be limited. The firms involved are likely to be small, limiting their ability to invest in R&D. Firms also face a number of uncertainties which may affect their R&D efforts, including uncertainties about future technological prospects or continued government deployment support. Even in latter stages of the market, firms are likely to under-invest in R&D because of knowledge spillovers.[151]

Government support of R&D therefore plays an important role in spurring wind power technology development, particularly in the early stages of the market. Such support can take many different forms. Government funding can be extended to firms, universities, or research institutions. The types of projects supported can also vary significantly. In this section, I discuss government R&D support in the three countries considered. The emphasis is on outlining how R&D support has changed over time, particularly concerning the type of projects, channels employed, and level of funding.

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[151] Knowledge spillovers are discussed in the literature reviewed in Section 1.2.

4.2.2.1 Denmark

One of the first R&D efforts by the Danish government was to refurbish between 1977 and 1979 the Gedser turbine, first installed in 1957, to use it as an experimental test site (Sawin, 2001). The government also worked with Danish utility companies to design, construct, and test two 630kW three-blade horizontal axis wind turbines, one based on blade pitching and the other using stall control. Over the years, other demonstration turbines were installed to help utility companies gain experience. Five 750kW turbines were installed in the early 1980s and two turbines of 1MW and 2MW in capacity were installed in the early 1990s (Sawin, 2001; Krohn, 1998).

Since the late 1980s, government funded R&D projects have typically involved several participants among utility companies, turbine manufacturers, and research centers. The government also encouraged industry co-financing. During the 1990s, the government typically financed between 50% and 85% of total project costs. A network of experts from industry, academia, and government research centers in collaboration with the Danish Energy Agency oversaw R&D planning and project allocations (ENS, 1999; IEA, 2001).By the end of the 1990s, Danish wind turbine manufacturers increasingly funded their own technology R&D efforts. A government strategy for wind power R&D issued in 2000 therefore called for the government to place greater emphasis on long-term technology R&D (Sawin, 2001; IEA, 2001). The composition of government funded projects increasingly shifted towards wind resource assessment methods, grid integration, and more long-term applied research pertaining to the design and development of increasingly large turbines. For example, in 1999 government funded R&D projects included wind resources assessments and forecasting for offshore sites, impacts

assessments of connecting large offshore wind farms to the electricity grid, and research on the design and development of large wind turbines. Between 2000 and 2003 new projects included work on component reliability, the demonstration of models of turbine aerodynamics, and research on material technology for blade surface coating (IEA, 2001; 2003). By 2007, research topics included designs of monopole offshore wind turbines, experimental research on rotor- and airfoil aerodynamics of multi megawatt wind turbines, and probabilistic models of component failures (IEA, 2008).

Much of the R&D projects funded by the government during the 2000s were led by public research organizations. However, by 2010, a large share of government R&D was allocated to firms for demonstration and testing of new technologies. For example, in 2011, the government supported projects by Danish firms for the demonstration of a partial pitch two-blade wind turbine, as well as 140m high concrete towers (IEA, 2012a).

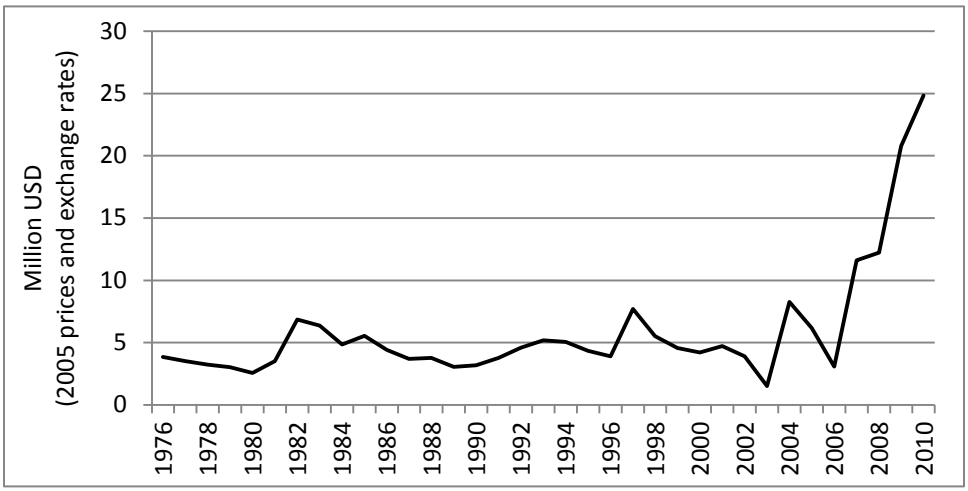
The Risø National Laboratory, originally a nuclear power research center, has played a key role in wind power technology development efforts in Denmark. Starting from 1979 Risø was asked by the government to operate a turbine test center. While initially focusing on small wind turbines, the center quickly broadened its scope to utility-scale turbines. The center started granting turbine certification to ensure that specific safety and reliability standards were met (Sawin, 2001; Krohn, 1998). By the early 2000s Risø managed the center, working with certification firms such as Det Norske Veritas (DNV) or Germanischer Lloyd (GL), and coordinated the elaboration of verification methodologies with international standardization bodies such as the International Electrotechnical Commission (IEC) (IEA, 2004).

The Risø Laboratory has also been heavily involved in government funded research. In 2002, Risø formed a consortium with leading wind power research institutions in Denmark to increase collaboration and address some of the key challenges faced by the industry (IEA, 2005). Most prominent among these organizations were the Risø National Laboratory and the Danish Technical University (DTU), which merged in 2007 to become DTU-Risø (IEA, 2009). Risø was selected to coordinate a project initiated in 2006 by the European Commission and bring together 38 participants from various countries to design wind turbines between 8MW to 10MW able to operate on wind farms of several hundred megawatts both onshore and offshore (IEA, 2006a).

Another important role of Risø has concerned demonstration and testing. Risø acquired and developed a test site for large turbines, inaugurated in 2002 with the installation of four turbines (IEA, 2003). By the end of the decade, two offshore demonstration wind farms totaling 16 turbines were to test foundation and other offshore technologies. A new national test bed was also being developed onshore with the objective of offering complete demonstration and testing facilities for commercial turbines. Furthermore, in 2012, a new 10MW capacity drive train test bed was being built by the new DTU Wind Energy Institute, pooling together core competencies of the Risø Laboratory and various DTU departments (IEA, 2012).

Figure 4.7 shows the evolution of government funding of wind power R&D. The trend shows a relatively stable support level around USD 5 million for much of the 30-year period between 1976 and 2006, after which government funding increased to over USD 11 million in 2007 and close to USD 25 million in 2011.

Figure 4.7: Government wind power R&D funding, Denmark, 1976-2010



Note: Compiled from Sawin (2001) and data sent to the author by the Danish Energy Agency. GDP deflator and exchange rates data from World Bank website (retrieved September 2012).

4.2.2.2 Germany

In 1976, West-Germany's government launched the Growian program which aimed to develop a 3MW, two-blade downwind turbine with a 100m diameter rotor. When installed in 1982, it was the largest wind turbine ever built and the first large-scale turbine to adopt variable speed operation. The turbine ran several hundred hours before being abandoned due to blade failures. Government funding was given directly to the aerospace manufacturers involved in the project and covered all costs incurred. When government funding ended, these firms did not so pursue the wind turbine technology development efforts (Sawin, 2001; Krohn, 1998).

In 1989 the government introduced the 100MW Demonstration Program, extended in 1991 to 250MW. The program aimed to test the prospects of wind power on a large scale. Only new turbines models were selected as part of the program. Turbines installed were monitored during ten years and data on operation and maintenance were collected, evaluated, and shared with all

actors in the industry through a Scientific Measurement and Evaluation Program (WMEP). This included detailed data on energy output, wind resources, as well as on turbine damages caused by storms, lightning, ice, and grid failures. This allowed the development of wind power prognosis tools used in the planning and management of wind farms (IEA, 2006b). As noted earlier in this chapter, a power generation subsidy constituted the main incentive for participation in the 100/250MW Demonstration Program (Sawin, 2001; IEA, 2001). By the end of the program in 1995, over 6,000 proposals had been submitted for a total of over 3,500MW in capacity. The program however only approved 1,223 proposals for 1,573 turbines installed and 384.5MW in capacity.[152] The last projects under the 250MW program were megawatt size turbines, installed in 1998 (IEA, 2001).

During the 1990s government funded R&D included projects on turbine site selection, wind resource assessments, research on turbine components, materials, and grid integration (Sawin, 2001). Funding was allocated to universities and research centers as well as firms. The government notably encouraged R&D collaborations between firms and research institutions. When projects involved firms, the government only funded a fraction of total costs (IEA, 2002a).

Towards the end of the 1990s government funded R&D also contributed to the development and demonstration of a number of large scale turbines by German firms (Sawin, 2001). For example, one project led by Enercon aimed to develop 3 to 4MW turbines and resulted in the installation in 2002 of a first 4.5MW turbine prototype at a test site (IEA, 2001; 2003). Similarly,

[152] The target of 250MW was established based on an assumption of 10m/s wind speeds (Sawin, 2001).

the government supported another project led by a company called Multibrid and which aimed to develop megawatt scale offshore turbines (IEA, 2001). This resulted in a 5MW Multibrid prototype turbine installed in 2004 at a test site (IEA, 2005). From 2005 onwards the bulk of government funded R&D projects started targeting offshore applications. Given the high share of offshore costs attributable to turbine foundations and construction, the government supported many projects in these areas. For example, the government provided funding for a project led by a company named Bard to develop a 5MW offshore turbine and its tri-pile foundation. A prototype was installed and testing began in 2008 (IEA, 2008). Other projects included the creation of an offshore foundation test facility as well as research on new dedicated offshore wind farm construction and logistic vessels (IEA, 2011; BMU, 2007b; 2009). The government also encouraged the creation of research networks, one of which was a multiyear program launched in 2006 focusing on offshore foundations. It brought together steel companies, offshore construction companies, a turbine manufacturer and research institutes to investigate the development of various types of foundations (IEA, 2006a; 2008; BMU, 2007b).

The government continued to support R&D in other areas, such as grid integration issues and component development. The latter notably included projects on new blade designs and improved blade manufacturing techniques (BMU, 2007b; 2008b). From 2005, a strong emphasis was placed on turbine weight reduction and involved several projects on new gear and gearless drive-train concepts for multi-megawatt turbines (IEA, 2006b).The government supported a collaboration between an academic research group and Vensys to develop a compact 2.5MW permanent magnet gearless turbine (IEA, 2007; BMU, 2008b).

In 2001, the government started planning for the construction of offshore condition measurement platforms to collect data for wind power development offshore and for the certification of offshore turbines (IEA, 2002). The first platform was erected in the North Sea in 2003 and started monitoring and collecting hydrological, meteorological, and physical data, which were made publicly available to research institutions and firms (IEA, 2003; 2005). A second platform was erected in 2007 while a third was erected in 2009, both with similar data monitoring capabilities as the first (IEA, 2008; 2011).[153]

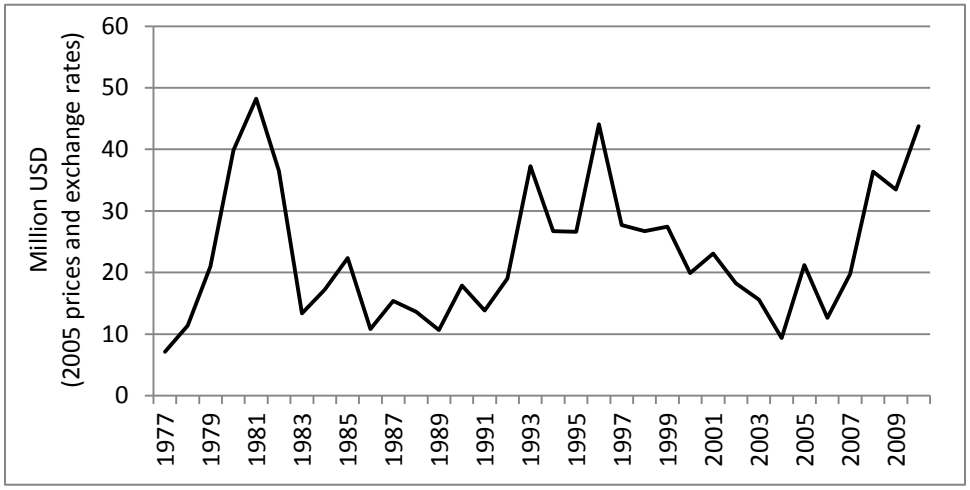
The first offshore wind farm in Germany, commissioned in 2009, was designed as a dedicated R&D test site. It consisted of six 5MW Multibrid turbines installed on jacket foundations, and six 5MW Repower turbines erected on tripod foundation. The government funded an extensive testing and monitoring program for the turbines and foundations. As in the case of the scientific monitoring of the 250MW Demonstration Program discussed above, the aim of the offshore program was to share data collected at the site with researchers and industry experts. In addition, a research program was launched at the site to further study various aspects of offshore operations. A specific research network bringing together academic institutions, research organizations, firms and government agencies was established to enhance cooperation (IEA, 2008; 2009; 2010).

