



Paper to be presented at the DRUID 2011

on

INNOVATION, STRATEGY, and STRUCTURE -
Organizations, Institutions, Systems and Regions

at

Copenhagen Business School, Denmark, June 15-17, 2011

Geometric Scaling, Long Term Reductions in Cost, and Implications for Public Policy: the case of wind turbines

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Abstract

This paper shows that long-term reductions in the cost of electricity from wind turbines have come more from increasing the scale of wind turbines than from increases in their cumulative production. This suggests that policies to promote the diffusion of wind turbines should consider scaling more than they should cumulative production, which current policies promote. Current policies primarily emphasize demand-based subsidies since many believe that these subsidies will encourage production and thus reductions in the cost of manufacturing wind turbines. However, by showing that increases in the scale of wind turbines has been the major source of cost reductions, this paper's results suggest that supply-based policies, such as those that fund research on better materials for wind turbine blades, will probably be more effective than those of demand-based subsidies.

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1. Introduction

An increasing demand for technologies that can help the world deal with energy, environmental, health and other problems increases the need for a better understanding of where long-term improvements in the performance and cost of technologies come from. The conventional wisdom is that the cost of producing a product drops a certain percentage each time the cumulative production of a product doubles in a so-called learning or experience curve (Arrow, 1962; Ayres, 1992; Huber, 1991; Argote and Epple, 1990; March, 1991), as automated manufacturing equipment is introduced and organized into flow lines (Utterback, 1994). Although such a learning curve does not explicitly exclude activities done outside of a factory, the fact that these learning curves link cost reductions with cumulative production focuses policy and other analyses on the production of the final product and imply that learning done outside of the factory is either unimportant or is being driven by the production of the final product.

A second limitation with learning and experience curves is that they do not explain why some technologies experience more improvements in cost and performance than do other technologies. For example, integrated circuit (ICs), magnetic disks, optical disks, fiber optics and the products that are assembled from them (e.g., computer and telecommunication systems) have experienced what some call “exponential” improvements in cost and performance in the second half of the 20th century. For example, the average price of a transistor dropped more than six orders of magnitude in thirty years and the average cost per computation dropped eight orders of magnitude in forty years (Kurzweil, 2005). Why did these technologies experience such levels of improvements while others have not?

The notion of geometric scaling may explain why some technologies experience more improvements in cost and performance than do other technologies (Kurzweil, 2005; Funk, 2011). Geometrical scaling refers to the relationship between the geometry of a technology, the scale of it, and the physical laws that govern it. Technologies that benefit from large

reductions (e.g., transistors and integrated circuits) or large increases (e.g., engines, production equipment, wind turbines) in physical scale often experience large improvements in cost and performance where the extents of these improvements can be analyzed using the concept of geometrical scaling (Nelson and Winter, 1982; Sahal, 1985; Lipsey et al, 2005; Winter, 2008). Nevertheless, many argue that insufficient research has been done on geometric scaling by social scientists and more research is needed (Winter, 2008). Research questions include: 1) how large are the benefits from large increases or large reductions in scale for specific technologies; 2) what determines the limits to this scaling; 3) what impact should the existence of these benefits from scaling and the limits to scaling have on policies?

After reviewing the relatively small literature on geometric scaling, this paper applies the concept to wind turbines, a technology that may help reduce carbon emissions and thus avert global warming (Zervos, 2008). It describes the scientific theory and shows the empirical evidence for a link between geometric scaling and long-term cost reductions in the electricity generated from wind turbines. By showing that long-term reductions in the cost of electricity from wind turbines have come more from increasing the scale of wind turbines than from increases in their cumulative production, this paper's results suggest that policies to promote the diffusion of wind turbines should consider scaling more than they should cumulative production, something that is ignored by existing studies (Nemet, 2009). Current policies primarily emphasize demand-based subsidies since many believe that these subsidies will encourage production and thus reductions in the cost of manufacturing wind turbines. However, by showing that increases in the scale of wind turbines have been the major source of cost reductions, this paper's results suggest that supply-based policies, such as those that fund research on better materials for wind turbine blades, are probably better than those of demand-based subsidies. This paper concludes by suggesting further avenues of management and economic research on wind turbines, other forms of clean energy, and new technologies in general.

2. Geometrical Scaling

Geometrical scaling refers to the relationship between the geometry of a technology, the scale of it, and the physical laws that govern it. Or as others describe it: the “scale effects are permanently embedded in the geometry and the physical nature of the world in which we live” (Lipsey et al, 2005). Technologies can benefit from either large increases or large reductions in scale and technologies that benefit from geometric scaling over a broad range of either *larger* or *smaller* scale typically have more potential for improvements in cost and performance than do technologies that do not benefit from geometric scaling or that benefit from geometric scaling only over a narrow range of scale (Lipsey et al, 2005; Winter, 2008).

For technologies that benefit from reductions in scale, the benefits can be particularly large. This is because for most technologies, the costs of material, equipment, factory, and transportation typically fall over the long term as size is reduced. However, the performance of only some technologies such as ICs and magnetic and optical storage experience increases in some aspects of performance as size is reduced. For example, placing more transistors or magnetic or optical storage regions in a certain area can increase the speed and functionality and reduce both the power consumption and size of the final product, which are typically considered improvements in performance for most electronic products. The combination of both increased performance and reduced costs as size is reduced has led to exponential changes in the performance to cost ratio of many electronic components (Kurzweil, 2005).

