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Resource and Environmental Strategies

ANALYSIS OF WIND TURBINE COST REDUCTIONS: THE ROLE OF RESEARCH AND DEVELOPMENT AND CUMULATIVE PRODUCTION

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Policymakers and energy modelers need to know the likely costs and benefits of promising technologies in order to assess alternative policy options. The costs and performance of renewable energy technologies can improve owing to technology learning and scale economies, which can be driven by policy. Thus, policy makers would value a better understanding of the causes of cost reductions in order to improve the effectiveness of policies to promote renewables. In this paper we discuss some of the factors affecting wind turbine technology costs and develop a simple model based on manufacturing output and research and development (R&D) spending. The results indicate that cumulative R&D and cumulative production are important factors that contribute to reductions in the cost of electricity from wind turbines. Policy makers and modelers can use this tool to asses policies such as the renewable portfolio standard (RPS) and R&D subsidies, as well as more general policies such as emission taxes or cap/trade systems.

TECHNOLOGICAL LEARNING

Conventional Learning Theory

In "The Economic Implications of Learning by Doing" (1963), Kenneth Arrow first observed that manufacturing costs tend to decline with the level of experience in manufacturing. The general learning curve model is shown in Box 1. Implicit in Arrow's model is the assumption that all cost reductions can be explained by cumulative production. However, other variables can affect cost reductions, through learning and innovation. By expanding the model to capture the other factors, a better representation of the relative impacts on costs can be achieved.

Box 1 General Learning Curve Model

$$C = CP^{\beta} \bullet A$$

<u>where</u>:

C	manufacturing cost per unit;
CP	cumulative number of units produced;
β	elasticity of the learning curve;
A	constant

Factors of Cost Reduction and Innovation

A variety of factors directly influence cost of production and, ultimately, the manufacturing cost per unit of a technology (e.g. $/kW installed or $/kWh of generation).

Materials

In any complex manufacturing process with multiple steps, **improvements in yield** for each step, especially later ones, can leverage significant cost reductions. For example if a machine packages finished units into crates but breaks half of them in the process, the indirect cost of the packaging machine is sizable. Because manufacturers study their existing processes and use trial and error to make iterative adjustments, increases in yield are, by and large, driven by cumulative production. If even greater improvements in yield are needed, R&D spending will be necessary to develop an entirely new process.

Manufacturers can also reduce costs by **reducing the amount of materials** used. As more units are produced, the manufacturer may experiment with design changes that reduce materials use, both in the product and as discarded waste, without sacrificing the performance of the product. A small level of R&D may be devoted to this cost reduction strategy, but experience, represented by cumulative production, is the predominant driver.

Another way to reduce costs is by **replacing expensive materials** with less expensive ones. Because the jump from one type of material to another is more involved than a simple reduction in material usage, R&D spending better explains this strategy. For example, suppose a manufacturer must develop a new chemical for use in production. New materials are developed through R&D and do not simply evolve through more experience with existing ones.

Throughput

With most production processes, **automation** greatly reduces costs by increasing labor productivity and throughput. Typically, a process is automated only after the manufacturer fully understands that process through sufficient manual production experience. Naturally, manufacturers will develop the actual process through R&D spending. Therefore, automation results from both cumulative production and direct R&D.

Accompanying the transition from manual assembly to automation is almost always an increase in **economies of scale**, because nearly any automated process has a greater throughput than the manual process it replaces.[1] An increase in economies of scale can be defined simply as an increase in capacity that leads to a greater production volume at lower unit costs. Scale is not so much driven by learning-by-doing or R&D as it is by market forces. If demand grows faster than supply, manufacturers will build larger facilities to keep up with demand. Thus, an expansion in capacity usually results in cost reductions due to economies of scale and other process improvements.

Design

Manufacturers can enjoy substantial cost reductions by **integrating a group of products** into one system, especially if those products have electronic components. Consumers no longer need to invest in a separate fax machine, copier and printer, because several producers have created all-in-one systems. Many of the functions are the same for all three (e.g. transferring images onto paper) and integrating the system can save money. In order to combine products, a manufacturer must develop a new design and possibly new production processes. As a result, integration is purely a matter of R&D.

