The Power of Economies of Scale:
A Wind Industry Case Study

Gary A. Nowakowski\textsuperscript{1,*} and David G. Loomis\textsuperscript{2}

\textsuperscript{1}U.S. Department of Energy (retired), United States
\textsuperscript{2}Professor of Economics, Illinois State University, United States
E-mail: ganowak4@gmail.com
*Corresponding Author

Received 02 March 2023; Accepted 09 March 2023;
Publication 16 May 2023

Abstract

This paper investigates the impact that economies of scale have had in the success of the wind industry in the United States since 1980 including the trend to larger wind turbines and wind farms and assembly learning curve effects. Analyses utilize average U.S. wind industry historical data to assess past performance and predict the future economic potential for both onshore and offshore wind turbine industries. The intent of this analysis is to serve as a case study to demonstrate the importance of selecting the right product design platform and how the ability to scale a technology can impact the success of products and, in this case, an entire multi-billion dollar industry. From the early stages of development, the wind industry recognized this opportunity and enabled the commercialization of larger and larger wind turbines and subsequently exploited the significant economies of scale possible in producing low-cost electricity via large, horizontal axis turbines and associated wind plants. The cost to produce electricity was reduced more than six-fold over this timeframe and is competitive today.
with conventional fossil-fuel power generation alternatives. The physics of horizontal axis wind turbines enables them to scale up disproportionately in electric power output and annual energy production with increased size/nameplate rating.

**Keywords:** Wind energy, economies of scale, wind turbines, learning curve effect.

1 Introduction

The U.S. wind turbine industry was established nearly four decades ago and has increased in wind turbine installations from less than 1,000 MW capacity when it was just a nascent industry in the mid 80’s to more than 136,000 MW in 2021. Since 2000, wind power generation experienced year-over-year growth of nearly 20% and now represents more than 9% of total U.S. power generation and exceeds hydroelectric power generation for the top spot in renewable power generation. This success can be attributed to many factors ranging from Federal and State policies and financial incentives to technology innovations and power production cost reductions. However, the ability to economically scale the size of horizontal axis wind turbines to multi-Megawatt power generation capacities once thought impossible often goes unheralded as a reason for continued LCOE reductions and the tremendous and rapid success of the wind industry. Between the mid-80’s and 2020, average onshore wind turbine size progressively increased from 30–50 kW to more than 2.4 MW and average wind farms increased in size from 20–50 MW to more than 200 MW. Meanwhile, the cost of wind turbine installations declined from over $5,800/kW to less than $1,500/kW and the levelized cost of electricity, LCOE, decreased from more than $0.30/kW-hr to less than $0.05/kW-hr on an unsubsidized basis. This paper investigates the impact that economies of scale have had in the success of the wind industry over four decades including the trend to larger wind turbines and wind farms and operation, production and assembly learning curve effects. Analyses utilize average U.S. wind industry historical data to assess and predict the future economic potential for both onshore and offshore wind turbine industries. The intent of this analysis is to serve as a case study for future entrepreneurs in their quest to develop new technologies that have the opportunity to succeed based on exploiting key business fundamentals such as economies of scale.

This article brings a new look to existing literature in the following areas: (i) Provides a condensed summary of four decades of U.S. wind industry
history and the continued push to enable larger and larger wind turbines as well as the importance of key financial incentives, policy decisions and technology development in the quest to achieve financial parity with fossil fuel power generation; (ii) Attempts to quantify the long term historical impact of economy of wind turbine and wind plant scale and learning curve effects on the relentless, four decade drive to reduce LCOE; (iii) Highlights the critical importance of the selection of Horizontal Axis Wind Turbines (HAWTs) as the technology platform and underpinning for the industry’s long term success in reducing LCOE, achieving financial competitiveness with conventional fossil power generation and becoming a multi-billion industry employing more than 120,000 people; (iv) Projects the future economic potential of both onshore and offshore wind and addresses potential diseconomies of scale that could result in turbine size limitations and result in an economic optimum.

This article is organized as follows: Section 2 sets the stage by providing a brief historical overview documenting the infancy and growth of the U.S. industry as larger wind turbines were continually developed and commercially introduced, enabled by technology innovation and R&D. Historical trends including average wind turbine specifications and performance is presented as well as industry challenges and impactful state and national policy decisions. Section 3 provides a brief review of key technology development and enablers which allowed the development and commercialization of larger and larger wind turbine turbines; Section 4 provides a description of the analytical approach and methodology utilized to estimate and compare the levelized cost of electricity, LCOE, of turbines and wind farms from a historical and future perspective. Section 5 addresses economy of scale impacts to the wind industry through analysis and existing literature. An attempt is made to quantify the LCOE impacts associated with the trend to increased wind turbine size and wind plant. Given that electricity is a commodity, LCOE is the predominant factor ultimately affecting product success and market share. Section 6 projects the future LCOE potential for both onshore and offshore wind and discusses the potential diseconomies of scale that could limit continued increases in turbine size and result in an optimum. Section 7 summarizes results and key takeaways.

2 Modern Wind Turbine Historical Overview

A brief historical perspective is provided below in order to establish the necessary breadth and perspective on the policies, research and development
and commercialization initiatives that were instrumental to the rapid success of the U.S. wind industry, a multi-billion dollar industry today. In addition, the history documents the continued march toward larger and larger wind turbine development and commercialization as the industry recognized and exploited the economies of scale advantages needed to achieve and exceed parity with conventional fossil fuel power generation.

Over the past four decades beginning in the early 80s, wind turbine manufacturers and researchers understood that the scaling of wind turbine size would benefit the economic viability of the industry. While early machines were in the 30–100 kW size range, the transition to larger units occurred rapidly, a tribute to technology development which enabled larger components and system designs.

In response to the high oil prices in the 1970s and oil crisis of 1973 and 1979, the U.S. Federal Government responded with financial incentives and increased emphasis on alternative energy technology development. Both NASA and the Solar Energy Research Institute, predecessor to the National Renewable Energy Laboratory (NREL), supported the early development of wind technologies in the U.S. The National Wind Technology Center located at the NREL Flatirons campus in Colorado still conducts state-of-the-art wind technology development R&D today.

In 1978, the Public Utility Regulatory Policies Act (PURPA) was enacted in the U.S. PURPA required that utilities interconnect renewable energy projects to the grid and mandated that utilities purchase renewable power at “avoided cost,” the cost for a utility to build its own power plant and generate electricity. This Act was a significant driver resulting in support of and a push for the commercialization of cogeneration and renewable energy technologies including wind power.

In the late 70s and early 80s, many wind companies were formed in the U.S. including wind developers Zond and Kenetech Windpower. They were among the first companies to build and install thousands of small 30 to 100 kW capacity wind turbines in the California mountain passes including Tehachapi, Altamont and San Gorgonio. The levelized cost of energy, LCOE, of these early turbines were in the $0.30 to $0.40/kWh range, not competitive with conventional fossil-fueled power generation. A 25% California tax credit was instrumental in spurring this early development. The majority of turbines resembled the ones of today in that most were horizontal axis turbines with three blades. However, they were much smaller, operated at higher rotational speeds and were usually erected on steel lattice towers. “Turbines would
frequently crash and burn, with pieces flying off or failing because they couldn’t handle the stiff winds of the mountain passes.” (Roth S)

“Between 1980 and 1988, the California market accounted for 97% of the total installations of wind power in the world.” (Bouamane 2011) Despite this great start, the U.S. wind market began to decline in the mid-1980s. By 1985, many of the energy tax incentives created by the Carter Administration had been eliminated along with much state support. Oil prices had fallen dramatically from the early 1980s highs, thus reducing interest in renewable energy wind systems.

