NEW PATH CREATION: AN EVOLUTIONARY PERSPECTIVE ON THE EMERGENCE OF THE WIND POWER INDUSTRY

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Abstract

In this paper it is argued that, if the evolutionary economics approach of path dependence is adopted to provide an explanation of technological change, it is necessary to explain how new economic pathways are created in the first instance. The explanation developed is that new economic pathways are created by the introduction of innovations in economic niches where the barriers to overcoming the dominant techno-economic paradigms are absent or reduced. They are created by the mindful deviation of specific agents such as entrepreneurs, corporations or users. In order to reach a critical mass that would constitute a new economic pathway they also need to diffuse to a degree where discontinuities take place both in their particular sectors and in the wider economy.

Introduction: The evolutionary turn in economic theory

Over the last two decades or so a growing dissatisfaction with some of the underlying assumptions of neo-classical economics, such as those of the hypothetical existence of rational average actors whose actions drive aggregate economies towards equilibrium, has led to an evolutionary turn in economic theory. Inspired by the work of the Austrian economist Joseph Schumpeter (1939, 1942) a number of distinguished economists such as Nelson and Winter (1982), Dosi et al (1988), Hodgson (1993), Arthur et al (1997), Foster (1997), Metcalf (1998), Potts (2000), Fagerberg (2003), Dopfer (2004), Metcalf and Foster (2004) and Witt (2003), have sought to understand how real economies evolve through time. Neo-Schumpeterian theories concerning the role of technological innovation in driving economic evolution have been prominent in explanations of such evolution (Dosi et al 1998, Witt 1993, Metcalf 1998). Between them they have studied technological innovation at the company level, competition, diffusion and structural change at the levels of markets and sectors, and growth, long waves and international trade at the macro level. Studies such as these have established the value of adopting an evolutionary perspective to understand the historical growth and change of real as opposed to hypothetical economies.

As this is still an emerging approach in economic theory there is, as yet, no settled view on which elements of evolutionary theory should be the standard analytical tools of analysis. So far, at least four main approaches to analysing economic change and innovation have been developed. These are the Darwinian inspired biological analogy and the notion of the co-evolution of institutions with economic change; complex adaptive systems theory; panarchy and path dependence theory.

This paper adopts the theoretical approach of the last of these four alternatives. In particular it seeks to address the question “How are new technological and industrial pathways created in the first instance?”

Following this introduction the next section examines the conceptual framework of path dependence and develops a theoretical framework for explaining how new technological pathways are created in the first instance. To date, much of the literature around evolutionary economic geography has focused on the geography rather than the economics of new path development. For example, Arthur (1989) and Klepper (2001, 2002) explore the geography of new path creation, but do not examine the necessary pre-conditions for the pre-formation phase that precedes or the economics of the initial creation of new economic pathways. This paper aims to redress that balance, by focusing more sharply on the economics rather than the geography of new path creation.

The constraining forces of increasing returns and contemporary paradigms that lead to path dependence are outlined. It is argued that, in the context of these parameters new technological pathways are created by innovation. The introduction of innovation has to overcome the conventional wisdoms of the dominant technological and techno-economic paradigms. Niche economic conditions and markets provide the necessary but not sufficient conditions for this to happen. In addition human agency and decision making are required to mindfully deviate from the existing paradigms. Such human agents are located in particular places and so detailed historical analysis can uncover the reasons why new economic pathways have been created in those localities. A further requirement is that innovation diffusion is sufficient to reach a critical mass sufficient to be able to claim that a new industry has been created. This also requires agency in the form of diffusion agents or collective public action. The rate and nature of early diffusion also determines the spatial location of new economic pathways.

A third section looks briefly at the methodology required to explore the arguments developed in the theoretical section. Here it is argued that detailed historical analyses are required in order to explain how specific new economic pathways are created.

The fourth section is divided into two parts. The first evaluates the theoretical arguments by conducting a detailed historical analysis of the creation of the direct current (DC) generating windmill industry in rural areas in Europe and the United States. The second part analyses the creation of the alternating current (AC) wind turbine industry in Denmark and California.

A final section draws these arguments and the historical evidence together. It evaluates the validity of the theoretical arguments as illustrated by the history of new path creation in the wind power industry.

Increasing returns, paradigms and path dependence

Joseph Schumpeter was one of the first economists to suggest an explanation for the periodic rounds of rapid change and development seen in the historical evolution of economies (Schumpeter 1939). He famously referred to such major changes as "gales of creative destruction". He argued that such changes are driven by the introduction of radical new technologies, the development of new industries and methods of production. They also lead to changes in political regulation, social structure and institutional arrangements. His work has inspired distinctive approaches to the analysis of change in capitalist economic systems.

Schumpeter argued that innovation is the key driving mechanism for generating commercialised technological and economic novelty. It is therefore argued here that it forms the essential basis for the creation of new economic pathways. Innovation is defined in the Oslo Manual as "The implementation of a new or significantly improved product (good or service), or process, a new marketing method, or a new organisational method in business practices, workplace organisation or external relations" (OECD 2005, p. 46).

Neo-Schumpeterians such as Dosi (1982) and Perez (1983) set about developing an evolutionary approach to understanding both continuity and change in economies. They argued that the processes of structural change and increasing productivity can be understood as driven by identifiable technical change and its subsequent diffusion in successive technological revolutions. Furthermore, they also argued that the introduction and diffusion of technical change is not a random phenomenon but is a path dependent process in which individual innovations are interdependent with others and grouped in to what Schumpeter had described as "clusters" of innovations.