A **larger product** is often less expensive to produce than a smaller one, assuming the larger product provides proportionately more utility than a smaller one. A larger capacity coal plant can be less expensive on a per kilowatt-hour basis than a smaller one. Costs per kilowatt-hour will go down proportional to the number of manufacturing steps (e.g. conveyer belts or stamping machines) that contribute to cost on the basis of throughput. In other words, the fixed cost of each throughput-related machine can be spread over more kilowatt-hours, thereby reducing the cost per kilowatt-hour.

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[1] Higher economies of scale do not imply an increase in the level of automation – a completely manual plant can be doubled in size without automation and still benefit from economies of scale.

An Alternative Conceptual Learning Curve

As discussed above, R&D, Economies of Scale (including scale of production and size of product) and Product Efficiency can lead to cost reductions that may not be represented by cumulative production. Based on our discernment of how firms actually reduce costs, the general learning curve model should be improved to explicitly incorporate the effects of R&D, economies of scale (both in production and size of product) and product efficiency. An Alternative Conceptual Learning Curve model includes these additional variables and is shown in Box 2.

Box 2 Alternative Conceptual Learning Curve

$$C = CP^{\alpha} \bullet RD^{\beta} \bullet ES^{\gamma} \bullet EP^{\delta} \bullet EF^{\varepsilon} \bullet A + C_O$$

where:

C	cost per unit
CP	Cumulative production;
α	elasticity of cumulative production;
RD	Cumulative R&D spending;
β	elasticity of R&D;
ES	Economies of Scale of manufacturing capacity;
γ	elasticity of Economies of Scale for manufacturing;
EP	Economies of Scale of product or unit size;
δ	elasticity of Economies of Scale for Product;
EF	product efficiency or capacity factor;
ε	elasticity of efficiency or capacity factor;
A	constant; and
C_O	long-term, mature cost

The conceptual model is meant to be a general model of manufacturing cost reductions. However, for a given technology the conceptual model may need to be altered by removing or adding terms for several reasons. Potentially variables may be co-linear, a reality not explicitly addressed by this model. Moreover, other functional forms might be more appropriate to account for deeper "regime" (i.e., discontinuous) shifts in the design of the process and/or product.

In our analysis of wind turbines, we use a variant of the Alternative Conceptual Learning Curve model. Unfortunately, the availability of data for wind turbines is quite poor, which limited the variables we could capture in our analysis. In addition, for wind turbines, economies of product and cumulative production are closely linked. Finally, for simplicity, we did not model turbine cost with an asymptote, which represents the long-term mature technology cost. Therefore, we examined cost as a function of cumulative R&D spending and cumulative production with the following representation:

$$C = CP^{\alpha} \bullet RD^{\beta} \bullet A$$

Separating cumulative R&D from cumulative production is relevant if each can individually impact technology learning and innovation. We briefly examined potential technology innovations for wind turbines to show how both cumulative R&D and cumulative production can contribute.

WIND TURBINES

Engineers reduce the cost of wind turbines with innovations that improve design, increase efficiency and optimize material use. We studied two types of wind turbine innovations: those that are the result of R&D and those that are the result of increased turbine production. Research and development is an important way to refine the design and improve material use, which lowers costs and increases the efficiency of electricity generation. Production innovations are achieved through increased automation, technology learning and economies of scale. To facilitate the discussion, the various subsystems of a wind turbine are displayed in Figure 1.

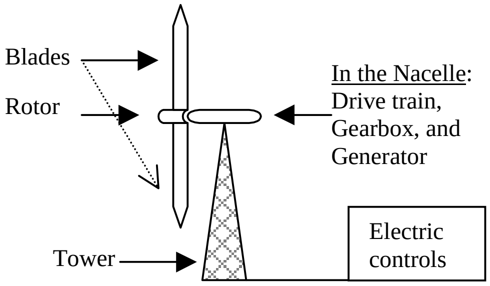

Figure 1. Wind Turbine System

R&D Innovations

Rotor Blades

Typically, wind turbines are three-bladed. In order to capture the maximum amount of wind at a particular site, the airfoil, or blade shape, is optimized for local wind conditions. Using computer models, engineers design airfoils to operate well despite debris on the blade, to bend under high winds and to operate under variable speeds. Due to the complexity of airfoil shapes, turbine blades are often handmade, typically of fiberglass or a wood-epoxy combination. Rotor blades account for between 11.2 - 16.5 % of the total cost of the wind turbine (including the tower) (Starcher 1998; PERI 1995; R. Lynette 1995; R. Lynette 1996). The cost and performance of rotor blades can be reduced through design, efficiency and materials improvements, as follows:

