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INNOVATIONS IN DANISH WIND TURBINE INDUSTRY

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1 INTRODUCTION

If we take a look at the development of electricity generating wind turbines, in the following called wind turbines, from about the first energy crisis 1973/74 until today, 2018, we can observe two characteristics – first the typical turbines have grown from a very small size of 40/50 kW installed upon a 15/20 meter high tower up to 4/6 MW and towers of about 75/100 meters. The second trait is that nearly all turbines made from many different designs during the first 10/15 years of the period have been converging in their design into accordance with one concept or model with three blades connected to a rotor axis which run a generator with a high speed after connection of the rotor with a gear in a closed nacelle placed at the top of the tower. In literature, that concept is usually called the Danish Concept.

In the social science literature of technical change which in practice usually has its theoretical foundation in economics, mainstream or evolutionary, many results or hypotheses are presented. Some examples can be mentioned:

- There will always be forces to develop and introduce new technologies (products, processes or organizational forms)
- There is a permanent tendency to substitute fixed material capital for circulating capital
- There is today a strong tendency to substitute or connect knowledge capital for material capital
- Most innovations are very small modification of existing technology, so called incremental innovations
- There are a few innovations far away from existing known technology, so called radical technology

In this paper I shall present three hypotheses about innovations – radical innovations, incremental innovations and learning experiences from former innovation work. These hypotheses shall be tested against empirical material from wind turbine history, especially but not only from Denmark.

2 SOME IDEAS FROM ECONOMICS OF TECHNICAL CHANGE

Joseph A. Schumpeter has very often been credited as the godfather of modern economics of technical change. However he had his forerunners in classical economics - Adam Smith with his factory of pins before and after extended division of labor in The Wealth of Nations[1], David Ricardo with his new chapter 31 On Machinery in his The Principles of Political Economy and Taxation, 3rd Edition from 1821[2], and Karl Marx with his theory of capital accumulation and with the tendency of fixed capital to substitute labor which is analyzed in different parts of Das

[1] Adam Smith: The Wealth of Nations. In two Volumes, 441 and 455 pages, Everyman's Library, Dent and Dutton, London and New York, 1964 [1776].

[2] David Ricardo: The Principles of Political Economy and Taxation, 3rd Edition, 300 pages, Everyman's Library, Dent and Dutton, London and New York, 1965 [1821]

Kapital, volumes 1, 2 and 3 published 1867, 1885 and 1894[3].

Schumpeter's contributions were not homogenous during his intellectual life. In 1911 his hero was the Industrial Captain who finds a possibility to combine new and old inventions and existing technologies in a new workable technology at an industrial scale and at the same time establishes a cooperation with a financial capitalist[4]. Thirty years after in 1943, he had changed this model into a very different model where the hero now is the giant corporation with its very big R&D department combined with its detained profits[5]. From the heroic individual he now has changed to the collective organizing and decision - making actor later on called the technostructure by one of his students, John Kenneth Galbraith in his book The New Industrial State from 1967.[6]

From Schumpeter's later works we find that he has his focus at radical innovations – for example the railway system. However he mentions also there will come a swarm of small or incremental innovations connected to the radical innovation. In the case of the railway system there came a lots of improvements of the locomotive, filling water upon the locomotive, the telegraph system and so on. Some of these innovations e.g. the telegraph were themselves radical and could be used outside the railway system.

A radical invention or innovation is usually characterized with use of natural laws in a new way or on the other hand, use of not before used or known natural laws. The locomotive is an combination of a steam engine and a wagon with not before foreseen potentialities in that combination.

There is another distinction between different innovations. Some are very specific in their application. For example a pharmaceutical substance. However there are many innovations which can be used in many different applications. They are called General Purpose Technologies GPT)[7]. For example the steam engine can be used as a stationary energy machine but also as mentioned above in locomotives. From the end of 19th Century until around 1913 steam engines were in competition with electric engines as well as combustion engines in cars. Steam, gas and electric engines had more market share than gasoline engines in the car market[8].

In a real economy investors – capitalists as buyers of capital goods or workers as buyers of

[3] Karl Marx: Das Kapital. Kritik der politischen Ökonomie, Erster Band, Dietz Verlag, 955 Seiten, Berlin, 1966 [1867], Zweiter Band, 559 Seiten, Berlin, 1965 [1885], Dritter Band, 1007 Seiten, Berlin, 1965 [1894].

[4] Joseph A. Schumpeter: The Theory of Economic Development, Transaction Publishers, 255 pages, New Brunswick, 2004 [1934]. Translated and revised from German Theorie der wirtschaftlichen Entwicklung, 1911.

[5] Joseph A. Schumpeter: Capitalism, Socialism and Democracy, 451 pages, Unwin University Books, George Allen & Unwin Ltd, London, 1966 [1943]

[6] John Kenneth Galbraith: The New Industrial State, 427 pages, Houghton Mifflin Company, Boston, 1967.

[7] Elhanan Helpman (Editor): General Purpose Technologies and Economic Growth, MIT Press, Boston, 2003.

[8] http://www.autolife.umd.umich.edu/Environment/E_Overview/E_Overview3.htm

durable goods e.g. homes or cars - usually make decisions under uncertainty. Even if there exist a known distribution of possible outcomes, that shall usually be irrelevant because the purchase situation only takes place very few times in your life. Therefore economic agents are risk averse – they prefer certainty for uncertainty even the statistical outcome is the same. An investor can naturally choose to make an uncertain investment if the probability multiplied with the prospective outcome is so large that it is interesting.

3 HYPOTHESIS 1 ABOUT RADICAL INNOVATIONS, HYPOTHESIS 2 ABOUT INCREMENTAL INNOVATIONS,AND HYPOTHESIS 3 ABOUT LEARNING FROM FORMER INNOVATIVE ACTIVITIES

3. 1 Hypothesis 1

Most innovations made inside firms are small or incremental. Radical innovations can sometimes be identified. From history the steam engine is one example, the electricity generating wind turbine is another and recombinant DNA technology is a third.

There are some common characteristics of radical innovations in modern time. First, the probability that an innovator will stumble over a method to transfer DNA from one organism to another is zero. The steam engine or the airplane were also results from development of theoretical work combined with lots of experiments. A typical inventor/innovator of new radical technology will often be a person with scientific competences who has worked with the topics in research e.g. in a PhD project or in other research. The organizational framework can be a new established firm, a research unit inside a university or it can be a separate unit inside an existing medium size or big firm. The important point is that the work can take place without interference from people who think they know everything about how to make innovations because they probably are competent in making incremental innovations.

Second, radical innovations are very often a result of a very long historical process that maybe only consists in combining already known modules. For example, the flight by Wright brothers December 17, 1903 at Kitty Hawk in North Carolina, U.S. was collectively a result of a history of gliders in practical flight from 1853 and individually the brothers had made many flights and experiments with gliders during the years before 1903. The "only" contribution the brothers made was in fact to install an internal combustion engine, which had been working in automobiles since 1885 to move the plane 20 feet above the ground and at a distance of 120 feet during 12 seconds. That contribution was decisive for moving machines heavier than air through the air[9]. In 1895, eight years before the Wright brothers were able to have a plane flying, Lord Kelvin made one of his many prognoses in which he said that a machine heavier than air was unable to perform a flight according to laws of physic[10].

[9] https://www.britannica.com/biography/Wright-brothers

[10] https://www.newscientist.com/article/dn13556-10-impossibilities-conquered-by-science/

Third, the airplane example above shows that even the innovation is important the real social and economic effects first will follow later on, sometimes many years after. The diffusion process are often the social important part of technical change. Many incremental innovations often characterize the diffusion process.

In several cases the radical innovations are so-called General Purpose Technologies (GPTs) mentioned above. The technology can have a very broad application area. The steam engine can generates mechanical energy in many different contexts from manufacturing, locomotives, steamships and automobiles. The recombinant DNA procedure moves DNA material from one organism to another. The procedure is common but naturally, the specific character of DNA shall be known.

