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Historical Trajectories and Corporate Competences in Wind Energy

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Abstract

This working paper surveys the business history of the global wind energy turbine industry between the late nineteenth century and the present day. It examines the long-term prominence of firms headquartered in Denmark, the more fluctuating role of US-based firms, and the more recent growth of German, Spanish, Indian and Chinese firms. While natural resource endowment in wind has not been very significant in explaining the country of origin of leading firms, the existence of rural areas not supplied by grid electricity was an important motivation for early movers in both the US and Denmark. Public policy was the problem rather than the opportunity for wind entrepreneurs before 1980, but beginning with feed-in tariffs and other policy measures taken in California, policy mattered a great deal. However, Danish firms, building on inherited technological capabilities and benefitting from a small-scale and decentralized industrial structure, benefitted more from Californian public policies. The more recent growth of German, Spanish and Chinese firms reflected both home country subsidies for wind energy and strong local content policies, whilst successful firms pursued successful strategies to acquire technologies and develop their own capabilities.

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Introduction

This working paper looks at the business history of the wind energy industry. The business history of green industries remains largely unwritten, reflecting a disciplinary split between environmental historians, most of whom had limited interest in firms, and business historians, most of whom have been slow to incorporate environmental issues in their research agendas.[1] An emphasis on large firms and capital-intensive industries has until recently compounded the neglect of green industries, as entrepreneurial firms were typically important in their formative stages. The most extensive studies have largely explored how, and why, large corporations grew in environmental awareness from the 1960s.[2] The growth of entrepreneurial firms in emergent industries, such as sustainable energy or organic food, is only now receiving attention.[3]

The existing literature on wind energy is primarily from public policy, economics and managerial perspectives rather than a historical one. The geographical distribution of wind power capacity has attracted particular attention. The global generating capacity of wind power grew from 13 megawatts in 1980 to 17,400 megawatts in 2000, and reached nearly 200,000 megawatts in 2010. However wind capacity has been highly skewed geographically. In 2010 the United States and China alone accounted for 42% of installed world power capacity (see **Appendix Table 1).** The relative importance of wind energy in electricity generation shows striking geographical variation. In 2008, wind supplied one-fifth of Denmark's electricity, and 13% of Portugal's, and 11% of Spain's. But in neighboring European countries, including Britain, France and Italy, as well as the United States, wind supplied less than 2% of electricity. In Japan the percentage was a tiny 0.3% (see **Appendix Table 2**).[4] Overall, wind power provides a meager 1% of global electricity.[5]

The literature has offered three main explanatory variables for such differences. The first is resource endowment. "Wind" is not homogeneous across the globe. Wind speeds vary in intensity and seasonality. Both northern Europe and California, two centers of wind power, have strong and steadily westerly winds. The East Asian region, in contrast, has a monsoonal seasonal wind. However while the world's leading producers of petroleum and coal can primarily explained by resource availability, there is there is only a very weak correlation between wind energy potential and installed wind capacity.[6]

A second variable is public policy. "Energy is *always* political", the energy historian Richard Vietor has observed.[7] Policy decisions, especially concerning access to electricity grids at favorable prices, alongside tax and other financial incentives, are widely perceived as key drivers behind the spread of wind energy.[8] There are several reasons why public policy is so important. First, alternative energy, including wind and solar, is not able to compete with conventional forms of power generation from fossil fuels, as well as nuclear energy.[9] Or more precisely, those conventional forms of power generation are often supported by subsidies of one sort or another, whilst alternative energy is competitive only if the externalities of conventional energy are included in the calculation.[10] These externalities are enormous, given that burning fossil fuels releases carbon dioxide which is the principle cause of global warming, whilst nuclear energy has an insolvable waste problem as well as safety risks, but the case for using dearer alternatives and paying higher electricity prices needs to be made in the political arena. Denmark's extensive subsidies to wind energy helped give that country one of the highest energy tariffs in Europe.[11]

Public policy is also important because of a key characteristic of wind – it is variable according to the weather. While solar energy supplies are totally weather – dependent – no sunlight, no energy – wind turbines keep turning even with very light winds, yet the amount of power generated varies greatly with wind speeds. This causes serious issues when wind supplies are connected to electricity power grids, as utilities require a baseload level of power. The solution lies primarily in geographical aggregation, which in turn requires the extension of transmission and distribution grids, and sometimes electricity exchanges between different utilities and sometimes countries. Much of the wind energy generated in Denmark, for example, has to be exported to Germany and to Norway and Sweden, where hydroelectric power systems enable electricity to be stored.[12] Public policy is typically crucial to finding solutions to the issue of wind variability.[13]

Public policy is also important because the construction of "wind farms", a term which originated in the 1970s to describe a cluster of wind generating units,[14] has a visual and sound effect which often provokes a reaction from local inhabitants, and can also have a significant effect on birds. The willingness of governments to explain the benefits of wind energy to their citizens, or else pay them off, is crucial.

The question then arises why countries adopted different policies towards wind and other forms of energy. The answer is complex, and beyond the scope of this paper, as it involves deep-seated variations in political systems, the power of vested interests, concerns about the security of energy supplies, and many other factors. In recent years, some sociologists have stressed variations in environmental awareness, and of social movement organizations, as being particularly influential in shaping policies towards the industry.[15]

The corporate structure of the industry present related, but distinct, idiosyncrasies. There are three types of business enterprise in this industry. The first are the electrical utilities which supply consumers. In some countries, at some times, utilities have generated their own wind energy. The second are the entities which generate the wind power. These might be individuals, co-operatives or, more recently large independent power producers which construct large wind farms. The third set of firms are the manufacturers who make the some or all of the components of turbines that generate electricity from wind, including clutches, gearboxes, rotor bearings, yaw motors, rotor hubs and blades. In a few cases, turbine manufacturers vertically integrate to generate power.[16]

The central concern of this paper is the turbine manufacturers. As **Appendix 3** shows, a listing of the largest firms in the industry over time shows an idiosyncratic pattern which is as curious as the geographical variations in the installation of wind energy. Firms from Denmark have been unusually prominent throughout the history of the wind energy business. US-based firms have also been regularly found among the leading wind energy companies, but their relative importance varied considerably over time, has rarely reflected the overall importance of the US market, and has involved a changing cast of actual firms. Subsequently, German and Spanish, and more recently Indian and Chinese firms, have emerged to become the largest manufacturers in the industry.

The following sections examine the evolution of the wind turbine business overtime.

Pre-History of Wind Energy

The business history of wind energy between the nineteenth century and World War 2 is a story of eccentric inventors and small-scale entrepreneurs. Nonetheless the period is important as a source of path dependences, as well as providing some fundamental technologies.

The possibility of using wind as an energy source was identified a long time ago. The first known windmill was built by Heron of Alexandria in the 2nd century AD. By the 8th century large horizontal axis windmills with four blades were in use in eastern Europe. During the 12th and 13th centuries the use of windmills became widespread for pumping water and grinding grain. The oldest were found in Turkey, Iran and Afghanistan, and they spread to Europe, beginning with Belgium and the Netherlands. In 1700 wind may have provided 2 per cent of Great Britain's power requirements – a relatively small amount compared to the 64 per cent from animals, and even the 12 per cent from watermills, but quite significant for driving waterwells, irrigation, and grain-grinding. The Industrial Revolution was the death knell for wind energy. By 1850 steam power provided 30 per cent of Britain's power, and wind was insignificant.[17] Wind energy lingered longer in countries which were slower to industrialize. An estimated 20,000 windmills were still in action in France by the end of the nineteenth century, primarily used for water pumping and cereal grinding, but soon they too were swept away.[18]

As the age of fossil fuels - coal, and later oil – took hold, wind energy became in part the preserve of the curious inventor. In 1887 the first windmill for electricity production was built by Professor James Blyth in Anderson's College, Glasgow. He built three different types of turbine, one of which powered his home for twenty-five years.

It was the distinctive geographical conditions of the expanding United States which prompted the first attempts to develop commercial businesses, using wind technologies for mechanical water pumping using small systems with rotor diameters of one to several meters. These systems appeared first with the Halladay windmill in the 1850s, developed by a Connecticut mechanic, and designed for the Great Plains. The market was the builders of the transcontinental railroads, which needed to draw water for their steam locomotives.[19] The original windmills were steadily improved, especially with the development of steel blades in 1870. Over the following decades low-cost American water-pumping windmills were made in large numbers, installed throughout the American heartland, and exported widely.

There was also experimentation using the multi-blade windmill design to generate electricity. The first use of a large windmill to generate electricity was a system built in Cleveland, Ohio, by Charles F. Brush. Brush was a serial inventor, who had made a considerable fortune from inventing an arc-light system. In 1888 he built a sixty foot tower in his backyard, and became the first person in the world to use wind to generate electricity. To store power, he installed batteries in his basement. It worked for twenty years, but could only produce 12 kilowatts from its 17-meter rotor blades. He dismantled his machine, and when he died in 1929, it still stood dismantled in his backyard.[20]

Inventors in northern Europe took the lead in trying to develop wind-electric generating systems. In Britain, wind energy remained largely the preserve of the inventor. In Britain, R. A. Fessenden constructed an experimental wind machine in London in 1894. He launched a start-up venture, the Rollason Wind Motor Company, to build machines for the countryside. Fessenden was a visionary, who proposed to build large windmills on coastal cliffs, which would lift seawater for storage, which would turn turbines and dynamos. Considerable numbers of machines were built, but the wider vision was not achieved.[21] British engineers continued to experiment with the cost and effectiveness of wind-energy systems. In the mid-1920s Oxford University engineers operated a windmill experimental station outside London.[22]

It was in Denmark that wind energy secured a broader basis. Denmark had a long tradition of using windmills to mill grain for flour. In 1891 Poul la Cour, a teacher at the Folk High School in Askov in the south of the country, began experimenting with how wind turbines could generate electricity. He became the first person in the world to carry out systematic experiments with artificial air currents in a wind tunnel. Like many subsequent "green" inventors and entrepreneurs, he was motivated by a societal vision. He disliked the poor social conditions in towns as they industrialized, and wanted to improve rural life so people who not leave for the towns. He figured electricity was the key, but as power plants were only built to serve the cities, he needed to find a way to generate electricity locally. The wind powered a dynamo to generate electricity. This electricity was to be led into a tank of water, which it would then separate into hydrogen and oxygen. This power was used to provide the lighting for the High School and the houses of the nearby village. [23]

La Cour's work should not be understood simply in terms of a single heroic inventor. La Cour drew on the research of two contemporary Danish engineers and scientists, H. C. Vogt and J. Irminger, who together with the American P. S. Langley, participated in formulating modern theory on aerodynamic lift and drag. La Cour also sought to institutionalize his work. To educate the rural population, he established a Society of Wind Electricians.[24] By 1918 250 electricity-producing wind turbines had been built in Denmark, 120 of which were connected to power stations.[25] There was also a small spillover effect of innovation over the German border, near Hamburg, where small electric systems were built.

In Denmark, and elsewhere, the interwar construction of national electricity grids supplied from coal-burning power stations posed an enormous challenge. The number of power stations in Denmark using wine turbines dropped from 75 to 25 between 1920 and 1940. Nevertheless La Cour and one of his students, Lykkegaard continued to manufacture turbines. A viable commercial opportunity, however, only occurred during wartime shortages of fossil fuels. Just as Danish wind turbines had flourished in World War 1, so they had another opportunity when World War II broke out, and the country was once again faced with scarcity of oil and coal.

