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## **A Comparative Assessment of Wind Turbine Innovation and Diffusion Policies. Historical Case Studies of Energy Technology Innovation**

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# Historical Case Studies of Energy Technology Innovation

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## CASE STUDY 11: WIND POWER.

### **A COMPARATIVE ASSESSMENT OF WIND TURBINE INNOVATION AND DIFFUSION POLICIES**

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#### **AUTHORS' SUMMARY**

Wind turbines have become a mainstream technology, a first choice for many when investing in new electricity generation facilities. This comparative case study addresses how governmental policy has been formulated to support the wind turbine innovation and diffusion process. Three innovation stages and corresponding innovation strategies are identified. The first stage is the early movers of the 1970s and early 1980s, including pioneer countries such as Denmark, the United States, Germany, and the Netherlands. The second stage is the booming markets of the 1990s, guided by the successful Danish innovation path of the 1980s. The third stage is the emerging markets of the 1990s and 2000s, including countries such as India and China. Within these different stages, common elements in government policy strategies can be identified as essential for a sustainable and successful innovation process. These can be summarised as:

- support diversity in technology and market formation
- research, development and demonstration (R,D&D) is necessary but not sufficient
- quality assurance is essential for new technologies
- support interaction and networking
- ensure support is stable, continuous and flexible

Taken together, these elements of a successful innovation approach show that government policy needs to support the development of the entire innovation system: not just the development of turbines and associated infrastructure, but also the involvement of actors, networks, and market institutions. The case of wind energy development in Denmark presents a good example of how and why such a systemic approach can succeed.

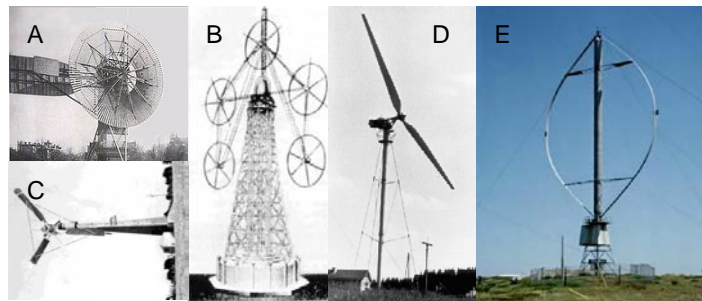
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## 1 INTRODUCTION: EARLY HISTORY OF WIND ENERGY

Wind turbines have become a mainstream energy technology, a first choice for many when investing in new electricity generation facilities. Wind energy represents the potential for a greener development pathway. The global commercial reach of leading wind turbine manufacturers is a marker of successful innovation processes. What is it then that characterizes the success story of wind turbine innovation? And what role has public policy played?

The first modern electricity producing wind turbines were developed already in the 1880s, but it was not until the 1970s that wind turbines were seen as an important innovation path for future development. The early years of wind turbine development were characterized by experimentation and development of different types of wind turbine concepts (see Figure 1). Wind turbines came to be partially successful in rural electrification, specifically in the time up to and during World War 1. In the 1950s the first grid-connected wind turbine, with a three-bladed rotor, was built. Research & development (R&D) efforts formed the basis of Juul's pioneering design of the modern electricity producing wind turbine, the 200 kW Gedser turbine, installed in 1957 and operational until 1967 (see Figure 1c). This in turn formed the basis of the so-called Danish wind turbine concept: three-bladed designs and the rotor position actively maintained upwind using an electrical motor. In 1961 a United Nations conference on new sources of energy was held in Rome at which different wind energy concepts and turbine designs were discussed (United Nations, 1964). A 1955 textbook, "The Generation of Electricity by Wind Power" by E. W. Golding, was republished in new editions and widely used during the 1970s and 1980s. Overall, the extended experimentation throughout the early and mid 20<sup>th</sup> century accumulated a platform of knowledge and concepts that the modern wind industry could build on.