On the other hand, some technologies benefit from increases in scale. In these cases, output is roughly proportional to one dimension (e.g., length cubed or volume) more than is the costs (e.g., length squared or area) thus causing output to rise faster than costs, as the scale of the technology is increased (Lipsey et al, 2005). For example, some argue that the output from steam, internal combustion, and jet engines has increased faster than has their costs as their scale was increased since the output from cylinders, pistons, and boilers is a function of

volumes while their costs are roughly a function of their outer surface areas (Sahal, 1985; Lipsey et al, 2005). Empirical analyses support this argument. Analyses have found that the prices per horsepower of large steam (10 times) and internal combustion engines (100 times) were 1/3 and 26% those of smaller engines respectively (von Tunzelman, 1978; Funk, 2011). Extrapolating these improvements to the full range of scale for which these engines have been implemented suggests that the real cost per horsepower may have dropped more than 99% over hundreds of years (Funk, 2011).

Similarly, others argue that the cost per passenger or freight-mile for ships, buses, trucks, and aircraft did not rise as fast as did their carrying capacity because their costs are roughly a function of the transportation equipment's external surface area while output is function of the equipment's volume (Sahal, 1985; Lipsey et al, 2005). Empirical analyses also support this argument. One analysis found that the price per capacity of large oil tankers and commercial aircraft are about 41% and 81% those of smaller ones respectively (Funk, 2011). Like the engines, extrapolating to the full range of scale for which transportation equipment have been implemented suggests that the real costs per capacity may have dropped by about 95% for oil tankers and 50% for commercial aircraft over the last 70 to 130 years (Funk, 2011).

The best known example of this type of geometrical scaling can be found in the production of liquids and gases, where there is a fairly large literature on scaling in chemical engineering journals (Mannan, 2005). While economies of scale refers to amortizing a fixed cost over a large volume at least until the capacity of the equipment is reached, geometrical scaling drives further reductions in the equipment cost per unit as the scale of the equipment is increased. For chemical plants, the equipment is basically in the form of pipes and reaction vessels. Scholars have noted that the costs of pipes (surface area of a cylinder) vary as a function of radius whereas the output from a pipe (volume of flow) varies as function of radius squared. Similarly, the costs of reaction vessels vary as a function of surface area

(radius cubed) whereas the output of a reaction vessel varies as a function of radius cubed. Empirical analyses has found that the costs of these plants only rose about two-thirds for each doubling of output and thus increases in the scale of chemical plants have led to dramatic reductions in the cost of many chemicals (Haldi and Whitcomb, 1969; Levin, 1977; Rosenberg, 1994; Freeman and Soete, 1997).

Some readers might call geometrical scaling and the activities associated with its implementation “learning” since all improvements involve some form of learning and a certain type of learning is probably required to exploit geometrical scaling. However, so-called learning or experience curves focus on cumulative production and imply that learning done outside of the factory is either unimportant or is being driven by the production of the final product. Furthermore, since much of the management literature on learning primarily focuses on the organizational processes that are involved with learning, this literature implies that the organization and not the characteristics of the technology is the bottleneck for improving the performance or costs of a technology (Arrow, 1962; Ayres, 1992; Huber, 1991; Argote and Epple, 1990; March, 1991). Thus, while the management literature on learning implies that solving energy and environmental problems is primarily an organizational issue, the concepts of geometrical scaling and technology paradigms remind us that the *potential* for improving the cost and performance of a technology depends on the characteristics of the technology. Without a *potential* for improvements either in the form of geometrical scaling or more generally a “good” technology paradigm, it would be difficult for organizational learning to have a large impact on the costs and performance of a technology no matter how innovative the organization is.

3. Research Context

Although humans have used the wind for thousands of years to do work in for example, a so-called wind mill, this paper is primarily concerned with more recent efforts to use wind

turbines to generate electricity in so-called wind farms. These wind farms are located in areas with high wind speeds and thus are located far from populated areas where demand for electricity exists. Since long and expensive transmission lines are required to connect the wind farms to populated areas, these wind farms typically contain a large number of wind turbines in order to reduce the cost of the transmission lines per wind turbine output.

Looking just at the wind turbine, the so-called horizontal axis wind turbine emerged as the dominant form (or so-called dominant design) of wind turbine in the 1980s. As shown in Figure 1, in this design three blades sweep an area in which the diameter of the area is called the rotor diameter (Bellarmine and Urquhart, 1996; Clausen and Wood, 1999; Veers et al, 2003; Shikha et al, 2005; Nemet, 2009). The rotation of this rotor turns a generator and the rotation of this generator creates electricity in the same way that the rotation of a generator creates electricity in a coal, nuclear, or oil-fired power plant. The main difference between the wind turbine and these other methods of generating electricity is that the kinetic energy of the wind drives the rotation of a wind turbine's generator while the kinetic energy of steam drives the rotation of a generator (through a steam turbine) in the latter three methods. As shown in Figure 2, in addition to the three blades which are together called the rotor, the wind turbine also consists of a drive train, generator, controls, and a tower. Because the blades and the tower represent the largest percentage of costs, this paper focuses on them and the interaction between their scale, costs, and power output.