There are also cases where the innovation can only produce one specific product. For example, insulin was discovered in human organism as a stuff of importance for using digested food as a source of energy. That scientific discovery was fundamental for later development in extraction and cleaning of animal insulin to be injected in human organism and restore its ability to transform food into energy.

Hypothesis 1 (H_1): during the last three hundred years, scientific and technical trained people have made most radical innovations. They can only make such innovations in firms or research units with accept from leaders and owners for experiments and mistakes. It will often be in new established firms or autonomous units in established firms[11].

3. 2 Hypothesis 2

First, we want to consider the incentives to allocate R&D resources into incremental resources. In modern capitalism, most markets are more or less monopolistic or oligopolistic. A firm can try to conquer larger market shares through a price war towards the other firms in the market. However, it will often be a more effective way to win such a war if you can make a better product for the buyer and/or make it cheaper. By making small technical improvements, the technical risks are small. However, the commercial risks can be more difficult to assess. For example, use of gasses (CO_2, N_2) to vacuum packed food has normally been considered as a quality neutral technology. However, it can be more difficult to find out reactions that can be expected from consumers. There can be some consumers, which are very positive and shall be willing to buy more and pay more. Other consumers are however against the innovation. However, as a whole the effects, risks, can usually be expected as moderate.

[11] I have had some inspiration to this hypothesis from Joel Mokyr: The Gifts of Athena: Historical Origins of the Knowledge Economy, 384 pages, Princeton University Press, Princeton, 2002. Another inspiration can be found in Gary P. Pisano: The evolution of science-based business: innovating how we innovate in Industrial and Corporate Change, Volume 19, Number 2 (2010), pp. 465-482.

From above we can expect that most firms think that the innovations they consider to take initiative to realize shall be incremental in technical and commercial sense. In different societies and at different times there can be very important differences in attitudes to a technology. One example can be mentioned in use of recombinant processes to manufacture a product which before has been manufactured by a traditional extraction process in e.g. manufacturing of rennet.

From above we can see that risks probably are small if the changes in technology including organization are close to the existing situation. Why are people in an existing firm usually supporting such a conservative strategy? An obvious explanation can be that top management and R&D personal have been recruited to perform and improve well in respect of one or a few products and/or processes. The firm has not allocated resources to think out of the boxes. Because such activities are not considered to generate value for the firm.

Hypothesis 2 (H_2): Well-established firms allocate their resources for technological innovations, from R&D via tests, approvals, modification of manufacturing equipment through marketing, close to the starting situation.

3. 3 Hypothesis 3

Some firms have innovative activities as well-integrated parts of their activities. Pharmaceutical firms are always trying to find new medicine, sometimes radical new molecules, sometimes improvement of existing medicine. Historically methods used to create new medicine has changed. From trial-and-error to advanced biotechnological methods during the last century. Scandals with new medicine have been important. Thalidomide disaster that were responsible for thousands of deformed newborn children from the end of 1950s and beginning of 1960 was a wake-up call and changed the governmental control of new medicine all over the world especially in the rich part of the world[12]. Naturally, innovative pharmaceutical firms also changed their internal systems and behavior because of the thalidomide scandal.

It is now an interesting question to ask if companies and other relevant actors outside the pharmaceutical industry and health care learned from mistakes and naturally also from successes in their innovative activities. There seem to be substantial differences between industries and technologies and between different countries. Agriculture, food, airplanes and cars are examples of products that in general are regulated and controlled. The mad cow diseases especially in Europe from 1984 and the following years came from manufacturing animal food from dead animals as sheep and cow that transferred Creutzfeldt-Jacobs disease first to sheep and cattle and then to human beings[13]. The EU and national regulation has strengthened. If we look at the car industry, we have had different examples of criminality and bad manufacturing from carmakers. In the criminality cases (beginning with Volkswagen and later on other especially German carmakers making fraud monitoring in Diesel engines) American university researchers

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[12] https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4737249/

[13] https://www.newscientist.com/article/dn91-bse-disaster-the-history/

discovered the fraud. The cases with bad manufacturing have been existent for many years. Scale and frequency of such bad manufacturing cases have grown during the last decade and have been found all over the world and in cars made by Toyota, Ford and Volkswagen and other traditional well-esteemed firms. In these cases, the initiative typically came from the car manufacturers after media had mentioned problems. The stories have typically been followed up in mass media because of often very high numbers of cars called back by firms for repair and adjustment.

There are some interesting examples of learning from successful innovations. An example can be Danish furniture from 1940s designed by architects employed in the Danish Cooperative Consumer Movement and manufactured in factories owned by the consumer organization. The furniture was high quality but reasonable low prices because of industrial manufacturing and cooperative ownership. After a saturation of the market in the end of 1970s and very high quality that meant that the furniture has a very long life the manufacturing closed down. However, from about 2010 demand from new generations grew and prices for old items of the classic Danish furniture rose. There were in some cases small changes in material and color compared with the original classical furniture. The main impression is that there were no changes in the furniture assortment half a century later. Sometimes there are no arguments for innovations![14]

It shall be noticed that successes and failures in innovations sometimes first can be observed several years after they have been taken in practical use. So-called side effects of asbestos, typically cancer, were first discovered 30-40 years after persons have been in contact with the stuff[15]. So what was first considered as an innovative success became many years after a very big failure.

Hypothesis 3 (H_3): Firms and R&D units try to learn from their successes and failures. Sometimes because government and public opinion act to protect other interests than firms interest. It shall be noticed that long reaction times can make learning processes slowly.

4 DANISH WIND TURBINE INDUSTRY AS FIELD FOR TESTING THE HYPOTHESES

The wind turbine industry is in general suitable as test field for our three hypotheses. We have a long history with the first electricity-generating windmill made by Blyth in Scotland in 1887. That history is detailed described in technological, economically, politically and socially dimensions so we have good data and information for our work. Denmark and to a certain degree Germany are the frontrunners in that history. It has to be mentioned that the Danish – German cooperation or at least reciprocal information streams started already few years after Poul la Cour in 1891 had established the Test Station in Askov, Jutland, close to then Danish - German border. He organized the annual accounts was translated into German (not English!). Albert Betz who became famous for his Betz Law from 1919 thanks Poul la Cour for his very important contribution to aerodynamics and wind turbine development (Poul la Cour died in 1908 only 62

[14] https://www.cbs.dk/en/the-press/news/your-choice-of-furniture-is-a-result-of-the-era-you-live-in
[15] https://www.mesotheliomahelp.org/asbestos/history/

year old). Later on Austrian Ulrich Hütter, working most of his life in Germany with wind energy and aerodynamics also in relation to gliders and planes, was a pioneer in using fiberglass to manufacture blades to big wind turbines already in mid-1950s. He taught the relevant people responsible for the development and building the Tvind Turbine 1975/78 how to use that new material[16]. Therefore, it is acceptable to use Denmark as a test field for our three hypotheses.

Before I shall look at the hypotheses, there are the two above mentioned main tendencies in wind turbine development after First Energy Crisis 1973/74 – 1) The permanent growth in turbine effect (and physical size) with a factor of more than 100 up to factor 150 for the biggest commercial turbines during the 45 year period, 2) From a situation with many different turbine concepts (horizontal or vertical axis turbines, upwind or downwind and many other differences in important dimensions) the development has converged towards one dominant concept (horizontal axis, three blades etc.) which is the so-called Danish Concept. The permanent growth in size of turbines can be explained from the fact that the kinetic energy inside the area swept by the blades is $\pi \cdot r^2$ (r = length of blades) which means that the energy to be harvested grows with the square of the blade length.