**FIGURE 1. HISTORICAL WIND TURBINE CONCEPTS.** NOTES: (A) THE WORLD'S FIRST AUTOMATICALLY OPERATED WIND TURBINE (12kW TURBINE), CLEVELAND 1888; (B) HERMANN HONNEF WIND TURBINE, GERMANY 1932; (C) JOHANNES JUUL'S 200 KW GEDSER WIND TURBINE, DENMARK 1957; (D) ULRICH HÜTTER WIND TURBINE, GERMANY 1959; (E) A DARRIEUS WIND TURBINE (NAMED AFTER THE FRENCH INVENTOR, GEORGES DARRIEUS) PATENTED IN 1931.

## 2 EARLY INNOVATION POLICIES IN THE 1970S AND EARLY 1980S

In the 1970s, the pioneer countries in supporting wind energy through innovation policies included, for example, Denmark, the US, Germany, the Netherlands, Great Britain and Sweden. However, two different approaches to technology development were taken (e.g. Sawin, 2001; Gipe, 1995). One line of public R&D programmes focused on large, megawatt scale turbines (see Figure 2). The R&D programmes were science-based, developing advanced turbines with high efficiencies to compensate for higher construction costs. Knowledge development was, however, complex. R&D resources ploughed into these

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programmes in countries like Sweden, Germany and the UK resulted in only a few 2 – 4 MW turbines with limited operating hours (Gipe, 1995; Heymann, 1998). The two-bladed 3 MW Growian turbine with 50m blades was an exemplar of unsuccessful rapid up-scaling. It managed 420 hours of operation over the period 1983 - 1987 after which it was demolished due to numerous severe design faults.

In addition, market-pull drivers for these megawatt scale turbines was limited. The intended owners and users were established utilities, but their interest in large and unproven wind turbines was limited, as were the market formation activities supported by governments (see, e.g., Kamp et al., 2003; Åstrand and Neij, 2006). The relative failure of this line of development focusing on large scale wind turbines did not, however, have larger financial consequences as investments were relatively small.

The other line of R&D programmes focused on smaller turbines for specific niche markets. In particular, the Danish, Dutch and US wind power policies supported the development of small, simple and reliable machines. In Denmark, the government also invested in market formation activities. As early as 1979, the Danish R&D programmes were combined with investment and production subsidies (similar to the feed-in tariffs for renewable electricity used widely today). The open availability of subsidies had unforeseen effects as smaller actors, such as farmers and entrepreneurs, entered the market. Their involvement in the innovation process turned out to be essential.

The combined technology-push and market-pull of early Danish innovation was symptomatic of a broader systemic approach to wind power. The development of a domestic market was promoted through wind resource mapping, grid connection regulations, guidelines and regulation on municipal planning (governing the permitting process), and information activities. Considerable emphasis was also placed on technological reliability. In 1978, the Test Station for Wind Turbines was established at the Risø National Laboratory, and from 1979 the Danish Energy Agency authorized Risø to develop a certification process for wind turbines which they could then issue and administer. The Risø National Laboratory's role in testing turbines, together with their more traditional forms of R&D, led to a fruitful three-way interaction between actors in industry, policy and research, with Risø providing manufacturers with essential technical and scientific support.

Like Denmark, the Netherlands introduced subsidies and set up a test station already in 1981. However, the Dutch approach was focused on supporting a competitive market, and manufacturers did not receive any support on how to improve the turbines (Kamp et al., 2003). This competitive approach in the Netherlands also meant more limited interaction between actors, and so less of the essential learning and feed-back processes seen in Denmark.

In the US, a number of subsidy schemes were introduced. As a result, the market for wind turbines took off rapidly, the number of wind turbine manufacturers increased, and the importing of turbines escalated, especially from Denmark (Loiter and Norberg-Bohm, 1999). However, the market boom required US manufacturers to develop wind turbines quickly and with inadequate operational testing at a time when US-manufactured turbine designs were still diverse, advanced, and so largely unproven (Heymann, 1998). Many of the US-manufactured wind turbines experienced severe operating problems. In 1985 only 38% worked properly compared to a figure of 98% for well operating Danish-produced turbines (Heymann, 1998). In 1986, the Californian market crashed due to the poor performance of many installed turbines and a reduction in government subsidies. Up until then, California had installed 1.2 GW wind power, representing 90% of the global installed capacity at that time (US DOE, 2008).