Multiple Styles of Wind Turbines in Various States of Repair on Altamont Pass (Kahn B. 11/1/20)

The opportunity for wind turbine developers turned positive again in the early 90s as a result of federal and state financial incentives. A federal Production Tax Credit (PTC) was established in 1992. The PTC incentivized electricity production. Wind power producers were paid 2.3¢ per kWh as a tax credit for electricity they produced for the first 10 years of operation. The PTC ended up being a key policy incentive driving wind power growth across the U.S. for nearly three decades, albeit with starts and stops based on congressional decisions throughout its history.
In the late 90’s and early 2000’s, the U.S. represented 14% of the world’s wind capacity with increasing interest by European countries such as Germany, Spain and Denmark. (Bouamane 2011) Commercial wind turbine rotors would increase to a diameter of 50 meters and an average nameplate capacity rating of 750 kilowatts, 10 times more than approximately 10 years prior. Enron purchased Zond Energy Systems in 1997 and continued wind turbine development of their 750 kW system including a 1.5 MW capacity turbine. The LCOE became more competitive falling to less than $0.10/kW-hr with turbine OEMs and wind developers eyeing future generation costs in the $0.05/kW-hr range. In addition, many states passed legislation requiring renewable portfolio standards (RPSs). RPS’s required that state electricity providers provide a minimum amount of electricity from renewable energy sources by certain dates. Initially, RPSs mandated future electric utility renewable power generation portfolios in the 10% to 20% range. Additional large corporate and international interest in the wind business occurred with General Electric, Florida Power and Light (now NextEra Energy), Gamesa, Gold Wind, and Siemens all entering the market. Vestas had been producing wind turbines exclusively since 1989 and continued to grow with the merger of NEG Micon in the same timeframe.

With average turbine capacities growing beyond 1 MW in size and the subsidized LCOE falling to levels competitive with conventional electric generation, U.S. wind industry growth accelerated with states such as Texas, Iowa, Colorado, Oklahoma, Kansas, Illinois and Minnesota leading the way. Over this timeframe, technological innovations enabled development of larger turbines at lower costs. “Economies of scale resulting from increased turbine size were followed by economies of scale in project size and volume production.” (Krohn et al. 2009). In addition, as the market expanded, greater production volumes allowed for investment in manufacturing facilities and opportunities to increase production efficiencies and lower turbine capital costs.

The initial period of capital cost reductions came to an end in the early-to-mid 2000s with installed wind farms achieving an average LCOE of approximately $0.08/kW-hr. Although balance-of-plant costs played a role, the increase in capital costs observed between roughly 2004 and 2009 were largely tied to increases in the price of wind turbines (Wiser and Bolinger 2011), (Ceña and Simonot 2011). After hitting a low of roughly $700/kW from 2000 to 2002, average wind turbine prices increased by approximately $800/kW through 2008, rising to an average of more than $1,500/kW. The increase in turbine prices over this period was caused by
several factors including supply-side constraints for key components such as bearings and gear boxes, increased material prices and energy and labor prices and a general recalibration of the wind industry involving an increase in turbine manufacturer profitability and increased costs for turbine warranty provisions.

Turbine hub heights increased dramatically between 2000 and 2010 rising from approximately 58 meters to 80 meters as wind developers recognized the significant advantage of capturing greater wind speeds and disproportionately greater energy capture at these heights due to the cubic relationship between wind speed and power output and the fact that higher hub heights captured higher wind speeds. Wind speeds tend to increase exponentially above the ground as the friction from ground-level obstacles such as vegetations, buildings, etc. becomes less. Even small changes in wind velocity effect significant increases in kinetic energy potential due to the cubic relationship with wind velocity. Increased hub heights and longer blades facilitated increases in capacity factors from 30% to 42%.

By 2010, material commodity costs and supply chain constraints subsided, and market demand remained high resulting in more stable turbine prices and installed costs. Driven by the European offshore wind market, turbine manufacturers continued to develop prototypes and commercialize larger turbines in the 3 to 6 MW range, many utilizing gearless, direct drive technology, thus reducing drivetrain complexity and increasing reliability.

Between 2010 and 2020, average U.S. onshore turbine rated capacity installations increased from 1.8 MW to 2.4 MW with blade lengths growing from 42 M to 58 M, representing a swept rotor increase of nearly 100%. OEMs continued to utilize longer blades as specific power (ratio of nameplate generation capacity to swept rotor area) decreased and capacity factors increased. The average installed cost of turbines dropped from $2.6M per MW to $1.43 M per MW and LCOEs continued to decrease by more than 50% from $.094/kW-hr to $0.043/kW-hr. Hub heights continued a gradual trend increasing from 80 meters to nearly 90 meters. Meanwhile, turbine installations continued to increase in the U.S. with more than 13 GW of installations in 2012 and 16 GW in 2020 alone. By 2021, wind power in the U.S. represented more than 9% of total electric production, more than the contribution from hydroelectricity. U.S. installations totaled approximately 136 GW by the end of 2021. Consolidation of wind industry sales in the U.S. continued with General Electric and Vestas turbines representing approximately 87% of new wind plant installations toward the end of 2021. The U.S.
initiated the phaseout of the PTC in 2016 with a gradual 20% annual reduc-
tion of the original $0.023/kW-hr per year with a sunset in 2020. Meanwhile,
major turbine OEMs continued the research, development and design of very
large wind turbines for the offshore wind marketplace with GE leading the
way with the development and prototype testing of the 12 MW–14 MW
Haliade-X turbine. Both MHI Vestas and Siemens Gamesa also introduced
giant wind turbines prototypes reaching 15 MW in size. OEMs also continued
to increase onshore wind turbine choices with platforms ranging from 2
to 4 MW capacities. While Europe had introduced offshore fixed platform
turbines in the early 1990s because of limited land availability, the first
commissioned offshore wind facility in the U.S. was Rhode Island’s Block
Island wind farm consisting of five 6 MW turbines, commissioned in 2016.
Currently, nine states along the East coast have an interest in offshore wind
development and there is over 40,000 MW in various stages of development.
This includes 19 projects in the permitting phase of development.

This brief historical summary clearly documents the four-decade industry
trend toward economies of scale and the cost benefits associated with larger
turbines and wind farms. The remainder of this paper attempts to address
and quantify the impacts of wind economies of scale on commercial wind
LCOE reductions over nearly four decades. The contributors to LCOE that
will be investigated include annual electric production, capital expenditures
and operating expenditures.