The development towards one and only one turbine concept, the Danish Concept, can be explained from one or two arguments. First from existence of externalities in development, manufacturing and servicing, that were growing because the winning concept was early in existence when the race between competing concepts began. Second the Danish concept were substantial better than the other relevant concepts e.g. the Darrieus concept with vertical axis. It had been mentioned in literature that the horizontal turbine was more stable than the vertical version. Another thing is that three blades also contributed to stability of the turbine compared with other possible blade number especially two blades, which was popular in Germany. In literature about the ways, many design concepts converge toward one concept, it is said that during the era of concept or standard wars it is more or less accidental which concept will be the winner. That war will typically take place after some viable concepts have been formulated. It is important to win a strong customer base. The Danish Concept were working in the mainline and in practice in the so-called Gedser Turbine developed by Johannes Juul, a student of Poul la Cour in 1903-04. Ulrich Hütter's method for design of blades and use of fiberglass was the missing link in the Danish Concept which was realized in the Tvind turbine 1975-78[17] His work with the Gedser Turbine started up when he became a pensioner. The turbine ran 1957/67 very successful without technical problems. That success had its explanation from security and backup systems for all relevant modules.

4. 1 Tests of hypothesis 1

4. 1. 1 The predecessors of modern radical innovations

[16] Preben Maegaard: Introduction, p. xxix, Preben Maegaard, Anna Krenz, Wolfgang Palz: Wind Power for the World: The Rise of Modern Wind Energy, 642 pages, Pan Stanford Publishing, Singapore, 2013.
[17] Ibid.

There were three radical innovations in wind turbines before 1973/74 which is startup of modern wind turbine development:

1) The Poul la Cour turbine 1891
2) The Agricco turbine 1918
3) The Gedser turbine 1957

The important characteristic with the Poul la Cour turbine from 1891 was a new design of blades (in Danish called "klapsejler" which means that the blades were like blinds at right angel to the length of the blade. They were able to go up and down according to the speed of the wind). The shape of the blades came from calculation of maximum of energy transferred to the blades from pressure and suck of the wind at the blades. la Cour worked together with two Danish engineers H. C. Vogt and Johan Irminger from knowledge about the Bernoulli principles about suck effect in opposition to Newton who stressed the point of pressure of the wind[18]. This understanding which was supplemented with experimental work with wind tunnels developed in U.K. and in other countries around 1871 which improved construction of the blades made the energy transferred to the axis and make mechanical energy grow from 6 % of kinetic energy to about 24 %. It was a better understanding of aerodynamics which was the important background for the la Cour turbine. His turbine was in fact a Dutch Mill with blades modified according to the improved understanding of aerodynamics.

The Agricco turbine was developed during First World War by two Danish engineers Johannes Jensen & Poul Vinding. It was marketed in 1919. The most remarkably was the blades that were shaped in an aerodynamic way inspired from the development of airplanes after the Wright brothers especially during the war. The efficiency of the Agricco turbine was 30 – 50 % higher than the best la Cour turbines. It came into production but after the end of the war cheap coal destroyed the economy in wind electricity. The production stopped in 1925. However, the Agricco turbine represented a radical progress in design of wind turbines. For example, some of the turbines generated AC electricity and were connected to the grid. We have here a radical innovation in technical sense. However, time was not favorable for an effective and modern wind turbine because of the big amounts of cheap coal. The technical qualities of the Agricco turbine survived during Second World War and in the post-war Gedser turbine. Commercial it disappeared in the middle of 1920s[19].

The third radical innovation before our period from 1973/74 was the Gedser turbine. The person behind that was Johannes Juul. He had been a student as wind electrician with Poul la Cour at Askov in 1904. When the expansion in wind energy stopped just after the end of First World War he studied and worked as independent electrician for some years until he got a job as responsible for the grid in a regional electricity utility (SEAS) South of Copenhagen. After the

[18] Guy L. Larose and Niels Franck: Early wind engineering experiments in Denmark, Journal of Wind Engineering and Industrial Aerodynamics, 72 (1997), pp. 493-497.
[19] http://runeberg.org/salmonsen/2/25/0229.html, pp. 223-224 (in Danish).

end of Second World War, he was able to get support from SEAS for working with two small wind turbines. Finally, he got public funding, in fact some small residual funds from the Marshall Aid for Denmark, for establishing a big test turbine in the small town Gedser at the Baltic Sea. It began to run in 1957 and ran until 1967 without problems[20].

The basic idea in the Gedser turbine was to take all the good things from the la Cour turbine, the Agricco turbine and the 21 F.L.Smidth turbines built and installed during the German Occupation 1940/45.Denmark had no coal and at that time no oil resources, so the big cement concern F.L.Smidth had an interest to generate electricity. Because of its activities in manufacturing of small planes, it had also some competences in aerodynamics. Johannes Juul was also very conscious of avoiding the bad things from the forerunner. His contribution was primarily to make a high security turbine. Where he found it possible and important he made backup systems to minimize down time of the turbine. He made also an effective blade brake. The turbine was a big one at that time with an effect of 200 kW.

The resulting Gedser turbine that had two minor forerunners also made by Juul was in the planning phase conceptualized as a downwind two-bladed turbine. However, the stochastic winds behind the tower caused several blade failures. He went back to an upwind design with active steering of the blades and at the same time to the three blades, he had worked with before[21].

An interesting observation with the three radical innovations mentioned above is that all the innovators were persons trained in scientific and engineering theories and practice (Johannes Juul was the only without a formal academic education. He had however the qualifications and became in fact appointed to honorary member of one of the two engineering associations in Denmark because of his inventions in other fields). It is important to mention that all the innovators mentioned besides their scientific competences also were active inventors with several patents approved and further were active innovators.la Cour was also a man with strong social and political engagement connected to the liberal movement in his time and with its social basis amongst the middle-sized farmers. For Johannes Juul the wind energy program was also an important part of a fight for national independence.

It can be mentioned that all three pioneers in the first electricity generating wind turbines - James Blyth 1887 in Scotland, Charles F. Brush during winter 1887/88 in U.S.A. and finally Poul la Cour in 1891 in Denmark - were academics. Blyth and Brush were engineers and la Cour a university educated physicist. Later on Ulrich Hütter were also educated as an aircraft engineer. Jean Marie Darrieus was an aeronautical engineer.

[20] https://en.wikipedia.org/wiki/Johannes_Juul
[21] https://en.wikipedia.org/wiki/Gedser_wind_turbine

4. 1. 2 Radical innovations after 1973/74 – only in the world of ideas?

During the seventy years timespan 1887/1957 I have mentioned three radical innovations in the wind turbine field in Denmark – the la Cour turbine 1891, the Agricco turbine 1919 and the Gedser turbine 1957. The two first mentioned innovations were radical based on new scientific knowledge in aerodynamics and tested against experiments. The Gedser turbine were more a synthesis of the la Cour turbines and the Agricco turbines with some learning from the F. L. Smidth turbines during Second World War. There were also some real innovations made by Johannes Juul, the man behind the Gedser turbine – for example a brake system with use of the blades. The real contribution was optimization of the turbine and the modules. It shall be stressed that the Gedser turbine had security and backup systems of the main modules. That were decisive for minimizing of down time and therefore maximizing of electricity generation.

Which radical innovations can be mentioned in time after 1973/74? There are many radical more or less futuristic ideas, which in principle can be realized. In fact, there are in several cases prototypes in use – from Google's Makani wind kite[22], through Mitsubishi Heavy Industries taking part in a project with a helium-filled balloon lifting a wind turbine to 600 meter above the ground[23] to Vestas's Four-in-one wind turbine, a high tower with four rotors each connected to a three-blade arrangement. There is a prototype of that Four-in-one wind turbine installed at DTU Risø Campus turbine[24]. In the UpWind project, an EU funded desk project ended in 2011, it was concluded that it was possible to upscale turbines from the existing Danish concept and possibly to > 8/10 MW even to 20 MW effect[25]. Naturally it will be necessary to develop hybrid materials for blades e.g. from fiberglass and carbon fibers.