Following a 2009 government review of wind power R&D, the Frounhofer Institute for Wind Energy and Energy Systems Technology was created, bringing together the Fraunhofer Center

[153] The second platform was purchased in 2010 by Garrad Hassan, an engineering service company specialized in wind power and other renewable energy industries.

for Wind Power and Offshore Technology (IWES), a new rotor blade competence center funded by the government, and the Institute fur Solare Energieversorgungstechnik (ISET), which was notably responsible for coordinating scientific monitoring of the 250MW Demonstration Program (IEA, 2009). The new rotor blade test center, which was built in 2008, was the first test facility for multi-megawatt rotor blades, and allowed extensive testing of full scale blades including simulation of offshore conditions (IEA, 2009). In 2011, the new IWES center also built a new drive train test center for gearless turbines in the 2-7.5MW capacity range (IEA, 2012a).

Figure 4.8: Government wind power R&D funding, Germany, 1977-2010



Note: Compiled from IEA (2012b). GDP deflator data from World Bank website (retrieved September 2012). Exchange rate data from European Central Bank website (retrieved September 2012).

Values exclude production subsidies extended to wind turbines for the 100MW and 250MW programs. It does however include costs associated with data collection and monitoring of these programs.

Figure 4.8 shows the evolution of government funding for wind power R&D. The trend shows periods of relatively high government funding followed by periods of more moderate support. The first spike in government funding, from approximately USD 7 million in 1977 to USD 48 million and 1981 before decreasing to USD 13 million in 1983, can be linked to the

government's efforts to develop large utility scale wind turbines. Funding averaged USD 15 million for the subsequent decade before a second spike in government funding, reaching USD 44 million in 1996 before progressively decreasing to under USD 10 million in 2004. During the the third and more recent spike, funding increased to close to USD 44 million by 2010.

4.2.2.3 United States

The bulk of government R&D funding during the late 1970s and 1980s was allocated to the development of large utility-scale horizontal axis turbines. Through a program coordinated by NASA, the government fully funded the construction of a series of turbine prototypes built primarily by aerospace firms. The aim of the prototypes was to serve as test beds for components and subsystems, as well as to generate experience to eventually develop commercially viable turbines. The first such prototype was a two-blade 100kW downwind machine installed in 1975. An upgraded 200kW version began operating in 1977. Between 1977 and 1979 four such models were installed across the country for testing. In 1979, a 2MW model, based on the same design configuration as the first 100kW prototype was erected but was dismantled in 1981, after only 130 hours of operation, due to structural problems. Design of a 2.5MW turbine began in 1977 and the first prototype was erected and began operation in 1981. Three prototypes were built, with the last coming online in 1986, but all were decommissioned in 1987. The last model to be erected in the series of government funded prototypes was a 3.2MW turbine installed in 1987. None of the prototypes erected have led to commercial developments (Sawin, 2001).

Other government R&D during the 1980s and early 1990s primarily aimed to support technology development efforts by firms. Aside from the prototypes mentioned above, this notably involved turbine components such as blades, which until then had been based on aircraft

wing designs. From the second half of the 1990s, the Department of Energy's Wind Energy Program, which has coordinated the bulk of government R&D funding since its establishment in 1973, started placing greater emphasis on applied R&D with the aim to develop more fundamental scientific and technical understanding of wind energy. By 2001, government funding was roughly evenly distributed among 'applied research', 'turbine development', and 'cooperative research and testing'.[154] For each firms' participation was given a prominent role. Typically, firms made technology and commercial decisions while national laboratories provided theoretical and technical support through research and performance testing (IEA, 2002a; 2006b). The DOE National Renewable Energy Laboratory (NREL), established in 1977, and the Sandia National Laboratory (SNL) have been the main national laboratories involved in wind power R&D (IEA, 2003; 2006b). However, over the years, R&D projects have also involved other government agencies and National Laboratories as well as various university programs (IEA, 2011).

The applied research component of the program has included experimental verification of aerodynamic models used in turbine design, testing of component fatigue under different wind regimes, research on new turbine control strategies to improve energy capture and reduce extreme loads. In addition, a number of projects have focused on low wind speed turbine designs (IEA, 2001; 2002a; 2003).

[154] In 2001 applied research accounted for 37% of total government funding, while turbine development and cooperative research and testing respectively accounted for 31% and 32%.

Turbine development research funds have been allocated over the years through competitive bidding and cost-sharing with turbine manufacturers. For example, one project with Enron started in 2000 aimed to test the company's 1.5MW pitch controlled and variable speed turbine. Another project started in 2002 assisted a company named Clipper to develop a prototype of a 2.5MW turbine with a drive train consisting of a novel single-stage gearbox with multiple generators. The prototype was erected for testing in 2005. Another project with General Electric aimed to develop a 3.6MW to 5MW low-wind speed turbine. Similarly, in 2010 a project was launched to assess technological options for turbines above 10MW (IEA, 2001; 2002a; 2003; 2006b; 2010; 2011; 2012a).

Another set of government-supported projects focused on advanced components. These were co-funded by government and industry with cost sharing based on the underlying technology risk of the projects. For example, in the early 2000s these included projects on the development and testing of new blade materials, new blade designs, various direct-drive permanent magnet generator systems, new gearbox concepts, and new converter systems. Since 2002, an important R&D direction has been the development of low wind speed technologies. Similarly, from around 2005 a growing number of government projects have focused on offshore technology development (IEA, 2001; 2002a; 2004; 2006a; 2011; DOE, 2012a). In 2006 the government supported the establishment of a Gearbox Reliability Collaborative, bringing companies, university programs, and National Laboratories, to validate new designs and provide advanced testing procedures of new gearbox concepts. Similarly, a blade Reliability Collaborative was also launched to bring together industry and research institutes to better design, test and monitor wind turbine blades.

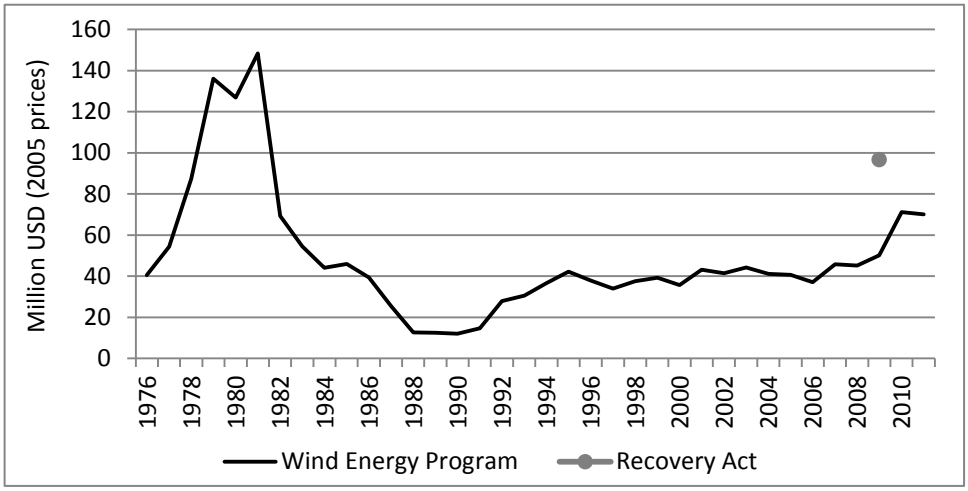
Many of the cooperative research and testing activities have involved NREL's National Wind Technology Center (NWTC), created in 1994. The center was the first wind turbine blade and system testing facility in the country. Towards the end of the 1990s, the center also started participating in the development of international turbine standards and began offering turbine certification services (Sawin, 2001; IEA, 2002a). The capabilities of the center have been expanded and improved over the years through the development of new test procedures and test beds, such as a 2.5MW dynamometer test facility built in the early 2000s and used to run a variety of drive-train tests. In the scope of the Recovery Act funds allocated to R&D research in 2009, the dynamometer test bed was upgraded to 5.5MW and plans for a new drive train test facility were approved with testing capabilities up to 15MW. NWTC has offered the only site in the country for full scale testing of megawatt scale blades up to 50m in length. However, in light of the increasingly large turbines being built, it sponsored in 2007 the development of two new blade testing facilities able to test blades up to 90m in length and provide certification services. Full scale turbine testing sites have also been created at NWTC as well as at university sites (IEA, 2011).

Cooperative research projects have focused on grid integration issues, removal of institutional barriers to wind power expansion, data collection and sharing from existing wind farms, the elaboration of design codes, or the development of high resolution wind resource mapping (IEA, 2001;2004; 2005; 2006b; 2008; 2009; 2010).

Figure 4.9 shows the evolution of government funding for wind power R&D. As in the case of Germany, the first spike in government R&D funding, from USD 40 million in 1977 to USD 148 million in 1981 and down to 44 million in 1984, was linked to early efforts to develop large

utility-scale wind turbines. Funding eventually dropped to below USD 15 million between 1988 and 1991 before increasing again and stabilizing at an average annual value of USD 40 million between 1994 and 2007. Funding has since increased, reaching USD 70 million in 2011. In addition, an exceptional funding of USD 96 million was made available in 2009 in the scope of the Recovery Act following the financial crisis of 2008.

Figure 4.9: Government wind power R&D funding, United States, 1976-2011



Note: Compiled from DOE (2010) and IEA (2010; 2011; 2012b). GDP deflator data from World Bank website (retrieved September 2012).

4.2.2.4 Summary

The discussion above highlights the diversity of approaches pursued by governments to support wind power technology R&D. In the early 1980s in both Germany and the United States the government launched programs aiming to develop large utility-scale turbines through collaborations with the aerospace industry. In both countries the programs were eventually abandoned, having failed to lead to any significant technological follow-ups, whether commercially or through further government R&D projects. One issue in both cases appears to

be that the government was unrealistic about the time needed for technology development. This is notably reflected by the overlapping timing of government funded turbine prototypes in the United States, that left no time for engineers and developers to monitor prototypes and draw on this experience to improve new models. Another important issue is that these projects were entirely funded by the government. The firms involved therefore had no financial stakes in ensuring the projects led to useful commercial technological knowledge. The projects appear to have been primarily driven by government policy objectives rather than based on real firm-level capabilities. In both Germany and the United States, the projects notably involved aerospace companies with no visible long-term interest in wind power.

The Danish government followed a more cautious and incremental approach. The process has centered on the funding of a variety of relatively small and targeted projects with clear timeframes, encouraging the involvement of multiple participants from research institutions and firms. The allocation of government funds has been based on proposal submissions by participants and a review and monitoring process by a group of experts coordinated by the government. The stability of the Danish approach is reflected in government funding which, in contrast to the United States and Germany, has remained relatively stable until it grew sharply in the mid-2000s.

This flexible and iterative project based approach became the norm from the 1990s in Germany and the United States as well. From then on government support for R&D in the three countries shared many common features. One of these was the central role of firms. The co-funding of R&D projects notably ensured firms involved had clear stakes in long-term technology development. A related feature of government R&D has been the support of new turbine

demonstration and testing. Germany's scientific monitoring in the scope of the 100/250MW Demonstration Program was unique in this respect because of the strong emphasis on information collection and sharing among all actors in the industry. In most cases, however, government sponsored demonstration projects aimed primarily to help firms accelerate the testing of new models, often featuring new technology features.

In parallel to supporting technology development at the firm level, governments also emphasized broader R&D goals, such as wind resource assessments, grid integration, and off-shore developments. Though firms were also encouraged to participate in such projects, these were typically led by government research centers and universities. The project based approach notably allowed governments to favor certain technological directions as technological knowledge accumulated, such as low wind speed turbine and offshore technology.

In each country the government also emphasized the pooling of technological knowledge, such as through research networks, and cooperative projects bringing multiple firms and research institutions together. In all three countries the government supported the establishment of large research institutes linked to turbine and component testing facilities. This notably led to the emergence of DTU-Risø in Denmark and NREL in the United States, which have been central to each country's technology development efforts. These centers have integrated centralized testing facilities, turbine and equipment certification capabilities, and a track record of R&D collaboration with industry.

4.2.3 The role of government policy in knowledge development

In Section 4.2.1 I described how government incentives introduced over four decades in Denmark, Germany, and the United States have led to the creation of new wind power technology markets. These have allowed firms and other agents involved in technology development to accumulate valuable experience with wind power technology. Similarly, in Section 4.2.2 I highlighted the breadth of efforts by the same governments and over the same period to support R&D. In this section I assess whether the resulting wind power technology deployment and government R&D funding can be linked to knowledge development. I use changes in patent application counts associated with wind power technology as an indicator of knowledge development for each country.