4. Research Methodology

The research for this paper included a broad search for relevant data in a large number of sources including technical reports from various Wind Energy Associations such as the World, the British, the Danish, and the American Wind Energy Associations (BTM, 2009; Burton, 2001; BWEA, 2000; DW, 2010; EWEA, 2010; IEA, 2002). From these reports it was found that good data on the cost and output of wind turbines is available much more at the level of

the wind turbine than at the level of the wind farm. Thus, this paper focused on wind turbines and the benefits from increasing the scale of them; this includes both the scale of the rotor and the tower height. Focusing on the wind turbine and the components of the rotor and the tower make sense because more than 2/3 the cost of electricity from wind turbines comes from the capital cost of a wind turbine and almost half the capital costs are in the rotor (including the turbine blades) and the tower (Krohn et al, 2009).

Data on the rotor diameter and output of wind turbines was taken from previous analyses of wind turbines and supplemented by analyses of more recently introduced wind turbines by one author of this paper. In particular, Henderson et al (2003) collected data on the rotor diameter (in metres) and power rating of the generator (in watts) from commercial turbines for both onshore and offshore applications. They analyzed wind turbines from leading manufacturers such as Vestas, Nordex, Bonus, and NEG Micon. Their analysis covered wind turbines with rotor diameter up to 80 meters.

This data was supplemented by a more comprehensive analysis of wind turbines by one of the authors, who was previously an employee of Vestas. This author collected data on rotor diameter, output, and maximum rated wind speeds for a larger number of wind turbines than was collected by Henderson et al (2003) and this analysis includes the most recently introduced wind turbines by a large number of manufacturers. These manufacturers include Vestas, GE Wind, Enercon, Windey, WinWind, Suzlon, Sinovel, Siemens, Sewind, Repower, Nordex, Mingyang, Hunan, Goldwind, Gamesa, Fuhrlander, Ecotechnia, Dongfang and Acciona.

Similarly, rotor cost data for these wind turbines was taken from three previous analyses of them. First, cost data for rotors introduced before 2000 were taken from Hassan's (2001) analysis of them. He provides cost data for them as a function of rotor area from Nordex, An-Bonus, NEG Micon, Vestas, Enercon, BWU-Jacobs, Enron-EW, Fuhrlander, NEG-Micon, PWE-1566, Sudwind, Made-AE, Second, data on cost per rotor area for more recently

introduced wind turbines with rotor diameters less than 50 meters were taken from EWEA (2010). Third, data on cost per rotor area for more recently introduced wind turbines with rotor diameters greater than 50 meters were taken from Hau (2008). Regression analysis of the collected data was performed to analyze the benefits from increasing the scale of the rotor diameter.

Finally, output and cost data with respect to tower height were taken from Hau (2008) and (Malcom and Hansen, 2006). This data was used to analyze the benefits of increasing the height of the tower.

5. Geometric Scaling in Wind Turbines

The theoretical output from a wind turbine can be calculated from basic physics. As shown in equation (1), the electric power (P) is in energy per second, it is generally expressed in watts, and it depends on the diameter of the rotor (D) squared and the wind speed (V) cubed.

$$\text{Turbine power output by Rotor } (P_R) = 3.229D^2V^3 \quad (1)$$

Equation 1 suggests a number of ways in which wind turbines might benefit from increases in their scale. First, the output from a rotor depends on the square of the rotor diameter (in meters) and thus the cost of electricity from the wind turbine might fall as the diameter increases, as long as the cost of the wind turbine rises at a rate less than diameter squared. Second, the cost of electricity from the wind turbine might fall as the diameter increases if larger diameter rotors enable a wind turbine to handle higher wind speeds. Although wind velocity is typically not constant and thus might be represented as a probability distribution, this paper treats it as a constant to simplify the analysis.

5.1 The Output from Wind Turbines

Empirical data confirms that larger diameter rotors lead to much higher power output. As shown in Figure 3, the output from a wind turbine does increase with rotor diameter and it is not just a linear function of diameter. Performing a least square fit of the turbine power output (in Kilo Watt) with respect to the rotor diameter (in meter) shows that the output increases even faster than does diameter squared, which is shown in equation (2).

$$\text{Turbine Power Output in Kilo-watt (P}_R\text{)} = 0.1034 * \text{Rotor Diameter}^{2.254} \quad (2)$$

The reason why the output from a wind turbine rises faster than does diameter squared in equation (2) is that equation (2) does not contain wind velocity, which as noted above has a large impact on output. It does not contain wind velocity since the turbines used for the collection of data on power and rotor diameter for Figure 3 operate under different wind speeds and these wind conditions are not known.

The impact of rotor diameter and other factors on wind speed was investigated in three ways. First, data on rotor diameter and on maximum rated wind speed were collected from various product catalogues. Performing a least square fit of the maximum rated wind speed with respect to the rotor diameter (in meter) shows that the maximum rated wind speed increases as a function of rotor diameter as shown in equation (3).

$$\text{Rated wind speed (m/sec)} = 9.403D^{0.081} \quad (3)$$

Second, partly since less of the wind can be harnessed at the tips of the blades than near the center of the rotor, larger rotors (as do larger gear boxes) translate a greater percentage of the available wind into electricity than do small rotors. Empirical data from one study (Gipe, 1995) confirms this theoretical argument. As shown in Table 1, larger turbines (>25 meters)

convert more of the wind energy to electricity than do small turbines (<25 meters).