Maybe the most radical innovation or rather diffusion of a radical innovation was use of fiberglass. A machine to manufacture the material was patented in the end of 19th Century. During the following years different types as stone wool was developed and manufactured for practical use. During the 1950s the Austrian-German physicist Ulrich Hütter, professor at the Technical University in Stuttgart used the material for blades in a 100 kW 2 blades wind turbine. At the same time, he was also active in its application in gliders. He had been a key person in Hitler's wind energy project from the end of 1930s until its end in 1942[26]. Ulrich Hütter became in 1959 professor in Stuttgart and took up his former work in wind energy[27]. He had later on an important role in Denmark as a consultant to the leader of the Tvind Turbine, Mogens Amdi Pedersen, in respect of how to use fiberglass to make the blades and especially fasten the blades to the rotor. The construction period of the Tvind turbine was 1975/78. The turbine was at the time when it was constructed the biggest turbine in the world with an effect of 2 MW. Because

[22] https://x.company/makani/
[23] https://www.richardvanhooijdonk.com/en/six-futuristic-wind-energy-innovations-will-blow-away/
[24] http://www.vindenergi.dtu.dk/english/news/2017/09/vestas-4-rotor-concept-turbine-one-year-after?id=e9073604-6ade-4481-865a-c71a067e58d4
[25] http://www.ewea.org/fileadmin/files/library/publications/reports/UpWind_Report.pdf
[26] http://www.stuttgart-buch.de/change-in-mobility/wind-as-energy-source.html
[27] Bernward Janzing and Jan Oelker: Hütter's Heritage: The Stuttgart School, in book from note 16, pp.387-405.

of some oscillations, the turbine has had a maximum capacity of 0.9 MW and never worked up to the originally planned effect[28].

Another radical innovation has been development of a technology to installation of offshore wind turbines. The first globally, not only in Denmark, was Vindeby in the Baltic Sea South of Denmark in 1991 in very shallow water. The most interesting development in off shore turbines is construction of floating platforms. North of Scotland Statoil has installed such a wind farm, Hywind, on floating platform[29]. The technological inspiration comes from oil extracting platforms in which Statoil is a very big player.

4. 1. 3 Radical organizational innovations

An often forgotten development of relevance for wind turbine diffusion is what has happened in manufacturing process of wind turbines. Already when la Cour lived, he had cooperation with two Danish iron foundries, which made standardized cogwheels to the Klapsejler according to instructions from la Cour. Local smiths could assemble the components into the turbine[30].

In literature, usually the Riisager turbines from 1978 manufactured in five identical exemplars are considered as the first serial manufactured turbines, It shall be stressed that modules already before were standardized and made in serial manufacturing.

When seven Danish wind turbine firms from 1981 until 1986 exported thousands of wind turbines to California, in some cases assembled them there, the need of manufacturing them in mass production became evident. It is important to stress that the Managing Directors or CEOs at that time in the mentioned firms were self-made people with a background as carpenters, smiths or working with machinery used by farmers in agriculture[31]. They were owners themselves or as member of a family owned firm. There were no academic educated people in the top of wind firms at that time. It changed after the California gold rush stopped in 1986 and all firms with exemption of Bonus Energy A/S went bankrupt. The banks typically claimed changes in owner structure to limited companies and professional managers as precondition for contributing to reconstruction of the firms[32].

The standardization, which was a precondition for mass production, had also another consequence, namely the possibility of outsourcing the manufacturing of modules and components.

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[28] Benny Christensen: History of Danish Windpower in book mentioned in footnote 16, p. 68.
[29] https://en.wikipedia.org/wiki/Floating_wind_turbine
[30] Footnote 16, different places.
[31] Peter Karnø: Dansk Vindmølleindustri – en overraskende international succes. 347 sider. 1991.Samfundslitteratur. Frederiksberg (in Danish).
[32] Ibid.

Mass production was not invented in manufacturing of wind turbines. The inspiration came from the automotive industry with Ford T and assembly belt organization 60 years before in 1908. The main point was that materials came to worker instead that workers came to materials[33]. That change has contributed to lowering costs per installed MW effect.

Another organizational innovation, which has not been presented as a radical innovation, is what has been called Big Data innovation. It is an IT system where all turbines installed by or at least manufactured by one of the big wind turbine firms - Vestas, Siemens-Gamesa or General Electric (GE) – is connected real time to one or more super computers[34]. The data are internal data from modules in the individual turbine or external data from the microclimate around the individual turbine or the windfarm in which the turbine is located. The data mentioned above can be used to listen to irregularities in the way the different modules in the individual turbine work. Other important information is precise data about wind speed and direction in real time, which can be used to optimize location of turbines. These data can be used to manage maintenance programs so down time of turbines can be minimized.

4. 1. 4 Conclusion

The technical radical innovations were made by people with scientific and especially with technological competences. Even if some of these innovators were not especially strong in research they understood science and had especially respect for experimental work in aerodynamics. They worked in autonomous groups and had strong enthusiasm for their work.

The radical organizational innovations mentioned above seem to be another thing. They were also more copying from other industries than being developed inside the wind turbine industry,

4. 2 Tests of hypothesis 2

As mentioned above the postulate of hypothesis 2 is that well-established firms allocate their resources for innovations close to the starting situation. The idea is that the existence of idiosyncratic resources, that means resources, which are specific for the considered firm, gives an advantage in searching of knowledge and in construction of new knowledge. Often some part of that knowledge is tacit knowledge, knowledge that is known and understood by some people inside the firm but not shared with people outside the firm. Often that knowledge is not disclosed in patent descriptions. It seems evident that there are so-called low hanging fruits, which can be picked to a low cost.

An example of such specific knowledge is the blades in Johannes Juul's Gedser turbines (and their two predecessors), First he tried with a two-blade version but discovered that it was more unstable compared with a three-blade model. Second, he tried blades manufactured from steel

[33] http://corporate.ford.com/innovation/100-years-moving-assembly-line.html
[34] https://www.siemens.com/innovation/en/home/pictures-of-the-future/digitalization-and-software/from-big-data-to-smart-data-machine-learning-in-windturbines.html

but found that they were destroyed in strong wind. The solution became a hybrid consisting of wood and aluminum. Third, he changed his wind architecture from being a back- runner to a front-runner. The smart thing with a back-runner was that the blades automatically adjusted themselves to the wind. The not so smart thing was that the tower shadowed for some part of the wind. The solution with the front-runner needed a machine, a yaw to adjust the blades against the wind[35].

In the examples mentioned above the incremental innovation are maybe first of all not innovations but changes in selection amongst different existent technologies. Sometimes with all our interest in innovation we forget the core piece in neoclassical textbooks namely influence from gains connected to choose one technology before another because of lower unit cost or changes of input prices to changes in input combinations.

4. 2. 1 Real incremental innovations after 1973/74

During the time after First Energy Crisis 1973/74 there can be identified two main challenges or aims formulated in engineering terms:

1) The continuous growth in size of turbines, measured in potential output of electricity, the so-called nameplate effect, the maximum effect of the turbine, from an average of 50/60 kW and very few test turbines with more than 100 kW effect in the beginning of the period. In the end of the period mentioned (2018), there are many different sizes of turbines running. The biggest turbines in commercial use are about 9/9.5 MW nearly 200 times bigger than the average size in 1973/74. It is important to know precisely the locations where the turbines are to be installed. For example, it is important to distinguish between the heights of the tower because the strength of wind is much higher 100 meter above ground than 30 meter above ground. Theoretical, ceteris paribus, the bigger size the lower unit costs of installed MW effect.

2) The other important aim has been to find a way to locate wind turbines offshore, at the sea in some distance from the coast. The explanation is the very simple that there is no hindrance for the wind at the open sea far away from the coast. In shallow water (< 50 meters), it is possible to install the turbine at a pile driven down in the sea floor. If the sea depth is more than around 50 meter, other solutions are to be developed. Usually it is a floating platform technology.

The first aim to let the size of the turbine grow is easy to understand because the kinetic energy in wind which is the pool from which the energy is transformed into mechanical energy equals the circle area swept by the blades:

(1) $A = \pi \cdot r^2$

[35] Footnotes 20 & 21 above.

where r is the length of the blades. The kinetic energy is the square of the length of the blades.