Danish industrial wind power developments were undertaken by two companies, Lykkegaard Ltd. and the cement group F. L. Smidth & Co., which, in cooperation with the aircraft company Kramme & Zeuthen, developed a new type of wind turbine with aerodynamic wings and a tower of concrete with an output of 40-70 kW. Smidth was a leader in linking wind turbine manufacturing with the field of aerodynamics. During World War II F.L. Smidth built a number of two- and three-bladed wind turbines. A three-bladed F.L. Smidth machine on the island of Bogø, built in 1942, was part of a wind-diesel system which ran the electricity supply on the island.[26]

Denmark was the only European country to have a wind turbine industry in the interwar years, albeit a small one, but a tradition of experimentation continued elsewhere. In the 1920's Professor Albert Betz of the German aerodynamical research center in Göttingen made path-breaking theoretical studies on wind turbines. During the same decade Hermann Glauert, a British aerodynamicist and Principal Scientific Officer of the Royal Aircraft Establishment, Farnborough, developed an aerodynamic theory for wind turbines. Both of these theoretical contributions laid foundation of today's rotor theory.[27]

In France, George Darrieus, was also an important innovator. During the 1920s he worked for the Compagnie-Electromécanique, an electrical machinery manufacturer, and he designed several wind turbines at Le Bouget near Paris. By 1930 he was planning to build a large turbine capable of producing 50kw of electricity, but his company decided this would be uneconomic. He also designed the first vertical axis wind turbine and patented the invention in the United States in 1931. The vertical axis of rotation enables the turbine to accept wind from any direction rather than being reoriented as the wind changes direction, but the invention was largely ignored until the late 1960s, when it began to be used in California and later elsewhere.[28]

Geographical conditions in the United States which provided the major entrepreneurial opportunity. By 1920, the two dominant rotor configurations (fan-type and sail) had both been tried and found to be inadequate for generating appreciable amounts of electricity. The further development of wind generator electrical systems in the United States was inspired by the design of airplane propellers and, later, monoplane wings. The first small electrical-output wind turbines simply used modified propellers to drive direct current generators. By the mid-1920's, 1 to 3-kilowatt wind generators developed by companies like Parris-Dunn and Jacobs Wind-electric found widespread use in the rural areas of the Great Plains. These systems were installed at first to provide lighting for farms and to charge batteries used to power crystal radio sets. But their use was extended to an entire array of direct-current motor-driven appliances, including refrigerators, freezers, washing machines, and power tools.

The Jacobs Wind Energy Company was among the most important new ventures. This was the creation of Marcellus and Joe Jacobs, whose parents had relocated them in rural eastern Montana. The family wanted electricity, yet needed to get gasoline from the nearest small town, which was forty miles away. The brothers first tried to build a wind plant from a water-pumping windmill. Both brothers were working full-time on the farm. Joe never received a formal training, whilst Marcellus only attended first year of high school where he picked up the basics of electricity, which was fundamental for people living on farms. Marcellus came back from school to the ranch and with his brother Joe they built their first turbine in 1922. After three years concluded that the multi-bladed wheel turned too slowly to produce enough electricity As Marcellus had learned to fly, he had the intuition that an airplane propeller might solve the problem. World War I left a tremendous amount of surplus, including plane propellers and engines, all these equipments were available for purchase at a low price and were used to develop wind turbines technology.[29]

Marcellus Jacobs invented the three bladed turbine which later became his trademark product in 1927, and officially started a business in 1929, supported by funds from neighboring farmers. The fact that the Jacobs farm was the only one light up at night provided a powerful demonstration effect for their machinery. People would see lights from several miles and would drive to Jacob's ranch to found out how they can get connected as well. In 1931 the small business moved to Minneapolis.[30]

Jacobs' wind turbines were used to provide electricity to rural areas where power lines where not installed and were mostly used to charge storage batteries, operate radio receivers and power light bulbs. The firm survived both the collapse of rural incomes with the Great Depression, and the Federal government's strategies, through the Rural Electrification Association (REA), to stimulate the severely depressed agricultural economies by extending the electrical grid throughout those areas. REA became a competitor to Jacobs, because they had excess capacity and saw the wind energy as a danger. Jacobs' key advantage rested in product quality, as the machines proved extremely durable. And whilst REA efforts to bring a cheaper and readily available source of power to rural areas has been blamed for the decline of the US wind industry, some rural areas continued not to be connected to the grid.[31] Jacobs machines were expensive pieces of equipment- mostly only larger landowners could afford them and they often had to borrow to buy them[32] - but they were decades the only option to get reliable electricity (see **Appendix 4** for machine prices in 1940s). By the 1950s the company may have built 50,000 wind plants.

Jacobs sold internationally, eventually to all five continents. A network of dealerships across the world sold machines to mostly affluent farmers with large piece of lands that needed power, and opted to use wind energy than use fuel that took a long time to arrive and was expensive to deliver. The company also built some high profile facilities which re-inforced its image. These included a joint American/British weather station at Eureka in the Arctic Circle, and plants alongside oil pipelines in South America and Arabia.[33]

Experiments with larger systems in the United States failed. A key figure was an engineer called Palmer Putnam, who became interested in a pioneering Russian wind power station built during the 1930s. He became interested in wind energy after building a house in Cape Cod, and worked with a hydraulic turbine manufacturer looking for diversification opportunities. He built a large turbine on a mountaintop in Vermont, funded by $1 million ($12 million in today's dollars) by the turbine company, and in October 1941 made history by delivering power into an electric utility's system. Between 1941 and 1945 the machine, which was connected into the Central Vermont Public Service Corporation's network, accumulated about 1100 hours of operation. However in 1945 one of the blades broke off, and the costs of repair were so great that It never operated again.[34]

The later importance of Danish and US-based firms in wind energy, then, had evident historical roots. In 1945 Jacobs Wind, Lykkegaard Ltd. and F. L. Smidth & Co were probably the largest firms active in the global industry, although they were very small-scale. The desire to bring power to rural communities was the most important factor in stimulating the emergent wind power industry. US firms, like Jacobs, were focused on the commercial opportunities this presented, and later pursued international opportunities which mirrored those in the American heartlands. A more distinctly social, if not environmental agenda, shaped La Cour's work in Denmark. The early Danish industry was characterized by more institutional development, including linking windmills to electricity grids. In both cases, however, the industry was highly constrained by the inability to deliver a supply of electricity which could compete with alternative sources of electricity, except in remote rural areas and in abnormal wartime conditions.

Fossil Fuels Triumphant 1945-1973

The postwar decades of fast economic growth and cheap fossil fuel supplies were not conducive to wind energy. There was almost a total disruption of the pre-war entrepreneurial trajectories

In the United States, large utilities and grids continued to expand their importance. Unlike most of Europe, which created national and often government- owned electrical utility industries, electricity remained privately-owned and regulated at state level. By the 1960s electrical utilities provided power to 90 per cent of American households from central power plants. While early in that decade coal still supplied well over half of the electrical utility industry, by the end of that decade coal's share had fallen to 47%, whilst oil had risen from 5% to 12% as world prices declined.[35] A new source of power had also emerged. The Atomic Energy Commission, created in 1946, raised expectations that a cheap and safe primary source of power was about to come on stream.[36] Thirty years later nuclear generated almost one-tenth of US electricity.

Against this unfavorable context for wind energy, there was further technical experimentation in the American industry building on the technical results of the Putnam wind turbine. Percy H. Thomas, an engineer with the Federal Power Commission, analyzed wind power electric generation using data from the Putnam machine, and concluded that larger machines were necessary for economic viability. He designed two large wind turbines in the size range of 6500kW and 7500 kW. He believed that these huge wind plants should be used in conjunction with hydroelectric power, especially in the West of the United States, where wind could be used when there was a water shortage, and water stored in reservoirs could be used when the winds were not strong.[37]

In 1951 Thomas approached the US Congress for $2 million to fund a prototype of his wind turbines. The plan envisaged development by a private contractor, but with the electric power integrated into the federal system. The draft bill contained several visionary notions that wind power might facilitate the conservation of non-renewables, and even have strategic benefits reducing dependency on foreign supplies. However, it found no political support. The Vermont failure cast a shadow over wind energy, quite apart from the economics of wind compared to alternative sources of fuel, as well as the consensus that nuclear energy had enormous potential.[38]

The existing entrepreneurial wind energy companies also faced an uphill struggle. Jacobs Wind reached its peak in terms of sales from 1946 to 1950, but subsequently growth tapered off, and it filed for bankruptcy in the late 1950s. Marcellus, who had been joined by his sons, started a new business in Florida, where they built what was then called "environmental subdivisions" involving environmentally-friendly construction and waste management. After a few years, they went back north to re-launch Jacobs Wind Electrics.[39] But by the early 1970s many of the windchargers built by Jacobs and other small firms such as Windcharger were rusting in junk piles on farms – and available for a new generation of wind entrepreneurs.[40]

The Danish firms encountered the same problems of competing with national electric power grid providing cheap energy from fossil fuels. There remained an interest in experimentation in Denmark, most importantly by Johannes Juul, the chief engineer at a power utility in Falster, in the south of the country, who was nearing retirement, and took up his old interest in wind energy acquired when he took one of la Cour's courses in 1903. In 1959 his Gedster turbine began operation. The design was less mechanically complex than the American Putnam design, and was fairly similar to Poul La Cour's wind turbine. It stood 24 meters high, a rotor diameter of 78 feet, and a generator of 200 KW, it produced 400,000 KW a year. Juul's key invention - emergency aerodynamic tip breaks - remains in use in turbines today.[41]

The Gedster was efficient and reliable, and ran for ten years as the largest turbine in the world until it was shut down in 1967. (It was refurbished and ran again in the mid-1970s, as NASA in the United States became interested in large wind turbines). The problem was cost. In 1962 the price per kw produced by the wind turbine was double that of the power produced by a power station using oil, which drove almost all of Denmark's electricity generation.[42] Danish government interest shifted to nuclear power as a potential source of energy, and research funds were allocated to the nuclear test plant of Riso, which was inaugurated in 1958.[43]

There was also experimentation, but no commercial development, in postwar Germany. Professor Ulrich Hutter, an Austrian engineer who was engaged in Nazi wartime experiments with wind power and other aerodynamic topics, became a researcher at the University of Stuttgart. He developed a series of advanced, horizontal-axis designs of intermediate size that utilized modern, airfoil-type fiberglass and plastic blades with variable pitch to provide light weight and high efficiencies. This design approach sought to reduce bearing and structural failures by "shedding" aerodynamic loads, rather than "withstanding" them as did the Danish approach. One of the most innovative load-shedding design features was the use of a bearing at the rotor hub that allowed the rotor to "teeter" in response to wind gusts and vertical wind shear. Hutter's wind turbine StGW-34, developed in 1957, achieved over 4000 hours of operation before the experiments were ended in 1968.[44]

The major conclusion coming out of these decades is that if path dependency was an important component in the growth of the US and Danish wind energy, then it was a tangential path. By the 1970s little remained of the earlier wind firms in either country. As remote rural areas in Western countries were connected to national grids, the need to take electricity to the countryside ceased to be a significant driver of entrepreneurial activity.

Divergent Paths 1973-1988

From the 1970s two exogenous factors significantly impacted the perceived opportunities for wind energy, and explain the rapid building of capacity in the United States and Denmark during the following decade.

The most immediate factor was the oil shock of the 1970s. The oil price rises of 1973-4 and 1978-9 ended for the moment the era of cheap oil which had characterized the postwar decades, while raising major concerns about the security of oil supplies. This encouraged governments everywhere to reconsider energy supplies and consumption, but with remarkable policy variations between countries. France and Sweden, for example, launched a major nuclear energy program; Japan launched an energy efficiency program; and Brazil began investing in the production of ethanol from sugarcane.[45] In the United States, some policies also focused on alternative energy, including wind.

A second factor was a rise in environmental awareness. This growth was steady rather than spectacular. Environmental concerns were stimulated by both a number of visible cases of pollution, especially the eutrophication of lakes caused by phosphates in detergents, and by lone voices sounding warning signals. The influential voices included Rachel Carson, whose book *Silent Spring*, published in 1962, sought to raise awareness of the devastating environmental impact of widely used and produced industrial products like DDT. A decade later *Blueprint for Survival* (1972), put together by Edward Goldsmith and the other editors of the *Ecologist*, called humanity to recognize what they defined as natural limits on economic growth.