One branch of research in this tradition has focused on the dynamics of the diffusion of new technologies (David 1985, Arthur 1989). In these studies it is argued that there is an inherent tendency towards technological “lock-in”. David’s work on the economic history of technology established the argument that the economy is built on the legacy of its own past. In this view economic history is seen as an irreversible process in which future outcomes are strongly dependent on past events. As a result the state of an economy at any point in time depends on the historical pathways taken up until then (Martin and Sunley 2006). In this view contemporary conditions are the result of a complex series of histories of how a particular set of outcomes have become what they are. These sets of past events have produced the pathways taken to the present by effectively closing off some possibilities and pursuing others. The present, however, controls which possibilities will be explored in the future.

Arthur (1994) argues that one of the main reasons for the path-dependent nature of the diffusion of technological innovation is increasing returns. This means that profits increase as production expands gaining competitive advantages for those technologies and firms that are already ahead and making it more difficult for other technologies and companies to catch up.

A second branch has focused on the concept of paradigms to explain the path dependent nature of the diffusion of technological innovations. Dosi (1982), building on the Kuhnian concept of scientific paradigms (Kuhn 1962), argued that technologies develop and diffuse along trajectories that are path dependent because of the influence of the technological paradigms within which they are developed. Such paradigms are the prevailing models for the solution of techno-economic problems (Markard and Truffer 2006). They may be defined as “a collectively shared logic at the convergence of technological potential, relative costs, market acceptance and functional coherence” (Perez 2010, p. 186).

For Dosi a technological paradigm involves a specific set of heuristics and visions on how to do things and how to improve them. They represent the conventional wisdom of the relevant community of practioners and their collectively shared cognitive frames (Dosi and Grazzi 2010). The development pathways of new technologies proceed along trajectories that are shaped and constrained by the paradigms within which they have been inaugurated. This is a path dependent process because the rate and direction of technical change are limited by the currently acceptable cognitive frameworks within any given technological paradigm.

Since Dosi's (1982) seminal contribution the concept of a strictly technological paradigm has been expanded by Perez (1983), Kemp et al (1998) and Geels (2004). Perez argues that radical technological innovations affect not only the industries in which they emerge but also diffuse to other sectors. In this way they can instigate change in the wider economy. She uses the concept of the techno-economic paradigm to describe these wider effects. For Perez, a techno-economic paradigm is "a best practice model for the most effective ways of using the new technologies within and beyond the new industries" (Perez 2010, p. 189).

The effects of technological and techno-economic paradigms influence strongly the trajectories of the individual technologies they contain and their diffusion through the wider economy. In addition, as those technologies diffuse through the economy, they also spread shared conventional wisdoms for decision making from their original industries and influence expectations, conventions and social institutions in the wider economy.

This expansion of the idea of purely technical paradigms to embrace their effects on decision making in the wider economy and society was taken a step further by Kemp et al (1998) with the concept of a technological regime. This may be defined as "the rule-set or grammar embedded in a complex of engineering practices, production processes, technologies, product characteristics, skills and procedures, ways of handling relevant artefacts and persons, ways of defining problems; all of them embedded in institutions and infrastructures" (Geels 2004, p. 903). As such, a technological regime consists of a powerful set of interlinked conventional wisdoms and practices that set the parameters of variation of innovating firms, research institutes and market rules within the wider society. Much like the previous concepts of technological and techno-economic paradigms before them it is argued that the path dependent trajectories of innovations are a function of the boundaries of the cognitive frameworks of the communities of practice engaged in their development.

Thus, studies starting from an evolutionary perspective that have analysed the historical development of technological innovations have concluded that they have followed path dependent development trajectories. The two main reasons for this have been argued to be the economic incentives of increasing returns and the bounded rationality imparted by technological paradigms. What these studies have not done so far, however, is to explain satisfactorily how radical change and gales of creative destruction are instigated given these powerful forces driving the existing directions of travel along particular trajectories. It is therefore important for this branch of evolutionary theory to have some explanation of how such changes are instigated and why and how new pathways are created in the first instance in order to lead into explanations of how their subsequent growth and development becomes path dependent. As Martin and Sunley put it “To be truly evolutionary, path dependent systems also need mechanisms that generate novelty and hence new pathways of development” (Martin and Sunley 2006, p.407).

It is argued in this paper that the creation and evolution of new economic pathways is driven, in the first instance by the introduction of innovations. Within the context of the evolutionary analyses of the constraining roles of technological paradigms reviewed above, therefore, the first major problem confronting the introduction of innovations and the creation of new economic pathways is how to get started in the context of the dominant techno-economic paradigm and its established network externalities, technologies, products and services (Markard and Truffer 2006). Some scholars of the sociology of technology and evolutionary economics argue that “niches” are required within or outside of existing knowledge structures and networks in order to make such a break (Geels 2004).

A niche may be defined as an application context in which the new product or technology is temporarily protected from the standards and selection rules of the prevailing paradigm (Kemp et al 1998, Hoogma et al 2002, Markard and Truffer 2006). Niches provide space for novelties to incubate without being subjected to prevailing competitive market pressures or the normal selection criteria that accompany the dominant techno-economic paradigm. The informal rules of niche environments are less articulated and subject to higher degrees of uncertainty than those of the established paradigms (Geels 2004). In niche conditions it is also possible to draw on new local or international knowledge in order to develop new business networks, value chains and user-producer relationships.

The first argument advanced in this paper is therefore that *a key requirement for the creation of a new economic pathway is an economic niche where the dominant networked techno-economic paradigm of the time is weak or not present*. Such niches may not be subject to “normal” competitive pressures.

While niche environments provide opportunities for innovations to be introduced, they do not of themselves create innovations. Those are introduced as a result of interactions between economic actors, policy makers and the users of innovations or their results. It is therefore necessary to have theory of agency that explains how specific actors create and introduce innovations in niche environments.