Third, other evidence for the impact of increased rotor diameter on efficiency can be found in the recent increase in rotor diameter by Vestas. Vestas recently released a new turbine with 112 meter rotor diameter compared to its previous product (V90 model) that had a 90 meter rotor diameter. Although both turbines have the same generator capacity of 3 MW, the larger diameter one is able to utilize more of the wind and thus generate more power than the smaller diameter one at wind velocities of eight to ten meters per second (See Figure 4). These wind speeds are the most common wind speeds in many regions.

Another scale-related design variable that impacts on wind turbine performance is the placement height of the rotor or so-called tower height. Since wind velocity is often lower near the ground due to uneven terrain or buildings, higher towers enable a wind turbine to utilize higher wind speeds as shown in Equation 4 (Hau, 2008). The factor ‘ α ’ depends on the condition of the terrain and in particular on the impact of the terrain on wind friction where field measurements show that the alpha is typically around 0.32 (Hau, 2008). Since wind power output varies with the cube of the wind speed as described by equation (1), higher towers and thus higher wind speeds can have a large impact on the output of the wind turbine. Combining equations (1) and (4) leads to equation (5). As shown in equation (5), since the exponent for the ratio of the two heights is 3α , an α of 0.32 would cause a doubling of the tower height to result in a 94% increase in power output.

$$\left(\frac{V}{V_{ref}} \right) = \left(\frac{H}{H_{ref}} \right)^\alpha \quad (4)$$

$$P = P_{ref} \left(\frac{H}{H_{ref}} \right)^{3\alpha} \quad (5)$$

5.2 The Cost of Wind Turbines

Now let's consider the cost of the wind turbines. Since more than 2/3 the cost of electricity from wind turbines comes from the capital cost of a wind turbine and almost half the capital costs are in the tower and the blades (Krohn et al, 2009), this section focuses on the tower and the blades. Beginning with the tower, this paper uses the results found by the so-called WindPACT analysis (Malcom and Hansen, 2006), which found a regression coefficient of 0.999 for equation (6). Representing the cost of steel as 'c' (\$/Kg) the tower cost curve can be expressed in terms of the tower height (H) and rotor diameter (D) as shown in equation (6).

$$\text{Tower cost (in \$)} = 0.85 (cD^2H) - 1414 \quad (6)$$

Comparing equations (5) and (6), the output from the turbine increases faster than do the costs as the height is increased. For example, if alpha is equal to 0.32 as was shown above and assuming a constant rotor diameter, increasing the height from 10 meters to 20 meters would cause the output to rise by 94% and the costs to rise by 9 percent. This suggests that higher towers, which are often needed for larger rotors, can lead to lower cost of electricity from wind turbines.

Turning to the blades, their costs are usually analyzed in terms of cost per area swept by the blades, or in other words, cost per rotor area. Figure 5 shows the cost per area versus rotor diameter. Two trends can be noticed in this figure. First, there are falling costs per area up to 50 meter-diameter rotors. Second, for diameters greater than 50 meters, the cost of the rotor per square meter exhibits an increasing trend. Performing a least square regression fit for the manufacturing costs against the rotor diameter for rotors less than and greater than 50 meters leads to equations (6) and (7).

$$D < 50 \text{ meters: Rotor cost per square meter (Euro/square meter)} = 434.D^{-0.0742} \quad (6)$$

$$D > 50 \text{ meters: Rotor cost per square meter (Euro/square meter)} = 96.7D^{0.3257} \quad (7)$$

Ideally we would like to compare equations (6) and (7) to equation (2) while also taking into account the benefits from the higher wind speeds that larger rotor diameters and higher towers can handle. However, since a single data base that contains data for all of these variables does not exist, equations (6) and (7) are only compared to equation (2). Translating equation (2) into output per square meter and then dividing equations (6) and (7) by the equation representing output per square meter gives us equations (8) and (9). Equation (8) shows the large benefits to increasing the scale of the rotor diameter. The cost per output falls very quickly in equation (8) leading to the large reductions in the cost of electricity for wind turbines that were installed in the 1990s.

$$D < 50 \text{ meters: Cost/output} = 434D^{-0.0742-0.254} = 434D^{-0.328} \quad (8)$$

$$D > 50 \text{ meters: Cost/output} = 935.2D^{0.3257-0.254} = 935.2D^{0.103} \quad (9)$$

This suggests that reductions in the cost of electricity from wind turbines, at least for diameters less than 50 meters, have come from increases in scale rather than from increases in cumulative production. If there were greater benefits from increases in cumulative production, wind turbine manufacturers would have made small wind turbines in large quantities. For example, since output is a function of rotor diameter squared, wind turbine manufacturers could achieve the same level of output with 100 10-meter wind turbines as with one 100-meter diameter wind turbine. Doing the latter would accelerate increases in cumulative production and according to the conventional wisdom lead to large reductions in the cost of electricity from wind turbines. The fact that they installed large wind turbines and that the large wind turbines, at least up to 50 meters, can produce electricity much more cheaply than smaller wind turbines suggests that most of the cost reductions have from

increases in the scale of wind turbines.