Environmental concerns rose up agendas at different times in Western countries. During the 1960s criticisms about wasteful packaging first appeared in the United States, and then in Scandinavia and Germany. Concerns about the pollution of detergents first occurred in Germany and Scandinavia.[46] In 1971 a new Danish government created a Ministry for combating pollution. Two years later the country passed its first Environmental Law. Nuclear power was perceived as the solution. In 1971 the electricity utility received approval to construct the country's first nuclear power plant.

For the first time, environmental issues began to be explored on an international level, possibly stimulated by the first images of earth from space in 1969. During the late 1960s, Scandinavian countries began to discuss environmental issues in the regional

Nordic Council. In the US, the first Earth Day in 1970 represented the culmination of growing public concern over environmental disasters. Senator Gaylord Nelson organized the first Earth Day celebration, which he modeled on the anti-Vietnam War teach-ins of the era. By some estimates, 20 million Americans participated in environmental rallies, demonstrations and other activities on that first Earth Day. The Friends of the Earth (FoE) was founded in San Francisco in 1969 by well-known American naturalist David Brower, a member of the Sierra Club. When the Sierra Club refused to oppose the development of nuclear power in the U.S., Brower left it and started his own group that became central to the rise of the new ecological movement. FoE spread internationally after a meeting of environmentalists from Sweden, France, the UK and the US in Sweden in 1971.[47]

It was during these decades when making wind turbines began to affect entrepreneurial cognition, although there is disagreement about the extent of its importance. Vasi has directly related environmental activism to the strength of Danish (and, later, German) business in wind generation, whilst suggesting it was less important in the US case.[48] Sine and Lee, however, also stress its role in generating entrepreneurial activities in the United States between 1978 and 1992.[49]

There is evidence that environmental concerns sparked entrepreneurial imaginations in Denmark, but within the broader context of the country's past heritage of wind energy which was available as a source of inspiration and competence. This led to significant innovations emerging from practical needs.

Christian Riisager, the source of one of those innovations, was a case in point. He was a carpenter in Jutland, who installed a waterwheel in the stream in his backyard to produce electricity for his garden. As the stream was weak in the summer, in 1975 he began building a wind turbine using Juul's design with materials such as wood and truck gears which he had at hand. After a series of accidents, he created a prototype 7 KW turbine, which he connected to the grid, for which he retrospectively secured permission from the local electricity distribution company. The turbine attracted journalists and he was soon making turbines for other people, which he eventually sold to a company in 1979.[50]

The Danish government provoked further environmental activism by launching a program in 1976 designed to transition the country's energy source from oil to coal and nuclear energy, with six new nuclear plants to be built by the end of the century. This provoked consider opposition, which included sparking new interest in alternative energy. A leading figure was Erik Grove-Nielson, an engineer who combined an interest in flying with concerns about sustainable lifestyles, acquired whilst in college in the early 1970s.[51] He was involved in campaigning against nuclear energy, and joined a new grassroots activist organization, the Organization for Renewable Energy (OVE) formed in 1976, which opposed the government's nuclear plans and promoted alternatives including wind and solar.[52]

At first experimenting with solar energy, Grove-Nielson began work on blade reliability and founded a bootstrap company, Økær Vin Energi, in 1977. He built a small business selling blades to self-builders. The venture struggled financially, surviving for some years with donations from OVE, but made critical improvements in blade design.[53]

There were further significant developments. The first was an institutionalization of the industry with the formation of the Danish Wind Turbine Owners Association on

May 4th: symbolically, the day Denmark was liberated from Nazi Germany. The Association was explicitly formed to oppose nuclear power and to promote solar and wind alternatives. It lobbied electricity boards, diffused information about wind, and facilitated design features to enhance the safety of turbines. In the same year the Danish Wind Turbine Test Station was founded by four engineers. When the government soon after required wind turbines to be certified before owner-users could gain access to subsidies, they began establishing testing criteria for gaining such subsidies.[54] In 1980 the first Wind Turbine Guild was established near Aarhus in Jutland. This was a partnership for tax reasons, but functioned as a co-operative.[55]

A second, very significant, development was the entry as turbine manufacturers of firms from other industries. Vestas, Nordtank and Bonus were small agricultural equipment manufacturers, the largest of whom employed 120 workers, who diversified into turbines.[56] Vestas, which grew to be the largest company, was founded by the son of a successful blacksmith in western Jutland, and built a business which also included household appliances.[57]

The diversification of Vestas and the other firms into turbines arose from a search for new opportunities because of stagnating agricultural markets and within the context of the second oil crisis, rather than environmental activism. The competences of these firms were based on their businesses of agricultural machinery. They knew how to build heavy machinery for a rural market.[58] These competences were augmented collaboration with activist entrepreneurs. In 1980 Vestas, Nordtank and Bonus bought blades from Økær Vin Energi. When another young activist, Henrik Stiesdal, who built an improved turbine, wanted to go to study at university, he licensed it to Vestas, providing the basis for the firm to build a turbine business which soon found a new market in the United States.[59]

Garud and Karnoe have described the development path of the emergent Danish industry as "bricolage." It was characterized by clusters of small, geographically clustered firms engaged in incremental innovation. The firms relied on skilled workers, technicians and a few practical engineers, and accumulated practical knowledge overtime. This reflected the Danish business system which featured many small and medium-sized firms, and a tradition of collaborative learning networks.[60] Geography was important in growing the infant industry in Denmark. The small size of the country enabled manufacturers like Vestas to directly service their turbines. This provided learning opportunities, as well as a strong demonstration effect for potential buyers who could see turbines working at a distance.[61] Meanwhile the Wind Turbine Owners' Association, which represented the large numbers of farmers and co-operatives which owned most of the turbines, was important in improving technological performance. Its association published data on reliability and performance, and comparisons with manufacturer's claims, and had an annual opinion poll on the quality of service of each manufacturer.[62]

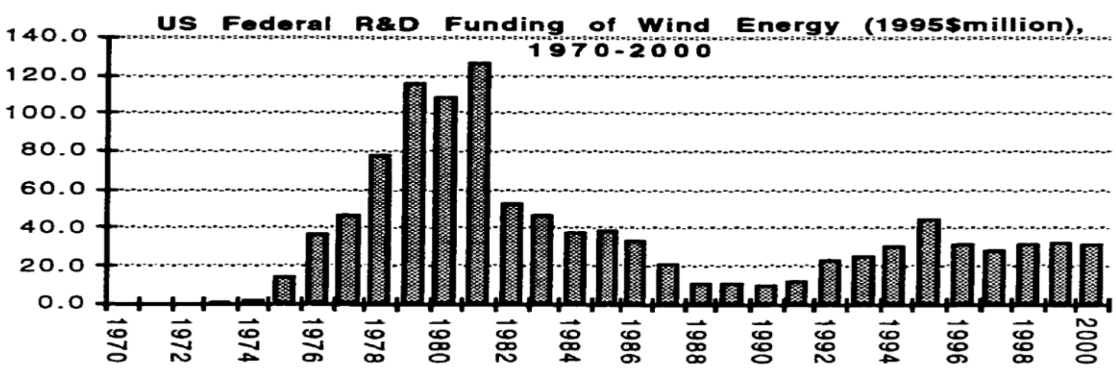
It was only with the second oil crisis that the public policy in Denmark became a significant stimulus for wind energy. In 1979 the government instituted a 30% investment subsidy for buyers of certified wind turbines. When this had little effect, subsidies were raised to 50%. More important, though, were voluntary agreements made in 1979 between the utilities and associations of wind turbine manufacturers. They agreed to pay owner-users for wind power at a guaranteed minimum price, and to share between the utilities and the turbine owners the cost of connecting the turbines to the grid. Initially they only applied to individually-owned turbines of less than 150KW, and to co-operatively owned turbines located near the co-operative.[63] These measures grew the Danish market, which reached 50 MW by 1985. Policies were not continuous, however, and in 1986 the special wind farm subsidy ended.[64]

In the United States, in contrast to Denmark, the oil crisis of 1973/4 resulted in a sudden government intervention into wind energy which, paradoxically, was to prove a crucial factor in the growth of Danish firms. The Federal government began to direct funds towards innovation in alternative energy. A lead role was taken by the space agency NASA, searching for a new role after the end of Moon landings.[65]Although the emphasis was on solar energy, it was predicted that wind would supply 5 % of US energy by 1979. The approach of this program borrowed much from the methods used to develop military aircraft. The Energy Research and Development Administration and then the U.S. Department of Energy selected subcontractors to build and test machines that would be commercialized; presumably by the subcontractors.

Although nuclear and coal were still seen as the main sources of electricity, in 1979, in the wake of the second oil crisis, President Carter announced a target that solar would supply 20 per cent of electricity by the end of the century. The Wind Energy Systems Act of 1980 also promoted an aggressive program of R & D to develop wind energy. Most of the funding was allocated to the development of multi-megawatt turbines, in the belief that U.S. utilities would not consider wind power to be a serious power source unless large, megawatt-scale "utility-scale" systems were available.[66]

Between 1973 and 1988 $380 million of US Federal money was spent on wind turbine development; comparative spending by the German and Danish governments was $78 million and $15 million respectively.[67] Following the pattern established by the Atomic Energy Commission's funding of civilian nuclear power technology, the government fully funded the design and building of large turbines by leading aerospace and technology firms, including Boeing, General Electric and Westinghouse. In 1979, although 31 companies and other institutions received funding, 87 per cent went to eight of them, all large contractors. Small companies received some money, but even research on small turbines was largely spent on big companies.[68] As Figure 1 shows, these high spending peaked around 1981, after which the Reagan Administration shifted gears and greatly reduced funding. In 1986 President Reagan removed even the solar panels which President Carter had installed on the White House. [69]

Fig 1 US Federal Funding for Wind Energy 1970-2000



Source: Janet L. Sawin, "The Role of Government in the Development and Diffusion of Renewable Technologies: Wind Power in the United States, California, Denmark and Germany", (Doctoral Dissertation, The Fletcher School of Law and Diplomacy, September 2001), p.101.

Whilst the entry of agricultural machinery manufacturers proved positive for the development of the Danish industry, the entry of US defense contractors and aerospace firms resulted in a technological dead-end. Although there were similarities between wind turbine and helicopter technology, there were also major differences, as wind turbines operate in relatively slow moving and fluctuating air currents, making it necessary to model aerodynamics in three dimensions rather than the two used in aircraft design.[70] The large turbines that were built experienced multiple technical failures. By the end of the 1980s they had almost all been discontinued. The entire episode, one author writes, had "little legacy."[71]

This was certainly not an exclusively American phenomenon. In Sweden, the government and electrical utilities opted for heavy investment in nuclear energy, and when a government R & D in wind energy started in 1975, it was almost entirely focused on giant turbines, with little result after two decades.[72] Given that Sweden shared the environmental awareness of neighboring Denmark, and had plenty of wind resources, the quite different energy policy choices made by the two countries is curious. It might well reflect the much greater importance of large firms in the Swedish economy, as its more centralized political structure. However even Danish power companies built two large experimental machines in the early 1980s, which proved too high cost to be commercial.[73]

A second set of public policies in the US aimed at stimulating demand for alternative energy proved far more important for the wind energy business. The Public Utility Regulatory Policies Act (PURPA) of 1978 opened the door to competition in the electricity supply by requiring utility companies to buy electricity from "qualifying facilities" or independent power producers, which included renewable power plants. This was the origin of so-called "feed-in tariffs" which, although they vary widely, offer grid access on the basis of long-term contracts which reflect the costs of renewable energy. The 1978 Energy Tax Act also offered a 30-percent investment tax credit for residential consumers for solar and wind energy equipment and a 10-percent investment tax credit for business consumers for the installation of solar, wind, and geothermal, technologies. The utility commissioners of individual states were left to implement the rules.[74]