A group of scholars, based mainly in business schools, have focused on the issue of human agency in new path creation (Stack and Gartland 2003). Prominent among these theorists have been Garud and Karnøe (2001). They argue that any theory of new path creation should attach a significant role to the importance of strategic agency and the considered “mindful deviation” of entrepreneurs from established paths. Puffert (2000) goes further in arguing that the very existence of established pathways may make actors more eager and motivated to attempt to make their new technologies and ways of doing things the basis of new pathways.

Garud and Karnøe argue that entrepreneurs of various kinds create new pathways as they navigate the current flow of events in “real time” and seek to set new processes in motion by “mindful deviation” (Garud and Karnøe 2001, p.2). The two ideas “real time influence” and “mindful deviation” distinguish the explanation of new path creation from those of subsequent path dependency.

The second argument advanced in this paper is therefore that *a further key requirement for the creation of a new economic pathway is human agency and decision making*. Such agents may be individual innovators and entrepreneurs, large corporations, public policy makers or users. These agents may introduce innovations in niches in a variety of ways. These include inventions, starting up new firms, diversification from large existing companies, public policies and regulations or trial and error by users (Kivamaa et al 2010).

One innovation, however radical, does not make a new economic pathway. Changes occur slowly at first while producers, designers, distributors and consumers engage in feedback and learning processes (Perez 2010). This is usually a cumulative process and critical mass builds up over time as clusters of innovations emerge in new economic sectors. This process is preceded by sometimes quite lengthy periods of individual inventions. After the accumulation of relevant inventions entrepreneurs begin to take up these new ideas and commercialise them as innovations

Eventually, in the case of successful innovations, a critical mass is reached where, in the face of existing network externalities, sufficient economic agents are prepared to switch to the new alternatives (Witt 1997). Critical mass is a well known phenomenon in non-linear dynamic systems (Lorenz 1993). It may be defined as a point of discontinuity that induces a dramatic turn away from an existing system (Witt 1997). Existing technological paradigms and network externalities always favour the existing and widely used product variants. For this reason success in the creation of new economic pathways comes down to the prerequisite to pass a critical mass (Witt 1997).

The diffusion of innovations is the key process that spreads their use from the original niche conditions to the point at which critical mass is achieved and a new economic pathway is created that represents a significant discontinuity with the existing paradigm or system. In contemporary economies, as with the introduction of an innovation, diffusion also requires agents. The roles of diffusion agents have a long pedigree in the diffusion literature (Brown 1981, Rogers 1995). Thus, when a major innovation is introduced commercial marketing agencies or in-house people are often given the task of promoting them and triggering a diffusion process (Witt 1997).

It has also been argued that external drivers are required in contemporary economies for the more radical technological innovations to diffuse (Kivamaa et al 2010). The transition from one economic pathway to another may well need to be organised by collective action. This is because setting the diffusion process in motion is like providing a public good. Without collective action, the early adopters would have to bear the initial network diseconomies while later adopters would profit from the investments of the early adopters (Witt 1997).

It is therefore argued in this paper that a third key requirement for the creation of a new economic pathway is *the diffusion of innovations to the point at which they reach a critical mass and a tipping point is reached between continuation with the existing techno-economic paradigm and the adoption of a new one.* Like innovation itself, this requires agency. In this instance the actors are different from those responsible for innovation. They may be concerned with the marketing of the new product or service. They may also be public policy makers driving the co-ordinated adoption of a new technology.

Methodology

In the course of his seminal analysis of "The Sources of Innovation" Eric von Hippel (1988) generated six detailed innovation histories of specific technologies using multiple sources of primary information. This technique provides more insights into the long-term evolution of innovations and the creation of new industries than can be gleaned from the statistical analysis of secondary datasets. It is therefore argued in this paper that the analysis of the three key propositions outlined above requires detailed histories of the introduction and diffusion of innovations. These histories should provide evidence on the dominant techno-economic paradigm leading up to the time they were introduced and the characteristics of the niches where they were weak enough to allow the introduction of contradictory practices and innovations. The detailed histories should identify the pioneers of whatever type who first introduced innovations and how and where they were able to do so. Finally, the analysis should examine the diffusion and its agents that led an innovation to the point at which it could be said that it achieved a critical mass and a new economic pathway was created.

Climate change and global warming is one of the most critical policy issues of this century. There is a widely acknowledge need to change the contemporary fossil fuel based energy regime, reduce CO_2 emissions and transition to a more sustainable technological regime. Clean energy technologies have a crucial role to play in such a transition but progress to date has not been fast enough to overcome rising levels of emissions. It is therefore important to understand how innovations in clean energy technologies are introduced and diffused through economies. For this reason wind power is selected for analysis in this paper in order to illustrate new path creation in the context of an identifiable techno-economic paradigm with important policy implications.

A recent book by Peter Musgrove (2010) provides a detailed history of technological developments for the use of wind power from its possible introduction as early as the seventh century, in what was then Persia, to contemporary offshore wind farms in Europe and the USA. Much of the information in the analysis that follows has been mined and re-interpreted from this comprehensive source. The creation of two new pathways using wind power to generate electricity is analysed. The first is the early use of wind power to generate DC in rural areas. The second analyses the start of the modern wind turbine industry.

New path creation 1- DC electricity generating windmills in rural areas

Emergence of the dominant techno-economic paradigm

The late 19th century saw rapid progress in electrical engineering that resulted in electricity being turned from a scientific curiosity into an essential prerequisite of modern life. It was an important driver of the second industrial revolution that took place roughly between 1820 and 1914. During that time a dominant techno-economic paradigm emerged for the generation, distribution and sale of electricity to intermediate and final consumers. This paradigm was based on the centralised generation of alternating current (AC) electricity by the use of mainly coal and later oil fired power stations. It also involved the establishment of a grid network for its distribution to consumers.