- **Design** – improved *blade twisting* (along the blade profile), *thickness* and *width*.
- **Efficiency** – better control of pitch, or blade angle; by using *partial span systems*[2] or *spoiler-flaps* (movable flaps on the trailing edge of the blade) to control speed and increase energy capture.
- **Efficiency** – *larger blade diameters* capture more wind.
- **Efficiency** – stall prevention by using *vortex generators*, or a series of small fins affixed at precise locations on the back surface of the blade to create a small amount of turbulence.
- **Materials** – stronger, lighter materials such *advanced fiberglass* and *wood-epoxy composites*, and potentially *carbon-reinforced plastics* in the future.

Drive Train

Wind drives the hub shaft at a relatively low rotational speed. This speed is much slower than that needed for an electric generator, so a gearbox is used to increase the rotational speed to approximately 1500-rpm. The gearbox is the most expensive part of the drivetrain, constituting 23.6 – 26.5% of the total turbine cost (Starcher 1998; PERI 1995; R. Lynette 1995; R. Lynette 1996). Even though the generator is not custom-made for wind turbines, it costs between 7.4 – 7.7% of the total (Starcher 1998; PERI 1995; R. Lynette 1995; R. Lynette 1996). Efficiency and material improvements promise to decrease costs in the drive train system in the following ways:

- **Efficiency** – improved generator design; *two-speed generators* allow for a wider range of wind speeds, increase the capacity factor and thus capture more of the wind's energy, or a *variable speed generator* continuously operates as the wind fluctuates within a fairly narrow range of speeds.
- **Materials** –gearbox elimination; *direct-drive generators* or by using *fully rated converters*.

Structure

The remaining structure of the wind turbine includes several subsystems, including the nacelle (the cover for the gearbox and generator that includes the wind monitoring equipment), the wind station and the tower. Although it is custom designed and manufactured for the wind industry, the nacelle is only 3.4 – 3.7% of the total turbine cost (PERI 1995; R. Lynette 1995; R. Lynette 1996). Lattice towers and tubular towers are used; the choice depends on the wind conditions and design of the rest of the wind system. Towers cost approximately 20% of the total system cost (Starcher 1998; PERI 1995; R. Lynette 1995; R. Lynette 1996); lattice towers are cheaper, but tubular towers protect maintenance workers in adverse weather conditions (Zond Z-750 series). Innovations are possible in both the design and materials for towers.

- **Design** – *tube-shaped towers* decrease air turbulence
- **Materials** – increased strength (through design too) allows for taller towers and more energy capture

Electronic Controls

Several wind turbine subsystems require electronic controls for them to work properly and operators require information about the turbines to optimize performance. Electrical controls constitute a

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[2] Research shows that changing a *portion* of the blade's pitch increases responsiveness, yet noise is problematic (EWEA 1996).

significant portion of total costs – between 10 and 16. 9% – and are often custom built for wind turbines (Starcher 1998; PERI 1995; R. Lynette 1996). Increased efficiency can reduce their costs:

- **Efficiency** – improvements in *feedback control* allow optimal operation of subsystems.
- **Efficiency** – constant power generation in variable wind conditions is attained by better *control electronics*, that permit generator speed to vary slightly as the torque on the drive shaft fluctuates.

Other Subsystems

The balance of system (including land purchase or lease, roads, equipment and foundation) constitutes approximately 25% of total wind farm costs (Starcher 1998; Spera 1994). Unfortunately, many of these costs are unavoidable since construction is often far from existing infrastructure and the electricity generated must be properly conditioned so that it does not damage the electrical distribution system.