These public policies shaped the fast growth of US wind energy capacity, and largely accounted for its geography – almost all the growth was in California. By 1990 most US, and over three-quarters of world, capacity was installed in California, where wind energy produced 1.1 per cent of Californian electricity at that date.[75] California had emerged as a hot bed of environmental activism and political action during the 1970s. The state banned oil as a fuel for electricity generation, and stopped the construction of coal-fired power plants due to concerns about air pollution.[76] It also attracted activists who helped shape state policies. Among them was Tyrone Cashman, originally a Jesuit, who became interested in ecological issues and wrote a Columbia University Phd on "Man's Place in Nature" in 1974. In 1977 he moved to a Zen Buddhist farm near San Francisco, where he encountered Sim Van der Ryn, a pioneering environmental architect, who had been appointed state architect by Governor Jerry Brown in California (1975-1983), and head of an Office of Appropriate Technology. Cashman joined the office, and became instrumental in securing the generous state tax credits for wind energy which helped drive its growth.[77]

During the 1980s the State government of California aggressively implemented PURPA, using Cashman's state investment credits to augment Federal tax credits. Investors in large systems, exceeding $12,000, in California, received an effective tax credit of 50 per cent in the early 1980s, thereby sharply reducing the up-front costs of investment. Another State policy, the Interim Standard Offer 4 (ISO4) launched in 1983, was even more important in driving the growth of the wind energy industry. The contracts were based on estimated long-term costs: they had a ten year fixed-price component followed by a 20-year period of floating prices.[78]

Almost all new capacity between 1983 and the mid-1990s came under these feed-in tariff contracts, which persisted after other public policies shifted. While Californian tax credits for wind energy declined from 25 per cent in 1985 to 15 per cent in 1986, and then disappeared, and oil and gas prices fell sharply in the mid-1980s, the ISOC contracts continued for the following decade.[79]

These policies transformed wind energy into lucrative opportunity. The time length of the California contracts and the fixed energy prices for the first years provided a guaranteed income stream, and were consequently highly effective in attracting entrepreneurial entry. The contracts also had major implications for fund-raising. Banks had not been willing to finance wind developers before the early 1980s. Wind developers could now use the contracts to readily raise finance.[80] Also important for fund-raising were State-sponsored "resource studies." California was ranked only the 17th state for wind energy in the United States, but other states – like North Dakota, ranked number one - conducted no such surveys. The surveys enabled entrepreneurs seeking finance to demonstrate availability of the resource.[81]

California's commanding role in wind energy rested on policy not geography. As wind turbines started to generate power, it was attractive to utilities serving coastal cities in California, because periods of high winds over the coastal hills correlated with high commercial and residential air conditioning loads in the summer. Yet the state was far from the top of states ranked by wind energy. Meanwhile there was little activity at the time in the US states with huge amounts of windy accessible land, including Montana, Nebraska, North and South Dakota, and Texas.[82]

The new generation of entrepreneurial entrants attracted to opportunities in California had even less continuity with the past than their Danish counterparts. Marcellus Jacobs re-entered the turbine business during the 1970s, designing a new7.5 KW turbine, but sold the business to the computer company Control Data Corporation at the end of the decade. Both politically conservative and independent-minded, he opposed government investment in the industry. This dislike also led him to oppose trade associations whose main purpose was to seek government funds, and distribute it to their members.[83] However the machines Jacobs and others had built were inspirations to a new generation interested in wind energy. These included Paul Gipe, who began searching for old wind chargers in Montana during the 1970s having concluded that finding renewable energy sources was vital, and seeking to "make a difference". In 1983 he wrote a book on rebuilding wind turbines, and moved to California.[84]

During the 1970s the first wind systems used in California had been imported from Europe and Australia, but the number of wind farm developers in California rose from 5 in 1981 to 50 by 1984. By 1984 local firms dominated the industry.[85] Four start-up firms owned more than one-half of California's installed capacity - these were Fayette, FLoWind, ZOND and US Windpower.[86]

Each firm had distinctive features. Fayette was a company started in Pennsylvania which, in 1977, was purchased by a 15-year CIA veteran, John Eckland, who had specialized in petroleum supply issues, and who had become interested in alternative energy through concerns about future energy security. After getting a patent for a solar energy device, he refocused on wind energy, and moved to Altamont, California in 1981, initially importing machines made in Pennyslvania.[87] By 1985 Fayette had 1,600 wind turbines in the Altramont Pass, making it the second largest in the state, though poor sitting of machines and other issues resulted in the firm's demise by the end of the decade.[88] FloWind, established at San Rafael, in 1981, was the sole US-firm to adopt Darrieus vertical-axis turbines. It also led a precarious financial existence, and failed in the early 1990s after not getting paid for a large Indian contract.[89]

The two remaining firms of the big four lasted longer. In 1980 James Dehlsen founded Zond Systems at Tehachapi. Dehlsen was a serial entrepreneur who had developed a product called Teflon, a fluid lubricant. He became interested in sustainability, and in 1980 sold his firm and used the proceeds to form Zond Systems, having become convinced both of the future of clean energy, and that government tax incentives would attract a lot of investors.[90] In 1981 he launched the Victory Garden wind farm, buying 450 of the machines produced by a local designer called the Storm Master. Dehlsen undertook direct negotiations with the local utility and secured a purchase contract, but the untested Storm Masters proved unable to withstand the region's strong winds, and Dehlen turned to Vestas to supply reliable turbines.[91]

U.S. Windpower, the firm which grew to dominate the American industry for two decades, was founded in 1974 in Cambridge, Massachusetts. The co-founders Stanley Charren and Russell Wolfe believed in the future potential of generating electric power by means other than fossil fuels, and wanted to create an energy company that used wind as its power source. Instead of building giant machines or tiny turbines, they opted to build intermediate machines which could be linked together by a computer communications system which would operate like a single power plant and be connected to the grid.[92] In 1978 they erected twenty 25KW windmills on New Hampshire's Crotched Mountain, which became the world's first wind farm, and gave birth to the dominant organizational form in the industry.

U.S. Windpower built its position by accessing finance. In 1978 its first public offering, for $1 million, failed. The company then hired managerial and other talent, one of whom was connected to California's Natural Resources Department. Funds were raised from angel investors, primarily wealthy New Englanders. In 1981 US Windpower moved its head office to Livermore, near Altramont, in California, and began to produce new wind turbines. In 1982 Merrill Lynch, to which industry insiders had recommended U.S. Windpower as the best wind farming firm, began bringing institutional investors to support the company's expansion. Its second generation system, the Model 56-100, which it began marketing in 1983, was a major improvement over previous helicopter blade-type systems. By the end of the decade it accounted for one-quarter of all the wind energy capacity in California.[93] The firm's revenues grew from $29 million in 1983 to $90 million in 1985, on which it earned a profit of $6 million.[94] In 1988 sales reached $148 million

The problem for most of the California wind companies was the quality of much of their equipment. There was also limited co-operation within the industry on standards and testing. Companies resisted "quality" standards when they were proposed, partly because they feared such standards would require costly design modifications to machines they wanted to sell.[95] The use of untested designs caused many wind farms to experience major reliability problems. In 1986 60 US firms produced turbines, but within three years this had fallen sharply as poorly managed firms struggled under the costs of repairs, warranty issues and complaints. The policy regime had distinct trade-offs. In a later interview Cashman justified its market creation function:

“We were stuck and I threw a stick of dynamite to break open a vicious cycle that was killing us. Nobody wanted to invest in new energy technologies. What we did was make it so seductive that they would invest- even if the wind turbines didn’t work. Without our program in Californian, the cultural knowledge would have been that wind power doesn’t work.”[96]

Yet tax credits encouraged speculative capital flows into the industry, which were more focused on tax advantages than generating electricity. The perception that unreliable wind farms were built for tax benefits damaged the reputation of the industry, and was ultimately instrumental in a backlash against it.

The situation laid the basis for the entry of foreign firms into the industry. While US Windpower manufactured thousands of its 50KW to 100KW turbines, they were only installed on its own windfarms. Other companies developed and managed windfarms, but installed turbines from foreign firms. Vestas opened an assembly facility in California. Zond bought three thousand Vestas machines for their Tehachapi farms during the first half of the 1980s. FloWind installed its own turbines, but also formed a joint venture with Danwin. [97]

The Danish firms offered three-bladed upwind machines derived from the Gedser mill design, a primitive and inefficient, but relatively well-understood configuration, suddenly modernized with the addition of fiberglass blades. They were armed with certification from the Danish test center at Riso, and with statistics that showed their designs were more reliable than their U.S. counterparts. In 1987 while US Windpower was the largest producer of turbines for California, the next five firms were Danish.[98] In that year 90% of new installations in California wind farms were Danish-built.[99]

California was not, however, an easy market even for the Danes. The strong exposure to the US market turned from an opportunity into a problem for Danish firms when the California tax credit legislation expired in 1985. Nordtank and Vestas went bankrupt after the US market collapsed. In the latter case, a major restructuring finally led to the establishment of a new company called Vestas Wind Systems A/S in 1987. After large parts of the Vestas Group have been sold off, the new company emerged focused on wind energy.

It was not only Danish firms which got a huge boost from the Californian wind rush. SeaWest chose Mitsubishi turbines for its wind farms. The entry of Mitsubishi Heavy Industries, a diversified manufacturer of power machinery, steel and shipbuilding, into wind power originated from the concern of one executive, Kentaro Aikawa, to develop a clean energy business following his experience in manufacturing boilers for thermal power plants, which burnt oil and coal. He built a geo-thermal plant, and then ordered a team to work on the development of a wind turbine in 1978. The team was only given a limited budget, and could only spend some of the time on the project, so they had to improvise. They used a tower they had found at the shipyards, and blades from a helicopter at Nagasaki airport which was about to be scrapped. They designed their own wind turbines. In 1980 they completed a 40KW wind turbine in Nagasaki Shipyard. It produced only a small amount of energy, and was used for internal use in the shipyard, such as boiling water for tea.[100]

The business slowly ramped up. In 1982 it sold a commercial 300KW wind turbine to an electrical utility which was installed on an island near Okinawa. In the following year the team used a skunk works manufactured their own blades, and was allocated to the project full-time. The team continued to experiment, changing its preference from European-style downwind system – the blades rotated clockwise – to an upwind system, where they rotated anti-clockwise.

Mitsubishi lacked a significant domestic market. The Japanese government's reaction to the energy crisis of the 1970s was to work towards securing stable oil supplies, to promote the development of nuclear power, and to encourage energy conservation. The perceived appeal of wind energy was diminished by Japan's geography. The country had only a limited amount of flat area, which was usually heavily populated, so windmills needed to be installed on mountains, which was very costly. Seasonal typhoon winds increased risks of machinery fatigue. The country is also surrounded by extremely deep water, which restricted off-shore wind-power generation when that technology emerged. The Japanese Building Code also stated that wind turbines over a certain height were to be classified as buildings; as a result government approval was needed prior to construction, creating an additional administrative barrier to new projects.[101] There were institutional obstacles because the country's ten electric companies. Led by the Tokyo Electric Power Company, monopolized the energy market, and had no interest in wind energy.[102]

Mitsubishi, therefore, had little option but to look abroad for markets, primarily to the United States. In 1987 the company sold 37 units in Hawaii, but its largest growth was the sale of 660 units at the Techachapi wind farm, one of the big three, in California. The project leader lived in California between 1987 and 1992, negotiating with residents.[103]

British firms also appeared, briefly, in the California wind rush. Howden, an engineering company which constructed cooling towers for nuclear reactors and had sold its first wind turbine in Britain 1982, supplied a 26MW of wind turbine capacity to Altamont Pass, California in 1984. The wind farm company was owned by Randy Tinkerman, who Governor Jerry Brown had put on the task force on wind energy five years previously, selected Howden in the belief that it would add credibility dealing with utilities.[104] It was a bad decision. The 33 meter Howden design was the largest wind turbine operating in California from 1985 until installation of the Vestas DWT turbines in the San Gorgonio Pass in 1990. The original Howden machine swept 2.5 times more area than Danish machines of the era. Yet there were serious reliability issues, reflecting the firm's recent entry into turbines, and only in 1990, after expensive modifications, did the Howden turbines produce yields comparable to other designs. Howden subsequently withdrew from the wind energy market.[105]

Table 1 gives the country of origin of the wind turbines installed in California by 1992. Non-US machines, overwhelmingly Danish, accounted for just over half of the turbines which had been installed.