On the other hand, equation (9) suggests that there may be some limits to scaling. The cost per output rises slowly as the rotor diameter is increased beyond a diameter of 50 meters. Although we cannot say with a strong probability that benefits to scaling do not exist for rotor diameters greater than 50 meters, it is clear that the impact of increased scale on cost per output is very different for rotor diameters greater than 50 meters than for those less than 50 meters. The reason for the change in the slope of the line in Figure 5 for diameters greater than 50 meters is that different kinds of materials are needed for diameters greater than 50 meters than for diameters less than 50 meters. While aluminum, glass fiber reinforced composites, and wood/epoxy based designs can be used for diameters of less than 50 meters, carbon fiber-based blades are needed for diameters of greater than 50 meters.

Carbon fiber-based blades have higher strength-to weight ratios than the other materials and these high strength-to weight ratios are needed to reduce the stresses on both the blades and the adjacent components such as the gear box, turbine, and the tower. The problem is that these carbon fiber-based blades have much higher costs than the previous types of blades. While the early types of blades can be manufactured with methods borrowed from pleasure boats such as “hand lay up” of fiber-glass reinforced with polyester resin in an open mould, the carbon-based blades require better manufacturing methods such as vacuum bagging process and resin infusion method that have been borrowed from the aerospace industry (Ashwill, 2004).

We can draw several conclusions from this analysis. First, the fact that the relationship between cost and output changed so abruptly as the rotor diameter increased beyond 50 meters provides further evidence that the conventional wisdom about costs falling as cumulative production rises is not very accurate. Not only have costs fallen as the scale of the wind turbine was increased for rotor diameters less than 50 meters, the abrupt change in the relationship between cost and output as the rotor diameters increased beyond 50 meters

suggests that cost reductions have slowed considerably or may have even been reversed. The conventional wisdom cannot address such situations since the conventional wisdom does not provide any details about the mechanism by which costs fall and in some ways implies that costs continue to fall particularly as automated production equipment is implemented and organized into flow lines (Utterback, 1994).

Second, the above analysis suggests that new materials and manufacturing processes for the turbine blades are needed to continue the cost reductions in electricity from wind turbines. Increases in R&D spending on these materials and their manufacturing processes are certainly important policy measures and it may be better to fund these supply-based measures than to fund demand-based subsidies. Cost reductions may also come from increasing the scale of the production equipment in the same way that increasing the scale of chemical plants led to dramatic reductions in the cost of chemicals (Axelrod et al, 1968; Haldi and Whitcomb, 1969; Levin, 1977; Rosenberg, 1994; Freeman and Soete, 1997). In the case of turbine blades, it is mostly about increasing the rate at which these blades are “cured” in large molds (Sutherland, 2000).

Third, another way to reduce the costs of these blades is to assemble large blades from smaller pieces on site with ultra-strong adhesives where improvements in the strength of adhesives are also being driven by the needs of the aircraft industry. Since molding costs rise faster than do the volume of the parts as the parts are made larger, assembling blades from smaller pieces can reduce the cost of their manufacture. Furthermore, doing this would also reduce the costs of delivery and installation, which is another problem that has emerged with large wind turbines. Transporting blades that have lengths larger than 50 meters is particularly a problem in cities and towns and this cost may represent as much as 20% of a wind turbine's total installation cost (Zervos, 2008). Assembling blades from smaller pieces on site would reduce the delivery and installation costs along with manufacturing costs. The challenge is to develop the adhesives necessary to prevent any chance of failure during

operation of the wind turbine.

Fourth, some of these kinds of improvements also provide partial support for the notion that costs fall as manufacturing processes are improved, automated manufacturing equipment is introduced, and the equipment is organized into flow lines (Utterback, 1994). Although the main analyses for this paper suggest that the largest reductions in the cost of electricity from wind turbines have come from increases in the scale of the wind turbine, further reductions in this cost, either in support of further increases in rotor diameter or merely for existing rotor diameters, may partly come from improvements in manufacturing processes.

6. Discussion

This paper explores the little understood phenomenon of geometric scaling. In contrast to the conventional wisdom that costs fall according to the so-called learning or experience curve (Arrow, 1962; Ayres, 1992; Huber, 1991; Argote and Epple, 1990; March, 1991) as automated manufacturing equipment is introduced and organized into flow lines (Utterback, 1994), this paper's results suggests that increases in the scale of wind turbine has played a larger role in the reductions in cost of electricity from them than has increases in their cumulative production. Using the scientific theory of wind turbines and empirical evidence from their operation, it showed how increases in rotor diameter and tower height led to large reductions in the cost of electricity from wind turbines.

Output increased faster than did cost as rotor diameter and tower height were increased. This is partly because output increases as the square of rotor diameter while costs rose much more slowly, particularly for rotor diameters that were less than 50 meters. It is also partly because increases in rotor diameter increased both the maximum allowable wind speed and the percentage of a wind's kinetic energy that is translated into electricity. The second factor is important because the output of a wind turbine is a function of wind speed cubed.

On the other hand, the benefits to increasing the scale of the rotor diameter seem to be

smaller for rotor diameters over 50 meters. This is because increasing the scale of the rotor diameter beyond 50 meters has required materials that have much higher strength-to weight ratios and thus much higher costs than do the materials used in smaller wind turbines. Thus, the realization of further cost reductions from increasing the scale of wind turbines will require the development of new materials with higher strength-to weight ratios. The development of these new materials will probably require further R&D spending on these materials and thus increases in the overall R&D spending by the industry.