Innovation in DC windmills

Initially this techno-economic paradigm did not apply much beyond urban areas. This left a significant niche in rural areas that were not connected to grid supplied AC electricity. As a result innovations in the generation of electricity using wind power were first developed and used in rural areas. There they were used to produce direct current (DC) electricity powering batteries. This type of current cannot be grid connected.

Early inventions had little impact on the supply of electricity. The first inventor to produce DC electricity using wind power was Professor James Blyth of Anderson's College, Glasgow. In 1887 he built and tested a traditional smock design windmill to supply electricity to his holiday cottage in Maykirk, a small village north-east of Dundee. Later he also invented the first vertical axis configuration windmill shown with the inventor in Figure 1. This required a force 8 gale to generate around 3 kW of electricity! His innovations were not developed elsewhere in Scotland.

In 1925 George Darieus, a French engineer, independently invented the modern vertical axis wind turbine. This was a much more sophisticated and efficient machine than that invented by James Blyth. But the Darrieus invention was also not taken up in his day. Eventually, however, it was rediscovered in the early 1970s by Raj Rangi and Peter South working in the Canadian National Research Council laboratories in Ottawa. As we shall see later it then inspired one of the few indigenous American successes in the design and manufacture of wind turbines during the Californian boom of the 1980s.

Figure 1.

These early inventions did not lead directly to the creation of a new industry generating electricity from wind power. Instead the most influential pioneer in this respect was the Dane Poul la Cour. He wanted to bring the benefits of electricity to people living in the countryside. He managed to secure funding from the Danish government to build his first windmill in Askov east of Esbjerg in 1891. These were also smock type mills with fantails to point them in to the wind and self-reefing shuttered sails. His first two windmills are shown in Figure 2.

Variations in the turning speeds of windmills due to fluctuations in wind speeds caused problems with battery storage due to the resulting variations in the dynamo's output. In 1891 la Cour also invented a device called a "kratostat" to smooth out these power fluctuations.

Figure 2

Diffusion agents

La Cour also contributed to the diffusion of these initial innovations. In 1903 he founded a Society of Wind Electricians that ran courses for electricians in rural areas and helped to establish rural power stations in Denmark. By the time he died in 1908 la Cour had been involved in the development of some 32 rural power stations all of which used wind power for the generation of at least part of their energy supply. Taken together the la Cour innovations and their diffusion may be seen as creating, de novo, a new small industry for the generation of DC electricity in rural areas using wind power. This new industry was not diversified out of any related industry. It also laid the foundations for the creation of a new industry that, in the late twentieth century, has developed into the Danish dominance of the design and manufacture of electricity generating wind turbines.

During the inter-war years in Denmark a small Danish company made further incremental innovations in electricity generating windmills. They used new knowledge developed in the design of aircraft wings in the aeroplane industry to improve the blade design of windmills. They were the first company to use metal-covered blades that had a streamlined, aerofiol cross-section. This is the first example of new knowledge being imported from another new industry into the design of windmills.

During this period wind powered generators began to diffuse slowly in Danish rural areas. One of the significant diffusion agents was the Lykkegaard Company. They made and installed around 20 machines before the Second World War. An example of these machines is shown in Figure 3.

Figure 3

An additional niche emerged for their machines after the war in Danish rural areas. At this time restrictions were imposed on Danish diesel fuel imports. This lack of fuel for diesel generators led to a new wave of interest in electricity generating windmills. As a result the Lykkegaard company made and installed around 60 of their four bladed windmills in the early 1940s.

A second example of the influence of the aeroplane industry on windmill design also emerged during the inter-war period in the American plains. There a combination of the lack of grid connections in rural areas and the start of regular radio broadcasts for entertainment in 1920 from Kripps's station WWJ in Detroit and the Westinghouse KDKA in Pittsburgh, led to the emergence of a niche market for electricity. This was met in the first instance by Marcellus Jacobs who produced expensive but reliable DC generating windmills (Figure 4). In this instance the three bladed rotors were inspired by the embryonic aeroplane industry. They were made of spruce with an aerofiol cross-section similar to aeroplane propellers of the time. The power output was controlled by varying the blade pitch using a centrifugal governor.

Figure 4

This innovation was diffused as several manufacturers developed such windmills to meet market demand in rural areas where mains electricity was not available. Jacobs and another firm, Wincharger, were the most successful of these firms. The new industry took off in the 1930s and tens of thousands of DC electricity generating windmills were sold in the US before the Second World War. This was the first example of a competitive mass market for electricity generating windmills.

A third example of the transfer of knowledge from different sectors into the design and manufacture of windmills is provided by the activities of the Danish engineering company F.L.Smidth & Co. They started to address the competitive limitations of the restricted power output from small windmills and constructed a few larger ones in

1941. They owned two subsidiary companies. One made small aeroplanes. Its knowledge of propeller design was transferred to and influenced the design of the rotors required by the larger Smidth windmills. The result was that the latter had aerofoil section blades, made with flexible laminated wooden spars and covered with a plywood or metal skin.

A second Smidth subsidiary specialised in concrete chimneys and grain silos. As a result most of the Smidth windmills were built not on metal latice towers as was the custom until then but on concrete towers as in Figure 5. These marked the high point of the development of DC windmills. During the 1940s innovators turned their attention to wind turbines generating AC electricity.