3 Analysis Approach/Methodology

Economies of scale has always represented a critical and fundamental busi-
ness principle responsible for the success of major industries dating back to
1913 and Henry Ford’s introduction of the first automobile moving assembly
line and division of labor. The basic objective is to reduce production unit
costs through increased utilization of capital assets via greater production
volume. Economies of scale occur when the average cost curve declines
over the relevant range of quantities, typically for two primary reasons:
(1) increasing and optimizing the scale of operations so that fixed and semi-
fixed production costs can be effectively spread over an increased number
of units of production and (2) utilization of learning curve operation, pro-
duction and assembly techniques and bulk material/component purchases as
production volumes increase, thus reducing variable costs. High fixed cost
businesses have a high proportion of costs that are independent of production
volume. Businesses requiring significant capital investment including brick
and mortar operations have traditionally been high fixed cost businesses.
Wind turbines and wind farms, because of their large upfront capital investment requirements, fit this category. The product, in this case, is a unit of electricity, a kilowatt-hour, kW-hr. The impact of larger turbines and wind farms on the cost to produce one kW-hr of electricity will be assessed in this paper and referred to as the “levelized cost of electricity” or $/kW-hr. For most industries, there is an optimum level of plant manufacturing size and production, after which unit costs begin to increase due to diseconomies of size and inefficiencies of operations that become too large. This potential limitation will also be explored. LCOE analysis was performed using the Net Present Value (NPV), Equation (1), below. LCOE is a life cycle cost concept that includes the cost of all physical assets and resources required to deliver 1 kW-hr of electricity. It is a metric commonly used to compare the cost competitiveness of alternative electric generation platforms. (Comello S, Glenk G, Reichelstein S; 3/17) LCOE NPV is the discounted total lifetime cost (Capital Expenditures, CAPEX, plus operational expenditures, OPEX) divided by the total lifetime discounted energy output (total annual electricity production or AEP) of an asset.

\[
\text{LCOE NPV} = \frac{\text{CAPEX} + \sum \text{OPEX}_i/(1 + \text{Rate})^i}{\sum \text{AEP}_i/(1 + \text{Rate})^l}
\]  

Where the following assumptions were made: “Rate” represents the Cost of Capital = 6%, Average onshore wind speed = 7.5 m/s, Turbine Life = 20 years.

Economies of scale impact the numerator and denominator. Increased wind turbine OEM volume production has a direct impact on lower turbine costs and the CAPEX. Economies of scale as represented by larger turbines and increased blade lengths result in a disproportionate increase in AEP (denominator) which directly reduces LCOE. Larger and less numerous turbines per wind farm also represent an economy of scale advantage via (a) reduced O&M costs and a lower OPEX since a lower number of turbines need to be maintained and serviced and (b) wind plant balance of system (BOS) costs are inherently lower on a “per MW basis” because of the need for less numerous roads, cabling, interconnections and installations, thus reducing the CAPEX. Finally, larger wind farms simply produce greater quantities of electricity/AEP, essentially spreading wind plant fixed and semi-fixed upfront planning and development costs over greater electricity production.

Input to the analysis is based on average wind turbine specifications, performance, and cost trends over four decades. Data collected include average historical O&M costs, installed turbine costs, blade lengths, power
coefficients, capacity factors, and turbine nameplate ratings. LCOE results are estimates based on calculations utilizing average data and trends. Results and conclusions can only be used to evaluate trends and are not applicable to specific wind turbine(s) given the great variation in performance and specifications which are dependent on location and equipment design.

LCOE is used by both the U.S. Energy Information Administration and the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, to evaluate and compare energy technologies on a cost basis. Cost-based analysis is the most consistent and accurate means to compare competing technologies because it eliminates the potential inconsistency associated with various market pricing methods. Table 1 provides examples

<table>
<thead>
<tr>
<th>References</th>
<th>Methodology</th>
<th>Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>International Renewable Energy Association, IRENA Renewable Power Generation Costs in 2020</td>
<td>LCOE analysis between 2019 and 2020</td>
<td>In 2020, the global average weighted LCOE from new onshore additions declined by 13% from 2019; offshore wind LCOE declined by 9%</td>
</tr>
<tr>
<td>Fraunhofer Institute for Solar Energy Systems, June 2021 Levelized Cost of Electricity – Renewable Energy Technologies C Kost</td>
<td>LCOE analysis of onshore and offshore wind in 2021 for Germany</td>
<td>Onshore wind LCOE estimated between $0.0394 and $0.0829; Offshore wind estimated between $0.0723 and $0.1213 Onshore wind is the second cheapest technology for electric generation in Germany today.</td>
</tr>
<tr>
<td>Renewable Energy 2018 122, 131–139 A Levelized Cost of Energy Model for Wind Farms that include PPAs M Bruck, P Sandborn, N Goudarzi</td>
<td>The article describes the development of a new model that estimates the LCOE for commercial wind farms under a power purchase agreement contract.</td>
<td>Developed cost model that can be used as a basis for negotiating power purchase agreement terms such as price schedule and performance metrics. Energy delivery limits imposed by current PPAs impact LCOE. The application of this model to real wind farms demonstrates that the actual LCOE is dependent on the defined minimum/maximum energy purchase limitations.</td>
</tr>
</tbody>
</table>

(Continued)
of extensive renewable energy analysis conducted world-wide and published utilizing LCOE as the basis for the methodology. It is largely considered the benchmark for comparing competing technologies ranging from fossil fuels to renewable and energy storage systems.

4 Enabling Wind Turbine Technology Development

Wind technology development has been a critical enabler in the development of large turbines and the reduction of power generation costs through
improved design and production methods and optimized, lower cost designs. Below is a sampling of key technology developments that occurred since the advent of the wind turbine industry in the U.S. and contributed to the success of the industry.

(i) Variable Speed operation: In the early 1990s, wind turbines were characterized by fixed-speed operation. This consisted of the coupling of a wind turbine, a gearbox and an induction generator directly. The turbines were simple and reliable, but inefficient and resulted in power fluctuations being transmitted to the grid. Variable speed generators represented a significant upgrade over fixed-speed systems and provided improved system efficiency and power quality and reduction of mechanical stresses due to wind gusts.

(ii) Permanent magnet power generators: The gearbox is easily the most maintenance-needy component in a turbine (Geartechnology.com). As a result, permanent magnet generators (PMGs) today have become an effective option and frequently utilized in large onshore and offshore wind turbines. The rotor hub is directly connected to the generator as a fixed unit without a gearbox.

(iii) Longer Blades: A major trend in wind turbines over the past few decades is the development of larger turbines (Figure 1) and use of longer blades. Engineering design and production of long blades has been one of the most important enabling technologies allowing advances in turbine size over the past four decades. Blade engineering design encompasses several considerations and trade-offs including (a) optimization of aerodynamic efficiency where the lift/drag ratio is maximized through airfoil design, (b) structural design enabling long cycle fatigue life with millions of load cycles while

![Figure 1](#)  
**Figure 1** Historical average U.S. onshore turbine blade length.
addressing gravitational and centrifugal forces and maintaining structural stiffness in long blades, and (c) use of construction materials resulting in lower weight through the use of glass/carbon fibers bonded with epoxy resins.

(iv) Greater Capacity factor: Average capacity factors increased from 22% to greater than 40% for U.S. onshore wind turbines over the past two decades. While capacity factor is not an enabling technology, but is important because it represents the percentage of electricity actually produced by a wind turbine(s) as a percentage of the maximum that it could produce over a time period, it is the result of many things including the optimization of turbine design decisions (such as generator size, blade lengths, and turbine control strategies), siting decisions affecting wind resources, planned and unplanned maintenance and service downtime, and electric transmission curtailments.