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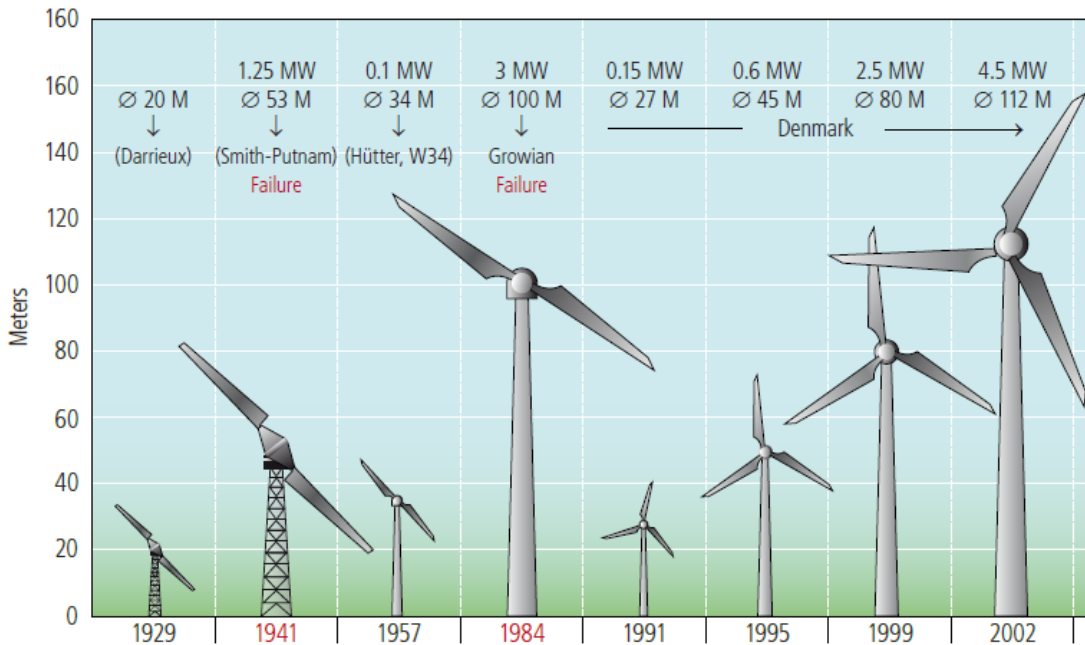
### 3 BOOMING EUROPEAN MARKETS IN THE 1990S

The experiences of wind energy development in the 1970s and early 1980s guided subsequent activity in the 1990s. The successful Danish innovation path of the 1980s was the guiding-star for many countries. Germany refocused on the production of less advanced small and medium-sized turbines in line with the Danish wind energy concept. Spain's approach for overcoming technical barriers to entering the wind turbine market involved a joint venture, Gamesa Eolica, between the Spanish turbine manufacturer, Gamesa, and the established Danish wind turbine manufacturer, Vestas. Established in 1994, Gamesa Eolica paid licensing fees to manufacture Vestas turbines in Spain. Like Germany, Spain came to manufacture turbines based on the Danish concept, benefitting from technology transfer and spillover of know-how. Like Denmark, Germany and Spain also introduced investment and production incentives to support market formation. In 1990 a feed-in law was introduced in Germany mandating utilities to purchase independently generated electricity under terms favourable for the wind turbine operators (Lauber and Mez, 2006). In 1994, a feed-in law with a premium price paid by the electricity utilities was introduced in Spain.