The patent data used here are drawn from the European Patent Office (EPO) Worldwide Patent Statistical Database (Patstat), which compiles patent information from over 100 countries and contains records dating back to the beginning of the 19th century.[155]

The dataset was treated in two ways prior to being used in the analysis presented here: first to select only patent applications linked to new knowledge generation; and second to select only the most important type of intellectual protection. Regarding the first treatment, patent applications either seek intellectual protection of new knowledge or the geographic or time extension of existing intellectual protection. The latter leads to the creation of patent families, which consist of the set of related patent applications associated with the same invention (OECD, 2009). The

[155] The version of the Patstat database used is from September 2010. The database is updated semi-annually.

emphasis here is on the generation of new knowledge and I therefore only consider the first type of patent applications. To do so I only select patent family heads (i.e. the first patent application of a patent family) and unique patent applications (i.e. patent applications not part of a patent family).

The second treatment focuses on the types of patent being sought. Though terminology and scope vary from one patent jurisdiction to the other, three broad types of patents exist. Invention patents are typically used to protect the most significant new technologies; design patents focus on protecting new design features; while utility models, only available in some countries, typically involve less stringent requirements compared to invention patents, and may be used to protect less significant technology developments. Invention patents can be considered at the heart of the technology development process as they are used to protect the most significant new technological features. I therefore only consider this type of patent in data presented here.

To identify patents associated with wind power technology I use the EPO patent classification for clean energy technologies.[156] For each country I look at two types of patent data. The first consists of wind power patent applications filed by the patenting authority of the country, thereby seeking intellectual protection within the country's borders. The second consists of wind power patent applications where one of the inventors or applicants is located in the country. For this second type the patents may therefore have been filed anywhere. The two types of patent data are closely linked and offer nuances to the assessment of patenting trends. The first is more relevant in the scope of deployment as the deployment policies considered in this chapter are

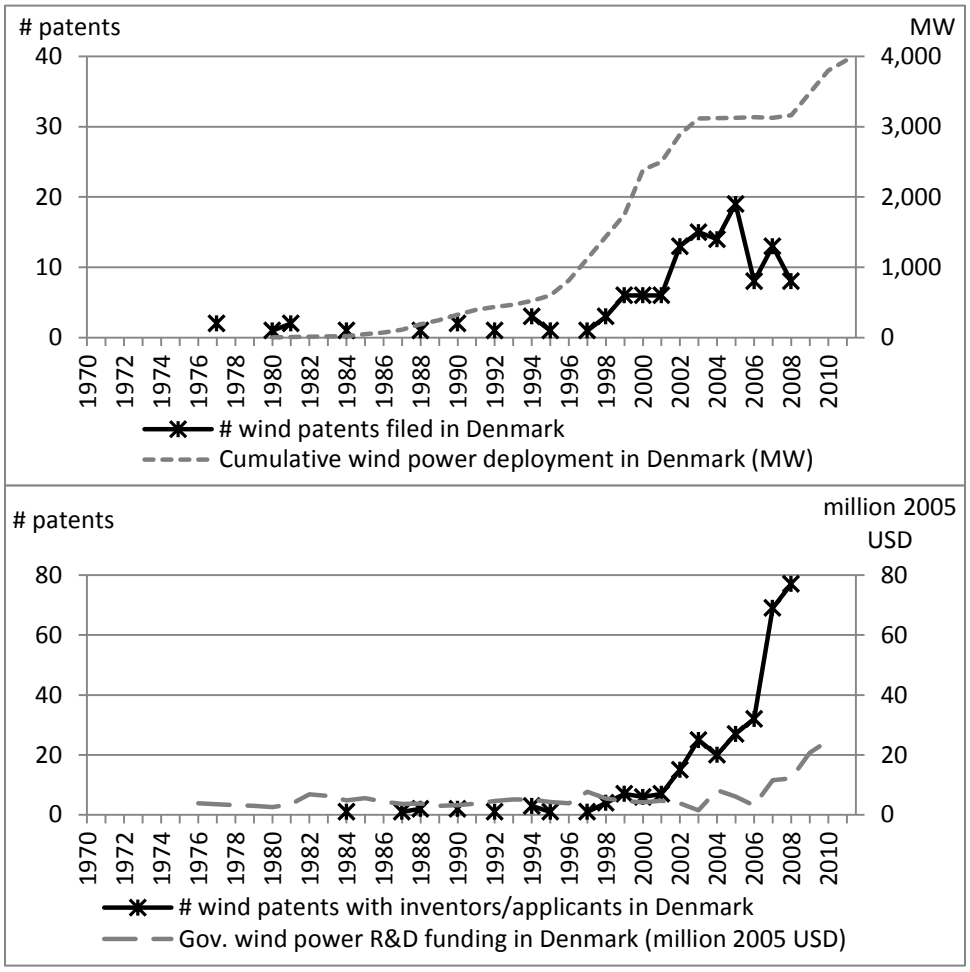
[156] See UNEP, EPO, and ICTSD (2010) and OECD (2011) for more details.

national yet typically do not discriminate on the nationality of firms involved or the place of filing of their intellectual property. In contrast, the second type of patent data is more relevant in the scope of government R&D funding as this has typically targeted national firms and research institutions (see Section 4.2.2 for details).

The emphasis in this section is in correlating changes in the rate of wind power patenting, deployment, and R&D funding. I do not attempt to compare the patenting rates (i.e. the number of patent applications in a given year) across countries as different countries have different intellectual protection regimes. Similarly, I also do not attempt to compare patenting rates across the two types of patent data as these are based on very different sample sizes. While information on country of filing is available for all patents in the Patstat database, only about half of all patents contain information on the location of inventors or applicants.

Figures 4.10, 4.11, and 4.12 show the evolution of wind power patenting, deployment, and government R&D funding in Denmark, Germany, and the United States respectively. In the case of Denmark (figure 4.10), the surge in annual patents filed in the country between the late 1990s and mid 2000s is well correlated with the rise in wind power deployment. The market stagnation between 2003 and 2008 can also be linked to a drop in patenting activity. The limited but stable patenting activity noticeable for both patent data types between the mid 1970s and mid-1990s corresponds to a stable trend in government R&D funding. The sharp rise in the number of yearly patents with inventors or applicants in Denmark is also well correlated to the rise in government R&D funding, though this rise may also be attributed to growing cumulative deployment.

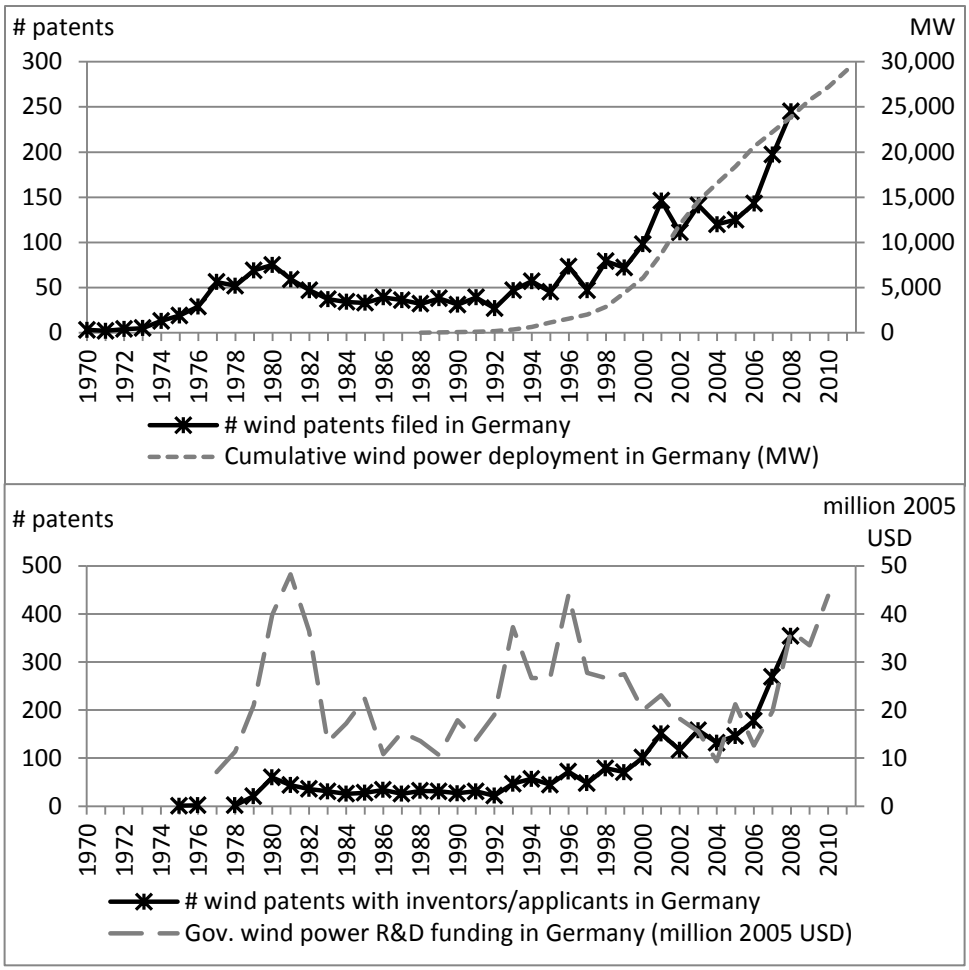
Figure 4.10: Wind power patenting, deployment, and government R&D funding in Denmark



In the case of Germany (figure 4.11) the timing of the overall rise in the number of yearly patents filed in the country from the late 1990s also corresponds to the increase in cumulative deployment. In addition, the modest increase in patenting activity during the second half of the 1970s can be linked to the surge in government R&D funding over the same period. Similarly, the rise in government R&D funding during the 1990s also corresponds to a rise in patenting activity. From the late 1990s, it is difficult to identify a correlation between patenting and government R&D funding as possible effects of government R&D funding are compounded with

those associated with the growth in wind power deployment. Nevertheless, the stagnation in patenting activity in the first half of the 2000s may be at least partially attributable to the overall drop in government R&D funding. Similarly, the rise in government R&D funding likely contributed to the rapid growth in patenting activity from the second half of the 2000s.

Figure 4.11: Wind power patenting, deployment, and government R&D funding in Germany

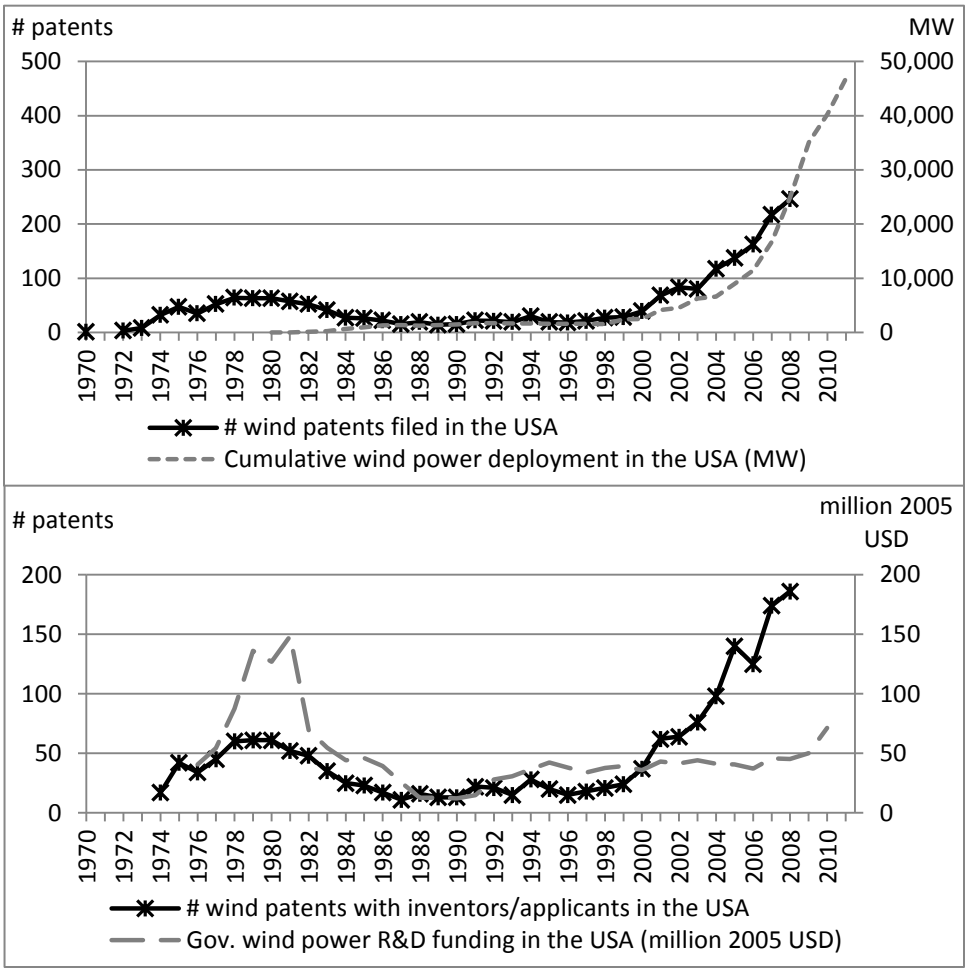


As in the case of Denmark and Germany, the rate of patents filed in the United States (figure 4.12) has increased sharply from the late 1990s, which corresponds to a sharp rise in cumulative wind power deployment in the country. Similarly to the case of Germany, the rise in patenting in

the late 1970s and early 1980s is correlated to the sharp rise in government R&D funding. Unlike the case of Denmark and Germany, however, the strong growth in patenting activity from the late 1990s is not accompanied by a rise in government R&D, indicating that deployment may be the main cause of the surge in patenting.