Figure 5

New path creation 2- paradigm shock and AC grid connected wind turbines

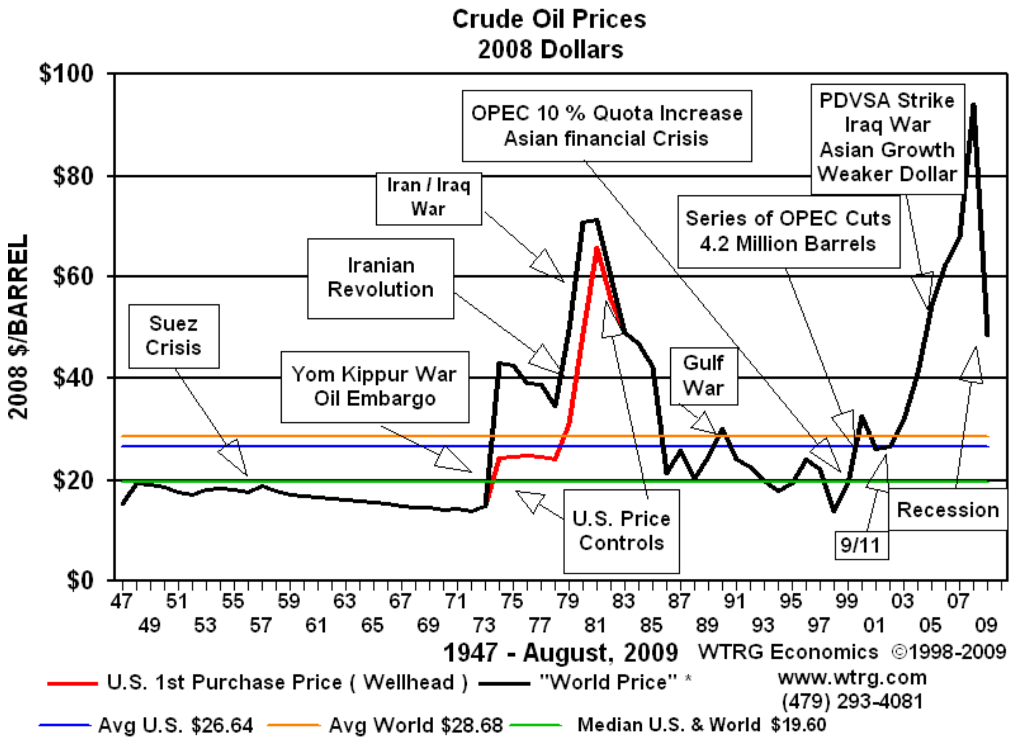
Paradigm shock

Despite the intellectual and practical dominance of the centrally generated and grid network distribution of electricity techno-economic paradigm from the nineteenth century onwards, some doubts were already being cast over its economic viability as early as 1881. In that year Sir William Thomson, in an address to the British Association in York, argued that there were limits to the supply of fossil fuels and that as consumption increased they would become more expensive. At that time he also suggested that wind power might be used to generate electricity (Musgrove 2010, p. 58). A similar view was expressed by Golding (1955) in a book entitled “The Generation of Electricity by Wind Power”. He pointed out that fossil fuels were being used up at an alarming rate.

As the War years receded, however, the dominant paradigm was reinforced by the widespread belief that cheap oil would be available for the forseable future and that nuclear power would provide an additional source of cheap energy. This was exemplified in 1954 in a speech by Lewis Strauss, the Chairman of the US Atomic Energy Commission, when he asserted that “our children will enjoy in their homes electrical energy too cheap to meter” (Musgrove 2010, p. 86).

The cheap oil underpinnings of this paradigm received a severe shock in 1973. Following the Yom Kipur War the price of oil doubled. It then fell back a little but doubled again following the Iranian Revolution and the Iran/Iraq war (Figure 6). These shocks challenged the dominant techno-economic paradigm and sparked widespread debates about how reliable and economic electricity should be supplied in the future. These debates provided inspiration and added impetus for the development of an alternative renewables based techno-economic paradigm for the generation of electricity that challenged the dominant centralised and fossil fuel based paradigm.

Figure 6. Oil price shocks 1947 to 2009



Source: WTRG Economics, London

Government created niche markets

As a result of this several governments introduced legislation that created frameworks that led to the emergence of niche economic environments for wind powered generation of electricity. A number of governments also embarked on programmes of research and development to produce radical innovations in the scale of wind turbine technologies to meet this demand.

Two of the most significant niche environments for wind turbines were created respectively by the Danish national and Californian State Governments. In 1979 the Danish parliament passed legislation that provided wind turbine purchasers with a 30% subsidy as long as the turbine was of an approved type. In addition, in the late 1970s, the connection of small AC turbines to the national grid in Denmark was formalised by Danske Elvaerkers Forening (Danish Association of Electricity Supply Undertakings). This allowed anyone with an approved wind turbine to connect to the national grid and to receive payments for any surplus electricity they supplied to the network. These niche market conditions were further extended with legislation that allowed individuals who had shares in co-operatively owned turbines in or near where they lived, to pay no tax on the income from electricity sales up to about nine thousand kWh. This together with the 30% capital subsidy made well sited and maintained wind turbines an attractive financial investment for local individuals and co-operatives.

Niche markets for indigenous renewable energy sources were also created in the USA. At the Federal level the Carter administration passed the Public Utilities Regulatory Policy Act (PURPA) in 1978. This required utilities to buy electricity from “qualifying facilities” (QFs) at a price that fully reflected the utilities’ avoided costs. These included both the capital and the running costs avoided by the utilities. QFs were defined as any that produced electricity from biomass or renewable energy sources.

In addition to this Federal requirement earlier legislation had also allowed a 10% tax credit for capital investment in any manufacturing sector. After the overthrow of the Shah of Iran in 1979 a supplementary tax credit of 15% was also allowed from 1980 for all energy related capital investments made before the end of 1985.

In California the Public Utilities Commission (PUC) set the rate for the level of avoided costs at which utility companies had to purchase electricity from renewable energy sources. This was set at the high end of such decisions around the country at about 7 cents per kWh.

The niche market for renewable energy sources was further strengthened by Governor Jerry Brown. He passed legislation that gave a 25% tax credit for all solar and wind energy investments made before the end of 1986. The tax credits totalling 50% for capital investment combined with the certainty that electricity generated from solar and wind sources could be sold to utilities at a favourable price created a niche demand for wind turbines among rich, high tax paying individual Californians.