The second aim is to locate wind turbines in locations with high speed and reasonable constant Speed of the wind. The power generated is:

(2) $P = ½ \cdot \rho \cdot A \cdot v^3 \cdot C_p$ in which the symbols mean the following:

P = Power (W)
ρ = Density of air (kg/m^3), depending of temperature or height above the sea level
A = Swept area (m^2)
v = Wind speed (m/s)
C_p = The Power Coefficient is the proportion of kinetic energy transformed into mechanical energy (theoretical maximum is the Betz Limit of 16/27 = 0,593, in practice it is today between 0.35/0.45 and depending of the concrete wind turbine)[36].

Of course, it is possible to pursue both aims at the same time – developing and installing still bigger turbines and locating them in places with still higher wind speed.

4. 2. 1. 1 Turbine growth

It is remarkable that the growth in turbine size has been continuously during the nearly half of century from the First Energy Crisis 1973/74.

One important characteristic of this growth is that in the U.S. it was a comprehensive serial of design, manufacturing, installment and running of wind turbines from 1974 until 1992. NASA was the governmental institution with overall responsibility for the program. Big industrial corporations had a strong influence in the committees just below NASA. After two small turbines in the beginning of the period – 100 and 200 kW, the program went up to three very big turbines – 2.0 MW in 1979, 2.5 MW in 1982 and 4.0 MW in 1982. The turbines were all two-bladed, some of them were downwind and other were upwind. In general, the program generated much new knowledge[37]. In respect of practical usable new technological proposals, the test turbines were without much success[38].

In Germany the few running turbines from which a program started were a small-scale size at 50/100 kW. The aim pursued was a Big Bang of 3 MW with the Growian (*Gro*sse *Wi*ndkraft *An*lage) turbine politically decided and with construction beginning in 1976, started up in 1983 and decommissioned in 1987. Officially, the aim with the Growian project was to test if it was possible to generate electricity from wind in Germany. However, it was explicit formulated from the dominant interests in business and electricity industry strongly connected with the nuclear power electricity developing and manufacturing industry and generation of electricity that the

[36] https://www.raeng.org.uk/publications/other/23-wind-turbine
[37] http://www.wikiwand.com/en/NASA_wind_turbines
[38] https://en.wikipedia.org/wiki/NASA_wind_turbines

project should demonstrate for anti-nuclear people and organizations (including the Green Party) that wind energy was a very bad idea. These dominant industrial and electricity business interests were strongly represented in the Growian steering committee. The Growian turbine became in fact attacked by technical failures. There were two main weaknesses – firstly the turbine had two blades and secondly the turbine was a downwind back-runner (Leeläufer). The two-blade concept was already at that time known to result in vibrations, which claimed stronger materials than the three-blade turbine. The back-runner gave less useful energy than the front-runner did because the tower shadowed for the wind. The turbine worked 420 hours during its lifetime from 1983 to 1987. It costed 87 million DM. In general, it was the biggest scandal in history of wind energy[39].

In Denmark two so-called Nibe turbines were installed 1979/80 (Nibe is a small town in Mid-Western Jutland). There were two purposes with these turbines. First to find out about the possibilities for use of wind energy to generation of electricity, second there should be made experiments with big turbines for future improvement of the turbines. There were over time several problems especially of technical character. Several component and modules broke down before expected. Finally, the turbines were stopped and decommissioned 2001.The Nibe turbines were in fact the Danish energy establishment's answer vis-à-vis the grassroots' turbines from same time. Especially the Tvind Turbine constructed and installed 1975/78 a 2 MW turbine, which was the biggest turbine in the world at that time. It shall be noticed that the Nibe Turbines had only a rated effect on 0.63 MW per turbine, 20 % of the Growian turbine[40]. It is important to notice that the Tvind turbine never ran with more than 0.9 MW even it was rated as a 2 MW turbine. The explanation was a miscalculation on vibrations of the turbine when the generation of electricity was over 0.9 MW[41]. However it shall be stressed, that the Nibe turbines were not in general total failures, but there were several broke downs in modules and components which had as result that the turbines did not were running for longer periods. The results in generation of electricity became in that way not satisfactory. The commercial results became consequently neither satisfactory.

The Danish way to let the turbines grow in size was a Step-By-Step strategy. The Step - By - Step strategy was a result of an energy policy without nuclear power. This strategy had strong support in the population but in opposition to the majority of the Parliament. It was the First Energy Crisis 1973/74, which changed the balance of power between the two strategies. Denmark was strongly dependent of imported oil and coal especially from Middle East. To diminish that dependence the wind supporters offered an effective and fast way to generate electricity – a wind turbine could be manufactured and generate electricity in less a year. Contrary it would take about ten year from a decision to build a nuclear power plant until there was electricity from that.

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[39] https://en.wikipedia.org/wiki/Growian

[40] Preben Maegaard: From Energy Crisis to Industrial Adventure: A Cronicle in book mentioned in note 16, pp. 181-247.

[41] http://dkvind.dk/fakta/M5.pdf . Here the explanation of 0.9 MW is however that there was not demand enough from the grid and a want to enlarge the lifetime of the turbine. After a later refurbishment the turbine is still working after 40 years.

A gradualist developing strategy of bigger turbines can be characterized by the Step-By-Step approach vis-à-vis the Big Bang approach. It is an approach, which seems more expensive and taking longer time than the American or German Big Bang. To go from 0.2 to 2 MW in one step compared with a sequence from 0.2 to 0.5 to 1.0 and further to 1.5 for ending with a 2 MW turbine seems naturally to be preferred. In practice, the answer is different. For example, a growth in length of blades from 10 to 30 meters is not a trivial matter. The material can still be resin improved glass fibers. The design has to be modified in order to get an optimal blade. That optimization can be difficult to determine if we only have mathematic models. It is better to supplement them with in site experiments. Even today new blades are tested for physical loads before they are approved for use in a new serial of new turbines. The empirical tests are in such cases more reliable than speculative formalism.

Today Danish wind turbine manufacturers make some of the biggest turbines globally. Vestas makes in cooperation with Japanese Mitsubishi Heavy Industries (MHI) the biggest commercial turbine with an effect of 9.5 MW[42]. The difference between Danish Vestas and German/Spanish Siemens Gamesa Renewable Energy (which was Danish Bonus Energy A/S until 2004 and still with important developing and manufacturing located in Denmark) on one side and some other German and American wind companies on the other side is not so seriously today as it was historically.

Above we have looked at the growth of the turbines from an engineering perspective. What can we say of the growth strategy from an economic perspective?

We have above-mentioned potential benefits from growing size of wind turbines. A basic question is to ask about costs to achieve the benefits from growth of turbines. From a superficial look the wind turbine-manufacturing firms has a low R&D intensity measured as R&D costs divided with turnover[43]. In average around 2 - 3 %. However, the figures are not giving the correct picture. Suppliers of modules or components have developed a good part of new technology in wind turbines and in manufacturing of these new turbines. For example, the development of control systems takes place in specialized firms supplying control systems. Statistically the only indicator of these improvements in control systems is the relatively growth in prices of control systems.

4. 2. 1. 2 Offshore location

When the offshore wind parks were constructed beginning from 1991, the most important radical innovation was clearly the platform technology. A less visible innovation process has taken place in nearly all modules and many components. It was clear for the engineers working with development of offshore wind turbines that rough climate often hinders access to the turbines from boats or helicopters. The minimization of down time of turbines is very important for generation of electricity.