The fact that the overall trend in the U.S. wind industry has involved larger and larger nameplate capacity turbine installations and a parallel trend to lower specific power (the ratio of a turbine’s nameplate rating in Watts and the turbines swept area in meter squared) provides supporting evidence that the industry has been able to continue to optimize the siting, design and specifications of wind farms to achieve greater annual energy production and higher capacity factors while resulting in continued reductions in LCOE.

5 Wind Industry Economies of Scale

Three economies of scale benefits were identified specific to the wind industry. They include the following:

1. Larger wind plants: Larger wind farms result in lower power generating costs because the upfront fixed and semi-fixed costs to plan and establish a wind farm can be “spread” over greater product output, annual electricity production, kW-hrs. Purchasing power also becomes a benefit when placing larger equipment orders ranging from the wind turbines to the BOS product needs.

2. Larger turbines: Larger turbines result in the need for a lower number of turbine installations for a given wind farm thus reducing the total turbine and BOS capital costs as well as O&M costs. Annual energy production, AEP, increases disproportionately with turbine nameplate rating due to
the squared power relationship between increased blade lengths and wind capture area, otherwise known as swept area, and power output.

3. Learning curve effects: The U.S. wind industry grew substantially between 2000 and 2009 achieving close to 10 MW in annual generating capacity additions. Since then, the industry vacillated in demand ranging between 1 MW and 14 MW in completed installations, averaging 7.5 MW per year. In the two decades since 2000, the U.S. wind industry was able to optimize manufacturing and installation businesses around these volumes resulting in design, production and assembly learning curve cost benefits and material and component volume purchasing breaks.

Each of these distinct areas will be discussed in more detail below.

5.1 Wind Plant Economies of Scale

Both the Energy Information Administration, EIA, and the Lawrence Berkeley National laboratory, LBNL, published wind farm data in Tables 2 and 3, respectively, which demonstrate the economies of wind farm scale ranging from 25 MW size to greater than 200 MW in terms of installed wind turbine plant cost ($/MW). EIA data was based on 2018 information and LBNL data was for the 2018/2019 timeframe. It should be noted that these wind farm costs are averages and individual wind farm costs can vary significantly depending on the site ground and wind resource conditions.

Both sets of data show decreasing, but diminishing installed cost benefits as wind farm size increases to greater than 200 MW. An installed cost reduction of 17% from $1,702/kW to $1,412/kW was based on the LBNL data as wind farm size increased from a 25–50 MW size range to greater than 200 MW. The same analysis conducted with the EIA data based on a wind

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Wind farm installed cost by total capacity utilizing EIA data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average Installed Cost, $/kW*</td>
</tr>
<tr>
<td>1–25 MW</td>
<td>1790</td>
</tr>
<tr>
<td>25–100 MW</td>
<td>1676</td>
</tr>
<tr>
<td>100–200 MW</td>
<td>1435</td>
</tr>
<tr>
<td>greater than 200 MW</td>
<td>1268</td>
</tr>
</tbody>
</table>

**LCOE analysis assumed 2.0 MW wind turbine installations.
The Power of Economies of Scale: A Wind Industry Case Study  

Table 3  Wind farm installed cost by total capacity utilizing LBNL data

<table>
<thead>
<tr>
<th>Average Installed Cost, $/kW*</th>
<th>LCOE**</th>
<th>% Reduction in LCOE (From $1702)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20–50 MW</td>
<td>1702</td>
<td>0.0496</td>
</tr>
<tr>
<td>50–100 MW</td>
<td>1547</td>
<td></td>
</tr>
<tr>
<td>100–200 MW</td>
<td>1520</td>
<td></td>
</tr>
<tr>
<td>greater than 200 MW</td>
<td>1412</td>
<td>0.043</td>
</tr>
</tbody>
</table>

**LCOE analysis assumed 2.0 MW wind turbine installations.

A farm increase in size from 25–50 MW to greater than 200 MW produced reductions in installed cost from $1767/kW to $1268/kW, a 28% decrease. LCOE analysis, which assumed wind farm installations of 2 MW wind turbines and a constant 6.0% cost of capital, showed a significant decrease of roughly 13.3% for the LBNL data and 18.8% for the EIA data.

Economies of wind plant scale are the result of spreading upfront fixed or semi-fixed planning and development costs over greater electricity production. In addition, larger wind farms provide the developer with greater purchasing leverage for turbines and BOS components and services. “Generally speaking, there are economies of scale in the construction of wind farms both in terms of the total size of the wind farms (the number of turbines sharing a common substation and sharing development and construction costs) – and in terms of the size of turbines. Larger turbines generally have comparatively lower installation costs per swept rotor areas and the cost of a number of wind turbine components such as electronic controllers, foundations and so on, varies less than proportionately with the size of the wind turbine.” (Krohn et al. 2009)

Figure 2 below is based on the 2018–2019 LBNL data (Table 3) and demonstrates the dramatic reduction of installed capital costs that occur as the wind plant is expanded from small installations to greater than 200 MW in capacity. Figure 3 plots that same data for CAPEX versus wind farm size. The curve fit for this data extrapolates upfront wind farm fixed planning and development costs of $9M (the y-intercept) (2019) with an assumption of 2 MW turbine installations, the historical U.S. average size for 2018/2019 timeframe. The larger the wind farm, the lower the installed costs since the upfront costs are spread over greater generation capacity. These costs are highly dependent on whether transmission line extension costs are required and included in the wind plant investment.
Many wind farm planning and development costs are relatively independent of wind farm size and contribute to the estimated $9M of fixed costs determined via the curve fit. Examples of fixed and semi-fixed costs include: (a) Siting of the wind farm including conducting wind resource assessments and transmission interconnection; (b) Providing education of the community on the wind farm and achieving local community buy-in; (c) Obtaining
siting and zoning permits including conducting the necessary environmental studies; (d) Securing power purchase agreements; (e) Obtaining necessary financing; (f) Establishment of contracts with turbine OEMs and O&M needs, and the wind farm developer including BOS such as foundation installations, electrical interconnection of turbines and tie-in to the transmission system; (g) Road improvements needed to handle heavy loads; (h) Delivery and use of the crane(s) needed to erect the turbines; and (i) Engineering and purchase of transformer(s) and substation for grid interconnection.

The 2019 NREL case study (Stefek et al. 2019) of a 600 MW Colorado wind farm identified wind farm development costs that included $4M for site certification and permitting alone, $6.7 M for engineering services and $4.26 M for legal services.

Another recent report (Key et al. 2021) determined that increasing the size of a wind plant from 150 MW to 400 MW in size could reduce BOS costs by 21%. The findings indicated that the BOS costs per kW decreased as plant size increased as a result of amortizing mobilization costs such as site preparation, electrical and substation installation and foundation installations.