The strong correlation between changes in wind power patenting rates and changes in policy induced wind power deployment and government R&D funding in the three countries considered strongly suggests that the hypothesis that government has been the main driver of wind power technology knowledge development is correct.

Figure 4.12: Wind power patenting, deployment, and government R&D funding in the United States



4.3 GAUGING THE PACE OF DEVELOPMENT OF THE WIND POWER TECHNOLOGY FRONTIER RELATIVE TO OTHER TECHNOLOGIES

This section aims to compare the pace of technology development at the wind power technology frontier to that of other technologies. Every technology has unique attributes, applications, costs, and relations to other technologies, which makes cross technology comparisons difficult. Nevertheless, certain broad metrics can help gauge the development of one technology relative to that of others. Section 4.3.1 focuses on 'market formation', one of the central functions of technology development systems, and uses market penetration rates as indicators. As in Section 4.2.3, Section 4.3.2 focuses on 'knowledge development' and uses patent application rates as an indicator.

4.3.1 Technology penetration

Technology penetration is a measure of the time it has taken a given technology to reach a certain market share and therefore provides some indication of the technology's development success. This is often depicted graphically by plotting the fraction of a given product (e.g. steel) or service (e.g. lighting or mobility) supplied by different technologies in a given geographic region over time. The result is typically a logistic curve (or s-shaped curve). As a technology is first introduced, often in niche applications, the initial technology penetration rate is generally slow. As the technology becomes increasingly established and costs are reduced, this initial phase is followed by a period characterized by higher and more sustained penetration rates. Finally the rate of penetration progressively slows as the technology reaches a plateau, or saturation level. This s-shaped sequence may be followed by a phase of decline, as the technology is substituted by another, superior technology (Grübler, 1990; 1991).

Grübler, Nakićenović, and Victor (1999) highlight important distinctions which need to be taken into account when considering technology penetration. One such distinction is between technology diffusion and technology substitution. The first refers to the penetration of a technology into a new market, often to provide services which were previously not available. The second consists of substituting technologies in an existing market, offering better services or lower prices.

Another distinction is between technologies and infrastructures (Grübler, Nakićenović, and Victor, 1999; Grübler, 1990). Infrastructures are a special type of technology that generates network effects, thereby allowing other technologies that are compatible with it to develop more rapidly and, conversely, raising barriers to technologies that are not. Examples of infrastructures are most prominent in energy (e.g. electricity transport and distribution networks), transport (e.g. road and fuel distribution networks), as well as communication industries (e.g. mobile phone or internet networks).

Grübler (1991) describes historical data from a sample of 265 cases of technology penetration in a variety of fields including energy, transportation, manufacturing, agriculture, consumer durables, communications, and the military. The sample also includes some economic and social processes, such as literacy or reduction in infant mortality. The analysis focuses on the diffusion time constant (Δt), which is the time for a technology (or process) to grow from 10% to 90%

market penetration.[157] The mean value of Δt for the sample is 41 years with a standard deviation of approximately equal size. Half of the sample has Δt of less than 30 years, and about three quarter has Δt less than 50 years. Grübler, Nakićenović, and Victor (1998) note that diffusion processes appear to progress more slowly than substitution, possibly because the introduction of new services adds to the time it takes for a market to form. Similarly, they underscore that the rate of penetration of new infrastructures is typically longer than most other technologies.

Ray (1988) focuses on six technologies which have played a central role in 20th century industrial development, such as various steel making processes, the use of tunnel kilns in brick making, and float glass manufacturing, and compiles data on the time taken to reach certain market shares from the date of first adoption. Ray finds that a 10% penetration was first reached between five years (in the case of float glass in OECD countries) and 18 years (in the case of continuous casting of steel in Japan). Subsequent penetration levels took less time, with the 90% to 100% penetration taking a maximum of approximately three decades from the time of first adoption.

Wind power technology reached the highest penetration rate in Denmark, accounting for close to 20% of the country's electricity production by 2010. It took approximately 10 years for the country to go from 10% of power generation to the 20% mark. Much lower levels of penetration have been reached in Germany and the United States, where wind power accounted for respectively approximately 6% and 2% of total electricity production in 2010.

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[157] When technologies do not reach 90% penetration in a given market Δt is determined as a theoretical value as if the technology would have followed its logistic growth all the way up to 100%.

It is difficult to compare these values to the historical technology penetration rates documented by Grübler (1991) as he focuses on the time it takes a technology to go from 10% to 90% market penetration levels, which is far greater than what has so far been achieved in the case of wind power. Still, if one assumes that going from 10% to 90% penetration levels is a linear process (i.e. that it corresponds to the middle section of the s-shaped logistic curve and that this can be assumed to be a straight line), then the mean Δt value of 41 years documented by Grübler (1991) implies that every 10% increment in new market penetration takes on average approximately 5 years. Similarly, a Δt of 50 years, which was higher than for 75% of the sample of technologies assessed by Grübler, implies that each 10% increment in new market penetration takes a little over 6 years. These values imply significantly faster penetration rates than the 10 years it took wind power to go from 10% to 20% market penetration in Denmark. This indicates that even in the best case of market penetration wind power is progressing slowly relative to other technologies.

Comparing observed wind power penetration rates to the data presented by Ray (1988) is also difficult as it is unclear what the date of first adoption should be in the case of wind power. As discussed in Section 4.1.3, there have been numerous precursors to the modern wind turbine, ranging back to late 19th century United States or early 20th century Denmark. In addition Ray (1988) focuses on the time needed to reach the 10% penetration level, which in the case of the three countries considered has only been achieved by Denmark.

Nevertheless, if we assume that the first adoption of wind power in Denmark took place in 1980 when the first turbines were installed in the scope of the deployment support policies discussed earlier in this chapter, then 10% market penetration was achieved in Denmark in

approximately 20 years. This is only slightly over the range of penetration rates documented by Ray (1989), indicating that wind power is progressing only marginally slower than the technologies considered. However the time between first adoption and 10% penetration would be significantly longer if an earlier date of first adoption was used. In addition, Denmark is the best case of wind power penetration. Considering wind power penetration in other countries would therefore lead to much slower rates of penetrations.

4.3.2 Technology patenting

As indicated earlier in this chapter, patent applications embody the development of novel technological knowledge. Comparing patenting rates associated with wind power technology and other technologies therefore provides useful insights as to the relative pace of wind power technology knowledge development.

Assessments of patenting trends at the technology or industry level are however difficult as patent classifications focus on characterizing the technical attributes of the technologies being patented rather than providing information on their use. Nevertheless, various studies have matched patent classifications with specific technologies and industrial sectors. Several have focused on comprehensively matching the entire patent classification with industrial sector classifications. For example, Verspagen et al. (1994) have identified a concordance matrix between the International Patent Classification (IPC) and the International Standard Industrial Classification (ISIC). Similarly, Johnson (2002) builds on the work of Evenson and Putnam (1988) to develop a similar concordance matrix by using data from the Canadian Patent Office, which between 1972 and 1995 systematically assigned both a patent and an industry classification code to new patent applications. Schmock et al. (2003) develop another

concordance table linking ISIC, the Statistical Classification of Economic Activities in the European Community (NACE), and the IPC, by analyzing the patenting activities of 3,000 firms classified by industry sector. Schmoch (2008) builds on this experience to develop an updated concordance table, linking the IPC classification to five broad technological areas, broken down into 35 subfields.

Because of their objective to comprehensively match patent and sector classifications, these concordance matrices necessarily remain at a high level of aggregation. Other studies have therefore focused on more specific technologies. The process typically involves iterative key word searches of the patent literature until a satisfactory concordance list is established. This type of exercise has notably been undertaken to identify patent classifications corresponding to high-tech sectors, used in cross country surveys of innovation (e.g. OCD, 2008; Eurostat, 2010).[158] Similarly, growing concerns about energy and environmental protection have led to a number of efforts to identify relevant patent classifications. The OECD and the EPO have identified patent classification concordance matrixes for a broad variety of environment-related technologies, including renewable energy technologies such as wind power (UNEP, EPO, and ICTSD, 2010; OECD, 2011).[159]

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[158] The high-tech sectors patent concordance tables used by Eurostat are available in the Patent Classifications and Technology Areas annex to the Patent Statistics Eurostat Metadata, available online at: http://epp.eurostat.ec.europa.eu/cache/ITY_SDDS/en/pat_esms.htm#diss_format

[159] This has contributed to a growing literature on patenting trends in the clean energy sector. See for example Dechezlepretre et al. (2008), OECD (2010), Lee, Iliev, and Preseton (2009), UNEP, EPO, and ICTSD (2010).

To compare patenting associated with wind power to other industries and technologies I draw on both comprehensive patent-to-industry and specific patent-to-technology concordance matrixes. As in the case of the patent data presented in Section 4.2.3, I use the EPO clean energy patent classification to identify patents associated with wind power.[160] I use the patent-to-industry classification matrix put forth by Schmoch (2008). Concerning patent-to-technology matrixes I focus on conventional energy technologies: fossil fuel power generation, oil and gas drilling, oil refining, nuclear energy, and hydro energy. For nuclear energy and hydro energy I use the EPO clean energy classification mentioned above. However, in the case of oil and gas drilling and oil refining IPC concordance tables were not readily available so I propose new concordance matrixes based on my own assessment of the IPC classification and patent literature. For fossil fuel power generation I also propose a new concordance matrix based on an extension of the matrix put forth by Lanzi, Verdolini, and Hascic (2011). For these three technology cases the resulting matrixes, as set forth in the Annex to this chapter, are necessarily not as precise as more established concordance tables and should therefore be considered with care and ideally complemented by further research.

The data presented here are drawn from the EPO Patstat database and the dataset was treated in the same ways as detailed in Section 4.2.3: first to select only patent applications linked to new knowledge generation; and second to select only the most important type of patents. However, unlike the analysis in Section 4.2.3, I adopt here a broader geographic scope and consider

[160] See UNEP, EPO, and ICTSD (2010) and OECD (2011) for more details.

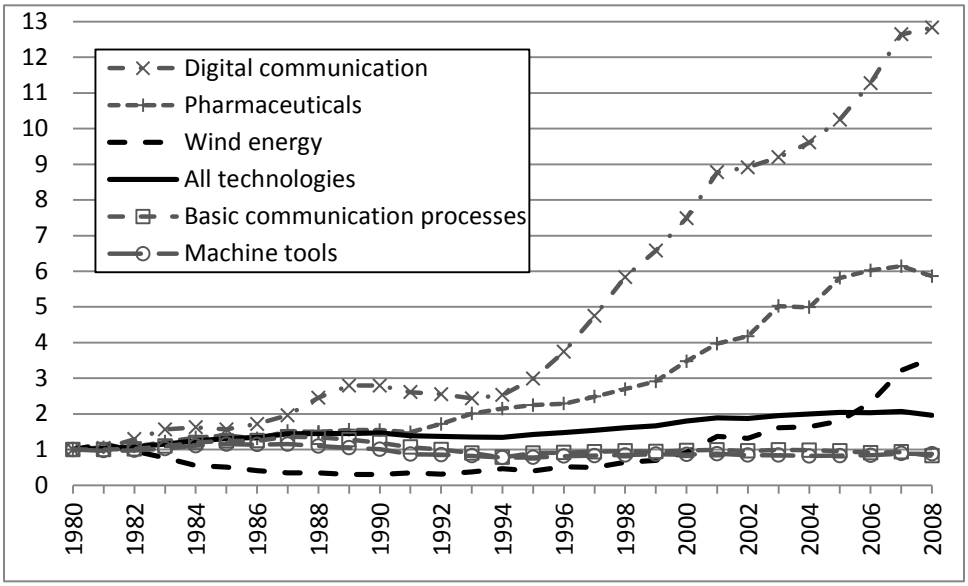
patenting trends at the global level as well as in Europe, and the United States, where wind power has been pursued most actively.

Figure 4.13 uses Schmoch's (2008) comprehensive breakdown of the IPC into 35 technological subfields. It shows global trends in annual patent applications between 1980 and 2008 for wind power, all 35 subfields combined (referred to as 'all technologies' in figure 4.13), as well as some of the subfields which have experienced the fastest and slowest growth in patenting by 2008. Looking at all patenting rates for all technology subfields combined is useful as it provides an indication of the overall rate of technology development at the global frontier. Because of difference levels of technology aggregation the trends in figure 4.13 are normalized using 1980 patenting values as the base year. As detailed in Section 4.2.3 in the case of Denmark, Germany, and the United States, 1980 is an interesting point of reference for wind power as it corresponds to the peak of the first wave of government support for wind power technology development.