This paper's analysis has important implications for public policy. While the conventional wisdom that costs fall according to the so-called learning or experience curve (Arrow, 1962; Ayres, 1992; Huber, 1991; Argote and Epple, 1990; March, 1991), as automated manufacturing equipment is introduced and organized into flow lines (Utterback, 1994), suggests that increasing the production of wind turbines through for example demand-based subsidies is the best policy, this paper's analysis suggests that supply-side policies may be a better policy. While demand-based policies may encourage the production and installation of wind turbines, they may not encourage increases in scale or the development of materials that will enable these increases in scale. Instead, supply-side subsidies such as direct funding of R&D on new materials may have a greater impact on further cost reductions than do demand-based subsidies.

This paper's results suggest a number of avenues for future management and economic research on wind turbines, other forms of clean energy, and new technologies in general. First, future research should look more closely at the materials needed to support further scaling in wind turbines and perhaps search for designs that may benefit from increases in scale more than does the horizontal-axis wind turbine. Although engineers in the wind turbine industry may understand these issues, it appears that public policy and management research is overlooking these issues and thus recommending policies that may not be appropriate.

Second, other research should look at the role of scaling in other forms of clean energy

such as in solar cells. If scaling is an important source of long-term cost reductions in solar and other new technologies, as some research suggests (Funk, 2011), supply-side policies may be more appropriate than demand-side policies, something that many business leaders such as Bill Gates also advocate¹. Third, research on scaling should also be conducted in order to better understand production functions (Winter, 2008). If scaling plays an important role in the long-term cost reductions of many technologies, the literature on production functions could benefit from greater research on scaling. Fourth, if firms are increasing the scale of wind turbines more than is economically viable, as this paper's research suggests may be happening, then research should look at why this is happening. Not only do some argue that firms implemented too large a scale of electrical generating plants in the U.S. in the 1950s and 1960s (Munson, 2005), the management literature suggests that firms often misunderstand new technologies for a variety of reasons (Tushman and Anderson, 1986; Henderson and Clark, 1990; Henderson, 1995). This suggests there is a cognitive side to scaling.

7. Conclusions

This paper shows that long-term reductions in the cost of electricity from wind turbines has come more from increasing the scale of wind turbines than from increases in their cumulative production. This suggests that policies to promote the diffusion of wind turbines should consider scaling more than they should cumulative production, which current policies promote through demand-based subsidies. This paper's results suggest that supply-based policies, such as those that promote improvements in the strength-to weight ratio of materials for wind turbine blades, will probably be more effective than those of demand-based subsidies.

¹ See Jason Pontin's interview of Bill Gates in Technology Review, Q&A: Bill Gates, The cofounder of Microsoft talks energy, philanthropy and management style, August 24, 2010, <http://www.technologyreview.com/energy/26112/page1/>, accessed on August 26, 2010.

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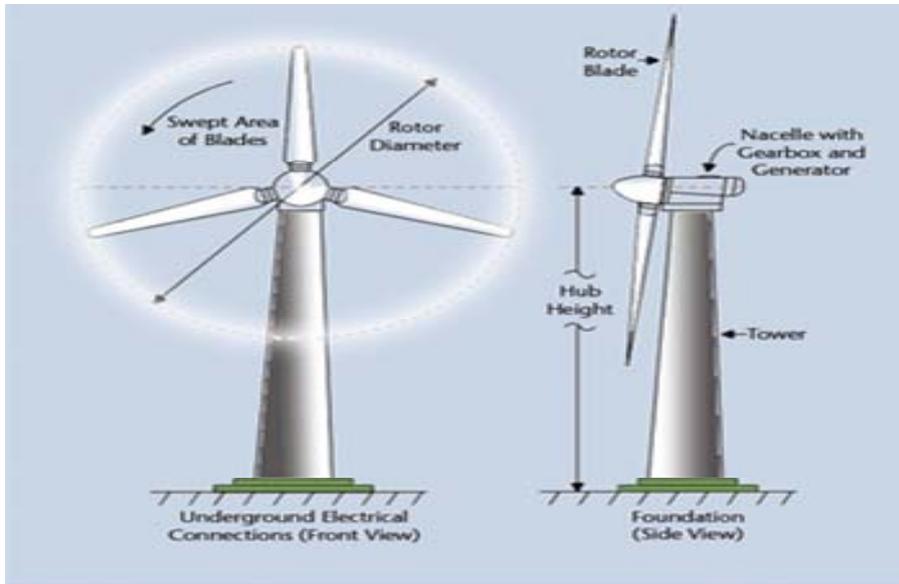
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Figure 1. Horizontal Axis Wind Turbine