5.2 Large Wind Turbine Economies of Scale

Wind turbine economy of scale manifests itself through several benefits. First, larger installed turbines means that the number of installations for a given sized wind farm is less which reduces BOS costs on a per-kW basis including things such as the installation and interconnection of electrical cabling, number of turbine access roads, transformer and switch installation(s), and lease agreements. Similarly, O&M costs are reduced due to a smaller number of larger turbines being maintained and serviced. One of the most important economy of scale advantages of horizontal axis wind turbines is the fact that as the nameplate capacity of the wind turbine increases, the swept circular area of the blades that capture wind energy increases in proportion to the square power of the radius (∼ length of a blade). So, as the radius or blade length is doubled, say from 10 to 20 meters, the swept area increases four-fold from 100 m² to 400 m². The potential power output subsequently increases disproportionately with an increase in turbine nameplate rating and blade length, thus resulting in greater annual energy production and lower LCOEs. In addition, over the past three decades, turbine specific power (Figure 4) continued to decline as longer blades have been paired with turbines, thus increasing annual energy production even more.
Table 4 summarizes the historical average installed turbine specifications and calculated LCOEs. The correlation between increasing turbine size and decreasing LCOE is clear. The one exception is the previously mentioned 2003 to 2009 timeframe in which installed costs increased due to supply chain shortages, higher commodity material prices and an overall resetting of business costs and profitability.

In order to demonstrate the power of economies of scale for a single horizontal axis wind turbine, HAWT, a short analysis was conducted which evaluated the benefits of increasing blade length 10% for a 2.4 MW wind turbine. The original turbine had 58 meter blades, but were increased 10% to 63.8 meter in length. Keeping all other factors constant resulted in an impressive AEP increase of 36% and a LCOE decrease of 17.4% from 0.0396 to 0.0327. Essentially, the fixed costs (initial turbine installation) were spread over the larger energy production, albeit with the addition of the variable cost associated with the longer blades. It is not surprising that OEMs have moved toward lower specific power turbines utilizing longer blades capable of capturing greater wind energy where wind conditions are acceptable. It is important to note that original equipment manufacturers and wind farm development partners would evaluate all of the design implications of longer blades on component and system performance, reliability and life prior to proceeding with such a decision.

### 5.3 Operation and Maintenance Benefits

Economies of scale have played a significant role in the reduction of wind farm O&M costs. O&M costs can vary widely among projects and are affected by age. For new commercial projects, O&M costs have decreased
### Table 4: Historical average commercial wind turbine specifications and performance analysis

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Average</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nameplate Rating</td>
<td>55</td>
<td>100</td>
<td>300</td>
<td>550</td>
<td>880</td>
<td>1430</td>
<td>1800</td>
<td>1940</td>
<td>1910</td>
<td>2000</td>
<td>2400</td>
</tr>
<tr>
<td><strong>Turbine Cost, $/kW</strong></td>
<td>Data not available</td>
<td>Data not available</td>
<td>Data not available</td>
<td>1854</td>
<td>818</td>
<td>1376</td>
<td>1537</td>
<td>1279</td>
<td>1185</td>
<td>1092</td>
<td>800</td>
</tr>
<tr>
<td>Installed</td>
<td>5947</td>
<td>3801</td>
<td>3,444</td>
<td>2193</td>
<td>1954</td>
<td>1755</td>
<td>2608</td>
<td>2273</td>
<td>1728</td>
<td>1800</td>
<td>1473</td>
</tr>
<tr>
<td><strong>CAPEX</strong></td>
<td>$327,085</td>
<td>$380,100</td>
<td>$1,033,200</td>
<td>$1,206,150</td>
<td>$1,719,520</td>
<td>$2,509,650</td>
<td>$4,694,400</td>
<td>$4,409,620</td>
<td>$3,300,480</td>
<td>$3,600,000</td>
<td>$3,535,200</td>
</tr>
<tr>
<td><strong>Capacity Factor</strong></td>
<td>22.0</td>
<td>22.0</td>
<td>22.0</td>
<td>22.0</td>
<td>32.0</td>
<td>34.0</td>
<td>31.5</td>
<td>37.5</td>
<td>38.5</td>
<td>40.7</td>
<td>42.0</td>
</tr>
<tr>
<td><strong>Blade Length, M</strong></td>
<td>7.5</td>
<td>9.0</td>
<td>15.0</td>
<td>21.0</td>
<td>27.0</td>
<td>36.0</td>
<td>42.1</td>
<td>46.8</td>
<td>48.5</td>
<td>52.0</td>
<td>58.0</td>
</tr>
<tr>
<td><strong>Swept Area, (M2)</strong></td>
<td>200</td>
<td>254</td>
<td>707</td>
<td>1385</td>
<td>2290</td>
<td>4072</td>
<td>5568</td>
<td>6881</td>
<td>7390</td>
<td>8495</td>
<td>10568</td>
</tr>
<tr>
<td><strong>Specific Power, W/M2</strong></td>
<td>275</td>
<td>393</td>
<td>424</td>
<td>393</td>
<td>384</td>
<td>351</td>
<td>326</td>
<td>282</td>
<td>258</td>
<td>235</td>
<td>227</td>
</tr>
<tr>
<td><strong>AEP, MW-hr/MW/Yr</strong></td>
<td>96,360</td>
<td>192,720</td>
<td>578,160</td>
<td>1,204,500</td>
<td>2,042,832</td>
<td>3,570,138</td>
<td>4,966,920</td>
<td>6,372,900</td>
<td>6,306,762</td>
<td>7,130,640</td>
<td>8,830,080</td>
</tr>
<tr>
<td><strong>O&amp;M Cost, $/kW-Year</strong></td>
<td>72</td>
<td>72</td>
<td>60</td>
<td>60</td>
<td>29</td>
<td>29</td>
<td>29</td>
<td>29</td>
<td>29</td>
<td>29</td>
<td>30</td>
</tr>
<tr>
<td><strong>LCOE from Calculation, $/kW-hr</strong></td>
<td>0.327</td>
<td>0.203</td>
<td>0.187</td>
<td>0.120</td>
<td>0.102</td>
<td>0.082</td>
<td>0.094</td>
<td>0.079</td>
<td>0.066</td>
<td>0.055</td>
<td>0.043</td>
</tr>
</tbody>
</table>

**Note:** Swept area, Specific Power, AEP and LCOE are calculated values, 2020 $.

from $70–$80/kW in the mid-80’s and $60/kW-year in the mid-90’s to less
than $30/kW-yr installed since 2010. (Wiser, 2018) Per the analysis below,
the decrease in O&M costs since the mid-90’s is estimated to contribute an
approximate 16% reduction in LCOE. This is a substantial contribution given
that O&M costs for onshore wind turbines typically only represent between
20 and 30% of the LCOE. A wind farm with larger and less numerous turbines
is simply less costly to operate and maintain. This occurs because a portion
of turbine preventative maintenance labor is independent of turbine size. This
includes gearbox oil replacement, routine greasing of common components
such as generator bearings, main shaft bearings, blade bearings, yaw and
pitch drives and hydraulic system maintenance for the breaking mechanism
and pitch control of blades. Additional maintenance requirements include
filter changes and the routine torquing of bolts. With less numerous turbines,
unplanned maintenance labor costs and component costs such as electrical
component failures and other part replacements would also be reduced.

Technology development has also played a role in the reduction of O&M
costs. Inspection and monitoring programs have generally improved with a
focus on preventive maintenance for gearbox, generators, blades, etc. Use of
condition monitoring, SCADA and artificial intelligence systems has enabled
the identification of trends in proactively maintaining critical components at
the lowest possible costs.