The figure shows that by 2008 the rate of wind power patenting more than tripled relative to the 1980 value. In contrast the rate of patenting for all technologies taken together approximately doubled by 2008. However for most of the 1980 to 2008 period, the growth in wind power patenting was slower than that of all technologies combined. The rate of patenting for wind power dropped below the 1980 level in the early 1980s and only reached that level again around 2000. For almost all of the 1980s and 1990s, the trend for wind power patents was below that of 'machine tools' and 'basic communications processes', the two technological subfields which by 2008 had experienced the slowest growth relative to 1980 values. The pace of wind power patenting surpassed these subfields only around 2000, and did not overtake the rate of patenting

in all technologies combined until 2006. In contrast, yearly patenting related to 'digital communication' and 'pharmaceuticals', among the fastest growing subfields, reached respectively approximately 13 and 6 times 1980 values.

Figure 4.13: Global patenting in wind power, all technologies, fast and slow performing subfields, 1980-2008, 1980=1



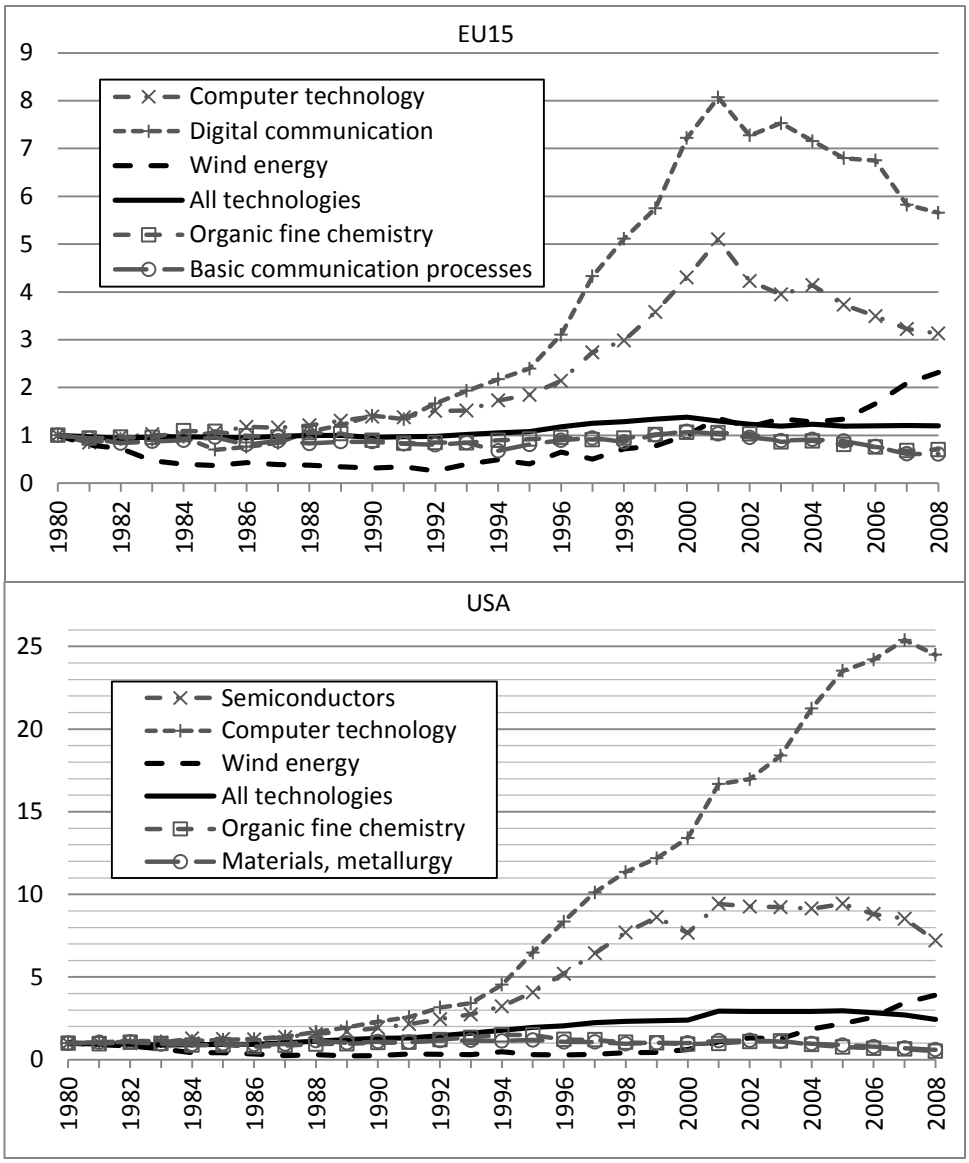
Note: 'Digital communication' and 'pharmaceuticals' were respectively the 2nd and 3rd subfields in 2008 in terms of highest patenting relative to 1980. Due to its very low patenting in 1980 'IT methods for management' was the subfield ranked 1st in 2008. 'Machine tools' and 'basic communications processes' experienced the slowest growth in patenting among the 35 technological subfields identified by Schmoch (2008).

Figure 4.14 is similar to figure 4.13 but focuses on patents filed in EU15 countries and in the United States. As detailed in earlier sections of this chapter, these are the regions where governments have been the most active in supporting wind power technology development since the 1970s. Between 1980 and 2008, the number of annual filings of wind power technology patent applications in EU15 countries and the United States together accounted on average for 81% of all wind power technology patents filed globally. Nevertheless, overall the same pattern

as that observed at the global level can be seen. When compared to the rate of patenting in the technology subfields identified by Schmoch (2008), in both regions wind power patenting grew more slowly relative to 1980 levels than the worst performing subfields for much of the 1980 to 2008 period. In EU15 countries, wind power patenting caught-up in 2001 with the trend of all technologies combined and reached over twice its 1980 level in 2008. In the case of the United States, wind power patenting only caught up with the trend for all technologies in 2007 and reached close to four times the 1980 value in 2008. In contrast some of the best performing subfields shown in figure 4.14 reached approximately six and three times their 1980 patenting rates in the case of EU15, and 25 and seven times 1980 values in the case of the United States.

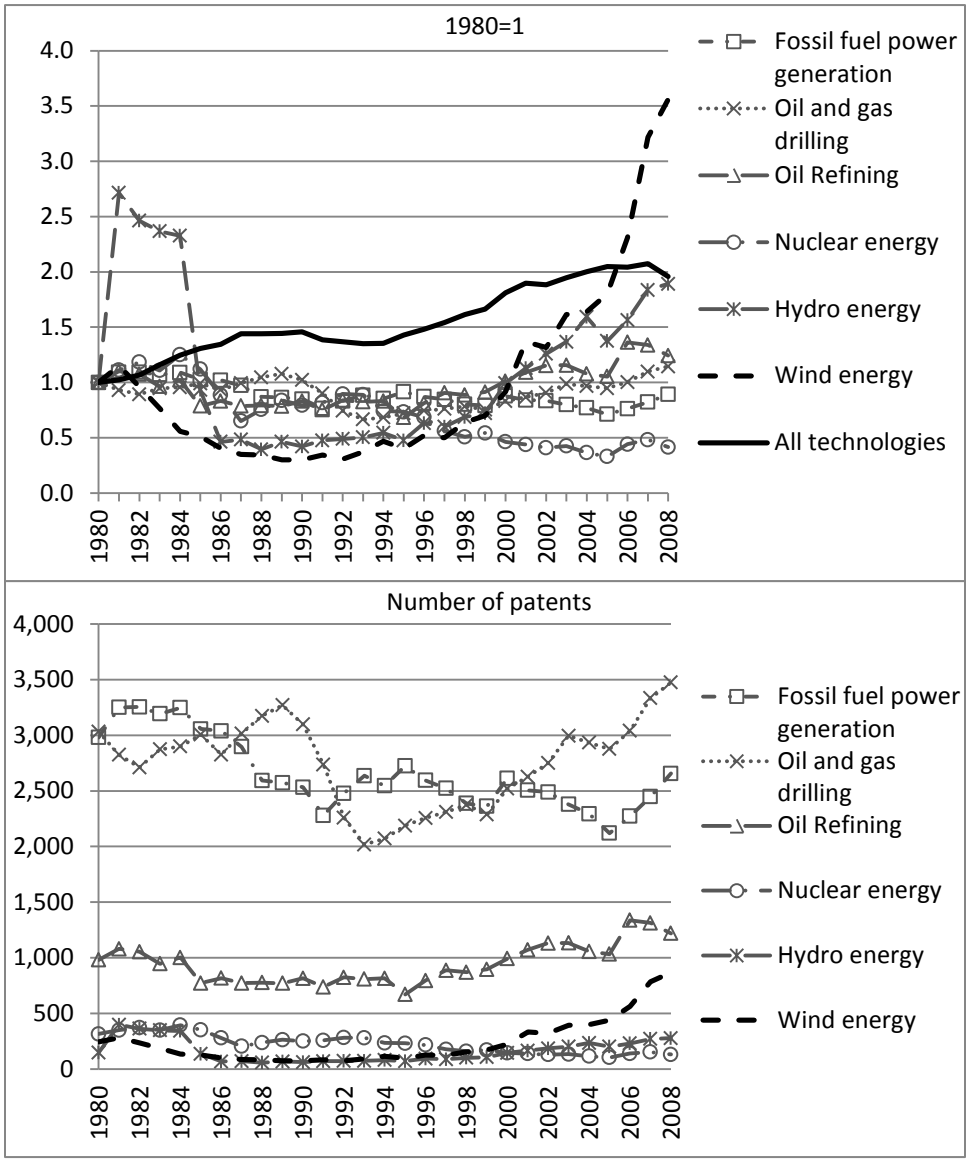
Figure 4.15 compares global patenting trends associated with wind power and some of the main conventional energy technologies. The upper chart normalizes the trends for each technology using 1980 as the base year. Similarly to figure 4.13 this also includes the trend for all technologies combined. The lower chart shows total yearly patent applications numbers associated with each technology. Comparing absolute values is difficult as there are inherent differences in the nature of technologies as well as the patent classification breakdown adopted in each case. Nevertheless, the technologies considered are linked to the same industry and looking at total patent numbers provides some insights as to the relative evolution of knowledge associated with various technologies.

Figure 4.14: EU15 and United States patenting in wind power, all technologies, fast and slow performing subfields, 1980-2008, 1980=1



Note: 'Digital communication' and 'computer technology' in EU15 and 'semiconductors and 'computer technology' in the United States were respectively the 2nd and 3rd subfields in terms of highest patenting in 2008 relative to 1980. Due to its very low patenting in 1980 'IT methods for management' was the subfield ranked 1st in 2008. 'Organic fine chemistry' and 'basic communications processes' in EU15 and 'organic fine chemistry' and 'materials, metallurgy' in the United States experienced the slowest growth in patenting among the 35 technological subfields identified by Schmoch (2008).

Figure 4.15: Global patenting in wind power and conventional energy technologies, 1980-2008



Patenting rates relative to 1980 values (upper chart) for all conventional energy technologies have remained below the trend of all technologies combined from the early 1980s on. For much of the 1990s, patenting rates for all technologies had fallen below 1980 levels. Only hydro energy, oil refining, and oil and gas drilling had patenting rates in 2008 above their 1980 values. In contrast, fossil fuel power generation and nuclear power had 2008 patenting rates below their

1980 levels. Nevertheless, the rate of wind power patenting was lower than that of all conventional energy technologies until the late 1990s, at which point it started to rise, eventually surpassing all conventional energy technologies around 2000.

In absolute terms (lower chart), until the second half of the 1990s, the total number of yearly wind power patent applications had been comparable to that of hydro energy, which until then experienced the lowest levels of patenting among the conventional energy technologies considered. Once the rate of wind power patenting started to rise, however, by the late 1990s wind power patenting numbers had surpassed those associated with hydro energy and nuclear energy, and reached close to 900 by 2008. In contrast, the number of patents associated with oil refining has remained roughly stable increasing from 1,000 applications per year in 1980 to 1,200 in 2008. Fossil fuel power generation and oil and gas drilling experienced still higher yearly patenting rates. Though the rate of patenting associated with fossil fuel power generation has dropped since 1980 it still accounts for over 2,600 patent applications per year. After dropping from approximately 3,000 applications in 1980 to 2,000 patent applications in 1993, patenting in oil and gas drilling has notably risen to approximately 3,500 applications in 2008. This represents close to twice the increase in the number of wind power patent applications over the same 1993-2008 period.

4.4 CONCLUSION

Section 4.2 highlighted the central role played by governments to both create markets for wind power and support wind power R&D efforts. The detailed policy timelines in the three countries discussed reflects the challenges of implementing policies which can provide fertile environments for firms to engage in technology development, whether through stable market

opportunities or sound R&D support. These policy efforts were highly correlated with wind power patenting trends, suggesting that government policy has played a central role in wind power technology development.

Section 4.3 underscored the slow pace of technology development relative to other technologies. Though data on wind power market penetration were not easily comparable to data for other technologies found in the literature, simple extrapolations indicate that wind power appears to be evolving at a slower pace than other technologies.