Innovations in AC wind turbines

The ability to meet this demand and supply AC power to local or national electricity grid networks required further innovations in addition to those developed by the early pioneers of DC generating windmills. The first wind turbine designed to supply AC power to the grid was constructed in 1931 at Balaclava on the north coast of the Black Sea (Figure 7). On the one hand it showed its antecedents in the traditional European post mill as it was turned to face the wind using the lattice descending from the nacelle to a track on the ground. On the other hand it was similar to later turbines in being grid connected via speed-increasing gearing and an induction generator housed in a nacelle at the top of the tower. Although it predated the first Danish wind turbine to produce grid connected AC electricity by some 20 years this invention does not appear to have had much influence on subsequent innovations in wind turbines.

Figure 7: First AC grid connected wind turbine

In Denmark early innovations in AC wind turbines were partly inspired within a local minority culture of enthusiasm for wind power. This developed in the context of concern with the uncertainty of fuel imports after the Second World War. Johannes Juul was one of the pioneer innovators. He was a student of Poul la Cour and managed to persuade the Danish utility SEAS to fund a research and development programme to produce electricity using wind power. As a result of this programme the first Danish wind turbine was built in 1950 at Vester Egesborg on the south west coast of Zealand. It was grid-connected using an induction generator and was left in service for a decade.

The successful operation of Juul's experimental turbines enabled him to secure funding from the Danish government to construct a larger model in 1957 at Gedser about 130 km south of Copenhagen (Figure 8). This has been in continual unattended operation since 1958.

Figure 8. First successful 200 kW AC wind turbine

One of the key technological problems confronting the designers of the first DC windmills and AC turbines was how to control the speed of the rotors in high winds. Innovators found two answers to this problem. The first was to have fixed blades that stalled automatically once wind speeds exceeded a certain level. At this point they then stopped generating electricity. In order to overcome both the windspeed and the variable generation problems automatic variable pitch rotor blades were required. Ulrich Hutter was one of the first pioneer innovators to solve this problem reliably. In 1958 he designed and built a 35 m, 100kW rated wind turbine at Strotton, Germany (Figure 9). This machine was innovative in two ways. First it had variable pitch blades and secondly they were, for the first time made of fibreglass.

Figure 9. First wind turbine with variable pitch fibreglass blades

These early incremental innovations gradually increased the power output of wind turbines. But none of them could generate more than 200 kW of electricity. At this level of productivity they could not compete in the markets outside their various niches. It became clear that power outputs in excess of 1 MW would be needed to make wind turbines economically competitive with other sources of energy at "normal" prices. During the 1950s, 60s, 70s and 80s various government wind power programmes were introduced to make step innovation changes to the output of wind turbines. Such governments included the UK, France, USA, Denmark, Germany and Sweden. They contracted such household names as John Brown, de Havilland, NASA, Westinghouse, General Electric, Boeing and Messerschmitt-Bolkow-Blohm to design and build much larger and higher output wind turbines than had been developed by the first individual pioneer innovators. The American Federal Wind Power Programme alone spent some $350 million in an attempt to produce such radical innovations. All these programmes, with the exception of the more incremental Danish approach, were expensive failures.

These government sponsored failures make the success of the Tvind teacher group in Denmark in designing and building the first reliable 1 MW wind turbine all the more remarkable (Figure 10). The Tvind teacher group did not accept that nuclear power was an acceptable addition to the dominant fossil fuel based techno-economic paradigm for the generation of electricity. As a result they set about demonstrating that wind power could provide electricity on a scale and at a price acceptable to electricity utility companies. They were led by pioneer innovator Amdi Peterson. To keep costs down they purchased a second hand generator and gearbox originally used on a mine hoist. A low speed shaft was bought second hand from a shipyard. Volunteers built the concrete tower. They went to Stuttgart to learn from Ulrich Hutter how to make variable pitch fibreglass blades. The grid was supplied via a rectifier converter that was purpose built for the turbine by students from the technical University of Denmark supervised by Ulrik Krabbe. The wind turbine was completed in 1978 and remains in operation in 2010. It laid the foundation through which Danish wind turbines have become commercially pre-eminent in world markets.

As the new wind turbine industry was being created in Denmark, some pioneer innovators began to specialise in their components. One such innovator was Erik Grove-Nielsen. In 1977 he set up a company called Økaer Vind Energi that specialised in the manufacture of fibreglass blades. Subsequent incremental innovations in the design and technology of these important components then made them the blades of choice by other wind turbine manufacturers.

Figure 10. First reliable 1 MW grid connected AC wind turbine

One of the few relatively successful innovations to come out of the American Federal Wind Power programme was stimulated by the rediscovery of the Georges Darrieus invention of a vertical axis wind turbine. This was first rediscovered in the late 1960s by Raj Rangi and Pete South working in the National research Council laboratories in Ottawa. In the USA work on Darrieus wind turbines was centred in the Sandia National laboratories in New Mexico (Figure 11).

Diffusion agents and critical mass

The diffusion of the pioneer innovations by la Cour and Juul to create a new industrial pathway in Denmark required a combination of diffusion agents and niche home markets. The main diffusion agents were agricultural machinery manufacturers. The incremental innovations made by the early pioneers and subsequently by wind enthusiasts demonstrated the practicality of generating grid connected AC electricity using wind turbines. Danish agricultural machinery manufacturers saw a market opportunity to diversify their product ranges. Their long experience of engineering robust and reliable agricultural equipment made Danish wind turbines as reliable as was possible for an entirely new product.