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[42] https://www.offshorewind.biz/2017/06/06/mhi-vestas-launches-9-5-mw-offshore-wind-turbine/

[43] https://www.statista.com/statistics/513743/vestas-research-and-development-costs-worldwide/ and https://www.vestas.com/~/media/vestas/investor/investor%20pdf/financial%20reports/2017/q4/2017_annual_report.pdf

After some experiences from real life, it became clear that modules and components shall be made of very high quality, reliability, and with long life in order to minimize repair and replacement. One of the first examples was a negative experience with the replacement of generator and transformer modules in all turbines in the offshore Wind Park Horns Rev 1 in the North Sea after defects. What the real background factors were is not clear because there were no problems with same type of turbines close to Horns Rev 1[44]. However it seems that saltwater and salty air do explain something. There were possibly also some problems with a batch of generators.

There is naturally not a free lunch here – a gearless direct drive generator that means less moving parts in the generator is substantial heavier than a generator with gear. For the big wind turbines with direct drive, the nacelle has a weight of 300/400 tons. That means that the requirement to strength of tower and platform will be higher because of the wind hits a higher mass.

The third important problem connected with offshore wind parks is as mentioned above to develop floating platforms. There has been several of such test turbines. The only wind park installed on floating platforms and running on commercial precondition is the Hywind Scotland Pilot Park located north of Scotland owned by Statoil. It began generating electricity in 2017[45].

Fourthly, it is difficult to come out to the turbines because of the hard weather most of the year. It is naturally an argument to use components and modules of high quality and monitoring treadles relevant data.

4. 2. 2 Conclusion

Well established wind turbine firms have focused their innovation activities in two main directions – enlarging the size of turbines (and enlarging the size of wind parks) and moving location of wind turbines to off shore. Even the Step-By-Step strategy has resulted in serious mistakes a la Growind there has been problems especially with the off shore turbines. The net result has been radical improvement in quality of components and modules. During the last years strong growth in productivity in manufacturing of turbines and installment.

4. 3 Tests of hypothesis 3

The third and final hypothesis mentioned above says, that firms try to learn from their successes and failures. Sometimes because government and public opinion act to protect other interests than firms interest. It is important to notice that long reaction times can make learning processes slowly.

[44] http://www.modernpowersystems.com/features/featurehorns-rev-reveals-the-real-hazards-of-offshore-wind-720/

[45] https://www.4coffshore.com/news/hywind-scotland-pilot-park-united-kingdom-uk76.html

4. 3. 1 Learning from success and failure

The hypothesis seems immediately to be nearly a banality - individuals, organizations and nations will naturally behave in accordance with which behavior results in success and escape in accordance with which behavior results in failure (B. F. Skinner)[46].

However, there are several problems with the content in that hypothesis. First we need to make a precise definition of speed and direction of technological change. Technological means here a product or a process specified in different dimensions. For example, a car with its main modules as chassis, engine, wheels, brakes etc. and the way these modules interact with each other is a technological product, including naturally the architecture that makes a car. The car manufacturing process with workers working along assembly belt, robots and modules is a technological process. Speed of such changes can naturally be specified as time from startup of the project to achieving the wanted result. Direction is maybe a more complex issue. Traditionally it has been understood in a two-factor production context as the relative proportion of labor vis-à-vis capital. I propose that we make the distinction capital intensive and labor intensive from the monetary figures and then make a more descriptive analysis of the processes.

What means learning in the learning hypothesis? Learning is the act of acquiring new or modifying and reinforcing existing knowledge, behavior, skill, value or preference that may lead to a potential change in synthesizing information, depth of the knowledge, attitude or behavior relative to the type and range of experiences. In the simple Skinner version, learning means that behavior, which results in success, will be repeated. Behavior, which results in failures, will be avoided[47]. Even we can find many examples confirming this interpretation of the hypothesis, there are empirics that seem to be against it. Such cases are probably the most productive for creating new knowledge and new technology.

Some well-known examples are the development and installment of very big turbines around 1980 as the German Growian turbines, Danish Nibe Turbines and some American NASA turbines[48].

They were with exception of the first NASA turbines at the time they were constructed, manufactured and installed much bigger than the already existing biggest turbines. It is interesting that all of them were failures or disasters in technical sense and partly because of those failures/disasters commercial failures. However, they were important step stones in learning processes towards the much bigger turbines we have today. The Growian turbine had a rated effect of 3 MW, the Nibe Turbines 0.630 MW and the different NASA turbines from 0.1 to 4 MW.

What the hypothesis 3 mentioned above is not considering is the ways failures can inspire learning in the techno structure or innovation system around wind turbines design, construction,

[46] https://www.simplypsychology.org/operant-conditioning.html

[47] Ibid.

[48] See footnotes 39, 40 and 41 above.

manufacturing and installation. As well known from life and literature, failures can stimulate making improvements much more than successful incremental innovations. What was the learning effect from the three different cases with very big turbines around 1980?

The German case was planned to develop the optimal turbine – it is well known that big turbines produce electricity as the square of the length of the blades. During the interwar-period, there were also activities to construct very big turbines. During Nazi time from mid-thirties until around 1942, there were several different activities to enlarge electricity generation from wind turbines. As it is well known Germany did not had enough energy resources inside Germany to run its industry and at the same time make war with Soviet Union and the West.

The Growian project had officially the purpose to test if it was a possibility to generate electricity from wind in Germany. However, it was in fact more or less explicit formulated, as an aim from the dominant interests connected with nuclear power electricity generation in Germany that the project should demonstrate for anti-nuclear people that wind energy was a very bad idea. Naturally, there were other social forces in German social and political life, which had a more constructive attitude. The Growian turbine became in fact hit by technical failures. There were two weaknesses – first the turbine had two blades and second it was a downwind back- runner (Leeläufer) instead of the upwind concept. The two-blade concept was known also at that time to result in vibrations, which claimed stronger materials than the three-blade turbine. The back runner gave less useful energy than the front-runner did because the tower shadowed for the wind.

In Denmark the purposes with the two Nibe turbines installed 1979/80 were first to find out about the possibilities for use of wind energy to generation of electricity, second there should be made experiments with big turbines for future improvement of the turbines[49][50].There were over time several problems especially of technical character. Several component and modules broke down before expected. Finally, the turbines were stopped and destroyed 2001.The Nibe turbines were the Danish energy establishment’s answer vis-à-vis the grassroots’ turbines from same time. Especially the Tvind Turbine constructed and installed 1975/78 as a 2 MW turbine which was the biggest turbine in the world at that time. However, it shall be stressed that the Nibe Turbines had only a rated effect on 0.63 MW per turbine, 20 % of the Growian turbine. In addition, for the historical truth it shall be stressed that the Tvind turbine has never run with more than 0.9 MW even it was rated to 2 MW. The explanation was a miscalculation on vibrations of the turbine when the generation of electricity was over 0.9 MW. However it shall be stressed, that the Nibe turbines were not in general total failures, but there were several broke downs in modules and components which had as result that the turbines did not were running for longer periods. The results in generation of electricity became in that way not satisfactory. The commercial results became consequently neither satisfactory.

The American NASA programs were in fact a serial of design, manufacturing and installment and running of wind turbines from 1974 until 1992.