Cumulative Production Innovations

Automated production

Several wind turbine components are labor-intensive to manufacture and assemble, because they must be handcrafted or assembled by hand. On many wind turbines, this includes the manufacturing of the blades, nacelle and some electric and control components, as well as the assembly of the rotor, hub and tower (PERI 1995). Since manufacturing and assembly of these components can cost over 30% of the total turbine cost, one main goal of the wind turbine program at DOE's Sandia National Laboratory is to decrease these costs (Ashwell, 1998). By altering the manufacturing process, their hope is to make lighter components more quickly and at less cost. For example, rotor blades that are pultruded (i.e. the raw blade material is pulled through the desired profile) weigh less than one-half of today's stiff systems and are projected to have manufacturing costs less than one-third as much (Cheney 1997). While pultruded designs increase automation, novel, handmade blade designs that incorporate twist and taper have increased flexibility, improved performance and weigh 20% less than pultruded blades. Although these blades are handcrafted layer by layer in a mold, their "improved performance achieves essentially the same cost of energy" (Cheney, 1997). For many wind turbine subsystems, the advantages of performance of handcrafted parts are superior to automation and will be until automation can replicate complex designs.

Economies of Scale

Turbine cost per capacity ($/kW) decreases with larger-sized turbines because scaling up the size of labor-intensive manufacturing does not increase cost proportionally. From 1992-1997, wind turbine size in Europe and the U.S. has increased tremendously, from a little over 200 kW / turbine installed to over 600 kW / turbine installed, a trend that BTM Consult believes "will most likely continue for several years ahead" (BTM Consult, 1998). Additionally, as more turbines are manufactured, costs continue to decrease because producers benefit from volume discounts on materials, declines in capital and operation costs, efficiencies from dedicated tasks (e.g. material handling) and by spreading R&D and other non-production costs over a greater number of units.

ANALYSIS

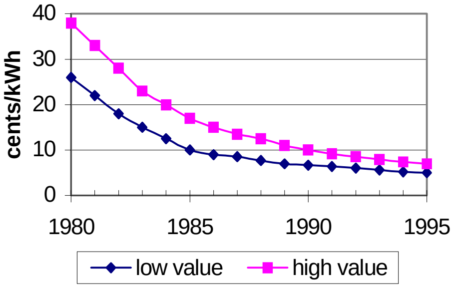
We developed a simple regression model of the cost of energy from wind turbines based on R&D, production and cost data over the past two decades. As mentioned earlier, data limitations did not allow us to examine all of the relevant variables in the Alternative Conceptual Learning Curve model, so we focused on cumulative R&D and cumulative production. Results from different modeling scenarios can indicate the relative importance of R&D and production in decreasing the cost of energy from a wind turbine.

Dependant Variable: Wind Turbine Cost

Wind turbine cost can be represented in two ways: either as the cost of installed capacity or as the cost of electricity generated. The cost of capacity is the installed cost of a wind turbine per unit of capacity ($/kW). The cost of electricity is the total amount of money needed to construct, finance and operate a turbine, levelized over its lifetime, divided by the expected annual electricity generation ($/kWh). Electricity generation is determined by the wind resource, turbine capacity, capacity factor and efficiency. In addition to the innovations that decrease the total installed cost of generation, improvements in financing terms or wind speeds and duration (i.e. better wind source) will decrease the cost of electricity.

Most analyses use cost of installed capacity to represent the cost of the technology, but this approach is inappropriate for wind turbines because it does not incorporate all potential capacity factor improvements. As with other technologies, design enhancements can boost the electricity generation per unit of capacity (capacity factor) by increasing the amount of time the facility is running. Wind turbines are unique compared to conventional power generation, in that capacity and output can be increased by accessing a better wind resource. Better resource characterization, taller towers, larger rotor blades and stronger materials combine to allow turbines to capture stronger and more erratic wind resources than previously accessible to wind technology. The cost of installed generation does not capture these increases in available energy and excludes an important factor that contributes to the increase in capacity factor. Therefore the cost per electricity generated is a better representation of the cost of wind turbines, because it incorporates increased capacity factor, and improvements in design and throughput.