Resources mobilised for wind power in the 1990s in Denmark, Germany and Spain supported both knowledge development and diffusion as well as market formation. With a few exceptions technology development focused on scaling up the smaller turbines that had dominated the market in the 1980s to improve wind capture and reduce the cost of generated electricity. The process of up-scaling more or less standardised turbines had already begun in Denmark in the 1980s as turbine sizes increased from 22kW to 500kW. In the late 1990s commercialized wind turbines had already reached 3MW (see Figure 2). Knowledge development efforts also led to major performance improvements: turbine availability reached 98% (i.e., downtimes of <2% due to technical reasons); efficiency increased dramatically; turbine noise was reduced; and impacts on grid stability were managed allowing penetration rates of over 10% of total electricity production. In all, developments showed that wind energy could be an important contributor in future energy supply systems.

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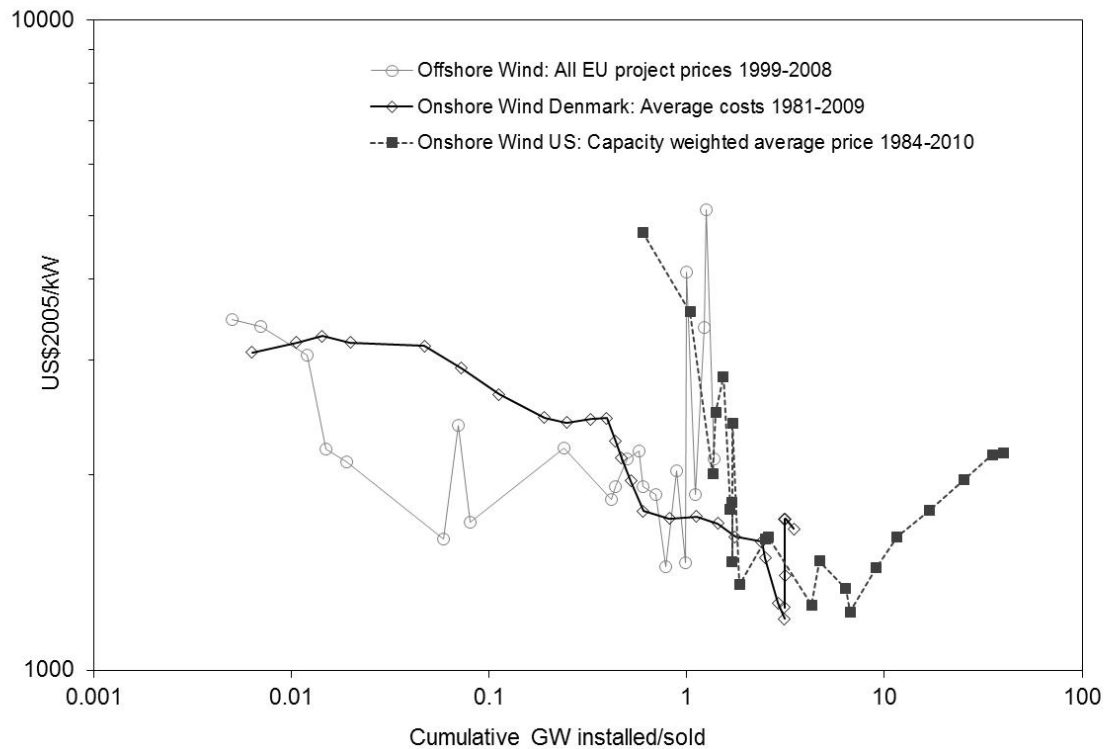
**FIGURE 2. SIZE OF LARGEST WIND TURBINES INCLUDING FAILURES.**

The development of wind turbines and wind generated electricity in the 1980s and 1990s also resulted in cost reductions attributable to various innovation processes (Neij et al., 2003). In Denmark, the cost of installed wind turbines (i.e. cost per kW) reduced by 5% from 1980 to 1985, and by 50% over the longer period from 1980 to 2000 (Neij et al., 2003). Due to successful up-scaling and improved efficiency, the cost reduction in generated electricity was even larger, falling by 70% during the period 1980 to 2000 in the case of Danish produced wind turbines (Neij et al., 2003). The development of larger turbines did, however, face economic and logistical constraints. Until the mid 1990s, up-scaling was limited by the cranes available for the erection of the turbines, and the process of up-scaling with its greater use of materials challenged further cost reductions.