Regarding the future, onshore wind turbine O&M costs are estimated to
fall another 8–10% by 2030. “There is however a consensus that O&M costs
are on a downward trend that is likely to continue and will further contribute
to lower wind energy generation costs, both onshore and offshore. The use
of larger machines is one reason for this downward trend as O&M costs benefit
from economies of scale.” (Milborrow D 2021)

### 5.4 Wind Turbine Analysis–2010 to 2020

Between 2010 and 2020, average installed turbine nameplate ratings
increased from 1.8 MW to 2.4 MW and blade lengths increased from
approximately 42.1 meters to 58 meters, a 37.8% increase. Rotor swept area
roughly doubled from 5,568 M\(^2\) to 10,568 M\(^2\) and annual energy production
increased from 4.996 M kW-hrs to 8.830 M kW-hrs. At the same time,
average installed turbine costs were reduced from $2,608/kW to $1,473/kW.
In the end, average installed turbine LCOE dropped from $0.094/kW-hr
to $0.043/kW-hr. The fact that increased blade length varies with power
production by a squared formula (due to circular swept area wind capture)
supercharged the positive return of increasing turbine size and respective blade lengths. Wind turbine technologies, alternative to the standard three-bladed horizontal axis wind turbine (HAWT) face a difficult competitive challenge due to the physical properties of the HAWT capturing wind over a circular area and the squared relationship between increased blade length and power output.

An analysis was conducted using historical data between 2010 and 2020 to estimate the impact of increased annual energy production and reduced installed costs on LCOE during this timeframe. Table 5 summarizes the analysis. The LCOE calculated for the average wind turbines installed in 2010 and 2020 was $0.0939/kW-hr and $0.043/kW-hr, respectively. In order to separate out the impact of increased AEP from reduced installation costs, the installation cost of an average 2010 turbine ($2.608 M per MW), was utilized to recalculate the LCOE impact of the higher installed cost on the 2020 turbine. Per the table below, when the higher 2010 installed cost was substituted for the 2020 LCOE calculation, it resulted in a LCOE of $0.0695/kW-hr.

The total LCOE reduction between 2010 and 2020 was $0.0509/kW-hr. Assuming average historical O&M costs were largely constant over this period of time, the LCOE difference of $0.0244/kW-hr represents the contribution of LCOE reduction due to annual energy production increases or $0.0509 (0.0244/0.0509) of the total LCOE decrease. The difference between $0.0509/kW-hr and $0.0244/kW-hr then represents the LCOE reduction attributed to installed cost reductions and equates to 52% of the total LCOE difference between 2010 and 2020.

Table 5 Analysis of the contribution of annual electric production increases versus installed cost reductions to turbine LCOE improvement between 2010 and 2020

<table>
<thead>
<tr>
<th>Difference</th>
<th>% of Total</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Year</th>
<th>2010</th>
<th>2020</th>
<th>Difference</th>
<th>% of Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbine Nameplate Rating, MW</td>
<td>1.8</td>
<td>2.4</td>
<td>0.6</td>
<td>48%</td>
</tr>
<tr>
<td>Blade Length, M</td>
<td>42</td>
<td>58</td>
<td>16</td>
<td>52%</td>
</tr>
<tr>
<td>Installed Cost, $M/MW</td>
<td>2.608</td>
<td>1.473</td>
<td>1.135</td>
<td></td>
</tr>
<tr>
<td>O&amp;M Cost, $/kW per year</td>
<td>30</td>
<td>30</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Annual Electric Production, kW-hrs/yr</td>
<td>4.967 M</td>
<td>9.040 M</td>
<td>4.073 M</td>
<td>81%</td>
</tr>
<tr>
<td>LCOE, $/kW-hr</td>
<td>0.0939</td>
<td>0.043</td>
<td>0.0509</td>
<td></td>
</tr>
<tr>
<td>LCOE, $/kW-hr (Assumes $2.608 M/MW installed cost for 2010 and 2020)</td>
<td>0.0939</td>
<td>0.0695</td>
<td>0.0244</td>
<td>48%</td>
</tr>
</tbody>
</table>
In summary, roughly 48% of LCOE reduction was the result of increased annual energy production due to larger wind turbines, higher hub heights, and longer blades. The remaining 52% in LCOE reductions could be attributed to installed cost reductions via economies of scale, optimized system and component designs, and production and installation learning curve effects.

5.5 The Learning Curve Effect: Turbine Manufacturing and Installation

A wind turbine is manufactured and constructed through both factory and on-site operations. Major components such as towers, blades and nacelles which consist of the drivetrain (gearbox and generator), transformer and power converter, enclosure, yaw and pitch systems, controls, and hydraulic systems are manufactured via individual factories and then shipped to the wind farm site and assembled on-site. Per the USGS, a wind turbine is composed of 71–79% steel, 11–16% fiberglass, resins and plastics, 5–17% copper and 0–2% aluminum. These commodity material costs greatly impact the cost of a wind turbine and its major components, often representing 50% or more of the total wind turbine cost.

The turbine foundation construction occurs on-site as well as the assembly of the components including the tower segments, nacelle placement on the tower, rotor attachment to the hub, electrical interconnections and underground cabling. On-site construction and assembly involves skilled labor ranging from electricians to cement masons, riggers, crane operators, and iron workers. Overall, wind turbine production and plant construction is complex requiring a large and diverse supply chain and a multitude of skilled labor requirements. With that said, costs are typically broken down and often presented in two simple categories: the turbine and the balance of system (BOS). The BOS consists of all labor, material and equipment costs necessary to construct and assemble the turbine on-site. BOS costs include planning, permitting, foundation construction, electrical infrastructure and assembly of the turbine. For onshore wind farms, the breakdown of installed costs is approximately 70% wind turbine and 30% BOS. The percentages are reversed for offshore wind with the turbine representing 30% and BOS contributing 70% of the total installed cost. The breakdown in costs for onshore wind farms is estimated as:

- Turbine Nacelle: 33.9%
- Blades: 19.5%
- Tower: 15.4%
The Power of Economies of Scale: A Wind Industry Case Study

Figure 5 Annual U.S. wind turbine electricity generating capacity additions between 2004–2020.

- Transport 3.1%
- Subtotal: 71.8%
- Contingency/other costs: 10–14%
- Electrical connection: 8–24%
- Foundation: 14–22%
- Development costs: 2–7% (IRENA Renewable Cost Database)

Per Energy Information Administration, EIA, data in Figure 5, the U.S. industry grew significantly between 2004 and 2009.

Learning curve cost reductions in which production and installation costs decline by a constant percentage each time volume doubles would have been significant during this growth period. However, annual capacity additions since the late 2000s have been inconsistent ranging from less than 1 GW in 2013 to more than 16 GW in 2020, often trending in response to Federal Production Tax credit decisions and timelines. With the exception of 2013, annual turbine installation additions were estimated to range from 2,000 to 7,000 units with USGS reporting an average of 3,000 units produced annually since 2005. Due to continued consolidation in the U.S. wind industry, as of 2020, GE and Vestas represented about 87% of the U.S. sales, thus expanding each company’s production volumes and potential efficiencies in the U.S. Despite a lack of consistent growth in U.S. turbine sales and installations since the late 2000’s, the industry was still able to optimize designs and improve manufacturing, construction, and installation techniques yielding impressive cost reductions. Analysis previously presented between 2010 and 2020 demonstrated CAPEX reductions to account for 40% of the LCOE
decline during this timeframe. Large OEM companies such as Vestas and GE utilized their tremendous supply chain leverage given that they competitively source components globally including large castings, gearboxes, generators and drivetrain components for their many factories.