Figure 2 Wind Turbine Cost of Electricity



Source: National Renewable Energy Laboratory

We used the levelized cost of energy over a 30-year lifetime as presented by the National Renewable Energy Laboratory for a wind speed of 5.8 meters per second (13 miles per hour) at 10 meters (33 feet) above the ground (NWTC 1997). Figure 2 shows a range of wind electricity costs for those conditions. We used the cost data from the lower curve, which is optimistic. Supplementary cost of energy information was difficult to obtain since it is dependent on the strength and duration of the wind speed, measurement height, as well as site-specific factors (e.g. topography, the presence of turbulence creators, such as buildings or trees, etc.).

Independent Variable: Cumulative Production

Cumulative production can be represented by total installed capacity or by total number of installed turbines. Total installed capacity is dependent on the size/capacity of wind turbines and the number of installed turbines. The average size of turbines has increased significantly in recent years and is directly dependant on R&D. Although the number of installed turbines can be affected by R&D (if the project calls for a specific capacity),[3] we chose to use the number of installed turbines for cumulative production.

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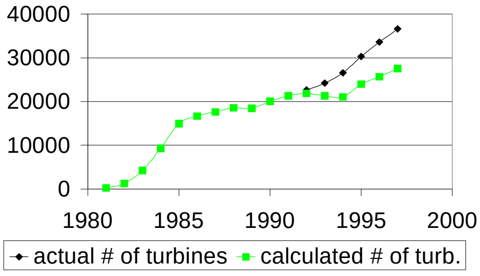
[3] We did not examine whether wind farms are designed based on land constraints (No. of turbines) or capacity requirements.

Figure 3 Number of Wind Turbines, installed and calculated



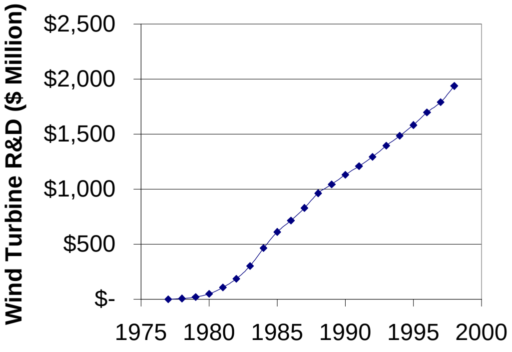
The number of turbines used in the analysis is shown in Figure 3. A report by BTM Consult provided worldwide data from 1992-1997 and is shown as the actual number of turbines in Figure 3 (BTM 1998). Turbines installed prior to 1992 were calculated using the total installed capacity divided by the average size of cumulative installed turbines (i.e. No. of turbines = installed capacity / Ave. size of turbines). *Capacity installed* worldwide was gathered from 1) the wind energy associations of the UK, Denmark, Germany and the U.S., 2) from the IEA for the Netherlands and Spain (IEA 1997) and 3) from BTM Consult for the rest of the world (BTM 1998). The second variable needed, the *average size of wind turbines*, was calculated using information from the BTM Consult report.[4]

Figure 3 shows that after 1992 the actual does not equal the calculated number of turbines. This is because prior to the 1990-1992 timeframe, wind turbines did not increase significantly in size. In the 1990s, lack of land availability stimulated design improvements, which resulted in average wind turbine size increasing from 200 kW to over 600 kW. The discrepancy between the actual and calculated data could reflect two problems. The first is that capacity data does not include retired and dismantled turbines, because this information was not reported. BTM Consult estimates that 350-400 MW total capacity has been taken off-line and that the adjustment particularly impacts the US figures (BTM 1998). The second problem is that the data for the average size of wind turbines and for the total capacity installed came from two different sources. For the analysis, we used the calculated number from 1980-1991and the actual number from 1992 on.

Independent Variable: Cumulative R&D

Cumulative R&D is represented by public funds historically spent on research and development by OECD countries. Private R&D figures are unavailable because companies are concerned with revealing their competitive secrets. If such data were available and included in our analysis, the results from the model might be significantly different. Cumulative public R&D figures are shown in Figure 4. U.S. R&D figures were provided by the U.S. Department of Energy (DOE 1998) and information for other industrialized nations was taken from the OECD (IEA/OECD 1997). The impacts of cumulative R&D were assumed not to reach the market until at least three years after the money was spent. Data on cumulative R&D in developing countries (especially India and China) was unavailable, but should be included in future analyses since some of these countries are developing the wind turbine technology.

