Title
WREF 2012: THE PAST AND FUTURE COST OF WIND ENERGY

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ABSTRACT

The future of wind power will depend on the ability of the industry to continue to achieve cost reductions. To better understand the potential for cost reductions, this report provides a review of historical costs, evaluates near-term market trends, and summarizes the range of projected costs. It also notes potential sources of future cost reductions.

Our findings indicate that steady cost reductions were interrupted between 2004 and 2010, but falling turbine prices and improved turbine performance are expected to drive a historically low LCOE for current installations. In addition, the majority of studies indicate continued cost reductions on the order of 20%-30% through 2030. Moreover, useful cost projections are likely to benefit from stronger consideration of the interactions between capital cost and performance as well as trends in the quality of the wind resource where projects are located, transmission, grid integration, and other cost variables.

1. INTRODUCTION

Wind power has become a mainstream source of electricity generation around the world. The future of wind power, however, will depend on the ability of the industry to continue to achieve cost reductions and, ultimately, to achieve cost parity with conventional sources of generation across a broad array of contexts and locations.

This summary report, developed as part of the International Energy Agency (IEA) Wind Implementing Agreement Task 26, *The Cost of Wind Energy*, provides a review of historical costs, evaluates near-term market trends, and summarizes projected costs for onshore wind.

2. HISTORICAL TRENDS IN THE COST OF WIND ENERGY

From the 1980s to the early 2000s, average capital costs for wind energy projects declined markedly. In the United States, capital costs were at their lowest from roughly 2001 to 2004, approximately 65% below costs from the early 1980s [1]. In Denmark, capital costs followed a similar trend, achieving their lowest level in 2003, more than 55% below the levels seen in the early 1980s [2] (Figure 1).

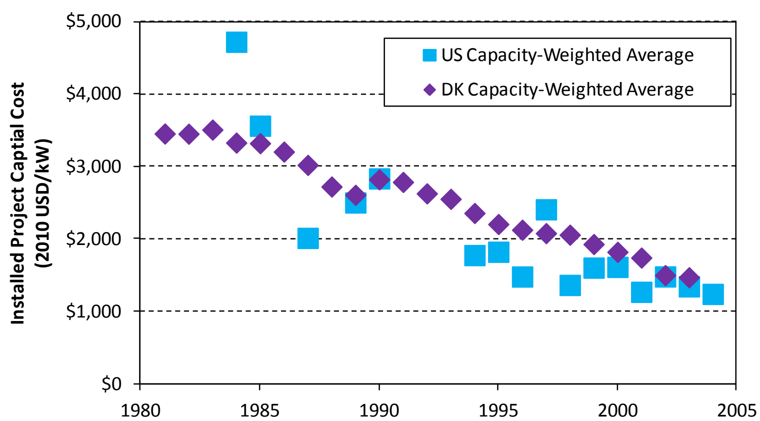

Fig. 1: Capital cost trends in the United States and Denmark between 1980 and 2003 [1-2].

Historical capital cost reductions were coupled with dramatic increases in turbine performance resulting from more advanced turbine components and larger turbines. Figure 2 illustrates the growth of turbine nameplate capacity, hub height, and rotor diameter over the past 30 years.

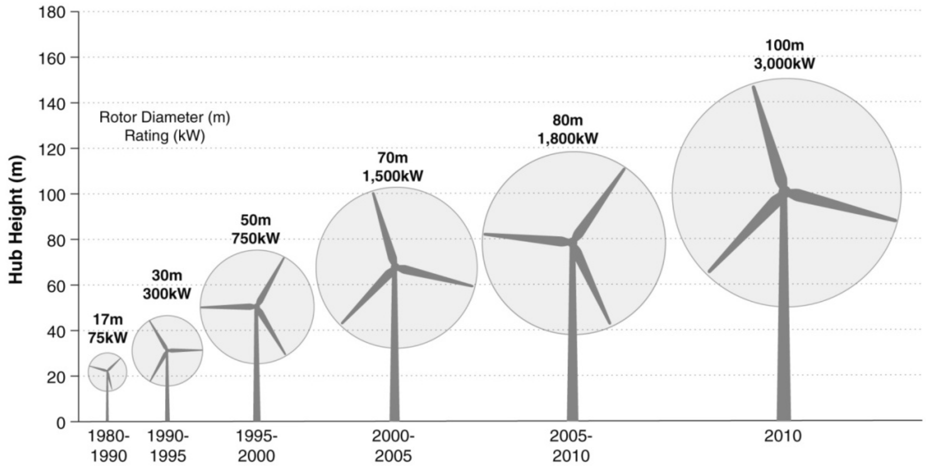

Fig. 2: Representative turbine architectures from 1980 to 2010; Source: NREL.