Table 1 Wind Turbines in California, 1992

Country of Origin	No. of Turbines	% Turbines
US	7,786	49
Denmark	6,778	43
Japan	660	4
Germany	283	2
Belgium	174	1
Britain	112	1
Netherlands	63	0
Total	15,856	

Paul Gipe, *Wind Energy Comes of Age* (John Wiley: New York, 1995), p.36.

The 1970s and the 1980s, then, were the decades when environmental activists and believers in the importance sustainable energy, such as Grove-Nielson, Paul Gipe, Stanley Charren and Russell Wolfe, and even the Mitsubishi executive Kentaro Aikawa, became significant actors in the industry. They were significant sources of innovation. Yet the successful firms outside the United States at least, whether Danish or Japanese, grew on the basis of capabilities from other industries. Access to capital was essential, which was why the Californian policies with guaranteed income streams were so important. US Windpower's rapid growth seems especially based on its access to outside finance. Mitsubishi's wind program was also cross-subsidized from its other activities, as the business was unprofitable. The business was almost closed on several occasions, and only broke-even around 2005, twenty-five years after it started.[106]

Between 1980 and 1988 the California market accounted for 97 per cent of the total installations of wind power in the world.[107] Cashman was probably right in concluding that the California era provided a breakthrough for the wind energy industry. However the combination of unproven technology and financial dependence the vagaries of US polices produced a risky and skewed environment, as the bankruptcies of many Danish and American firms indicated.

Shifting Geographies 1988-2000

There were three major shifts in the world wind energy industry between the late 1980s and 2000. First, there was an enormous increase in installed capacity. Second, there was a shift in the geography of wind energy. By 2000 the United States contributed only 14 per cent of capacity, about the same as Denmark and Spain, a country which had no wind energy in the 1980s. Germany had risen from nothing to account for the largest, 17 percent, share of world capacity.

A third change was the ranking of largest firms. By 1996 US Windpower among the only US firm in the top ten for cumulative installed capacity, which was dominated by Danish firms. Both German and Spanish firms had emerged from nowhere as significant firms in the industry. Measured by annual installations, Danish firms populated most of the top ten positions, along with German firms, led by Enercon, and

Spanish firms, led by Gamesa. In most years, the ten leading firms accounted for 90% of turbine sales worldwide.[108]

Policy shifts were the drivers of the changing geographical distribution of wind energy. In Germany and Denmark, high feed-in tariffs drove the installation of 50-kW, then 100-kW, then 200-kW, 500-kW and then 1.5 megawatt wind turbines by cooperatives and private landowners. In 1998 95 per cent of wind turbines in Germany were operated by private individuals or co-operatives.[109]

The German government had first become interested in renewable energy in the wake of the first oil crisis. A wind power development program began in 1975, focused on the creation of utility-scale wind turbines. The Federal government invested $55 million in a 3MW, two-bladed, downwind machine built by an aerospace company called the Growain which, as in the United States, became plagued by reliability problems.[110] As in the United States, federal funding peaked in the early 1980s, and had fallen to $4 million by 1984. Wind energy remained marginal in the country for the remainder of the decade.

It was new policies launched in the 1990s which transformed the situation. Germany, like Denmark, had a growing environmental movement, initially focused on anti-nuclear protests. When the government responded to the oil crises by providing incentives for coal production, this stimulated growing concerns about acid rain. From the late 1970s a number of environmental NGOs emerged which framed debates about how to support renewable energy. In 1989 the German Ministry for Technological Development (BMFT) began offering subsidies for wind turbines accepted into the agency's research program.[111] In 1990 the Electricity Feed Act, the first feed-in tariff legislation in Germany, provided guaranteed payments over lengthy periods, with incentives to invest in efficiency.[112] There was also extensive tax breaks for renewable energy technology installation. For a number of years there were no limits on the amount of income tax deductions that could be made for investments in wind energy.[113] In addition, several state governments, especially in the north of the country, launched ambitious wind programs.[114]

In Denmark, when the voluntary agreements between the utilities, manufacturers and turbines broke down in 1992, the government introduced a feed-in tariff that maintained previous payments for wind power, though making wind turbine owners pay for connecting their turbines to the low-voltage grid. In 1991 subsidies for wind power producers were introduced. The powerful OVE organization lobbied for these policies.[115] In 1994, the government required municipalities to plan for future wind turbine construction, and began offering subsidies for the removal of older, inefficient, or loud turbines with new machines.[116] There was further innovation during these years – the first offshore windfarm was created at Vindeby in 1991. Overall 12% of Danish electricity generation came from wind by 2000.

The impact of policy was explicit in Spain also. This country, which had a dictatorship until 1975 and a limited environmentalist movement, seemed an unlikely candidate to become a leader in wind energy. The “movida”, the countercultural movement which emerged after Franco’s death, included some environmental concerns, and in 1979 the government launched a research and development program for the use of wind energy as a source of electricity. An experimental plant was built in Punta de Tarifa in 1983, and three years later the government facilitated the installation of the first small-scale wind farms through agreements with autonomous communities, utilities and private companies.[117] Yet the role of wind energy remained minimal until the European Union's regional development fund emerged as a subsidy for alternative energy projects. By 1992 there were 14 wind farms across Spain, but the major policy development was the Electric Power Act in 1997, which initiated an aggressive feed-in tariff policy.[118] This took place in the context of the European Commission's proposal in 1997 that the EU should aim to reach a 12% share for renewable energy in electricity generation by 2010, which in turn released further funds. By 2000 Spain's wind energy capacity was approaching Denmark's.

Elsewhere in Europe, neither the British nor the French governments had historically shown interest in wind energy. Great Britain was notorious for being a windy island, but the state-owned Central Electricity Generating Board, which monopolized electricity supplies after 1948, had no interest in connecting with wind turbines. During the 1960s, as elsewhere in Europe, there was a shift out of coal to cheap supplies of oil, though this was delayed by political protection of the large coal industry. The government also strongly encouraged a nuclear energy program, largely an outgrowth of the defense industry.[119]

Ironically, the privatization of electricity generation in 1989 provided the context for a shift in policies. The British government was left owning the nuclear energy facilities, which no one wanted to buy, and which supplied about one-fifth of the country's electricity. As a result, it imposed a "non-fossil fuel obligation" which obliged regional electricity companies to provide a portion of their supply from non-fossil sources. This was intended to help the nuclear industry, but wind energy also qualified, and provided an opportunity for entrepreneurial entrants. The first commercial wind farm in Great Britain opened on farm near Delabole in Cornwall in 1991. A farmer, Peter Edwards, who had become interested in wind energy over the previous decade, installed ten wind turbines using a bank loan, a small grant from the EU, and an equity investment from the electricity utility. The turbines were carefully positioned in existing hedgelines, with cables underground so that normal agricultural use could continue. Overall, however, low prices and short contracts kept capacity small up to 2000.[120]

In France, the state-owned electrical utility Electricité de France (EDF) controlled market entry after 1948. There were a handful of independent wind turbines in France at that time, but access and contract conditions were unfavorable. EDF invested heavily in nuclear power during the 1970s in the wake of rising oil prices and the nationalization of French oil and gas interests in Algeria, which had supplied much of France's supplies.[121]

Wind energy remained marginal in French electricity generation. There were a number of disastrous experiments, including a turbine installation off the coast of Brittany which was destroyed during a storm and abandoned just before the oil crisis of 1973. In the early 1980s, France had only 12 wind turbines connected to the grid, and installed by private and public initiatives in order to bring power to remote rural areas in the south east of the country, but these were subsequently abandoned. In 1989, Espace Eolien Développement, a small wind energy consulting firm, conducted a preliminary feasibility study on the construction site of a wind turbine on the grounds of a hospital in Dunkirk, and an application for funding from the European Commission was submitted. In 1989, the European Commission agreed to finance one-half of a 300 Kw turbine, now located for safety reasons on the coast. The wind turbine was erected and connected to the network for EDF in 1991. The experiment was successful, but the extension of wind energy encountered great opposition in France from people concerned about the visual and sound impact of the machines. Ten years later France still had one of the smallest wind energy capacities in Europe in 2000, and derived four-fifths of its electricity from nuclear power.[122]

Meanwhile, public policy shifts led both to the overall decline in importance of the US market, and a major geographical shift. In the 1990s, the California wind farm market began to slow sharply because of the expiration or forced re-negotiation of attractive power purchase contracts with the major California utilities. Prior to 1994, Hawaii was the only state outside of California where there was significant wind power capacity.[123] Growth now started elsewhere as green policy initiatives were launched in Minnesota, Colorado, Iowa, Texas and elsewhere. By 2000 12 states had specific standards for the quantity of electricity sales from renewable energy.[124]

These policy shifts had a direct impact on new entrepreneurial entrants into wind energy. While Danish firms had become heavily dependent on foreign markets, the sudden growth of German and Spanish firms was directly related to the growth of their national markets. Both new markets were supplied primarily by local firms, who created new industries almost from scratch. In France and Britain, where there was little policy support for wind, no major wind firms emerged.

In Germany, Aloys Wobben emerged as the leading entrepreneur in the emergent industry. He was initially trained as an electrical engineer, who had worked in renewable energy during his work as a scientific assistant at the Technical University of Braunschweig. With his close friend Meinhard Remmers, he built was his first wind power plant in his back garden in 1975. A decade later his company, Enercon, produced 55kw turbines with a gearbox and capable of variable speed. As in Denmark, geography mattered. Enercon's turbines were initially located around Ostfriesland in Lower Saxony, where they were made, and from the beginning the firm provided service maintainance. As in Denmark, this simplified service and provided feedback to Enercon, enabling it to continuously improve design. In 1992 Wobben created windmills that were gearless and functioned without hydraulics, which were more environmentally friendly as no oil was required to drive the machinery.[125] The widespread use of gearless, direct-drive, generators would, however, remain limited until recent years, when the growth of offshore wind farms greatly stimulated their use.

Between 1992 and 2000 60 per cent of new wind capacity in Germany was locally-made. The government's BMFT subsidy was initially targeted at German firms, with two-thirds of the support given to local companies rather than Danish suppliers, enabling the German firms to build scale in the market.[126] Wobben secured about one-third of the German market for turbines, and accounted for most of the German machines sold abroad, while a second tier of manufacturers emerged, including the firms of Tacke, AN Wind and DeWind.[127] Germany also became a center for component manufactures. Winergy became of the world's leading gearbox manufacturers.[128]

While public policies were evidently critical for the sudden emergence of the German industry, Wobben joined the ranks of entrepreneurs with an explicit environmental agenda. In an interview in 2004, he observed:

"Our planet is already damaged. We have lost animal species, the state of the atmosphere is weak and we have to protect what is left. It should be immediately forbidden for everybody to increase emissions."[129]

Public policy was equally important in the emergence of locally-owned firms in Spain. Gamesa, which became the largest Spanish firm, was founded in 1976, and its initial activity was the construction and sale of industrial machinery and equipment. During the 1980s, after being taken over by Iberdrola, Spain's second largest electrical utility, based in Bilbao, and a local bank, Banco Bilboa Vizcaya Argentaria, the firm invested in new technologies for emerging businesses including robotics, microelectronics, the environment and composite materials.