Figure 4 Industrialized Nations' Wind Turbine R&D



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[4] The report lists the average size of cumulative wind turbines installed in 1992 for: Denmark, Germany, Spain, Sweden, the UK and the USA. Because each country has a different amount of total capacity installed, a weighted-average of global turbine size was calculated using the average size and cumulative number of wind turbines in each of these countries. The resulting average size of wind turbines in 1992 was 112 kW / turbine. The average size of wind turbines in 1981 was assumed to be 50 kW and we assumed a linear increase in size from 1982-1992. A sensitivity analysis explored non-linear progressions and showed that the shape of the curve does not impact results.

The Wind Model

We performed a regression analysis to identify the relationship between the dependent and independent variables. We then used the model results to project the cost of electric energy from the most efficient turbines and best sites to the year 2020, under assumed rates of change of R&D and production.

At first, we ran a regression analysis on all available data, which spans from 1981 – 1995. The results were curious; they showed that while the equation was statistically significant, the coefficient for the number of turbines was positive, indicating that as turbine production increases, so does the cost of electricity. Since this is counterintuitive, an explanation was sought. Figure 3 shows that from 1981 – 1995, the number of turbines increased rapidly and then decelerated after 1985 to a more gradual rate of increase. We hypothesized that this variation in market growth impacted the regression results. Therefore, we concluded that attempting to fit a simple regression over a time period with two distinctly different rates of market growth would yield an implausible result.

What historical factors caused this discontinuous growth in the number of installed wind turbines worldwide? From 1981-1985 more than 95% of the world's new wind turbines were installed in California. In addition to the federal tax incentive of 25% of wind turbine capital cost, California provided a 25% capital tax write-off, which totaled half of a project's capital cost.[5] Installations fell off after 1985 because the federal tax incentive was discontinued and the California tax credit was reduced to 10% of capital costs. The industry received large incentives in a short period of time such that installed capacity increased at a rapid rate. Technology developers were unable to improve designs and decrease costs fast enough to entice continued market growth at the same rate as with the subsidy. In essence, there were two growth scenarios, that of the California market and that of the world market that resulted after the "California wind rush." When the regression was run again using data from 1985 – 1995, the results turned out to be statistically significant and the coefficient for the number of turbines was negative.

Box 4 presents the results from the 1985-1995 regression analysis and shows that the model and each of its variables are statistically significant.

Box 4 Regression Results and Significance

R	R square	Adjusted R square
0.996	0.993	0.991

Model F-stat	Significance
548.887	0.000

Variable	Value	t-stat	Significance
"A"	5287	14.403	0.000
α	-0.552	-7.433	0.000
β	-0.282	-2.624	0.030

The relationship can then be represented by:

$$C = 5287 \bullet CP^{-0.28} \bullet RD^{-0.55}$$

Historical annual growth rates (1986-1995) for R&D (7%) and the number of turbines installed (7%) were used to project the cost of energy out to 2020. A sensitivity analysis was performed by looking at 0, 0.5, 1.5 and 2 times the annual growth rate for R&D and 0.5, 1.5 and 2 times the annual growth rate for the number of turbines.

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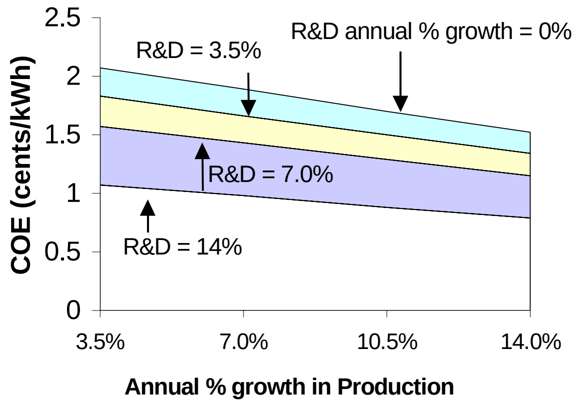
[5] Information on the history of tax incentives comes from Loiter 1997.