The combined effects of falling costs and enhanced performance had the impact of dramatically reducing the levelized cost of energy (LCOE) for onshore wind energy between the early 1980s and the early 2000s. Data from three different historical evaluations, including internal analysis by the Lawrence Berkley National Laboratory (LBNL) and the National Renewable Energy Laboratory (NREL), as well as published estimates from Lemming et al. [3] and the Danish Energy Agency (DEA) [4], illustrate that the LCOE of wind power declined by a factor of more than three over this time period (Figure 3) from upwards of $150/MWh in the 1980s and1990s to about $50/MWh in the early 2000s.

The initial period of significant cost reductions came to an end in the early-to-mid 2000s. Data from the United States, Denmark, Spain, and Europe indicate capital cost increases began rising around 2004 and continued to rise through at least 2007–2009 [1-2, 5].

An important exception to this general trend of substantially rising capital costs from 2004 to 2009 was China. Specifically, the emergence of a handful of strong domestic original equipment manufacturers (OEMs) resulted in significantly lower capital costs in China (i.e., $1,100/kW–$1,500/kW [2010 U.S. dollars] in 2008–2009) than witnessed in Europe or the United States [6].

The increase in capital costs observed in most markets from 2004 and 2009 has been largely tied to increases in the price of wind turbines [5, 7]. Turbine price increases have been driven by turbine upscaling (which also continued to bring about in performance improvements), increases in materials prices, energy prices, labor costs, manufacturer profitability, and—in some markets—exchange rate movements [2, 7]. Many of the same factors also resulted in higher costs for other forms of electricity generation equipment (e.g., [8-9]) over a similar timeframe. Figure 3 shows the increase in LCOE from 2004 to 2009.

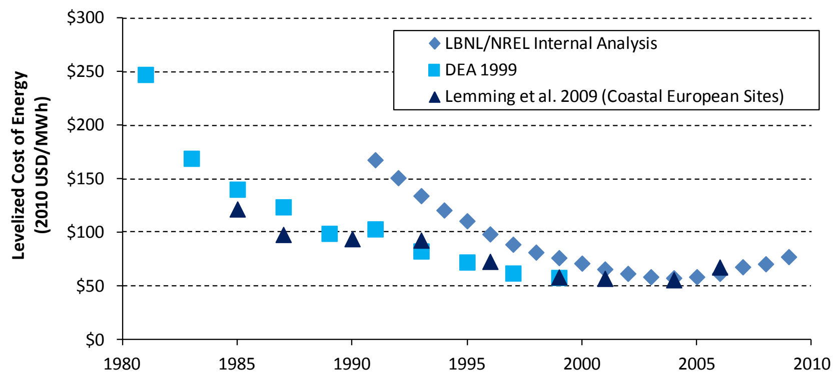

Fig. 3: Estimated LCOE for wind energy between 1980 and 2009 for the United States and Europe (excluding incentives); Sources: LBNL/NREL (internal analysis), [3-4].

3. RECENT AND NEAR-TERM TRENDS IN THE COST OF WIND ENERGY

Since peaking in the late 2000s, project capital costs have declined but still have not returned to their historical lows. At the same time, however, performance improvements have continued. Preliminary analysis conducted by Wiser et al. [10] suggests that projects installed with current state-of-the-art technology in the United States will experience sizable capacity factor improvements within a given wind power class, relative to older technology. Moreover, the most significant performance improvements are occurring in equipment designed for low wind speed sites or those sites that meet IEC Class III wind conditions (typical average hub-height wind speeds of 7.5 m/s). As a result of these technical and design advancements, Wiser et al. [10] find that the amount of U.S. land area that could achieve 35% or higher wind project capacity factors has increased by as much as 270% when comparing today's turbines to those from the 2002–2003 era.

Modeling that applies recent capital cost and performance data from the United States and Denmark for projects expected to be built in 2012–2013 suggests that the LCOE of onshore wind energy is now at an all-time low within fixed wind resource classes and particularly in low and medium wind speed areas where the most significant technology improvements have occurred (Figure 4). This latter fact has significant implications for the amount of land area where projects may be potentially viable. In the United States, for example, the available land area capable of generating wind energy at an unsubsidized LCOE of $62/MWh (2010 U.S. dollars) is estimated to have increased by 42% relative to the land area that could achieve this LCOE using 2002–2003 turbine technology [10].