Gamesa entered the wind energy business as big utilities started placing large orders to benefit from government grants, and as the Spanish central government and regional governments imposed aggressive local assembly and manufacture requirements before granting development concessions. In 1994 Vestas, in order to access the Spanish market, formed a joint venture with Gamesa, called Eolica. Vestas took 40% of the shares of Eolica, Gamesa took 51%, and the regional government the remainder. In 1996 Eolica began the development, construction and sale of wind farms in Aragon with the La Plana III wind farm development. Gamesa used the joint venture to develop its own technological capabilities, and in 2001 the Spanish bought out the Vestas share in the joint venture, with Gamesa maintaining the intellectual property rights to continue to use Vestas technology in Spain and elsewhere.[130]

While German and Spanish firms grew rapidly, US-based companies based through turbulent times. US Windpower survived the slowdown of the Californian market by diversifying into other energy-related ventures, particularly construction services and energy management services. In 1988 it renamed itself Kenetech Corporation, which became a holding company for such diversified activities. In response to the challenge that the fixed-price purchase contracts it had signed in the mid-1980s would expire after 1991, it invested in a new generation of wind turbines. It launched the Model 33M-VS in 1991 after spending $40 million in research and development. Despite falling oil and gas prices, it continued to seek growth, and raised $92 million for new expansion in 1993.[131]

Like the other surviving US wind firms, Kenetech sought to develop markets beyond California in Washington, Montana, Oregon and Minnesota.[132] However a report by an investment advisor that the Model 33M-VS had major technical problems resulted in a growing financial crisis, as investors launched class-action law suits, and a collapse in the stock price. This compounded other serious issues, including an accumulating stock of machines for the Pacific Northwest where windfarm proposals had been delayed because of concern for birds, and the company went bankrupt in May 1996. Kenetech did leave an important legacy on the American market, however. In 1995 it successfully sued Enercon for patent infringement, and won, blocking Enercon from selling its variable speed technology in the American market. US firms were then able to use this ruling to force European manufacturers, including Vestas, to make special modifications in their turbine models to get around the patent infringement issues. This became a considerable competitive obstacle.[133]

Zond was the remaining large US company. It started to build its own Z series turbines rather than use those of Vestas, though its machine resembled the Danish machines, so it was not seeking to invent a new type of turbine. The failure of Kenetech, however, left Zond unable to raise funds. This led to a takeover by Enron, primarily a natural gas producer and trader, bought the company, followed soon afterwards by the acquisition of German-based Tacke.[134]

Enron had entered the solar power business three years previously in partnership with the oil company Amoco. It was attracted to green power for multiple reasons. There were large subsidies available, and it provided a veneer of respectability for a company engaged in increasingly illegal practices. In 1998 Enron won a contract to provide wind power to all of the fourteen Californian facilities of Patagonia, a prominent green manufacturer of outdoor clothing that decided to use only wind energy. Enron also used its investments to secure Federal tax credits.[135] Enron Wind's sales went from $50 million in 1997 to $800 million in 2001.[136]

This period, then, saw major change in the corporate structure of the wind energy industry. The collapse of the California wind boom led to a period of upheaval in the American industry, with leading firms bankrupted or taken over, and the entry into the industry of Enron. Many of the leading Danish firms were also bankrupted by the Californian implosion, but emerged under new leadership. In Europe, huge public subsidies, and favoritism for local firms, resulted in the entry of German and Spanish firms.

2000-2011

The rapid growth of wind energy capacity is the most obvious feature of the last decade, but although the trend was sharply upwards, this disguised an industry still subject to policy shifts and changing fashions. The financial crisis of 2008 and 2009 diminished interest in new wind projects in the United States and Europe. But political unrest in the Middle East and a major nuclear power plant incident in Fukushima Daiichi Japan in March 2011 stimulated interest again in alternatives to oil and nuclear. A widening in the geographical distribution of wind energy was a more consistent trend. In 2000 Germany alone had one-third of world capacity, with Denmark, Spain and the United States accounting for another 14% each. A decade later Denmark's relative importance had shrunk, and it represented less than 2% of the world market, while the United States had resumed its place at the center of the industry, with 21% of world capacity. China had come from nowhere to rank as the country with the largest installed capacity. India had a further 7%. In Europe, even the wind industry laggards such as France, Great Britain and Italy saw rapid growth in the wind capacity, each country accounting between 3% and 4% of global wind capacity by the end of the decade. There was a striking growth in wind energy in Portugal after 2005. Five years later it had as much wind power capacity as Denmark.

In part the growth of wind power was driven by technological progress which sharply reduced costs and thus made wind energy more attractive. While a 50 kW machine was considered large in 1980, in recent years 1.5 MW to 2.5 MW machines have become standard.[137] Blades grew from 8 meters long in 1980 to 40 meters, and more than 60 meters for offshore applications. While in the early 1970s small turbines might generate power for $0.30 per kilowatthour, by the late 1990s costs at medium-sized wind farms had fallen to $0.08 per kilowatthour. Ten years later costs were lower still.[138]

Government subsidies and feed-in tariffs were, as before, decisive. In a number of countries there was a sharp rise in support for alternative sources of energy, including wind, driven by growing concerns regarding greenhouse-gas emissions, but also by strategies to diversify sources of energy supply as oil and gas prices soared, especially between 2005 and 2008, and again in 2011. The sudden growth of wind energy in France, Great Britain and Italy reflected policy shifts which were influenced by the first EU directive for promoting renewable energy use in electricity generation, issued in 2001.

The French adoption of feed-in-tariffs in 2001 was a direct response to the EU directive, which required France to increase its share of renewable energy as a whole from 15% to 21 per cent by 2010.[139] Initially the French government continued to limit the amount of wind energy that could be connected to the grid, however. An entrepreneur who started a wind farm business in 2002 later recalled

"In 2001while I was talking to people around me about my project, they would not understand or see the potential of wind energy. They thought I was just a utopian, for most people in France wind turbines were just a gadget…France is a country of nuclear. We have always been taught in school that nuclear energy is clean, and cheap, and readily available."[140]

It was only in 2005 that government restrictions were lifted in certain regions.[141]

The rapid growth of the Portuguese wind energy sector also took place within an EU context. In Portugal, the government of José Sócrates, a former environment minister, launched a massive renewable energy program after 2005 awarded 15-year inflation proofed-fixed contracts to expand the wind energy industry. This resulted in a large 15 per cent rise in electricity prices over the following five years, and even then electricity prices were held down, resulting in growing public debt. The country had decided not to pursue nuclear power during the 1970s, in part because it was subject to earthquakes, and so was heavily dependent on fossil fuels. Observers noted that wind farm contracts were awarded to firms with close connections to the ruling party. In contrast, environment or green concerns, although part of the official discourse, appear not to have been significant drivers of change.[142]

Government financing was especially critical for the emergent offshore wind power sector, which remained primarily confined to the coasts off Britain, Denmark, the Netherlands and Sweden, along with a small offshore wind farm installed in China in 2009. The unproven technology made it virtually impossible to attract private sector finance.[143] Concerns about safety, visual impact, tourism and much else regularly caused huge delays in regulatory approvals, as a ten-year saga to build a 130-turbine offshore farm in Nantucket Sound off Cape Cod which began in 2001 testified.[144]

In the United States, the wind sector also resumed growth from the late 1990s due to Federal government production tax credits in 1999, 2001, 2003 and 2005. The market continued to be volatile, however, as these were annual measures, and there would be no new installations when the annual credit expires. In 2006 Congress put the tax credit in effect for three years and, together with renewable production standards in 22 individual states, this drove a sharp rise in capacity.[145] In 2009 the American Recovery and Reinvestment Act provided new Federal funding, including loan guarantees and tax credits, for renewable energy.

There were also major new initiatives from states. In 1999 in Texas, then-Governor Bush, signed off on a landmark provision requiring utilities to get 2,000 megawatts of their electricity from renewables by 2009, setting off the largest annual increase in wind-farm construction in U.S. history. The following decade saw the spread of adoption by U.S. state governments of Renewable Portfolio Standards , which ensure that a minimum amount of renewable energy, including wind but also solar, biomass, and geothermal energy, is included in the state's portfolio of electric generating resources. Research by Lyon and Hin has shown that environmental concerns do not appear to explain why some states have pursued these policies. Rather, the existence of strong organized renewable energy interests, a small share of natural gas in the electricity fuel mix, and a strong Democratic presence in the state legislature, appear decisive.[146]

In India and China, too, public policy lay behind the growth of the wind industry. In India, there was an early interest in wind energy. The National Aeronautical Laboratory in India began experimenting during the 1960s and 1970s, with few results. In 1983, India initiated a national wind power program with three components: wind resource assessment, demonstration projects, and industry-utility partnerships, but little happened until the "private power policy" in 1991 provided greater incentives. In 1995 the government mandated state electricity boards to ensure grid compatibility with planned wind developments. Financial incentives included 100% depreciation of wind equipment in the first year of project installation, and 5 year-tax holidays.[147]

By 1995 India was already approaching the capacity of Denmark, but government policies were fluctuating and erratic, leading to some states starting to support the wind power companies themselves, which helped to promote further growth, which became substantial after 2000.[148] India's Electricity Act of 2003 required state-level energy regulatory commissions to encourage electricity distributors to procure a specified minimum percentage of power generation from renewable energy sources.[149]

In China, the first turbines were installed in the Xinjang wind power project in 1988, which was supported by the Danish government. During this period Western donor countries provided funding for wind projects, conditional on importing turbines from the countries.[150] In the mid-1990s, China's signing of international environmental treaties, especially the Kyoto Protocol, was accompanied by foreign governments and bilateral agencies providing money and technological assistance to the Chinese government to help create a renewal energy program.[151] In 1994 the government mandated electricity grid operators to facilitate interconnection of wind farms, set a purchase price for wind energy, and stipulated that any cost of wind power over conventional power had to be paid for by the grid. Between 1995 and 2000 there was a substantial increase in wind power installation, almost all using imported turbines.[152]

Subsequently, the government switched to tendering government-selected sites that were auctioned off to potential developers. A condition was imposed on the developers of project that 70% of the turbines used had to be made in China.[153] China's first Renewable Energy Law, issued in 2005, defined the strategic priorities and responsibilities for the development of wind energy and other non-fossil energy sources. It stated that 15% of national energy consumption was to be sourced from renewable energy by 2020. Large state-owned power companies were obliged to ensure that wind power accounts for at least 5% of their total energy output by the same year. Although there were environmental concerns behind this strategy, the government was also concerned to develop a strong industry for technological and employment reasons. In 2009, China finally introduced a feed-in tariff for wind power generation, which applied for 20 years of a wind farm's operation.[154] As elsewhere, there were strong regional differences in wind power installation. China's wind power capacity became concentrated in nine provinces, mainly located in the northern part of the country, which accounted for 86% of national capacity in 2008. [155]

The large shifts in the corporate structure of wind energy are suggested in **Appendix Table 3.4**, which shows the top firms for installations in 2010. While Vestas remained the leading firm, it was now the only Danish firm in the list. Germany's Enercon was also found on both lists. The single US firm was the GE, whilst Spain's Gamesa along with one Indian and four Chinese firms were now on the list.

There were two driving forces of this changing structure. The first factor was government policies which in many European and Asian cases included stipulations requiring local manufacture and in some instances favored local firms. The second was the growing scale of the industry as technological development resulted in the commercial production of larger, more efficient wind turbines. There was an increase in the size of commercial wind farm developments. Whereas in 1995 three-quarters of sales of wind turbines were single or small wind farm sales up to 5 MW, by 2002 nearly 65 per cent of sales were to commercial and utility owned wind farms. An offshore market also emerged as a key growth market due to the more attractive wind conditions available offshore. These developments made the industry much more capital-intensive, encouraging consolidation or the entry of bigger, well-capitalized firms. And whilst capital-intensity rose, the risks do not go away. In particular, the US market remained volatile.[156]

The process of consolidation in the Danish industry, which was extremely dependent on international markets, was driven especially by the trade-off between growing capital-intensity of the industry and its continued risks. Vestas listed on the Copenhagen Stock Exchange in 1998, and used its new capital to acquire Danish makers of components, including Cotas in electronics (1999) and Wincast in castings (2003).