Figure 11. Darrieus vertical axis wind turbine

One of the first diffusion agents to diversify in this way was Vestas. In the 1970s it was a leading Danish manufacturer of mobile cranes and agricultural equipment employing about 100 people. It diversified by buying the manufacturing rights to the successful HVK wind turbine developed by Karl Erik Jorgensen and Henrik Stiesdal (Figure 12). Production started in 1979. The firm is now the largest producer of wind turbines in the world with over 13,000 employees in 2007 (Musgrove 2010, p. 107).

By 1980 the new wind turbine manufacturing pathway had been created in Denmark. At that time there were a dozen manufacturers producing grid connected AC wind turbines with rotors ranging from 5 to 15 metres producing 5kW to 55kW of electricity. Further incremental innovations increased their efficiency throughout the 1980s. This increase in productivity was sufficient to compensate for the removal of the Danish government’s 30% capital purchase subsidy in 1989.

Figure 12. The first Vestas HVK wind turbine

Farmers continued to provide the first niche market for wind turbines in Denmark. They would use about 40% of the electricity generated on the farm themselves and sell the surplus back through the grid to the electricity company. Other individuals and co-operatives also purchased turbines for their own use and to sell electricity back through the grid. These purchases by local final consumers helped with the general acceptance of the introduction and diffusion of wind turbines by local communities. Unlike in the UK few problems were experienced in Denmark in obtaining planning permission for their construction.

As a result there was a steady home market for wind turbines in Denmark throughout the 1980s. During the decade steady sales of around 140 units per year were made in this home market. The most successful diffusion agents were companies that diversified out of the manufacture of agricultural equipment. These included Vestas, Bonus, Micon and Nordtank. They were accustomed to dealing with farmers and their requirement for equipment that was both robust and easy to maintain.

The most dynamic new niche market for wind turbines, however, was created at the beginning of the 1980s in California by a combination of:

- The Carter Public Utilities Regulatory Policy Act 1978 (PURPA), Federal tax credits of 25% for manufacturing and energy related capital investments made before the end of 1985.
- The Californian Public Utilities Commission (PUC) high set rate for utilities' purchase of electricity from renewable energy sources of about 7 cents per kWh.
- The Jerry Brown tax credit of 25% for all solar and wind energy investments made before the end of 1986.

These government concessions created a boom market in California that started in 1981 and expired in 1986 as the Californian State tax incentives were withdrawn and the price of oil slumped back to not far short of what it had been before the Yom Kippur War of 1973. Nevertheless, during this period more than 12,000 wind turbines were installed in California.

American manufacturers were not able to meet this surge in demand as the new wind turbine pathway accelerated to critical mass in California. The main reason for this was that most American manufacturers could not produce as robust and reliable machines as the Danes. US Windpower was a notable exception to this rule. This company pioneered the organisational innovation of wind farms. They developed the first one consisting of only 20 machines in New Hampshire in 1980. They recognised the market opportunities afforded by the tax credits available in California. As a result they leased large tracts of land in the Altamont Pass some 60 kms east of San Francisco. They secured zoning approval, contracted with the local utility company for grid connection and installed 100 of their machines in 1981 (Figure 13).

In order to supply this new market US Windpower moved the manufacture of their turbines from New England to the Altamont Pass. As a result a new manufacturing pathway was created de novo in this location. The company, however, used all its production to supply its own wind farms. It did not sell to other developers. This provided market opportunities for other manufacturers.

Figure 13. US Windpower first wind farm in California

Two other American companies were responsible for diffusing Georges Darrieus inspired vertical axis wind turbines. The companies were Flowind and VAWT Power. They manufactured a 17 m, 100 kW rated design pioneered in the Sandia National laboratories in New Mexico. Several hundred were installed in the Californian wind farms of the early 1980s (Figure 14). Although relatively successful by American standards they proved less reliable than the conventional Danish three bladed horizontal axis wind turbines that were also available. As a result of this scarcity of supply of reliable wind turbines from indigenous American firms, Californian wind farm developers increasingly turned to Danish manufacturers.

Zond Systems was a pioneering American wind farm development company formed by Jim Dehlsen in 1980. It was one of the first to start buying Danish turbines. It contracted with Vestas to supply 150 wind turbines in 1983. Starting from scratch in 1980 it was operating and maintaining some 2,000 wind turbines by the early 1990s. Californian wind farm developers such as these created a large market for the diffusion of Danish innovations in wind turbine technologies. As a result, during the early 1980s the leading Danish manufacturers, Vestas, Bonus, Micon and Nordtank were exporting around 70% to 80% of their total production to California. Thanks to the generosity of the Californian financial incentives, significantly increasing returns accrued to Danish manufacturers as a result of these exports. A turbine that could be sold in Denmark for $31,000 could be sold to Californian investors for between $100,000 and $180,000 (Musgrove 2010, p. 117).

These Californian boom conditions came to an end as the Federal and local tax credits ran out in 1985/86 and the price of oil slumped. The market for wind turbines continued at a reduced level, however, as a result of local utilities’ contracts to purchase electricity from renewable sources.

Figure 14. Darrieus type vertical axis wind farm

Summary and conclusions

The DC era of the creation of new industries designing and manufacturing windmills for generating electricity illustrates the significance of the existence of niches where pioneer innovators can start new industries. In this case the niches were geographic areas where the dominant techno-economic paradigm for the generation and supply of AC electricity did not apply. The limited extent of electricity grid networks stimulated inventors like James Blyth and Georges Darrieus to find new ways of providing electricity in the areas beyond these networks. Their inventions were not taken up at the time and so did not create a new industry. The most influential innovator in this respect was Poul la Cour. He also started the diffusion process through his education programme for rural electricians. This helped to create a small new industry in Denmark.