ASA/DOE/DOI Wind Turbines

Model	Rating kW	Swept diameter, m	Description	Prime contractor	Years in service	Remarks
MOD 0	100	38	Two blades, downwind and upwind	NASA design with Lockheed blades	1975–1982	Prototype only at Sandusky
MOD 0A	200	38	Two blades, downwind	Westinghouse	1977–1984	Four units installed for field trials
MOD 1	2000	61	Two blades, downwind	General Electric	1979–1981	One installed at Howard's Knob. World's first turbine to achieve 2 MW power output.
MOD 2	2500	91	Two blades, upwind	Boeing	1982–1988	Three installed near Goodnoe Hills as a wind farm. Fourth and fifth units sold to utilities, Pacific Gas and Electric demolished in 1988
WTS 4	4000	79.2	Two blades, downwind	United Technologies	1982–1994	One turbine installed at Medicine Bow, Wyoming and another smaller 3 MW WTS 3 version in Sweden
MOD 5A	7300	121.5	Two blades, upwind	General Electric		Never built
MOD 5B	3200	97.5	Two blades, upwind	Boeing	1987–1996	One installed at Oahu, Hawaii

[51]

If we look at the three mentioned cases above they are in fact not as identical as I first thought. It is correct that in all three cases there were serious technical problems. It is also correct that these

[51] See note 39

technical problems had something to do with the very big size of the turbines compared with what was the standard size of wind turbines at that time (< 100 kW). It was probably not only a question about *size* but also maybe more important a question about *speed of growth* in size from one state to another. The problem here is that we cannot expect linear connections. For example, the growth in length of blades made new requirements to strength and weight. Until Second World War, wood was often used as material for blades. With bigger turbines, new materials were sought. Steel and aluminum were favorites. Another material was fiberglass that became the winner. It is interesting in respect of material for blades that the new suppliers were companies which in beforehand worked with the material. Not specifically with blades. Therefore, one of the winners was a Danish company established as furniture factory in 1940, which in 1954 manufactured a small sailboat. In 1952, it changed its name to LM Glasfiber. First in 1978 it manufactured the first blade for wind turbines. The conclusion seems to be that it was more important to be technological strong in fiberglass than it was to be strong in manufacturing of blades for wind turbines. That is an important observation, which also can be observed in other technologies. It was in general not the former manufacturers of horse cabbage, which took over and became manufacturers of cars. It was manufacturers of internal combustion engines or other engines.

However, it is interesting to observe that there are different ways in which the new turbines as a whole were designed, developed, manufactured and installed. The big German electricity producing companies dominated the Growian organization. Because the electricity industry was against wind energy and pro-nuclear power, the Growian project was more or less determined to be a failure.

The Danish case was also strongly influenced from the electricity industry. However, the strong grassroots movement was not only customers of electricity but also active in development and manufacturing of wind turbines. The many small wind turbines developed, manufactured, and installed a little before and at the same time were very visible successes and the big turbines had to be compared with. Even the industrial establishment, electricity top and mainstream politicians were pro-nuclear and against wind energy, they had to listen to the massive alternative sustainable energy forces in Danish society. The fact is that Denmark never got nuclear power. The two Nibe turbines had a rated effect of 0.63 MW per turbine. However, there were some experiences in Denmark to develop, manufacture and install big turbines. Johannes Juul's Gedser Turbine running from 1957-67 had a rated effect of 0.20 MW and the Tvind Turbine had a rated effect of 2 MW even it only worked with 0.90 MW. So there were some knowledge about manufacturing big turbines and let them work successful.

The American NASA projects are in fact interesting in several dimensions. First they represented a very strong growth in rated effect from 0.1/0.2 MW in the end of 1970s to a very big turbine with an effect of 2 MW which ran 1979/81. The turbines were all two-bladed and some of them were downwind and the other upwind.

4. 3. 2 Conclusion

The three examples of mega wind turbines in U.S.A., Germany and Denmark are examples of not-learning. They can be considered as constructions, from beginning of 1970s to-mid 1990s from the energy-establishment that did not wanted success for wind energy. Later on a more nuanced learning of the three examples has been done. The Growian is still a scandal, but the American and the Danish cases gave some knowledge mostly from their failures.

5 DISCUSSION

It is interesting to notice that the stated aims in the debate in Denmark about use of wind energy to generate electricity have changed over time. Poul la Cour stressed from the beginning in 1891, the importance of provision of electricity to rural districts of the country. In same year, the first DC utility began to generate and distribute electricity in Odense a big provincial town in Denmark[52]. His argument had relevance in Denmark until about First World War because the electricity companies generated and distributed electricity as Direct Current (DC), which could only be distributed over short distances, 5 km, before it became transformed into heat. From 1907, development of Alternate Current (AC) began and there was a system with DC in towns and AC in rural districts. During the period, 1914 - 1945 including the two World Wars, focus aim became self-sufficiency or diminishing dependency of imported energy fuels. During the period Denmark did not had oil resources and during the two wars could only import small proportions of normal fuels as coal and oil. Therefore, wind resources were welcome as supplement. From 1973-74 the aims with wind energy in Denmark have been a constructive self-sufficiency answer on the question of future energy and against nuclear power which was the other alternative. Additionally wind generated electricity diminishes leak of CO_2 compared with use of coal, oil and natural gasses.

Poul la Cour understood very well that good science was an absolute precondition to make wind energy competitive vis-à-vis other electricity fuels. However, he also knew that grassroots were important for the long-term survival of the idea. He started up a Danish Society of Wind-electricity in 1903 with a Periodical of Wind-electricity. More was needed, namely skilled electricians to install and servicing wind turbines. He started up such education. That group of people had the relevant competences to make the la Cour turbines run between the wars when there were no new installed turbines. An effect was also that ideology and enthusiasm about wind energy survived and in fact was decisive for Johannes Juul's work from the end of Second World War and culminated in the Gedser Turbine beginning to run from 1957 and stopped in 1967. Johannes Juul was as 17 - 18 year young man a student in wind-electricity of Johannes Juul 1903 - 04. Even today, we can find a strong interest in wind energy and today supplemented

[52] H.C. Hansen:

with interest in solar energy. There are in Denmark today 4 different societies and museums with focus at renewable energy especially at wind energy[53].

In the text above, I have looked at factors behind allocation of resources towards radical innovations and incremental innovations. It will naturally be very relevant to look at which factors determine that a new radical innovation will be of social and private importance including economic importance. It will be much more difficult to answer such a question. Chris Freeman mentions in his first book on industrial innovation the example that artificial leather came to the market in beginning of 1950s when Argentina had serious economic problems and expanded its slaughtering of cattle. The consequence from that was an expansion of natural leather to lower prices than before. The demand of artificial leather declined and first after many years, the artificial leather became a viable innovation[54]. The conclusion from that example is that a radical and good quality innovation cannot be guaranteed to be a commercial or social success.

different concepts in Danish wind turbine manufacturing – the Danish concept were the most disseminated. However, the Darrieus concept with the vertical axis were also When we look at big well-established firms, it seems in many cases that they are inventive measured by their patenting behavior and innovative measured from their new products and processes. However often inventions and innovations take place in small new established firms, which are bought by the big companies when they have made successful inventions and maybe have started to make innovations. It is a smart way for minimizing risk for the big firms – they are screaming the successful inventions and beginning innovations, which are very expensive. The well-established firms have capital from former blockbusters and monopolistic market position. The small firms with radical new ideas do not have or cannot easy get access to capital.

As mentioned above during the first few years after 1973 -74 there were several popular. Probably because it was favored by many senior engineers. For example, the first Vestas turbine expected to be brought to market was a Darrieus turbine. After some tests in 1979, it was rejected and instead the firm made their first commercial turbine according to the Danish concept from a license they bought. In that way Vestas learned very fast from a failure and were able to go to America and be an important player into the Californian Gold Rush 1981- 86. It seems that the background for the reduction in numbers of firms manufacturing turbines after 1986, when the Californian market disappeared until 2004 when Siemens bought Bonus Energy, was not quality problems. After the merger, we have only two or maybe 1½ wind turbine firms in Denmark because the Danish part of Siemens has diminished relatively after the fusion of Siemens and Spanish Gamesa in Siemens Gamesa. It was capital provision problems and large scale cost reduction, which made it profitable to merge.

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[53] Energimuseet i Tange, Poul la Cour Museet i Askov, Nordisk Folkecenter for Vedvarende Energi and Danmarks Vindkrafthistoriske Samling.

[54] Christopher Freeman and Luc Soete: Success and Failure in Innovation. The Economics of Industrial Innovation, 3rd Edition, Routhledge, 1997.