Looking at the evolution of patenting rates confirms that knowledge development associated with wind power technology has been slow relative to other technologies for much of the 1980-2008 period. Whether at the global level or in regions most active in supporting wind power through government policy, until the late 1990s, the rate of wind power patenting relative to 1980 levels was among the lowest compared to all technology subfields. It only reached the rate of growth in patenting experienced by all technologies combined in the early 2000s in the case of the EU15 region and not until 2007 in the case of the United States. Wind power patenting rates then started increasing at a faster rate, though in 2008 these were still far below rates experienced by the most dynamic high-tech sectors, such as computer technology, digital communication, and semiconductors. Looking at conventional energy technologies provides a point of comparison with established technologies in the energy sector. The rate of wind power patenting relative to 1980 was below that of all conventional technologies for much of the 1980s and 1990s. However, by the early 2000s it had surpassed that of all conventional energy technologies and subsequently rose at a much faster rate. Still, comparing numbers of actual patent application

filing shows that wind power is far behind patenting rates in a number of technologies, particularly fossil fuel power generation and oil and gas drilling.

The above discussion highlights the unique nature of wind power as a policy driven technology. Though wind power was a relatively novel technology in the 1980s and 1990s, the rate of patenting during this period was slow relative to all other technology subfields, including the most mature of technologies. The relative slow pace in knowledge development can be attributed to limited government support. In particular, the largest rise in wind power patenting in the three countries considered were all associated with the rapid increase in cumulative wind power deployment starting from the late 1990s and early 2000s. The pace of policy induced wind power deployment can therefore be identified as the main limiting factor in the pace of wind power knowledge development.

4.5 ANNEX: INTERNATIONAL PATENT CLASSIFICATION (IPC) CONCORDANCE TABLES FOR FOSSIL FUEL POWER GENERATION, OIL AND GAS DRILLING, AND OIL REFINING TECHNOLOGIES

The following tables set forth the IPC codes and selection rules used to identify patents associated with fossil fuel power generation, oil and gas drilling, and oil refining technologies. These were used to extract patent data using the European Patent Office (EPO) Patent Statistics Database (Patstat).

Technology	Subfield	IPC code	
Fossil fuel power generation*	Coal gasification	C10J 3%	
	Improved burners	F23C 1%	
		F23C 3%	**
		F23C 5/02%	**
		F23C 5/06%	**
		F23C 5/08%	**
		F23C 5/14%	**
		F23C 5/24%	
		F23C 5/28%	**
		F23C 5/32%	**
		F23C 6%	
		F23C 7%	**
		F23C 9%	**
		F23C 13%	**
		F23C 15%	**
		F23B 10%	
		F23B 30%	
		F23B 40%	**
		F23B 50%	**
		F23B 60%	**
		F23B 70%	
		F23B 80%	
		F23B 90%	**
		F23B 101%	**
		F23B 103%	**
		F23D 1%	
		F23D 7%	
		F23D 9%	**
		F23D 11%	**
		F23D 17%	
	Fluidised bed combustion	F23C 101%	**
		B01J 8/20%	
		B01J 8/22%	
		B01J 8/24%	
		B01J 8/26%	
		B01J 8/28%	
		B01J 8/30%	
		F27B 15%	
		F23C 10%	**
	Improved boilers for steam generation	F22B 3/08%	**
		F22B 5%	**
		F22B 7%	**
		F22B 9%	**
		F22B 11%	**
		F22B 15%	**
		F22B 17%	**
		F22B 19%	**
		F22B 21%	**

		F22B 23%	**
		F22B 25%	**
		F22B 27%	**
		F22B 29%	**
		F22B 31%	
		F22B 33%	***
		F22B 35%	**
		F22B 37%	**
		F22D%	**
	Improved steam engines	F01K 3%	
		F01K 5%	
		F01K 23%	
		F01K 7%	**
		F01K 9%	**
		F01K 11%	**
		F01K 13%	**
	Super-heaters	F22G%	
	Improved gas turbines	F02C 7/08%	
		F02C 7/10%	
		F02C 7/105%	
		F02C 7/12%	
		F02C 7/14%	
		F02C 7/141%	
		F02C 7/143%	
		F02C 7/30%	
		F02C 7/36%	**
		F02C 3%	***
	Combined cycles	F01K 23%	***
		F02C 6%	***
	Improved compressed-ignition engines	F02B 1/12%	
		F02B 1/14%	
		F02B 3/06%	
		F02B 3/08%	
		F02B 3/10%	
		F02B 3/12%	**
		F02B 7%	
		F02B 11%	
		F02B 13/02%	
		F02B 13/04%	
		F02B 49%	
	Co-generation	F01K 17/06%	
		F01K 27%	
		F02C 6/18%	
		F02G 5%	
		F25B 27/02%	
	Other	F23K 1%	**
		F23K 3%	**
		F23N%	**
		F23R%	**

Patent selection rules for fossil fuel power generation:

Exclude patents with EPO_CLASS_SYMBOLS:	Y02E10:4%; Y02E10:6%; Y02E10:1%; Y02E50:1%
Exclude patents with IPC_CLASS_SYMBOL:	B6%
	F24%
	F27B 1%; F27B 3%; F27B 5%; F27B 7%; F27B 9%; F27B 11%; F27B 13%; F27B 14%; F27B 17%; F27B 19%; F27B 21%; F27D%
	G01T%, G21%, F02C 1/05

* Based on Lanzi, Verdolini, and Hascic (2011)
** subfield not in Lanzi, Verdolini, and Hascic (2011)
*** subfield only partly in Lanzi, Verdolini, and Hascic (2011)

Technology	**Subfield**	**IPC code**
Oil Refining	Oil refining	C10G%

Technology	**Subfield**	**IPC code**
Drilling in oil and gas industry	Chemistry	C09K 8%
	Drilling	E21B 4% E21B 7% E21B 10% E21B 11% E21B 12% E21B 15% E21B 17% E21B 19% E21B 21% E21B 23% E21B 25% E21B 27% E21B 28% E21B 29% E21B 31% E21B 33% E21B 34% E21B 35% E21B 36% E21B 37% E21B 40% E21B 41% E21B 43% E21B 44% E21B 45% E21B 47% E21B 49%
	Offshore drilling vessels	B63B 21/50% B63B 35/44%
	Machinery	F03B 13/02%

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- Chapter 5 - Conclusion: Catching up and its Implications

5.1 THE CASE OF WIND POWER IN CHINA

5.1.1 Summary of research findings

The research in this thesis aimed to answer the question of whether Chinese firms could catch up with the technological frontier in the scope of new climate friendly energy technologies. The hypothesis that indeed they could catch up was articulated along two complementary arguments: one focused on developments in China while the other focused on developments at the frontier.

The first argument was that the Chinese government was able to create relatively large domestic markets for climate friendly energy technologies and that Chinese firms benefited from a strong technology development system with a powerful and proactive government at its heart. The assumption was that this would provide the necessary conditions for Chinese firms to make rapid technological progress. The second argument was that due to limited government support over the years in both Europe and the United States, the frontier of new climate friendly energy technologies had evolved relatively slowly, making it easier for Chinese firms to catch up.

The analysis focused on testing these arguments in the case of one climate friendly energy technology: wind power. I discuss in Section 5.2 how the hypothesis could be further tested by extending the analysis to other technology case studies.

Chapter 2 detailed the convergence of trends of leading Chinese firms with firms at the technological frontier using various wind turbine technology indicators. It highlighted that by the beginning of the 2010 decade, Chinese firms were developing wind turbines increasingly similar to those produced by frontier firms. The chapter also assessed the evolution of technological

capabilities among some of the leading Chinese turbine manufacturers. This showed that the firms had rapidly improved their capabilities and were increasingly introducing new technologies based on their own technological development efforts. In sum, the chapter showed that catching up by Chinese wind turbine manufacturers was well underway.

The chapter notably underscored the pivotal role of technology transfer from foreign firms in the process of accumulation of technological capabilities by Chinese firms. In particular the transition from licensing of turbine designs and blueprints to the joint-development of new turbine models with foreign firms appears to have played a key role in allowing Chinese firms to gain access to core technologies and accelerate the rate of technological learning.

Chapter 3 focused on the first argument of the research hypothesis and described the main features of the Chinese wind turbine technology development system. It highlighted the policies introduced by the government to create a rapidly growing wind power market in China. More importantly, however, it described the steps taken by the government to ensure that Chinese firms would enter the domestic turbine manufacturing market and progressively come to dominate it.

The competition which ensued among domestic turbine manufacturers to secure orders for their products was arguably the main driver of the technology development efforts of Chinese turbine manufacturers documented in Chapter 2. Nevertheless, the government was also actively engaged through a variety of regulations to spur rapid technological progress, both in terms of turbine size and ownership of intellectual property. This government activism was visible in other aspects of the Chinese wind power industry, notably to ease bottlenecks in grid expansion. The Chinese system was also characterized by the strong influence the government had on firms,

many of which were state-owned. The exertion of this influence was facilitated by industry associations, which helped the government closely monitor industrial progress.

The Chinese system faced a number of challenges to ensure the continued progress of the industry. Of these, the most significant was whether the system could transition from a model of technology development based on technology transfer to one based on its own innovation efforts. As noted above, by the beginning of the 2010s, the main turbine manufacturers had started to introduce turbine models based on independent technology development efforts. However these were still drawn to a large extent on earlier transfers of turbine designs and blueprints. The main emphasis of R&D efforts by Chinese firms was on short-term problem solving and incremental improvements to existing technologies. The government's R&D support system was also geared towards tackling the industry's most pressing needs. Research institutions notably played a relatively small part in the technology development system, primarily aimed at providing short-term technological assistance to the industry.

To some extent, overcoming technological challenges in the short term was suitable for purposes of catching up. However, as Chinese firms increasingly compete with frontier firms, such a shorter-term outlook to technology development is likely to be insufficient. More ambitious, independent technology development with a longer-term outlook will be needed.

There were some signs that a transition was already occurring. A few firms and research institutions had started ambitious frontier-like technology development efforts. Other firms had acquired European engineering firms to assist them in their R&D needs. The government was also aware of the limits of the existing R&D support system and was exploring ways to better complement firm R&D efforts. While it is too early to tell whether these signs were outliers or

precursors of further change to come, the fact remains that some of the basic ingredients for innovation-based technology development were present.

Chapter 4 focused on the second hypothesis argument and assessed the role of government in the evolution of the wind power technology frontier. Using patenting rates as an indicator of knowledge development, the chapter first showed the high level of correlation since the 1970s between changes in government wind power support policies and patenting activity associated with wind power in three of the most active countries. The analysis then showed, using both technology penetration rates and patenting trends, that the evolution of the wind power frontier was slow relative to most other technology sectors globally. Only once policy-induced wind power deployment accelerated from the early 2000s did patenting activity started to grow at a more sustained pace than all technologies taken together. In sum, the chapter showed that the wind power frontier was evolving relatively slowly due to limited government support, thereby facilitating the process of technological catch-up by Chinese firms.

5.1.2 Extending the assessment of technological catch-up

The assessment of technological catch-up presented in Chapter 2 faced a number of limitations. For example, the comparative assessment of turbine performance based on capacity factors did not capture the bulk of the rise in turbine capacity observed in China because a track record of electricity production data for larger turbines was not yet available. Extending the analysis of capacity factors over time would therefore be an important step to complement the assessment of technological catch-up.

It would also be useful to complement the capacity factor analysis with a comparative assessment of turbine operation and maintenance (O&M) using data, for example, on the frequency with which turbines have to stop operating and the time spent on repairs by problem area.[161] Such data were not available for Chinese wind farms in large part because there appeared to be no systematic data collection efforts for O&M. However, two industry associations indicated that they had received backing from the government to expand data collection efforts in this direction. If access to such data can be made available for both China and frontier markets, such assessments may therefore become possible.

One technology dimension which was not discussed concerns the exports of Chinese wind turbines abroad. At the time of this research, Chinese manufacturers had just begun to export turbines and there was therefore little track record to work with.[162] However as Chinese turbine exports continue to rise it will be possible to compare the performance of Chinese turbines with frontier models in other markets, thereby complementing the analysis undertaken in Chapter 3.

5.1.3 Considering a more dynamic assessment of technological catch-up

The methodology adopted for this research considered developments in China and at the frontier independently. The only link between the two settings explicitly considered was the assessment of technology transfer from the frontier to China. This simple approach helped to identify and assess the most important drivers of technological catch-up. However, technological development efforts in both settings are likely to have interacted in dynamic ways – i.e. changes

[161] Such data are notably recorded and made publicly available for turbines installed in the German 250MW Program, discussed in Chapter 4. See for example WindStats (2011).

[162] In 2010 China only exported 13 turbines (WPM, 2011).

in one setting are likely to have affected development efforts in the other. In particular, the analysis presented in previous chapters raises questions concerning two types of dynamic interactions. The first relates to the technology transfers described in Chapter 2. The second relates to wind power deployment policies discussed in the case of China in Chapter 3, and in case of the Denmark, Germany, and the United States in Chapter 4. Each is briefly discussed below.

5.1.3.1 Technology transfers to China

The discussion in previous chapters underscored the critical role of the evolution of the means of technology transfer adopted by Chinese wind turbine manufacturers – from licensing, to joint development, firm acquisitions, and more targeted technical assistance contracts. In particular joint-development agreements were identified as having been particularly important. Not only did such agreements provide access to technological knowledge, but they also facilitated learning by Chinese firms through extensive and close collaboration with foreign firms.