APPLICATION

Projection of COE

Using the regression model, the cost of electricity was projected out to 2020, assuming continuation of historic growth rates in R&D and turbine production. As shown in Figure 4, the cost of electricity from the most efficient wind turbines located at the best sites is projected to decrease substantially in the future. The figure also graphically shows how closely the model approximates the historical cost of electricity. Because we did not attempt to model a non-zero asymptotic wind turbine cost, the cost of electricity under these assumptions declines to 1.5 cents per kWh by 2020.

Figure 5. Impact of 1) R&D and 2) Production on Wind Turbine Cost of Electricity in 2015



Separating the Impact of R&D and Production

The relative impacts of R&D and turbine production on the cost of wind electricity in 2015 are shown in Figure 5 for a variety of scenarios. The steeper the slope of the curves, the greater the influence of turbine production. To take a closer look, assume that annual percentage growth of R&D is constant at 7% over the timeframe, such that you follow the “R&D = 7%” line. An increase in the annual percentage growth of production from 7% to 14% decreases wind turbine cost by 24%.

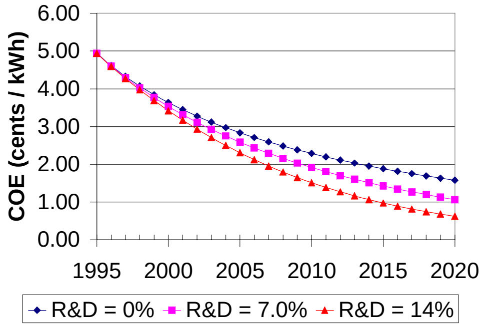
The influence of increased R&D annual percentage growth on the cost of electricity is represented by the decrease from one line to the next. For example, assume that the annual percentage growth in production is constant at 7%. An increase in R&D annual percentage growth rate from 7% to 14% decreases cost by 40%. Note that the top line reveals the decrease in the cost of electricity when R&D spending remains constant.

Comparing the relative influence of the slope of the lines to the downward shift of each R&D line shows that both R&D and turbine production have a sizable impact on decreasing costs and that R&D has a larger impact than production. These results can be taken as indicative rather than conclusive owing to the data limitations and the inherent uncertainties in statistical analyses. Nonetheless, policymakers concerned with sustainable energy use may wish consider these results when deciding on the scale of wind turbine R&D budgets.

A Closer Look at the Influence of R&D

Figure 6 shows the decrease in cost of wind electricity over time with different annual percentages of growth for R&D. The current level of public spending on R&D for wind turbines (0% annual growth) is projected to decrease wind turbine COE significantly, as shown by the top line. However, if the annual percentage growth in R&D were increased to 14%, the COE would decrease even more considerably.

Figure 6. R&D’s Influence on COE for Several Annual Growth % Rates



CONCLUSIONS AND FUTURE RESEARCH

In this analysis the impact of R&D spending on the COE of wind turbines is separated from that of cumulative production. While increasing the installations of turbines is an important factor for decreasing costs, it appears that R&D has a greater influence. Policy makers should take this into consideration as they consider how and where funds should be spent on energy technologies.

The model's regression presents a statistically significant relationship between money spent on R&D, the number of wind turbines installed and the resulting cost of electricity. This model can be used as a decision tool by policymakers or modelers in two ways. The first is by inputting an assumed level of production and R&D into the model to find the cost of wind electricity predicted for a given year. Alternatively they can determine a cost goal for a certain year and calculate how much R&D and cumulative production are required to meet that goal. Such information may prove valuable for understanding the relative roles of supply push (R&D) or demand pull (subsidy or RPS) policies in driving down the cost of wind turbines to compete with conventional forms of electricity generation.

Furthermore, our research leads us to conclude that better data collection and availability by the DOE and industry groups is necessary to better understand the relative impacts of R&D, cumulative production and other factors that may influence cost and performance. A significant amount of information was difficult to obtain, and we believe it is in the best interest of the wind turbine industry to gather existing data and to begin collection of relevant information that relates to economies of scale, economies of product and product efficiency. With a richer database, other variables and functional forms could be explored better, and more robust and nuanced results obtained.

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