In recent years, prices of wind turbines have increased. One explanation is that rapidly increasing demand for wind turbines on the world market has made it possible for turbine manufacturers to increase the price tag of their products. Another explanation is that the world prices of industrial commodities such as steel and copper have increased, driving up turbine costs. Moreover, cost is no longer declining as a result of turbine up-scaling; the maximum size of turbines has stabilized since the early 2000s.

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**FIGURE 3. INVESTMENT COSTS OF WIND POWER AS A FUNCTION OF CUMULATIVE EXPERIENCE: LEARNING CURVES.**

NOTE: LOG-SCALE X AND Y AXES. SOURCE: EDENHOFER ET AL., 2011; JUNGINGER ET AL., 2010.

These cost dynamics are summarised in Figure 3 as a learning curve which expresses investment costs (or market prices) as a function of cumulative experience using installed capacity as a proxy. Note that although data are often reported as capital costs rather than price, it is typically extremely difficult to find reliable cost data.

A declining price profile associated with learning improvements is clearly seen in the early Danish and US onshore wind markets, followed by a distinctive reversal and upward price trend, particularly in the US. This emphasises the contingency of cost improvements on market conditions and technological maturity. A similar overall trend is becoming evident in the much less mature offshore wind markets in the EU, with prices also strongly affected by siting issues and distance to shore.

#### 4 EMERGING MARKETS IN THE 1990S AND 2000S

India and China also developed highly supportive policies and markets for wind energy in the 1990s. Both countries mandated grid compatibility with wind development, and developed national legislation and financial incentives to support wind energy (Liu et al., 2002; Lewis, 2007; GEF, 2008). Technology and knowledge development was supported through licensing arrangements with foreign wind turbine manufacturers, and through domestic R&D programmes. Knowledge development was further supported through the development of international networks. In India the wind turbine manufacturer,

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Suzlon, located research centres in the Netherlands and Germany (Red Herring 2005) and established their international headquarters in Denmark. In China the wind turbine producer, Goldwind, developed know-how by sending employees abroad to obtain advanced training. In parallel, both India and China developed duties and related taxes to encourage domestically manufactured wind turbines and components (Lewis, 2007). China even mandated domestic products as part of their market formation incentives.

Consequently, wind turbines diffused rapidly from the mid 1990s. But industry development faced a number of difficulties due to poor wind resource data, weak grid systems, poor installation practices, and unsatisfying performance of locally produced wind turbines (Lewis, 2007; Rajsekhar et al., 1999). As a result, the cost of generated electricity was higher than expected. To overcome performance problems, India and China both developed certification programmes for domestically produced turbines (Lewis, 2007).

The innovation path in India and China has been characterized by a massive support for domestic market formation, using spillovers of know-how from foreign manufacturers and support for local knowledge development related to improved wind resource data, grid development and improved technology performance. The process of licensing the production of foreign developed wind turbines resulted in the introduction of somewhat old and small models due to the requirement for domestic manufacturing units. But this emphasis on domestic manufactures allowed the use of local labour assets and the production of wind turbines at a low cost. Domestic production also provided cost reductions related to logistics and transaction costs. In all, the massive and aggressive policy structures of India and China have allowed for an impressive increase in domestically produced wind turbines over the last ten years.