The analysis presented focused on the implications of such technology transfers for Chinese firms but it did not consider the perspective of the foreign firms involved. In would thus be useful to identify the reasons which led these firms to agree to transfer their technologies and help their Chinese counterpart assimilate the knowledge received.

The foreign firms involved were either dedicated engineering services firms or second-tier turbine manufacturers (in terms of manufacturing output). In each case, they were based either in Europe or the United States. One possible reason may therefore be that access to the Chinese market offered business prospects far greater than what they would have experienced otherwise.

It would follow that these foreign firms were ready to forgo some of their technological knowhow in exchange for access to the Chinese market. In contrast, leading frontier turbine manufacturers were unwilling to risk losing their technologies, even if this meant playing a smaller role in the Chinese market.

Another possible reason for the technology transfers observed may be that entering the Chinese market gave foreign firms access to manufacturing capabilities on a scale which allowed them to eventually compete internationally. The rationale would be that as long as they offered high quality engineering services to their Chinese counterparts, they would remain indispensable. This may notably explain the acquisition of European engineering design companies by Chinese manufacturing firms (e.g. Vensys of Germany by Goldwind; Darwind of Holland by XEMC) or the willingness expressed by one leading Chinese turbine manufacturer to continue relying on such transfers for future models.

In any event, the transfers of technology by European and United States firms described in this research appear to be linked to the magnitude of the market opportunities in China relative to those in other markets (at the frontier or elsewhere). It is likely, therefore, that if market creation efforts in advanced economies (described in Chapter 4) had been more significant, or conversely if China had not created as large a market (described in Chapter 3), then these foreign firms may not have been as willing to engage in technology transfers and forgo some of their technologies. Further assessing the rational for foreign firms to engage in technology transfer would therefore be a useful complement to the assessment of technological catch-up presented in Chapter 2.

5.1.3.2 Wind power deployment support policies

Chapters 3 and 4 respectively detailed wind power deployment support policies in China and three leading advanced economies. The emphasis was on describing policy changes and their effects on deployment within national boundaries. The rationale for such policies was only tangentially discussed. The introduction to Chapter 3 notably highlighted energy security, climate change, and indigenous knowledge development as some of the issues behind the Chinese government's interests in wind power. Similarly, the discussion in Chapter 4 noted that in the case of the United States and European countries energy security concerns played an important role towards the end of the 1970s and from the 1990s climate change mitigation became an important motive for the continued support to wind power. Yet as noted in Chapter 1, industrial leadership is another important component of the political discourse regarding government support for the development of climate friendly energy technologies. It is therefore likely that policy efforts to support technology development in different countries were not independent of one another as these may have been perceived as a threat to technological leadership aspirations. The sharp rise in wind power deployment in China may notably have influenced policy support in advanced economies. Similarly, the pace of development in leading advanced economies likely played a role in guiding policy efforts in China. A thorough assessment of the evolution of the main drivers of wind power deployment support policies in different countries would therefore be a useful complement to the research presented in previous chapters.

5.2 OTHER NEW CLIMATE FRIENDLY ENERGY TECHNOLOGY CASE STUDIES

The analysis presented in this thesis showed that the arguments of the hypothesis were indeed valid in the case of wind power. However, the hypothesis concerns new climate friendly energy technologies more broadly. A more complete assessment would therefore require testing the validity of the hypothesis for other new climate friendly energy technologies.

As noted in Chapter 1, new climate friendly energy technologies refer to technologies which emit no or only limited amounts of greenhouse gases, which have the economic and technical potential to have a significant impact on global greenhouse gas emissions, but which have currently only fulfilled a fraction of this potential. Aside from wind power, the main new climate friendly technologies therefore consist of other renewable energy sources, such as solar energy or biomass, as well as CO_2 capture and storage technologies (CCS).[163]

As detailed in previous chapters, in the case of wind power, testing the research hypothesis rests on a detailed assessment of technology progress, firm capabilities, and the role of government in the technology's development system. Nevertheless, without undertaking such an in-depth assessment it is possible to identify whether other new climate friendly energy technologies may hold some of the characteristics outlined in the research hypothesis. In particular, the hypothesis underscores two important variables. The first is that the Chinese government is able to create a relatively large domestic market by international standards for the technology. The second is that progress of the technology's frontier has evolved slowly relative

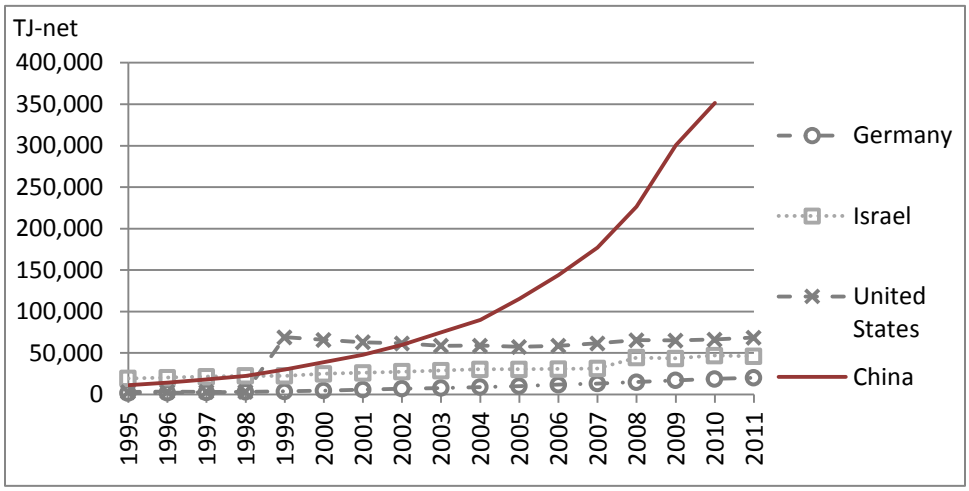
[163] As noted in Chapter 1, nuclear energy may also be included in the category of new climate friendly energy technologies though it is not considered here.

to other technologies. I therefore discuss some other potential case studies based on these two variables and contrast them to the case of wind power discussed in this thesis.

5.2.1 The large domestic market variable

Wind power was an interesting technology case study as the Chinese government had already created the largest domestic wind power market in the world. Another candidate case study technology in this respect is solar hot water heater technology, as China has long had the largest market in the world for solar hot water heaters. However, market trends in other leading nations shown in figure 5.1 underscore that solar hot water heater technology has not attracted much policy support in these countries. This raises questions as to whether the prospects of this technology to mitigate climate change at a global level is significant and, therefore, whether it should be considered as a new climate friendly energy technology in the scope of this study.

Figure 5.1: Solar thermal production in China and the three leading countries



Note: Data from IEA (2012).

Data consists of solar thermal net direct-use measured in tera joules. Germany, Israel, and the United states were the countries with the highest solar thermal production in 2010.

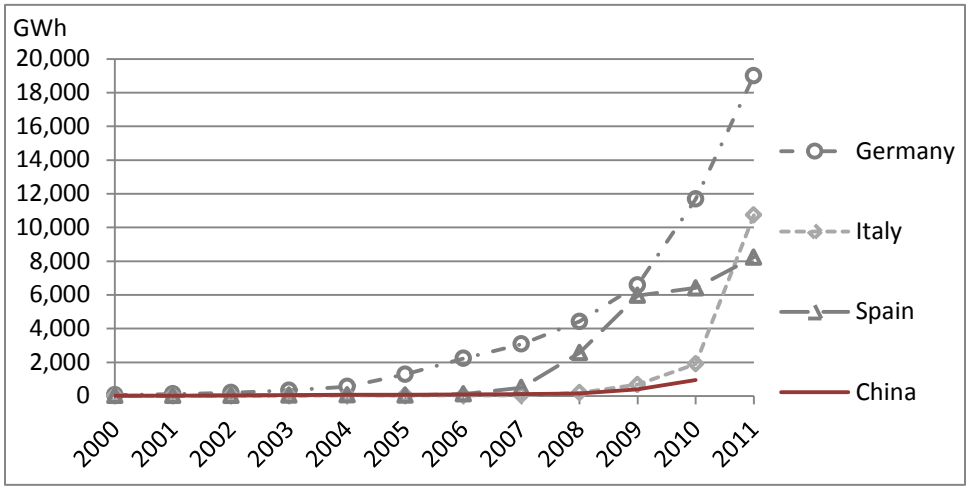
At the time of writing, no other climate friendly energy technologies appeared to meet the large market criterion. However, this does not mean other technologies will not do so in the near future as China is likely to expand its support to other climate friendly energy technologies. Indeed, as noted in the introduction to Chapter 3, the 12th five-year plan, clearly identified clean energy technologies as priority areas for the country. Two potential future technology cases seem particularly relevant and are briefly discussed here: solar photovoltaic, and CO_2 capture and storage.

Figure 5.2 shows the evolution of power production from solar photovoltaic (PV) in China and in the three leading countries in 2010. The figure reflects that the Chinese domestic market was still small in 2010 relative to leading countries. It is also interesting to note that solar PV market growth only started from 2000. In contrast, wind power deployment discussed in Chapter 2 started much earlier. In the case of Germany, the largest market in the world for solar PV, the market started to grow from the early 2000s. In the case of Italy, the second largest market in the world, market growth did not begin until 2008. As in the case of wind power, these national solar PV markets emerged in response to government support policies.

One important characteristic of the solar PV market is that Chinese firms were important suppliers of PV modules to European and other markets, in large part due to lower costs of production. In 2011, the largest nine Chinese firms (in terms of total PV capacity produced) accounted for approximately 30% of global production (REN21, 2012). Nevertheless, the Chinese government enacted a domestic feed-in tariff law in 2011 to support the expansion of a domestic solar PV market. This led to a rapid growth in installed capacity, from a total of

approximately 3GW installed by the end of 2011 to an estimated total of approximately 7GW by the end of 2012.[164]

Figure 5.2: Solar PV electricity generation in China and three leading countries



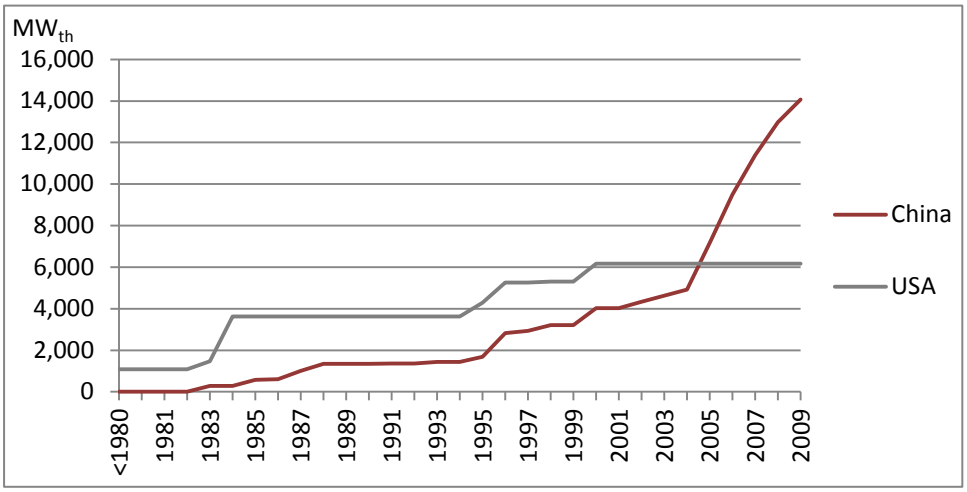
Note: Data from IEA (2012).
Germany, Italy, and Spain were the countries with the highest solar PV electricity generation in 2010.

With respect to CO_2 capture and storage (CCS), deployment globally was still at an early stage with only few demonstration projects, for the most part linked to enhanced-oil-recovery. At the time of this research no CCS projects were underway in China. However, CCS is an amalgamation of various different technologies. In the scope of technological catch-up, considering CCS in its entirety may be misleading. One can notably distinguish between CO_2 capture technology and CO_2 storage technology. One promising approach to CO_2 capture technology is to remove CO_2 from the energy production process prior to combustion of the fuel. In this process the gasification of fuels typically plays a central role. Gasifiers convert fuels into

[164] Data from WSJ (2013).

synthetic gas which is then used for various other thermo-chemical processes. China has been active in the development of gasification technology for many years as the government has sought ways to use its large coal resources as feedstock for industries other than power generation, such as chemicals and plastics. China has notably become a leading market for gasification technology. Figure 5.3 shows the evolution of the gasification market in China and the United States, the two largest national markets in the world. China became the leading market in terms of synthetic gas production in 2004 and by 2009 had over twice the installed production of the United States.

Figure 5.3: Synthetic gas production capacity from gasifiers in operation in China and the United States



Note: Data from NETL (2010)

The cases of hot water heaters, solar PV, and gasification appear to be promising case study technologies with respect to the large domestic market variable. In the case of solar hot water heaters China already had a very large market by international standards. Similarly, though CCS technology is still in its infancy, China already plays a leading role in terms of gasification

technology. Finally, while the Chinese solar PV market is still relatively small, the government's introduction of deployment support policies may change the market landscape in the future.