The largest scale new industry for the design and manufacture of electricity generating windmills was created in the American plains by a number of companies the most notable of which were Jacobs and Wincharger. They emerged in the niches outside the dominant techno-economic paradigm provided both by the lack of grid networks in rural areas and the demand in those places for electricity in order to listen to the new radio broadcasts of entertainment. These companies were exemplars of the agents that both innovated and diffused electricity generating windmills. They met the first mass demand for windmills in their tens of thousands.

Wind powered DC electricity generating industries were created de novo in both Denmark and the USA. In Denmark it was started by the pioneer innovator Poul la Cour towards the end of the 1890s. It developed slowly over several decades mainly by a process of incremental innovation. Towards the end of this development period in the early 1940s, some knowledge was imported from other unrelated sectors most notably propeller technology from the aeroplane industry and concrete technology from the chimney and grain silo industries. This only represented a branching process in the case of the Danish firm F.L.Smidth & Co because they also owned subsidiaries in these sectors.

In the USA one of the key pioneer innovators was Marcellus Jacobs. During the 1930s he and his company introduced and diffused reliable DC generating windmills across the American plains. In this instance some knowledge was imported in the early days of the industry from the embryonic aeroplane industry. This influenced the aerofoil design of the three bladed rotors.

With the benefit of detailed historical knowledge it is possible to see that the locations of the production sites of these new industries were not a matter of serendipity. Instead they were the result of the coincidence of two main factors. The first was niches in the form of rural markets for electricity that were not being supplied by the AC grid network of the time. The second was pioneer innovators who recognised the potential demand for electricity and were able to design and build reliable machines for local DC production.

The grid connected AC era was ushered in by the Danish and German innovators Johannes Juul and Ulrich Hutter. For the first time the dominant fossil fuel based techno-economic paradigm was subjected to a serious external shock as a result of the rapid increase in oil prices following the Yom Kippur War in 1973.

One of the reactions of governments to this shock was to create niche market conditions outside the normal competitive economic environment for the generation and supply of electricity. Two key examples of government created niche market conditions were Denmark and California. In the former a capital subsidy for the purchase of wind turbines was provided together with a formalised system that allowed local individuals and co-operatives to connect to the grid and receive payments for any surplus electricity they supplied. In California Federal and State tax credits combined with a relatively high feed in tariff made investment in developer provided wind farms a good investment for high net worth Californians.

Government attempts to contract radical innovations in wind turbine technology from aircraft, engineering or construction companies to supply niche markets of these kinds were mainly an expensive failure. As a result the first reliable 1 MW turbine was constructed, mainly from second hand parts, by the Tvind teacher group in Denmark. This demonstrated the practicality of constructing turbines on such a scale. The niche conditions created by the Danish government also created a home market of local final consumers for wind turbines. This was met by Danish agricultural machinery companies who diversified to create the new industry. They continued to develop the technology over some ten to fifteen years as a result of incremental innovations. They were also the key diffusion agents in developing these innovations and sales to a critical mass at which point it could be said that a new industry had been created.

During the 1980s the niche economic environment provided by the Federal and State Governments in California created a dynamic market demand for wind turbines. American firms such as US Windpower, Flowind and VAWT Power could only meet a limited part of this home market. This opened up opportunities for Danish companies such as Vestas, Bonus, Micon and Nordtank to diffuse the new technology into a large export market. At this time the newly created pathway entered a later phase of path dependence marked by positive lock-in resulting from rapidly increasing returns. The basis of this phase was that Danish firms were exporting around 70% to 80% of their entire wind turbine production at prices in California that were some three to six times greater than could be obtained in the home market. These boom conditions declined as the American tax credits were withdrawn and the price of oil slumped in the second half of the 1980s.

The two examples of new technological path creation suggest that dominant techno-economic paradigms set the conventional technological wisdom and economics within which new pathways have to emerge. In both the case histories analysed here such new pathways were created in niches where the dominant paradigm did not reach or was modified by collective action. In the first case the niches were geographic areas where the networks of the paradigm did not extend. In the second case the economic environment in which the new pathway was created was modified by collective government action so that “normal” competition did not apply.

The technological innovations that eventually emerged in these niches took a long time to develop. In the case of DC generating windmills it took nearly four decades and numerous incremental innovations to move from the first windmill to generate electricity to the first commercially produced windmill in Denmark. It then took a further two decades and additional incremental innovations to arrive at the first AC grid connected wind turbine. In the early days of these innovations the sources of the specialised knowledge required to make them was confined to individual innovators and companies. Later, some knowledge was imported from unrelated industries such as aircraft manufacturers and concrete technology. In contrast government contracted attempts to identify supposedly related industries to produce radical innovations in wind turbine design and development were a costly failure.

A number of different diffusion agents and processes were involved in the development of innovations to a critical mass and the creation of a new technological/industrial pathway. Education provided one early form of diffusion. In this instance rural electricians were trained to be able to construct DC windmills in rural areas in Denmark. In the main, firms provided the main diffusion agents for the new technology. The most successful were agricultural equipment manufacturers who diversified into the manufacture of wind turbines. Their success was based on a combination of practical experience and continuing incremental innovation. In addition they had long standing relationships with final consumers and so understood their requirements as customers.

To sum up, the illustrations of new technological path creation analysed in this paper suggest that new path creation and the location of new industries is not a random process. It depends on the existence or creation of niches where the dominant techno-economic paradigm does not reach or is held at bay by collective action. It requires the mindful deviation of innovators from the prevailing paradigm and the time for incremental innovations to emerge and develop into a new technological trajectory. The combined location of niches and innovators determines the geographic distribution of the birth of a new pathway. The development of a new pathway also requires agents capable of diffusing innovations to the point at which a critical mass is reached and a new technological pathway is created. Innovative firms most often provide this kind of agency. Those that have high levels of knowledge of customer requirements and market demand appear to be the most successful.

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