Consolidation and professionalization of management became the central themes of the company's development. In 2003 Vestas acquired the second largest Danish turbine firm NEG Micon, which was itself the result of a merger between Micon and Nordtank in 1997. Both firms were dependent on world markets, but had rather different profiles. While Vestas was particularly strong in the United States and Germany, NEG Nicon had remained in Spain after Vestas had sold its interest, and had also invested in the Indian market. Vestas had six Danish factories, two facilities in Sweden, one in Norway, three in Germany, and one each in Britain and Italy. In addition to six Danish facilities, NEG Nicon also manufactured in Spain and Britain, and assembled nacelles (turbine covers for components) in Spain, India and China.[157]

In 2005 Vestas, in the midst of another financial crisis with its share price collapsing, recruited Ditlev Engel, the chief executive of the Danish paint company Hempel, as its chief executive. Engel encouraged a greater professionalization of the management, and especially the research and development functions.[158] In 2007 a large research and development center was opened in Singapore. Although he lacked both a wind energy and an environmentalist background, Engel was also vocal in campaigning for support for clean energy systems.[159]

There was also consolidation in the German industry. Enercon retained its leading position, but as elsewhere large engineering firms entered the industry. Siemens had begun experiments with wind turbines in 1980s, but the business remained small until

2004, when the company entered wind energy on a large-scale by buying Bonus in Denmark, which was then the fifth largest turbine manufacturer in the world. In 2005 Siemens acquired Winergy, the world's largest gearbox manufacturer.

The changing shape of the wind energy was also evident in the US industry. The bankruptcy of Enron resulted in the entry into wind power of GE, which had long produced turbines for power generation, and which outbid Caterpillar and other firms to purchase the wind-turbine manufacturing assets of Enron in 2002. GE acquired 1,600 employees worldwide with operations in Tehachapi, Calif., and manufacturing operations there and in Germany, Spain and the Netherlands, and became at a stroke one of the world's largest wind energy business, for the quite modest price of $358 million.[160]

GE transferred not only capital but marketing capabilities to wind energy. In 2005 it launched the "ecomagination" initiative which put all its environmental products under a single brand. By 2009 GE's ecomagination products had $18 billion in revenues (out of a corporate total of $157 billion), although the inclusion of nuclear power technology and fossil fuel power components because they were more energy-efficient than their predecessors raise issues of legitimacy. By then GE had over 13,800 worldwide wind turbine installations comprising more than 20,000 MW of capacity.[161] Like Siemens, the company was able to acquire capabilities it did not possess. In 2009, for example, it acquired ScanWind, a Norwegian company which developed advanced wind turbine drive trains and control technologies for offshore turbines.

The entry of Siemens and GE through acquisition into wind energy was symbolic of the sector's transition from entrepreneurial firms to big business. On a smaller scale, the large French transport and energy company Alstom entered turbine manufacture by buying Ecotècnia, a company founded in Barcelona in 1981, with an international business, mainly in southern Europe.[162] These corporate giants provided a sounder financial basis for the further growth of the industry, as their deep pockets made them less likely to shift strategies in an industry plagued by shifting public policies, as well as still-emergent technologies.

This decade also saw the emergence of non-Western firms in wind energy. In barely over a decade, both India and China transitioned from having firms with no wind turbine manufacturing expertise to companies capable of manufacturing complete wind turbine systems with locally-made components. This was despite both countries having severe power infrastructure problems manifested by blackouts and other major reliability issues.

The first Indian wind turbine firm opened in 1991, when the Khemka business group formed a joint venture with Micon, NEPC Micon, but by the end of the decade it and other international firms had been overtaken by Suzlon. This company was established in 1995 by a small family firm in Gujarat that diversified into wind energy from the textile industry. The survival of the 20-person firm was in jeopardy because of soaring electricity supplies, which were also erratic. Tulsi Tanti, who was trained as a mechanical engineer and was working in the family business, solved the problem by investing in two European-made wind turbines. When the manufacturer failed to fit them, Tanti installed them himself. After successfully installing the machines and reducing his power costs, Tanti opted to go in the business and founded his own company, Suzlon Energy, in 1995, based on a vision of future demand. He later observed:

> "I had a very clear vision, if Indians start consuming power like Americans, the world will run out of resources. Either you stop India from developing or you find some alternate solutions."[163]

The firm grew, within the context of a favorable policy context, by combining an innovative business model with acquiring foreign technology through various means. Tanti offered a full-service to customers from identifying sites, to providing the turbines, to providing operating maintenance. While customers were responsible for one-quarter of up-front investment, Suzlon helped arrange the remainder. Its' staff accompanied customers to banks to explain the benefits of wind energy providing a reliable energy source at a capped price.[164] The erratic nature of the Indian electrical grid gave Tanti an opportunity to compete with non-consumption of energy rather than, as in developed countries, with an established, cheap, supply. Suzlon was able to build scale by using the existing family business connections: its first customer was the family textile company, while its first outside order was to a petrochemicals company that supplied another Tanti family business. A breakthrough came when it persuaded the Bajaj group, one of India's ten largest businesses, to purchase its turbines.[165] Tanti lobbied the state government of Maharashtra to provide a tax break that allowed customers to offset their windmill costs with a credit on their sales tax bill; this provision was instrumental in persuading firms like Bajaj to buy wind turbines.[166]

Like Gamesa, Suzlon built its technological capabilities through alliances with foreign firms. The first of these was a second-tier German company, Sudwind, which in 1995 agreed to share technical knowledge in exchange for royalty payments. When the German company went bankrupt in 1997, Suzlon hired its engineers and began manufacturing its own turbines. Shortly afterwards it acquired AE-Rotor Technick, a bankrupt Dutch company which made rotor blades. As it built capabilities, it opened an international marketing headquarters in Denmark in 2004 to be close to the best industry expertise. By then Suzlon had captured half the Indian market.

Tanti sold the original textile business in 2001, and Suzlon went public in 2005. This provided the funds for the company to acquire Hansen Transmission in 2006. This Belgian company was one of the world's leading manufacturers of gearboxes and drive trains for wind turbines, and the $563 million paid was the second largest-ever foreign acquisition by an Indian company. Hansen was then listed on the London Stock Exchange, providing a further large source of funds. In 2005 Suzlon started building a blade manufacturing plant in Minnesota, which offered a generous state tax credit, and within three years the US market had become the industry's second largest. In 2007 a majority shareholding was acquired in Repower Systems, the third largest German turbine manufacturer with strengths in offshore turbines, for $1.84 billion. This acquisition made Suzlon the third largest wind energy company.[167]

A number of Chinese firms also developed rapidly, although unlike Suzlon, their growth was primarily based on their domestic market. The largest Chinese company, Sinovel, was established in Beijing in 2006, and had its origins in heavy engineering company. The company was associated with a company linked to the son of China's Premier Wen Jiabao.[168] Xinjiang Goldwind Science and Technology originated in 1998 in northwest China, the first site of large-scale wind power in China. It was majority-owned by the Chinese government. Like Suzlon, Goldwind acquired its technology through alliances with second-tier firms rather than market leaders. It obtained its first turbine technology through purchasing a license from Jacobs, a German company subsequently acquired by Repower. It subsequently acquired further licenses from other German firms, Repower and Vensys.

Like Spain and Germany, the Chinese government enforced strict local content requirements, which enabled the rapid growth of Sinovel, Goldwind and other firms as they could meet them more quickly than the European companies, which needed to build capacity in China.[169] The state-owned Chinese electricity utilities showed a clear preference for purchasing from Chinese firms. The locally-owned firms benefitted greatly from lower costs, enabling them to charge 20%-30% less than their international competitors in the China market, in a market in which low wind tariffs resulted in a high cost-consciousness.[170] The growth of Sinovel and Goldwind was facilitated by access to the capital markets to fuel their growth: Goldwind raising almost $1 billion in 2010, and Sinovel making an IPO in Shanghai in 2011.

The age of the visionary entrepreneur in wind energy was not yet over – Tulsi Tanti and Aloys Wobben would both qualify. But as wind had become big business, so the balance within the industry shifted to firms such as GE, Siemens and politically connected Chinese firms. As the industry matured, the opportunities for new entrants to turbine manufacturing to emerge were much reduced, unless their home market was huge and they were supported by their government, as in China. The rapid growth of the Portuguese wind capacity was enabled by turbines from Spain and China, for example, rather than from local firms, although EDP (Energias de Portugal) , the country's biggest electricity utility, built on its expertise running wind farms in Portugal to buy a US wind farm company in 2007.[171]

Concluding Remarks

This working paper has stressed the limited impact of geography and natural endowment in explaining the global distribution of wind energy capacity. Location certainly matters when wind farms are built, but public policy has been the key variable in the spread of wind energy since the 1980s. While a concern for sustainability, and growing awareness of the impact of climate change, has influenced policy, in many cases it has not been the decisive factor. Beyond periodic concerns about the cost and reliability of fossil fuel supplies, industrial policy and the lobbying of vested business interests emerge as decisive influences, even if policies were packaged in the language of sustainability.

The country of origin of the leading firms is also not well explained by natural resource endowment. Denmark was well-positioned in wind capacity, but the firms of other "windy" European countries did not see an equivalent emergence of major wind companies. Conversely, Mitsubishi Heavy Industries emerged as a significant firm in wind energy (although rarely in the top ten firms) despite Japan's unhelpful geographical and climatic conditions for wind, as well as a minimal home market.

Geography was not altogether irrelevant in explaining the country of origin of firms, however. Both in the United States and Denmark, the existence of rural areas not supplied by electricity provided the initial stimulus to entrepreneurs and innovators. Subsequently, proximity emerged as an advantage in incubating corporate capabilities. The Danish companies, and Enercon in Germany, grew by providing service and maintenance as well as turbines to purchasers, and this was helped by smaller distances than in the United States. Geographical proximity between manufacturers and end-users established a feedback loop which was important in building firm-level capabilities.

Governments were the problem rather than an opportunity for wind turbine entrepreneurs before the 1980s. They played virtually no part in supporting wind energy – or rather, wind energy found its market in rural areas which lacked electricity supplies, and it was rendered uncompetitive when governments built national grids which took fossil-fuel generated electricity to rural areas. After World War 2 fossil fuels were cheap and plentiful. During the 1970s, when the oil crises stimulated major shifts in energy policies, the US and many other governments the US and many other Western governments preferred nuclear energy as the primary alternative source of electricity. To the French and many other governments, it offered plentiful energy with a proven technology, unlike the "gadgets" of wind companies. It also had a convenient linkage to defense capabilities. Under the influence of NASA and similar agencies, credibility was seen to lie in size. The US and other governments spent huge sums of money trying to develop giant machines, whose failures further damaged the reputation of wind energy, whilst achieving few technological advances. The funds allocated to giant aerospace or other large industrial corporations had virtually no benefits. It was a classic example of the risks of governments investing large amounts of money in green energy technologies which are flawed.[172] Notably, the basis of the competitive Danish industry was laid without support or even encouragement from its government.

From the 1980s public policy became much more important as an influence on firm growth, although in unexpected ways. Californian feed-in tariffs and other measures stimulated the entry of a new generation of US firms, but did not incentivize them to develop reliable machines. As a result, the main beneficiaries were Danish and other foreign manufacturers who were able to supply more reliable machines, and service them effectively. Although the collapse of the Californian wind boom proved disruptive to the worldwide industry, it enabled corporate capabilities to be built on an impressive scale.

Public policy was crucially important for explaining the rapid success of many new entrants. The combination of strong policies to support wind energy and local manufacture requirements provided an enormous stimulus for the emergence of local firms in Germany, Spain and China. India's Suzlon was also the beneficiary of favorable government support, but its story was a more entrepreneurial one, as it grew rapidly as a more globally active company than the Chinese wind companies, with limited protection from its government.

Important as public policy was for the growth of turbine companies, the building of firm-level capabilities was also essential in an industry which was both technically difficult and vulnerable to policy shifts. Visionary entrepreneurs were important in the industry, although the vision changed over time. Historically, the primary vision was about bringing electricity to rural areas. This tradition continued in India with Tulsi Tanti, who sought to provide reliable electricity to firms and consumers plagued by supply problems and high costs. From the 1970s some entrepreneurs began to enter the business through environmental concerns. In the case of Aloys Wobben, they built highly successful businesses. It was striking, though, that some of the industry's most successful firms, whether the Danish companies or Suzlon, entered wind energy from other industries entirely, bringing in their own distinctive capabilities and connections.