5.2.2 The slow frontier variable

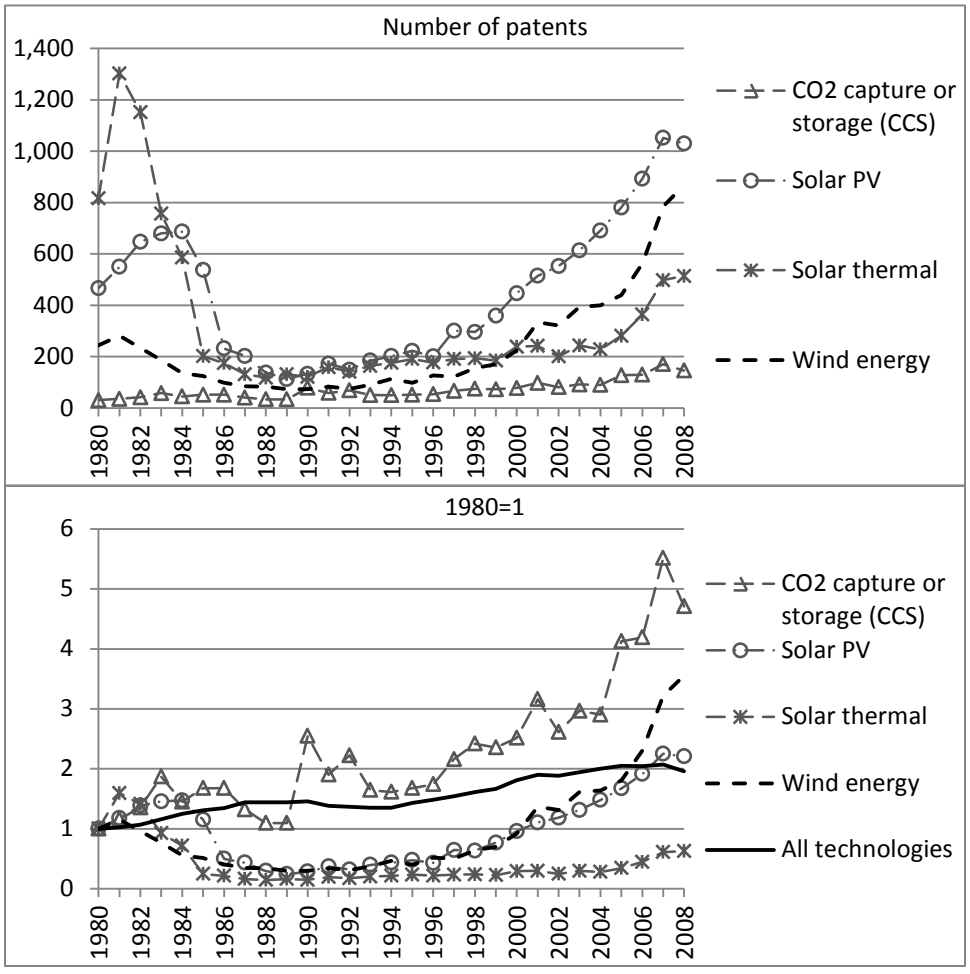
Patenting rates were used in Chapter 4 as an indicator of the evolution of the wind power technology frontier relative to other technologies and sectors. I adopt the same approach here to compare patenting rates associated with some of the climate friendly technologies discussed above. The upper chart of figure 5.4 shows the evolution of the number of annual global patent applications associated with solar thermal technology, solar PV, CO_2 capture and storage, as well as wind power.[165] The chart shows that apart from the early 1980s period, during which solar technologies saw relatively high levels of patenting activity, the overall trends for solar technologies were comparable to that of wind power. Solar PV is the only technology for which patenting numbers were slightly above those of wind power from 1980 to 2008. CCS patenting activity in contrast was by far the lowest throughout the period.

The lower chart shows the same data normalized using 1980 values. This chart also includes as a reference the trend for all technologies and all sectors combined (see Section 4.3 for details). One of the characteristics of wind power discussed in Chapter 4 was that its patenting rate relative to 1980 only surpassed all technologies taken together around the mid-2000. This trend is closely matched by that of solar PV. In contrast the trend for solar thermal technology shows that patenting levels have remained below 1980 levels from the early 1980s and throughout the

[165] Solar thermal in the EPO patent classification includes technologies associated with solar thermal plants used in power generation, which is a different type of technology than the solar water heater technology discussed above.

entire time period considered. The trend line for CCS remains slightly above the line for all technologies taken together before increasing at a much faster pace from the mid-1990s. However, this reflects the much lower patenting levels discussed above rather than particularly high patenting activity.

Figure 5.4: Global patenting in four new climate friendly energy technologies, 1980-2008



These trends indicate that the frontier of other new climate friendly technologies has evolved at a similar, if not slower pace than that of wind power. Following findings discussed in Chapter 4 concerning the pace of the wind power technology frontier relative to other technologies and

sectors, we can therefore conclude that the frontier for these other climate friendly technologies has also evolved relatively slowly.

5.2.3 Summary

Solar hot water heaters, solar PV, and CCS technologies appear to be suitable potential case study technologies to further assess the validity of the hypothesis outlined in Chapter 1. Such case studies would also likely offer some interesting contrasts compared to the case of wind power discussed in previous chapters. Markets for solar thermal technology and gasification have notably developed prior to the formulation of the Chinese government policy goals pertaining to the development of climate friendly technologies. The extent to which the evolution of this policy context has influenced the role of government in the respective systems of technology development is notably interesting. In the case of solar PV, the fact that China has been an important supplier to world markets implies that large Chinese PV manufacturers already exist and have experience with the technology. The role of government in this system of technology development is therefore likely be more focused on enhancing technological attributes than on ensuring the engagement of Chinese firms in the domestic market. In addition, the case of PV will shed light on the role of a large domestic market, which is central to the research hypothesis.

5.3 IMPLICATIONS FOR GOVERNMENTS OF ADVANCED ECONOMIES

The analysis of technological catch-up by Chinese wind turbine manufacturers detailed in previous chapters highlights how in less than a decade the Chinese government was able to create a system of technology development capable of spurring rapid technological progress.

Though many uncertainties remain with respect to the ability of Chinese firms to engage in innovation based technology development, it is likely that they will continue to enhance their capabilities and increasingly compete with firms at the frontier. This would undoubtedly have important economic consequences, notably with respect to the ability of Chinese firms to capture growing export markets for wind turbines and turbine components.

As noted in Chapter 1, many governments of advanced economies have stressed the economic importance of successfully developing new climate friendly energy technology industries. I therefore discuss below some of the lessons which can be drawn from the case of wind power for governments of advanced economies wishing to encourage industrial development associated with new climate friendly energy technologies. I discuss the need to enhance the intensity of government technology support policies before considering one important implication related to the nature of command and control policies.

5.3.1 Increasing the intensity of government support policies

Chapter 4 highlighted the correlation between changes in government support policies for wind power technology and the level of knowledge development activity using patent application rates. It also showed that for much of the period from 1980 to 2008, development activity related to wind power was low relative to other technologies and sectors. Only from the early 2000s did patenting activity start to rise at a fast rate relative to all other technologies taken together. Still, relative to 1980 levels, wind power patenting activity only surpassed that of all technologies taken together around 2005. In addition, when compared to several other conventional energy technologies the growth in patenting activity relating to wind power remained small in absolute numbers.

The relative low level of knowledge development associated with wind power indicates that there is significantly scope for enhancing the pace of knowledge development at the frontier. However this will require governments of advanced economies to increase the intensity of their support policies.

The discussion in Chapter 4 highlighted that the rise in policy induced wind power deployment starting from the year 2000 in Denmark, Germany, and the United States played a particularly important role in spurring growth in patenting activity in those countries. The ability of governments to further increase the pace of deployment in these countries varies from case to case. In Denmark for example, wind power already accounted for approximately 20% of electricity consumption in 2010. In contrast, in Germany and the United States, wind power production was still a relatively small share of total electricity production, indicating that the pace of wind power deployment in these countries may be increased. Offshore wind power notably offers large market growth prospects, particularly for countries such as Denmark which have already heavily exploited onshore opportunities. Offshore wind power also raises new technological challenges, for example linked turbine foundations, O&M, or wind farm construction. Tackling these challenges will induce firms to develop new technologies and help maintain competitive advantages.

The evolution of wind power deployment support policies in Denmark, Germany, and the United States highlighted a number of bottlenecks which hampered wind power technology deployment. One notable example was linked to power system infrastructures. In particular, building new transmission lines, connecting offshore wind farms, as well as managing the balancing of electricity systems appeared to have put a strain on efforts to expand wind power

markets in each of the three case study countries. These bottlenecks indicated that wind power held certain characteristics which make it incompatible with the pre-existing organization of electricity grid infrastructures. As noted in the discussion on technology diffusion rates in Section 4.3, historically infrastructure technologies have required longer timeframes to evolve, which may in part explain the relatively slow penetration rates for wind power. Nevertheless, overcoming these infrastructure hurdles would contribute to accelerate market growth.

Another important bottleneck to the growth in wind power deployment is institutional in nature. The pace of deployment is a reflection of the ability of governments to support through policy higher levels of deployment. This may be limited by budgetary constraints, inadequate government operational capabilities, as well as political resistance to wind power. In any event, addressing these institutional constraints would accelerate the pace of deployment and provide greater certainty to firms about future market prospects. The latter would notably allow firms to adopt longer term horizons in their technology development efforts.

The discussion in Chapter 4 showed that the correlation between government R&D funding and patenting activity was not as strong as in the case of technology deployment. Nevertheless, government R&D funding can play an important role in supporting technology development efforts by firms resulting from their growing market experience. The review of government wind power technology R&D support measures in Denmark, Germany, and the United States notably highlighted how these aimed to complement firm technology development efforts. Government R&D support targeted such activities as long-term technology development, for example by providing assistance to firms with the development and testing of new innovative technologies; industry-wide services, such as data monitoring and infrastructure research; and formation of

research networks, for example by coordinating projects involving multiple firms and research centers. Such R&D activities are all the more important since, as noted in Chapter 3, these are some of the activities lacking from the Chinese wind turbine technology development system. Governments in advanced economies should therefore consider increasing their support to wind power technology R&D and continue to target activities complementary to those undertaken at the firm level.

5.3.2 Command and control policies and their implications for technological catch-up

Chapter 1 highlighted that governments had two broad options to mitigate climate change and support the development of new climate friendly energy technologies. On the one hand, governments could seek to internalize the climate change externality by either introducing a tax on greenhouse gas emissions or by limiting total emissions using an emission permit trading scheme. On the other hand, governments could adopt so called command and control policies, which directly support or discourage specific industrial activities or technologies. In the first case, technology decisions are to a large extent made by firms in response to changes in the production costs they face. In the second case, decisions are to a large extent made by governments by favoring certain technologies and discouraging the use of others.

In practice, the choice between such instruments has many implications beyond technology choices. Command and control policies notably give governments a certain amount of discretion with respect to the activities or technologies they target. These may therefore have more political appeal than emissions taxes or trading schemes. The discussion in Chapter 4 on wind power support measures in Denmark, Germany, and the United States also highlighted that energy security, not climate change, was the main driver of the early stages of government support for

wind power. In particular the oil shock of 1973 decisively brought energy security concerns to the fore of the agendas of most advanced economies and effectively initiated what would become an intricate web of government support measures directly targeting the development and deployment of wind power. In contrast, the accumulation of scientific evidence linking emissions of greenhouse gases from fossil fuel burning to climate change only progressively became an important driver of government support for climate friendly energy technologies starting from the 1980s and 1990s. By that time, wind power technology support policies were already part of the policy landscape of many countries.

Nevertheless, the case of wind power technology catch-up discussed in previous chapters raises an important issue with respect to the merit of using command and control policies to support climate friendly energy technologies in advanced economies over emissions taxes or trading schemes. By clearly identifying the targeted technology, the means by which it is being supported, and possible long-term objectives, command and control measures also provide clear guidance to nations wishing to engage in technological catch-up. Returning to the definition of technological catch-up introduced in Chapter 1 as ‘entities at lower levels along a technological path rising at a faster pace than the evolution at the technological frontier’, command and control measures effectively sign-post the path to the frontier and beyond. As discussed in Chapter 3, in the case of wind power such policies in Europe and the United States contributed to fulfilling the ‘guidance of search’ function of the Chinese wind turbine technology development systems.

In contrast, adopting emissions taxes or tradable permit schemes in advanced economies would provide greater autonomy to firms at the frontier to make technology choices. This would therefore remove much of the technology guidance to other nations implied by command and

control policies as firms have a natural tendency to conceal technology choices to protect their position in the market. Emissions taxes or trading may notably foster new, unforeseen technology ventures among firms, similar to the more radical innovations discussed in the literature review in Chapter 1. This would likely help firms in advanced economies as the ability to innovate, after all, remains the greatest competitive advantage they have over firms in rapidly emerging economies such as China.

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