Drawing of the rotor and blades of a wind turbine, courtesy of ESN

Figure 2. Typical horizontal axis wind turbine with major core components

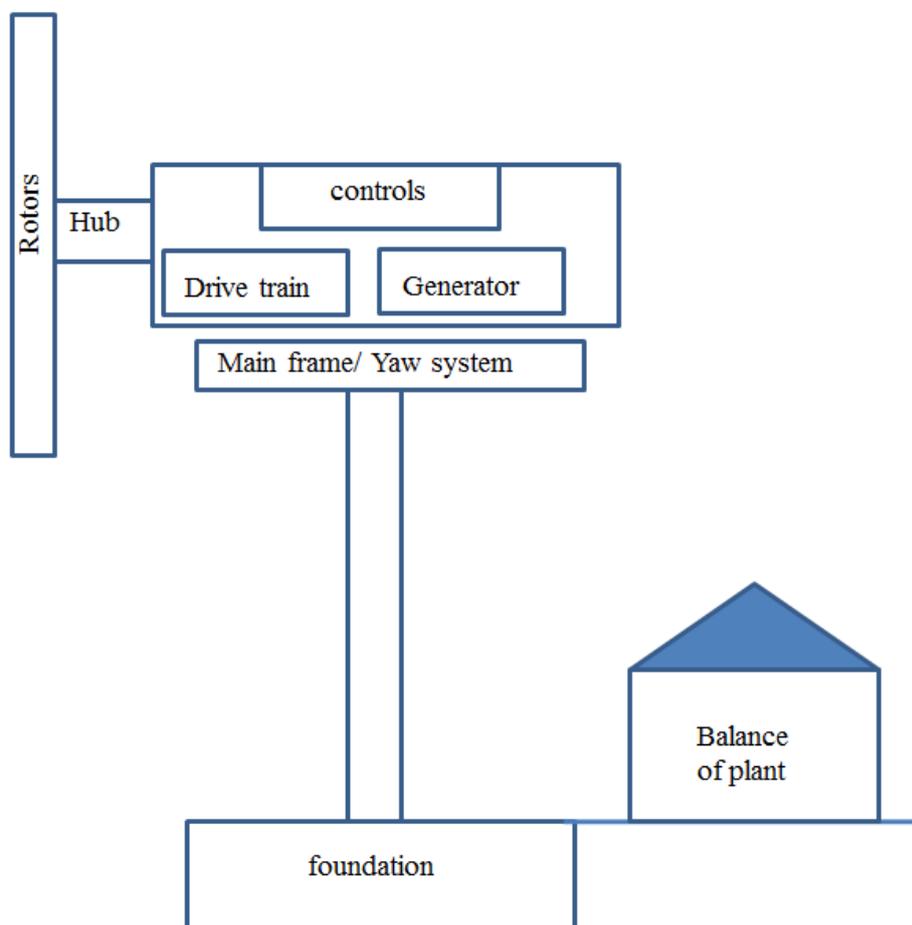


Figure 3. Power Output vs. Rotor Diameter

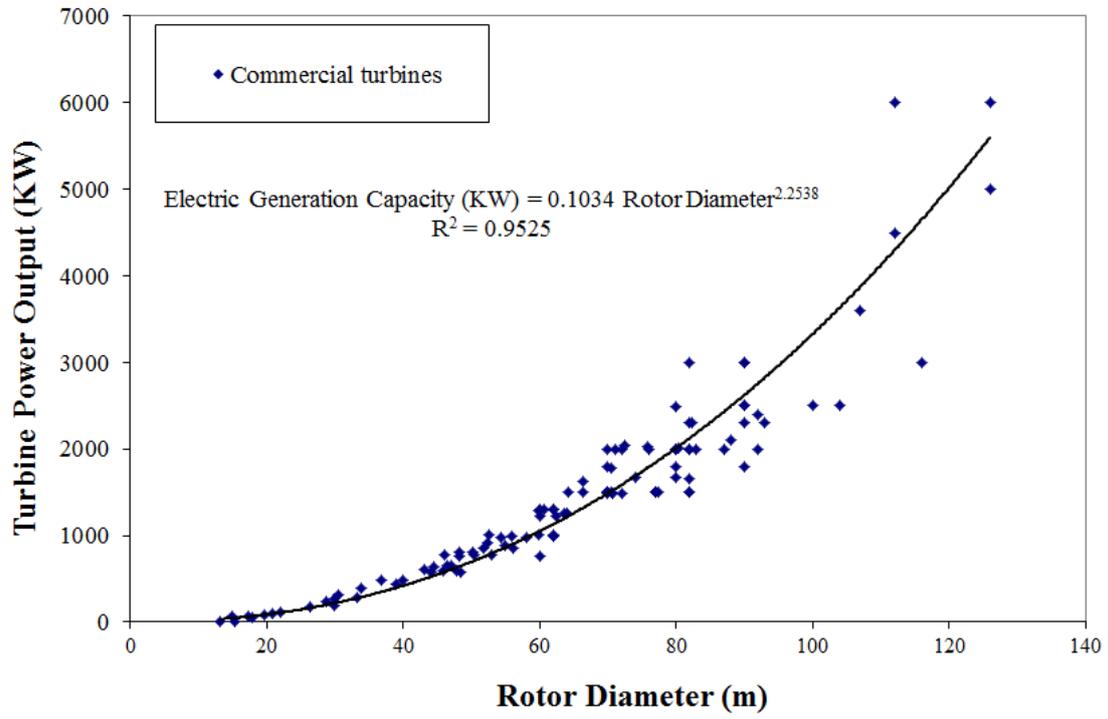


Figure 4. Output vs. Wind Velocity for two different rotor diameters (112 vs. 90 meters)