Below are study results (Elia and Rogan 2020) that concluded turbine price reductions (including turbine foundation construction) occurring between 2005 and 2017 were achieved through the following learning curve drivers with the approximate contributions:

- Learning by deployment was the largest driver and was responsible for 50% of the cost reductions.
- Learning by R&D accounted for 16% of the cost reductions.
- Supply chain cost reductions were responsible for 17% reduction through increased competition and cooperation in optimizing designs with the OEMs.
- Market dynamics accounted for an estimated 17% of the cost reduction. This was driven by market demand and competition between OEMs.

According to study results, wind turbine pricing, including foundation construction, was reduced from $1,348/kW to $925/kW during this timeframe, a 31% or $423/kW price reduction (2016 $). This cost reduction included changes in materials, labor, legal and financial costs.

In summary, while turbine cost reductions are heavily dependent on material commodity prices such as steel and fiberglass, supply chain leverage and learning curve effects played a significant impact role in turbine price reductions between 2005 and 2017.

6 Future Wind Economic Prospects
6.1 Onshore Wind Future Potential
Onshore wind turbines have continued to increase in size over the last four decades. The average newly installed turbine nameplate rating in 2021 was approximately 3.0 MW. Today, turbine OEMs offer onshore wind turbine platforms between 2 and 4 MW capacity with 6 MW machines now available through several OEMs. Turbine selections are dependent on wind plant location and wind resource characteristics as well as transportation logistical limitations. Turbines are often customized so that smaller diameter rotors are paired with turbines in high, gusty wind regime areas and larger rotors are recommended for more moderate wind regions to increase the wind capture area and operate more economically. A brief analysis of a 3.45 MW wind
The Power of Economies of Scale: A Wind Industry Case Study

Table 6  LCOE analysis of a 3.45 MW reference onshore wind turbine

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbine nameplate Capacity, kW</td>
<td>3450</td>
</tr>
<tr>
<td>Mass, Kg</td>
<td>134,009.35</td>
</tr>
<tr>
<td>Air Density, Kg/M3</td>
<td>1.23</td>
</tr>
<tr>
<td>Swept Area, M²</td>
<td>14,526.76</td>
</tr>
<tr>
<td>Blade Radius, M</td>
<td>68.00</td>
</tr>
<tr>
<td>Wind Velocity, M/S</td>
<td>7.50</td>
</tr>
<tr>
<td>Kinetic Energy</td>
<td>3,769,012.86</td>
</tr>
<tr>
<td>Annual Potential wind Energy, kW-hr</td>
<td>33,016,552.68</td>
</tr>
<tr>
<td>Capacity Factor</td>
<td>0.43</td>
</tr>
<tr>
<td>Est. Real Annual Potential Wind Energy, kW-hr</td>
<td>13,206,621</td>
</tr>
<tr>
<td>Opex</td>
<td>1,147,565.62</td>
</tr>
<tr>
<td>Capex, 2020$</td>
<td>4,830,000.00</td>
</tr>
<tr>
<td>Cost of Capital</td>
<td>6%</td>
</tr>
<tr>
<td>Years of Operation</td>
<td>20.00</td>
</tr>
<tr>
<td>Annual O&amp;M Costs, $/kW-year</td>
<td>$29</td>
</tr>
<tr>
<td>Annual O&amp;M Cost/year, $/Year</td>
<td>$100,050</td>
</tr>
<tr>
<td>NPV Numerator</td>
<td>5,977,565.62</td>
</tr>
<tr>
<td>NPV Denominator</td>
<td>151,478,903.26</td>
</tr>
<tr>
<td>LCOE, $/kW-hr</td>
<td>0.0395</td>
</tr>
</tbody>
</table>

Table 6 summarizes the characteristics of a 3.45 MW reference turbine as provided by NREL in a recent 2020 Wind Market Technologies report and intended to provide a perspective on future land-based wind turbine unsubsidized LCOE potential which falls below $0.04/kW-hr.

As shown in Figure 6, land-based LCOE has continued its decreasing asymptotic trend, albeit with diminishing benefits over four decades and the wind industry has continued to develop and offer larger turbines as a result. As an example, the average size of newly installed onshore turbines in 2021 rose to 3.0 MW from 2.7 MW just a year earlier. (Wiser and Bolinger, August 30, 2022) However, the ability and cost to transport and install large turbine components such as long blades and large diameter tower sections for onshore wind development will limit turbine installation size. Local, state and Federal permitting challenges such as the Federal Aviation Administration’s (FAA) willingness and timeline to approve “determinations of no hazard to air navigation” for turbine heights greater than 499 feet will also challenge large onshore turbine installations. Meanwhile, a recent research analysis of land-based wind turbines projected a 3.5 MW turbine to represent the minimum LCOE after which diseconomies of scale prevailed and LCOE increased. “By analyzing cost scaling trends, we found that both BOS costs
and LCOE decrease as plant size increases, increase with hub height and reach a minimum at a 3.5 MW turbine rating.” (Key, Roberts, Eberle, 2021) In this analysis, taller hub heights eventually resulted in larger foundations and consequently increased material, crane, and labor costs thus increasing LCOE as turbine nameplate ratings increased beyond 3.5 MW capacity. The analysis identified lower cost foundation design as a prime area for additional research and development. The wind industry is currently conducting R&D including prototype testing to address many of these potential limitations with concepts including the on-site manufacturing of spiral towers, use of concrete towers or hybrid steel/concrete towers, segmented blade designs, self-erecting towers and smaller, lighter drivetrains. (Khan and Khan Omadath, 2017)

6.2 Offshore Wind Future Potential

Though there are many East coast offshore wind projects in the planning and development phases, the U.S. has limited offshore wind experience with only two operating projects, the 2016 30 MW Block Island wind farm off the coast of Rhode Island consisting of 6 MW turbines and Dominion Energy’s 2020 Virginia Beach pilot 12 MW plant consisting of 2–6 MW turbines.

Offshore wind development takes the benefits of economies of scale to a whole new level. While the U.S. average newly installed onshore wind turbine in 2021 was 3 MW in size, the average world-wide offshore wind turbine had a nameplate capacity rating of 7.4 MW, albeit with a LCOE of roughly twice that of onshore systems.

A typical cost breakdown for offshore wind turbines includes roughly 70% BOS versus 30% for onshore turbine installations. “Unlike onshore wind projects, offshore wind farms must contend with installation and operation and maintenance (O&M) in harsh marine environments making these projects...
costlier and giving them significantly longer lead times. The planning and project development required for offshore wind farms is more complex than that for onshore wind projects. Construction is even more so, increasing total installed costs.” (Taylor et al. 2020). As a result of high BOS costs which can be more than two times that of land-based installations, offshore wind installations require very large and less numerous turbines to be economically viable. AEP is then maximized via ultra-large turbines and BOS and O&M costs, on a per-kW basis, are reduced as a result of a lower number of turbine installations for a given wind plant. In addition, larger offshore MW wind farms (∼1,000 MW) are needed to spread upfront planning and development fixed costs over the greater electricity production and contribute to lower LCOEs. The lowest average offshore installed costs in 2019 were more than double that in the U.S. for onshore wind.