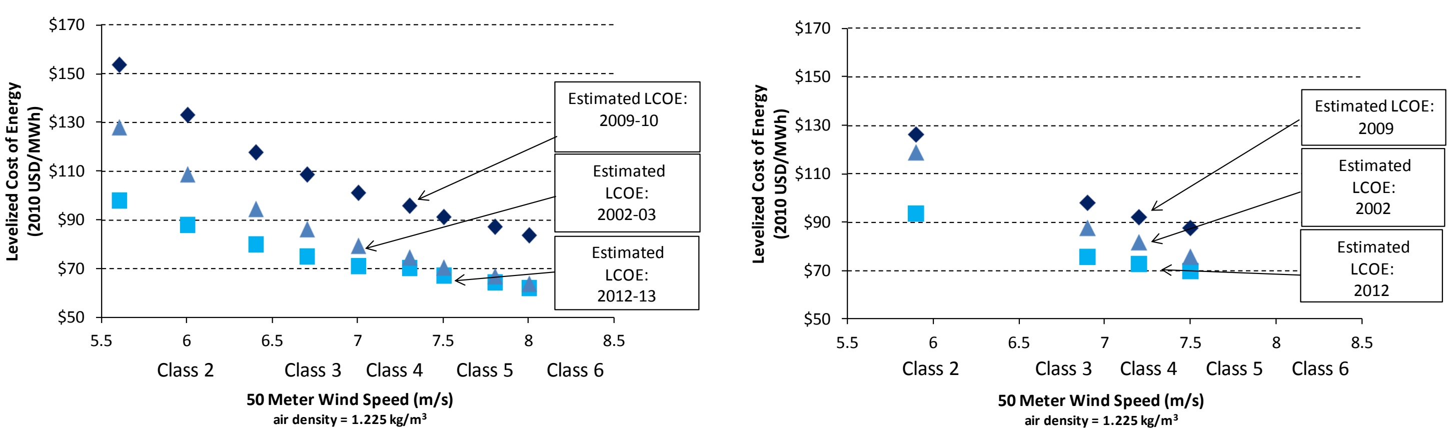

Fig. 4: LCOE for wind energy over time in the United States (left) and Denmark (right) [10-11].

4. LONG-TERM TRENDS IN THE COST OF WIND ENERGY

In the future, several studies suggest that the LCOE of wind energy is likely to continue to fall on a global basis and within fixed wind resource classes. Figure 5 presents the estimated cost reductions anticipated by 13 recent analyses covering 18 cost scenarios. Many of these studies utilize an iterative projection process involving historical trends and learning curves in combination with expert input, engineering models, and near-term market analysis (e.g., [3, 12-14]).

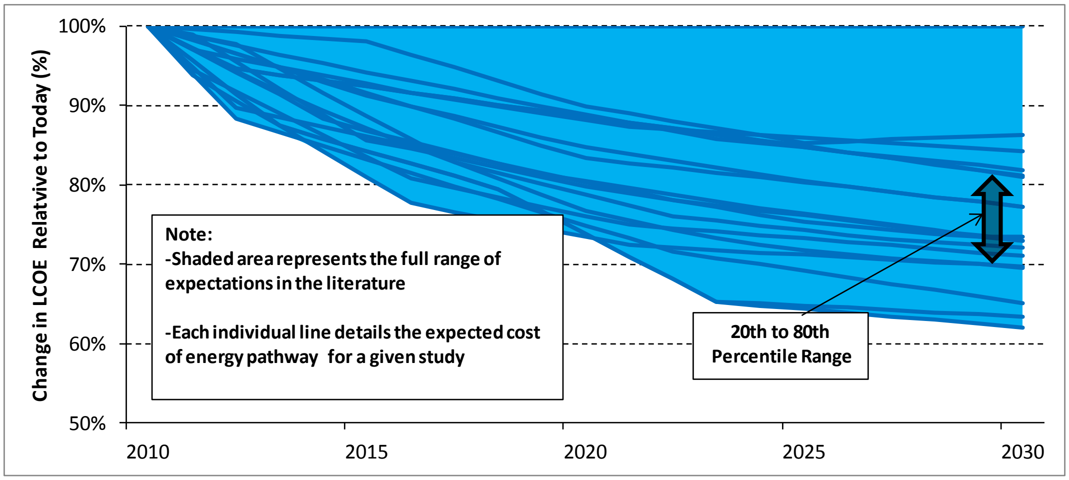

Fig. 5: Estimated range of future wind LCOE across 18 scenarios [3, 13-22]

The data presented in Figure 5 suggest an approximate 0%–40% reduction in LCOE through 2030. By focusing on the results that fall between the 20th and 80th percentiles of scenarios, however, the range is narrowed to roughly a 20%–30% reduction in LCOE. Initial cost reductions range from 1%–6% per year. By 2030, all but one scenario envisions cost reductions falling below 1% per year.