## 5 ELEMENTS OF EFFECTIVE INNOVATION POLICIES

From this comparative analysis of the innovation paths of wind energy in different countries, some key elements in government policy strategies can be distilled as being essential for a sustainable and successful innovation process. These elements are set out in detail below, and summarised here as follows:

- support diversity in technology and market formation
- research, development and demonstration (R,D&D) is necessary but not sufficient
- quality assurance is essential for new technologies
- support interaction and networking
- ensure support is stable, continuous and flexible

Taken together, these elements of a successful innovation approach show that government policy needs to support the development of the entire innovation system: not just the development of turbines and associated infrastructure, but also the involvement of actors, networks, and market institutions. The case of wind energy development in Denmark presents a good example of how and why such a systemic approach can succeed (Borup et al., 2009).

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## 5.1 Diversity in technology and market formation

Entrepreneurial experimentation in the early to mid 20<sup>th</sup> century provided important experience of wind turbine design, and a necessary foundation for strong policy support in the early 1970s. However, in the 1970s many countries focused financially or even exclusively on large and advanced turbines as the single option to meet energy demand in the immediate future. Yet the support of these large, complex wind turbines came to have no impact on the development of commercial turbines in the 1980s as the risks and costs were too high, and with few actors willing to commit investment. Wind turbine deployment was driven not by the traditional utilities and energy companies, but by small and medium-sized enterprises and individuals. These actors, not envisioned as core to the development of wind energy from the start, chose to invest in smaller, more reliable and less costly turbines. This illustration of the difficulties in foreseeing a technology's early evolution emphasises the importance of supporting a diversified innovation portfolio in terms of both technologies and actors. By making it possible for all types of actors to gain support (e.g., investment subsidies), countries like Denmark and the US successfully supported early market formation. Other governments which foresaw utilities as the main users fruitlessly targeted funding at incumbent actors who were insufficiently interested in a new technology.

## 5.2 Targeted research, development and demonstration (R,D&D)

In many countries, wind energy innovation was initially supported through research, development & demonstration (R,D&D) as the first stage in a linear innovation process. But R,D&D funding alone did not give rise to any commercial turbines. In contrast, Denmark and the US had already started to support market formation in the late 1970s and early 1980s, allowing small and medium sized enterprises and individuals to access the subsidy programmes. These broad user-oriented initiatives contributed to important learning-by-using, providing essential feedback to the development of wind turbines.

Initial R,D&D expenditures in Denmark were approximately EUR 47 million up to 1990 whereas equivalent expenditures in Germany during the same time period were more than five times higher at EUR 227 million (Neij et al., 2003) and early US expenditures more than twenty times higher (Heymann, 1998). Yet Denmark more effectively supported the innovation path of wind turbines. How R,D&D resources were targeted, as well as their magnitude, was critically important.

## 5.3 Quality assurance

The certification process developed in Denmark as early as the late 1970s was an essential part of the successful development of Danish wind turbines. The Netherlands also developed a test station to guarantee wind turbine quality, but this was less successful (see below). Countries without testing and certification processes for emerging wind turbine models experienced severe problems in market trust, as in the case of early developments in the US. In recent years, India and China have developed technology certification programmes to ensure high quality domestic wind turbines.

## 5.4 Interaction and networking

Interaction and networking between innovation actors is important. A successful model and example of early experience in policy support for networking was the development of the Danish test station which supported interaction and knowledge transfer between turbine owners (users), manufactures and researchers. This contrasts with experience in the Netherlands where the test station supported competition rather than cooperation among domestic producers.

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## 5.5 Stable, continuous, but flexible support

The history of wind turbine development is long, with many technology and policy failures along the way. Denmark provided a continuous and stable system of support since the mid 1970s, as did Spain from the early 1990s. This stability in innovation and diffusion policies underwrote knowledge development and market formation activities that in turn supported successful innovation outcomes.

From the relative failure of innovation efforts in the 1980s, Germany rebuilt their innovation and diffusion policies in the 1990s on the basis of the successful Danish approach, applying production incentives in the form of a feed-in law to support market formation. By being flexible and adapting their support structure, Germany became a major player in global wind markets. Over the years, many other countries have come to develop their support structures in a similar way.

## 6 FURTHER READING

An excellent, comprehensive account of early developments in the wind industry with country comparisons can be found in Gipe, 1995.

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