6 CONCLUSION

We have identified three radical innovations in Danish wind turbine history since 1891:

1) The la Cour turbine from 1891
2) The Agricco turbine from 1918
3) The Gedser turbine from 1957

In all three cases the key persons were educated in natural science and with competence in engineering. The la Cour activities took place in an institutional set up at the Test Station in Askov, Jutland, where he was a teacher in natural science at the Folk High School. The Test Station was funded to a substantial degree by government. The Agricco turbine was developed by two engineers from their own money and manufactured by a machine manufacturing firm according to their instructions. It was a technological success. It was not viable in commercial terms because resuming of the cheap coal and oil provisions from abroad after the end of First World War. Finally, the Gedser turbine was funded from Marshall Help fund and funds from the semi- public Electrical Utility Company, SEAS, in which Johannes Juul had worked many years before he became a pensioner after the end of Second World War.

The Agricco turbine represented a break with the la Cour turbine because it incorporated the aerodynamic experiences from flight development especially from First World War. The Gedser turbine was a synthesis of all progress in wind turbine development from la Cour including the F. L. Smidth turbines installed during Second World War. The intention was to cancel all mistakes. Governmental support was decisive for two of the three mentioned radical innovations. However the most important fact to stress in all three cases was that the man or cooperative men with the important ideas had relatively high degree of autonomy to make decisions they found necessary or optimal naturally within financial restrictions.

Poul la Cour's radical innovation especially in its diffusion became a social success and to some degree a private economic success, not so much for la Cour as for the industrial partners manufacturing the most important components and modules. The Agricco turbine designed by Johannes Jensen and Poul Vinding in 1919 was more effective than the la Cour turbine. However, the end of First World War opened up international trade routes including trade in coal and oil. That meant that the advanced Agricco turbine could not be competitive in private economic sense. The production of it stopped in the end of 1920s. The Gedser turbine was not conceived as a commercial turbine. It was a test turbine and worked without breakdowns more than 10 years. The Danish nuclear lobby in electricity system and industry as a whole were against wind energy from different arguments – the cost price of electricity was about 100 percent above cost price of electricity from coal and oil. Additionally wind electricity was unstable because of the wind. Electricity engineers also preferred nuclear power electricity because it was stable. It was the First Energy Crisis 1973 -74, that changed the power balance between wind energy on one side and coal, oil and nuclear power on the other side. Costs of electricity generated from fossil fuels grew strongly compared with costs from wind electricity. The self-sufficiency problem in Danish energy provision was solved to a certain degree very fast compared with the alternative nuclear power.

The three radical innovations mentioned in the text above were all based on research-based ideas. In the la Cour-case the innovator was himself an active scientist. However, it was the experimental work with wind tunnels, which was important to improve output of energy from wind. The Agricco-case represented incorporation of accumulated aerodynamic knowledge from Wright brothers until First World War. The blades were strongly inspired from wings in an airplane. However, there were several other important improvements as automatic yawing and pitch regulated blades. It was also the first wind turbine, which delivered AC electricity to the grid. We do not know very much in detail about the way Johannes Jensen and Poul Vinding worked. We know that they were educated engineers. Johannes Juul, the man behind the Gedser turbine did not had an academic education. He had an education as wind electrician from the la Cour education in Askov. After end of First World War, he had been educated as electrician and worked as such. Later on he worked with product development in SEAS (public utility in electricity). He became honorary member of one of Danish engineering association.

The problem today is not lack of radical innovations – there are several concepts. However, there are still potential low hanging fruits from the Danish concept, which seem more promising than trying to develop a radical new concept. First they are not very risky. These potentialities are connected to turbine growth and offshore location.

It is interesting that all large turbine manufacturers today manufacture big turbines. The biggest wind turbines delivered by the three non-Chinese big manufactures today - Vestas, Siemens Gamesa and General Electric have effects about 8 – 9.5 MW. However it is interesting to notice that the way different companies in different countries came from their start position in the end of 1970s, when they manufactured turbines with effect about 50 – 60 kW, to 2 – 3 MW, were very different. The American and the German approach was to go directly to 2 or 3 MW. The rationale was that a big turbine with a factor 40 to 60 times higher effect than the standard state-of-the-art would represent much better economics compared with the small turbines. That strategy can be called the Big Bang strategy. The Danish Step-By-Step strategy to come from small turbines to bigger size was to grow gradual but fast to higher size. Compared with the Big Bang strategy many non-linarites in material and air flows were discovered in practice and could be alleviated from one generation of turbines to the next.

Probably the different strategies between U.S.A. and Germany on one side with their Big Bang and Denmark with its Step-By-Step can be explained from their firm structure – U.S.A. and Germany have very big firms as Boing, Westinghouse and General Electric in U.S.A. and MAN and big electricity utilities in West Germany. In Denmark all wind turbine firms at that time were small and came from manufacturing of agricultural equipment where that market disappeared after a strong investment period from 1971 until 1975 a period in which Denmark became member of the Common Market with its strong subsidizing of agriculture. However history is a little bit more complex. The Gedser turbine which ran 1957 – 67 had an effect of 200 kW. It ran without repair and maintenance and without accidents or serious down time because of security and backup systems. The stop of the turbine after a technical breakdown in a bearing in 1967 took place because pro-nuclear and anti-wind industrial and electricity company forces used the opportunity to stop it. From 1975 to 1978 after American NASA paid for repair. the turbine delivered important data for some additional years. Another big scale wind turbine was the Tvind turbine constructed with an effect of 2 MW 1975 – 78. Because of oscillation problems it has never worked with more than 0.9 MWh. When it began to run, it was the biggest turbine in the world. These two relative big turbines have been very important for Danish and global wind turbine development. However, they were not Big Bang turbines. And especially the Gedser turbine with its back up and security systems were humble towards technical problems. The two Nibe turbines were more like Big Bang in Danish scale. They showed the same problems as in U.S.A. and Germany.

The offshore location development started up with Vindeby wind farm consisting of 11 turbines in 1991. The location is in the Baltic Sea south of the island Lolland. SEAS the electricity utility company which also supported the Gedser turbine in 1950s was one of the partners. However until 2017 offshore wind parks were located in shallow waters (< 50 meter) in which the turbines can be erected on piles driven down in se sea bottom. In 2017 we have the first offshore wind installed at floating platforms North of Scotland with Norwegian Statoil as a main partner.

A point of discussion is the question of continuous growth of turbines in combination of offshore location. The three manufacturers of the biggest turbines today mentioned above in addition with other manufacturers are working with design of still bigger turbines. Maybe growth of turbines will stop about 12 MW. Onshore because of NIMBY (Not-In-My-Back-Yard) in most parts of Europe and offshore at shallow water close to coast. The problems with very big turbines located far away from coasts are difficulties to construct stable platforms. That means it can be more economic cost-efficient to locate a higher number of smaller turbines offshore than a smaller number in the wind park.

Finally we have looked at learning from success and failure in innovation of wind turbines. We found that the American and the German Big Bang strategies in which the aim was to design and manufacture very big turbines with effect 40 – 60 times bigger than what had been done before with success. Especially the German Growian project was a disaster, probably planned by German nuclear power lobby from industry and politics. The American projects represented much more mixed results and not a conspiracy against the aim to find out the possibility to design and manufacture big viable turbines. The technical problems came more from big business engineering arrogance. The NASA funding for refurbishment of the Gedser turbine shows serious interest to know something about wind turbines.

The more humble attitude in Danish wind turbine companies learned from a long history starting with the la Cour turbines in 1891 and culminating with the Gedser turbine 1957 – 67 and its revival 1975 -78 was decisive for the 7 Danish companies erecting 25 percent of all wind turbines during the Californian Wind Rush 1980 –

86. The well documented track of quality and very low down time of the Gedser turbine was what convinced the Californian investors and authorities.

One more comment about learning from success and failure. When Vestas in 1979 had developed their first turbine for the market, which was a Darrieus turbine, the result was not satisfactory. Vestas do not has told the outside world precisely what problems were. We have only been told that there were technical problems. However the firm bought from another firm by license a design according to the Danish Concept and learned in that way that the darling of many engineers - the Darrieus Concept - should not be trusted in. All the seven Danish wind turbine companies delivering to California 1981 – 86 were using the Danish Concept.