5. DRIVERS OF FUTURE WIND ENERGY COST REDUCTIONS

A large number of technological and market-based drivers are expected to determine whether projections of future costs are ultimately realized. Performance improvements associated with continued turbine upscaling and design advancements are anticipated, and lower capital costs may also be achievable. Possible technical drivers frequently include reduced component loading through a combination of improved materials and enhanced real-time controls capabilities and increased reliability. Reduced component loading is expected to encourage continued cost effective turbine scaling (e.g., growth in both hub heights, rotor diameter, and machine rating), while increased reliability will reduce operations expenditures and minimize turbine downtime. Manufacturing improvements and innovations in logistics challenges are also expected to further reduce the cost of wind energy. Table 1 includes a summary of anticipated sources of future cost reduction as suggested by bottom-up engineering analysis and expert elicitation.

The magnitude of future cost reductions, however, is highly uncertain. Although costs are expected to decline into the future, a resurgence in turbine demand—similar to those observed between 2004 and 2009—could counter these cost reductions. Continued movement toward lower wind speed sites may also invariably increase industry-wide LCOE, despite technological improvements. On the other hand, increasing competition among manufacturers in general could drive down the LCOE of onshore wind energy to a greater extent than otherwise envisioned.

TABLE 1: POTENTIAL SOURCES OF FUTURE COST OF ENERGY REDUCTIONS IN WIND ENERGY

R&D/Learning Area	Potential Changes (For more detail on technology changes and expected impacts, see references below)	Expected Impact
Drivetrain Technology	Advanced drivetrain designs, reduced loads via improved controls, and condition monitoring [23]	Enhanced drivetrain reliability and reduced drivetrain costs
Manufacturing Efficiency	Higher production volumes, increased automation [24], and onsite production facilities	Enhanced economies of scale, reduced logistics costs, and increased component consistency (allowing tighter design standards and reduced weights)
O&M Strategy	Enhanced condition monitoring technology, design-specific improvements, and improved operations strategies [25]	Real-time condition monitoring of turbine operating characteristics, increased availability, and more efficient O&M planning
Power Electronics/Power Conversion	Enhanced frequency and voltage control, fault ride-through capacity, and broader operative ranges [26]	Improved wind farm power quality and grid service capacity, reduced power electronics costs, and improved turbine reliability
Resource Assessment	Turbine-mounted real-time assessment technology (e.g., LIDAR) linked to advanced controls systems, enhanced array impacts modeling, and turbine siting capacity [26]	Increased energy capture while reducing fatigue loads, allowing for slimmer design margins and reduced component masses; increased plant performance
Rotor Concepts	Larger rotors with reduced turbine loads allowed by advanced controls [27] and application of light-weight advanced materials	Increased energy capture with higher reliability and less rotor mass; reduced costs in other turbine support structures
Tower Concepts	Taller towers facilitated by use of new design architectures and advanced materials [24, 28-29]	Reduced costs to access stronger, less turbulent winds at higher above-ground levels

6. CONCLUSIONS AND FUTURE WORK

Over the past 30 years, the cost of wind energy has significantly decreased, due to both capital cost reductions and performance improvements. However, from roughly 2004 to 2009, continued performance increases were not enough to offset the sizable increase in capital costs of this time period, resulting in an overall increase in the cost of wind energy. Nevertheless, as capital costs have moderated from their 2009–2010 levels, the cost of wind energy has fallen and is anticipated to be at an all-time low within fixed wind resource classes for projects coming on line today.

Looking forward, a variety of factors suggest that the LCOE of wind energy will continue to fall on a long-term global basis and within fixed wind resource classes. Most recent estimates project that the LCOE of onshore wind could fall by 20%–30% over the next two decades.

However, other factors may put upward pressure on wind energy costs, such as continued movement towards lower wind speed sites and local factors such as transmission needs. With these and other factors in mind, it is of utmost importance to consider the interdependence of capital costs and performance and to evaluate the future cost of wind energy on an LCOE basis. Such evaluations must consider trends in the quality of the wind resource in which projects are located, as well as development, transmission, integration, and other cost elements that may also change (and increase) with time and deployment levels.

Further improving our understanding of possible future cost trends will require additional data gathering and improved modeling capability. Robust data collection is needed across the array of variables that must be factored into estimating LCOE and in each of the wind energy markets around the globe. Also needed are data on the many contextual factors that impact the overall cost of wind energy and that may also vary with time, such as interconnection costs, permitting costs, and the average wind speed of installed projects. Such data would allow historical LCOE trends to be more closely analyzed, with insights gleaned both through advanced learning curve analysis as well as bottom-up assessments of historical cost drivers. More advanced component, turbine, and project-level design and cost tools would allow for more sophisticated cost modeling and provide greater insights into possible future costs based on changes in material use and design architectures. Together these efforts would enhance our ability to understand future costs, prioritize R&D efforts, and understand the role and impact of deployment incentives in the future.

7. ACKNOWLEDGEMENTS

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