The firms which succeeded were those which followed distinctive paths of learning. This involved building capabilities incrementally, as in the case especially of firms based in Denmark. It turned out that the decentralized and small-scale firm structure in that country was highly effective in generating the incremental improvements for wind turbines which, over time, resulted in reliable machines. In the cases of Gamesa, Suzlon and the Chinese firms, the acquisition and absorption of technology was critical. They identified partners from which to acquire technologies, absorbed the technologies, and developed their own capabilities.

The underwhelming performance of US-based firms is surprising, given both the long tradition in wind energy, exemplified by Jacobs Wind, and the enormous importance of the US market after 1980. Whilst inconsistent and fluctuating Federal and state energy policies were unhelpful, they do not explain why US firms proved weak at developing internationally competitive products in which their Danish counterparts, also heavily dependent on the American market, excelled. There was no single explanation for this, but rather a combination of factors. While Jacobs incrementally improved its technology very much as later Danish companies did, this tradition was not strong in most the entrepreneurial entrants from the 1970s. Instead, there was a rush to capture lucrative contracts dependent on public policies which were both generous and transient, and a failure to develop institutional structures for the industry as a whole. The industry manifested some of the most problematic features of American capitalism, with strategies being driven by pressures of financiers attracted by government incentives and tax-brakes, and mostly anxious to make a quick return in an industry which faced considerable technical challenges. In this respect, it was appropriate that the American industry ended up largely owned by a firm such as Enron.

Perhaps the most striking change over the last decade has been the change in the competitive landscape. Vestas remained the market leader, reflecting its home country’s deep expertise, the firm’s continued strengths in high-end technology, and its highly global presence. But the maturing of wind technology, the growth of capital-intensity, especially in offshore wind, and the rise in importance of large utilities and independent power producers as consumers of turbines, helped drive a transformation of the industrial structure which has seen the entry and rapid rise in market share of engineering powerhouses, such as GE and Siemens, and wholly or partly state-owned Chinese firms with low-cost bases. These are now prominent actors in an industry in which, in many countries, access to contracts depends on the industrial policies of, and political contacts in, host countries.

Appendix Table 1 Cumulative Installed Wind Power Capacity in Top Ten Countries 1980-2010 (in MW)

Year	U.S.	China	Germany	Spain	India	Italy	France	U.K.	Portugal	Denmark	World
1980	8	n.a.	0	0	0	0	0	0	n.a.	5	**13**
1985	945	n.a.	0	0	0	0	0	0	n.a.	50	**1,020**
1990	1,484	n.a.	62	0	0	0	0	0	n.a.	343	**1,930**
1995	1,612	38	1,130	140	576	32	3	200	n.a.	637	**4,780**
2000	2,578	346	6,113	2,235	1,220	427	66	406	100	2,417	**17,400**
2005	9,149	1,260	18,415	10,027	4,430	1,718	757	1,353	1,022	3,127	**59,091**
2010	40,287	42,287	27,214	20,676	13,065	5,797	5,660	5,024	3,702	3,752	**194,300**

Source: Global Wind Energy Council, Global Wind Energy Statistics 2010; compiled by Earth Policy Institute; Janet L. Sawin, "The Role of Government in the Development and Diffusion of Renewable Technologies: Wind Power in the United States, California, Denmark and Germany", Doctoral Dissertation, The Fletcher School of Law and Diplomacy, September 2001.

Appendix Table 2 Electricity Generation by Energy Source in Selected Countries at benchmark dates 1975-2008 (Thousands GW and % Share)

Country	Product	1975	1980	1990	2000	2008
U.S	Electricity Generated	1918	2286	3029	3816	4152
	Nuclear %	9.0	11.0	19.0	19.8	19.4
	Hydro %	15.6	12.1	9.4	7.2	6.7
	Geothermal %	0.2	0.2	0.5	0.4	0.4
	Solar %	0.0	0.0	0.0	0.0	0.1
	Wind %	0.0	0.0	0.1	0.1	1.3
	All Combustible Fuels%	75.2	76.7	70.9	72.5	72.1
Denmark	Electricity Generated	17	25	24	34	35
	Nuclear %	0.0	0.0	0.0	0.0	0.0
	Hydro %	0.1	0.2	0.1	0.1	0.1
	Geothermal %	0.0	0.0	0.0	0.0	0.0
	Solar %	0.0	0.0	0.0	0.0	0.0
	Wind %	0.0	0.0	2.5	12.3	19.7
	All Combustible Fuels%	99.9	99.8	97.4%	87.6	80.2

Germany	**Electricity Generated**	**360**	**437**	**509**	**538**	**599**
	Nuclear %	6.5	12.0	28.4	29.8	23.5
	Hydro %	5.0	4.6	3.8	4.8	4.4
	Geothermal %	0.0	0.0	0.0	0.0	0.0
	Solar %	0.0	0.0	0.0	0.0	0.7
	Wind %	0.0	0.0	0.0	1.7	6.8
	All Combustible Fuels%	88.5	83.4	67.8	63.7	64.6
Spain	**Electricity Generated**	**79**	**105**	**145**	**214**	**302**
	Nuclear %	9.2	4.7	35.9	27.9	18.7
	Hydro %	33.7	28.9	17.8	14.7	8.5
	Geothermal %	0.0	0.0	0.0	0.0	0.0
	Solar %	0.0	0.0	0.0	0.0	0.8
	Wind %	0.0	0.0	0.0	2.2	10.6
	All Combustible Fuels%	57.1	66.4	46.2	55.2	61.4
Portugal	**Electricity Generated**	**10**	**15**	**27**	**42**	**45**
	Nuclear %	0.0	0.0	0.0	0.0	0.0
	Hydro %	60.8	53.8	33.5	27.5	16.2
	Geothermal %	0.0	0.0	0.0	0.0	0.0
	Solar %	0.0	0.0	0.0	0.0	0.1
	Wind %	0.0	0.0	0.0	0.4	12.9
	All Combustible Fuels%	39.2	46.2	66.5	72.1	70.8
France	**Electricity Generated**	**179**	**247**	**401**	**517**	**550**
	Nuclear %	9.8	23.5	74.3	76.6	76.2
	Hydro %	33.4	28.2	14.1	13.7	12.3
	Geothermal %	0.0	0.0	0.0	0.0	0.0
	Solar %	0.0	0.0	0.0	0.0	0.0
	Wind %	0.0	0.0	0.0	0.0	1.0
	All Combustible Fuels%	56.8	48.3	11.5	9.7	10.5
Italy	**Electricity Generated**	**141**	**178**	**205**	**263**	**307**
	Nuclear %	2.6	1.2	0.0	0.0	0.0
	Hydro %	30.1	26.6	16.9	19.1	15.2
	Geothermal %	1.7	1.4	1.5	1.7	1.7
	Solar %	0.0	0.0	0.0	0.0	0.1
	Wind %	0.0	0.0	0.0	0.2	1.6
	All Combustible Fuels%	65.6	70.8	81.6	79.0	81.4
United Kingdom	**Electricity Generated**	**254**	**266**	**300**	**361**	**373**
	Nuclear %	10.4	12.1	19.5	21.7	12.8
	Hydro %	1.9	1.9	2.4	2.1	2.5

	Geothermal %	0.0	0.0	0.0	0.0	0.0
	Solar %	0.0	0.0	0.0	0.0	0.0
	Wind %	0.0	0.0	0.0	0.3	1.9
	All Combustible Fuels%	87.7	86.0	78.1	75.9	82.8
Japan	**Electricity Generated**	**456**	**552**	**810**	**1019**	**1040**
	Nuclear %	5.2	14.3	16.30	30.3	23.7
	Hydro %	18.7	16.5	19.4	9.5	7.9
	Geothermal %	0.0	0.0	0.10	0.3	0.2
	Solar %	0.0	0.0	0.00	0.0	0.2
	Wind %	0.0	0.0	0.00	0.0	0.3
	All Combustible Fuels%	76.1	69.2	64.2	59.9	67.7
China	**Electricity Generated**	**NA**	**NA**	**590**	**NA**	**3221**
	Nuclear %	NA	NA	0	NA	2.0
	Hydro %	NA	NA	21.2	NA	16.2
	Geothermal %	NA	NA	0	NA	0
	Solar %	NA	NA	0	NA	0
	Wind %	NA	NA	0	NA	0.5
	All Combustible Fuels%	NA	NA	78.8	NA	81.3
India	**Electricity Generated**	**NA**	**NA**	**275**	**NA**	**785**
	Nuclear %	NA	NA	2.0	NA	1.7
	Hydro %	NA	NA	25.8	NA	14.6
	Geothermal %	NA	NA	0	NA	0
	Solar %	NA	NA	0	NA	0
	Wind %	NA	NA	0	NA	1.6
	All Combustible Fuels%	NA	NA	72.2	NA	82.1

Source: OECD, *World Energy Outlook, 1999;2000; 2001;2002;2003;2004; 2010*, OECD. China and India data: IEA, International Energy Statistics, Electricity Generation by Source 2008.

Appendix Table 3 Largest Wind Turbine Manufactures by Benchmark Dates

Table 3.1 1945

Jacobs Wind (US)

Lykkegaard Ltd. (Denmark)

F. L. Smidth & Co (Denmark)

Source: Author estimate

Table 3.2 Largest Wind Turbine Manufacturers by Cumulative Installed Capacity (%) 1988

US Windpower (US) 26.1

Vestas (Denmark) 13.2

Fayette (US) 11.0

Micon (Denmark) 11.0

Flovin (US) 7.1

Bonus (Denmark) 6.3

Nordtank (Denmark) 5.2

Danwin (Denmark) 4.0

HMZ (Netherlands) 3.0

Howden (Great Britain) 2.3

ESI (US) 1.8

Mitsubishi (Japan) 1

Table 3.3 Largest Companies by % Cumulative Installed Capacity 1996.

Vestas (Denmark) 20.6

US Windpower (US) 11.1

Micon (Denmark) 8.4

Enercon (Germany) 8.0

Bonus (Denmark) 7.3

Nordtank (Denmark) 6.8

Tacke (Germany) 4.5

NEPC (India) 4.2

Mitsubishi (Japan) 3.2

Windworld (Denmark) 2.9

Nedwind (Neths) 2.4

Windmaster (Belgium) 2.2.

Source for Tables 3.2 and Table 3.3: Peter Karnoe, *Dansk Vindmølleindustri – en overaskende international success* (Copenhagen: Samfundslitteratur, 1991), p.29; Peter Karnoe, "When Low-tech becomes High-tech; The Social Construction of Technological Learning Processes in the Danish and the American Wind Turbine Industry", in Peter Karnoe, Peer Hull Krisensen and Poul Houman Andersen (eds), *Mobilizing Resources and Generating Competencies* (Copenhagen: Copenhagen Business School Press, 1999), pp.184-5.

Table 3.4 Leading Wind Turbine Manufacturers in 2010 (%)

1. Vestas (Denmark) 14.8
2. Sinovel (China) 11.1
3. GE Wind Energy (US) 9.6
4. Goldwind(China) 9.5
5. Enercon (Germany) 7.2
6. Suzlon (India) 6.9
7. Dongfang Electric (China) 6.7
8. Gamesa (Spain) 6.6
9. Siemens Wind Power (Germany) 5.9
10. Guodian United (China) 4.2

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Appendix 4 Jacobs Wind Electric Company Pricing for Model Super Automatic Wind Electric Plants (Turbines and Towers), 1947.

Model	Capacity	Price	In 2011 prices
Turbine Model 45	300 KWh/month, 32 volt Plant	$595	$5,962
Turbine Model 60	400 KWh/month, 32 Volt Plant	$695	$6,964
Turbine Model 60 B	400KWh/month, 110 volt plant	$795	$7,966
Steel Tower	48 ft	$135	$1,352
Steel Tower	80 ft	$312	$ 3,126

Source: Jacobs Archives, Minnetonka, Minnesota.

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