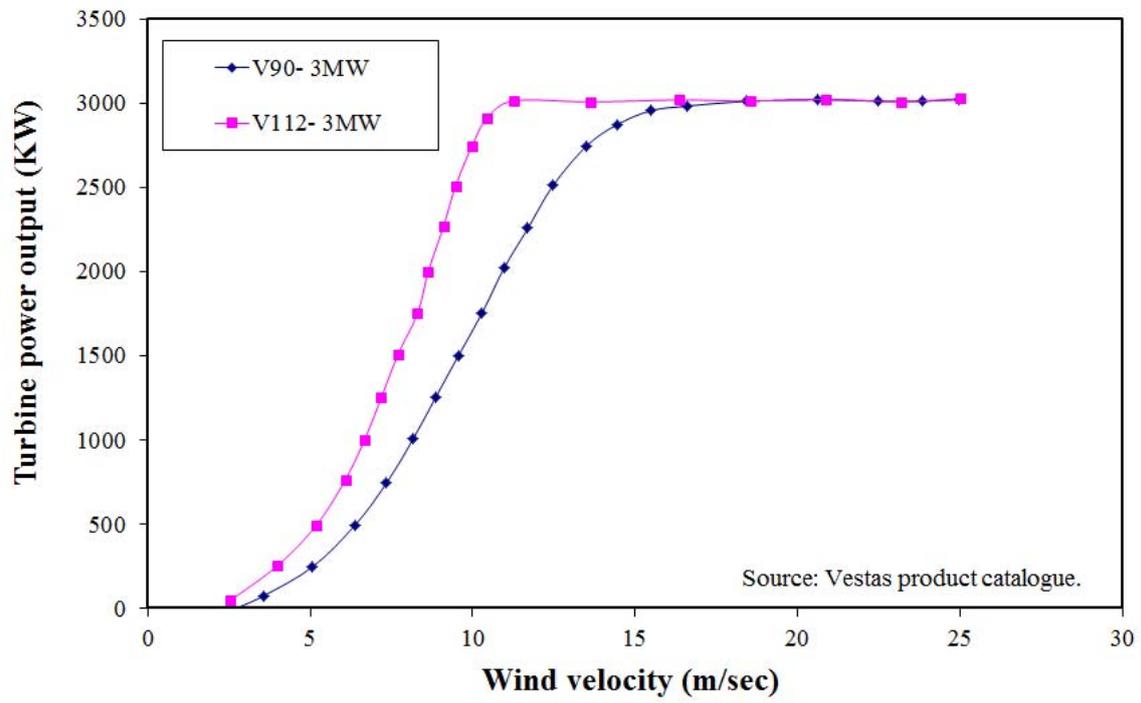


Figure 5. Typical specific manufacturing cost of rotor on per unit swept area for different rotor diameter.

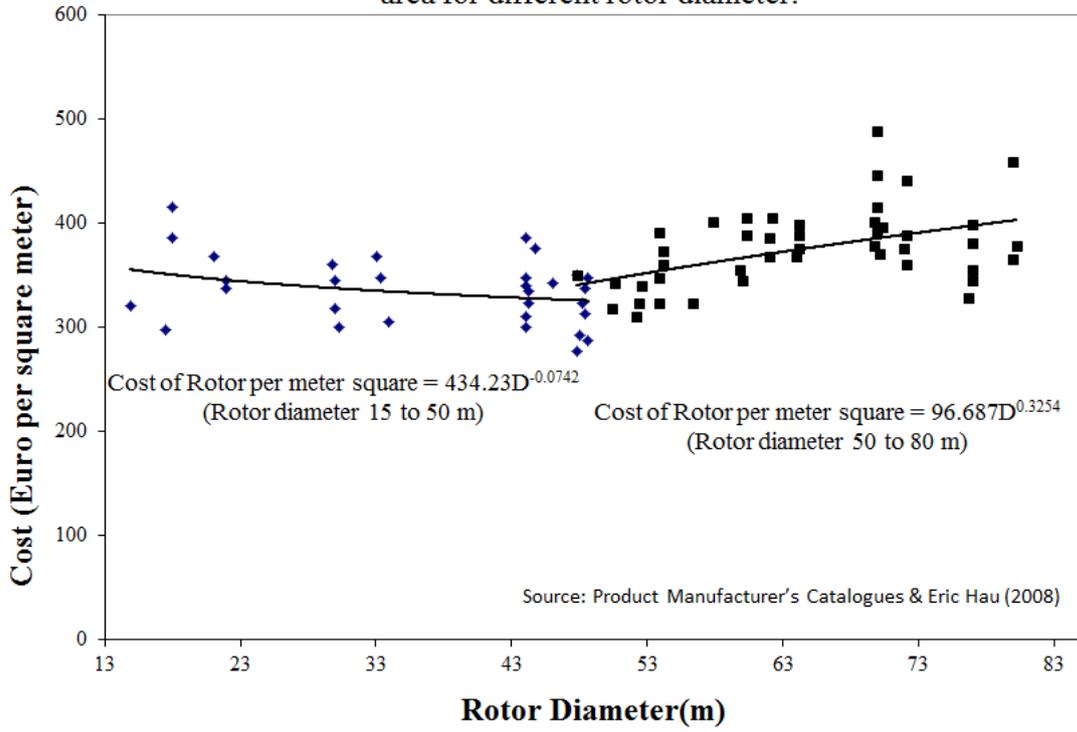


Table 1. Efficiencies of small and large turbines

Average wind speed (m/sec)	Maximum Power density achievable (W/m²)	Small turbine (<25 meters) efficiency	Large turbine (>25 meters) efficiency
4	75	19%	35%
5	146	20%	37%
6	253	18%	35%
7	401	17%	31%
8	599	15%	26%
9	853	14%	21%

Source: (Gipe, 1995)