As a result of the higher proportion of BOS costs, offshore wind LCOE has its own and unique signature. An analysis of average 2019 offshore wind turbine specifications as reported by IRENA included a 6.5 MW turbine capacity, 52% capacity factor, $75/kW-yr O&M costs, and 80.5 meter blade lengths. Utilizing these turbine specifications and a 9.0 m/s wind speed yielded a LCOE of $0.0826/kW-hr. The average world-wide installed offshore wind turbine in 2021 was 7.4 MW with a CAPEX of $3,700/kW and a LCOE of $0.084/kW-hr. Larger turbines like the GE Haliade-X 12–14 MW versions (107 meter blades) are being demonstrated, and likely to continue the trend toward lower offshore wind LCOEs.

“Developers generally prefer to use the largest wind turbine available for a given project which reduces BOS and O&M costs on a per-kW basis.” (Musial et al. 2022) Per the DOE Offshore Wind Market Report, 2022 Edition, publicly available information on a large coastal Virginia project proposed by Dominion Energy involving 176 fixed bottom 14.7 MW turbines reported a CAPEX of $3,788/kW and an estimated LCOE of $0.077/kW-hr. Projected capacity factor was 43%. While transportation logistics is a significant onshore challenge, it is less of an issue for offshore wind installations since production of components can be done near the shoreline/waterways allowing for transportation by barge or ship.

6.3 Diseconomies of Scale

Economies of size generally have an optimum followed by diseconomies of size. However, for offshore wind turbines, OEMs have continued to spend tens of millions of dollars toward the development of giant turbines in the
10 MW to 15 MW range and the assumption is that the projected LCOE’s for these machines continue to decline. Per Professor Simon Hogg at Durham University, “There has to be a physical limit although nobody has put a number on that.” (Baraniuk, 2021) “Instead, it is the practicalities of putting these machines in place and maintaining them that might first become problematic” (Baraniuk, 2021) Besides the diminishing LCOE scaling cost benefits and less appealing risk/reward tradeoff associated with larger turbines that are represented by a decreasing asymptotic relationship, future issues leading to wind turbine installation diseconomies of size include key component costs increasing disproportionately with nameplate rating and reduced wind turbine system life and reliability as well as higher O&M costs due to an increase in the fatigue of blades, hubs, bearings, drive shafts and towers.

Many turbine components scale up in cost in proportion to nameplate capacity rating or scale up disproportionately in cost. (Fingersh et al. 2006) The scaled component costs can exceed the benefits of AEP as turbine nameplate rating increases. As an example, a 2019 NREL analysis (Bortolotti et al. 2019) determined that as blades increase in length, weight and cost disproportionately increase with turbine nameplate rating with an approximate 2.4 power relationship between nameplate rating and cost per the Table 7. Another analysis conducted for onshore turbine towers concluded that upscaling of 80 m steel tubular towers was not cost effective. The researchers recommended continued research in development of concrete, space frame or hybrid concrete/steel towers in order to cost effectively scale towers. (Levandowski, 2015) This scaling trend portends to limits in turbine size barring future R&D breakthroughs. Besides blades and towers, gearboxes and bearings also scale up disproportionately in mass and cost with nameplate rating consequently detracting from the AEP production benefits of larger machines.

Longer blades could eventually pose component life and reliability risks due to higher levels of centrifugal and gravity forces and differences in bending moments across the swept area since wind speeds can differ by several meters per second from the tip to the bottom of the massive swept area.

<table>
<thead>
<tr>
<th>Blade Length, m</th>
<th>Blade Weight, Kg</th>
<th>Blade Estimated Cost, $</th>
</tr>
</thead>
<tbody>
<tr>
<td>33</td>
<td>4,335</td>
<td>58,146</td>
</tr>
<tr>
<td>65</td>
<td>14,255</td>
<td>154,090</td>
</tr>
<tr>
<td>100</td>
<td>49,977</td>
<td>547,723</td>
</tr>
</tbody>
</table>

(Bartolotti, Berry, Murray, Gaertner, Jenne, Damiani, Barter, Dykes 2019).
Reliability and life issues could take years of actual operational experience to make determinations on optimum size, especially for the behemoth offshore turbines currently undergoing prototype testing.

7 Summary

Economies of scale has been and continues to be a significant driver in the success of many industries including the wind industry in the U.S. and Internationally.

Due to the high upfront capital cost requirements, the wind turbine industry has benefited from economies of size/scale possible by producing more product, electricity in this case, at a lower cost through the continued design and implementation of larger wind turbines and wind plants as well as the implementation of learning curve production and assembly techniques.

As individual turbines and their blades have grown larger over the past four decades, enabled by technology development, it has resulted in greater turbine AEP and a reduction in the number of turbine installations for a given wind farm. Subsequently, the balance of system costs and operation and maintenance costs have declined on a per MW basis, thus reducing LCOE. The historical correlation between increasing wind turbine nameplate capacity rating and decreasing LCOE is abundantly clear, albeit with diminishing returns. Since the inception of the wind industry, the cost to produce electricity declined more than six-fold as turbines consistently increased in size from 30 to 50 kW in the early 80s to 3.0 MW average newly installed capacity in 2021 and is competitive today with fossil fuel power generation. As of 2021, wind power generation represents more than 9% of the total U.S. power generated and the wind industry supports over 120,000 jobs and annual investments totaling Billions of dollars. Below are key takeaways from this study.

- A huge benefit of modern-day wind turbines is the horizontal axis, three bladed turbine designs in which the wind energy capture area, otherwise referred to as the rotor swept area, increases in proportion to the square power of the blade length subsequently resulting in a 4X power generation potential with a 2X increase in blade length. As turbines have increased in nameplate power capacity, AEP has increased disproportionately and contributed to lower LCOEs. The supercharged, squared power electric production possible via increased rotor diameters and associated swept areas have made horizontal axis wind turbines the wind turbine of choice across the U.S. and the world and has allowed the turbine scaling necessary to drive down LCOEs to be competitive with conventional fossil fuel technologies.
• Wind farm size is important to the success of achieving low LCOEs, albeit with slowly decreasing benefits after 200 MW onshore wind farm capacity. One recent study (Key et al. 2021) determined that increasing the size of a wind plant from 150 MW to 400 MW in size could reduce BOS costs by 21%. The findings indicated that the BOS costs per kW decreased as plant size increased as a result of amortizing mobilization costs such as site preparation, electrical and substation installation and foundation installations. This is an excellent example of economies of scale where large upfront fixed and semi-fixed planning and development costs can be spread over increasing production (kW-hr electric production). As a result of this effect, most onshore wind farms today exceed 200 MW in total capacity with many reaching 400 MW in total capacity. Offshore wind farms require even larger wind farms to be most cost effective due to even greater upfront planning and development costs.

• Onshore wind turbines in the U.S. evolved from an average 30 to 50 kW four decades ago to an average installed turbine capacity today reaching 3.0 MW and wind plants exceeding 400 MW in size. Wind farms now produce electricity at an unsubsidized LCOE less than $0.05/kW-hr, competitive with conventional fossil fuel technologies. In the meantime, wind turbine platforms are being offered in the 2-4 MW capacity which portend to LCOEs below $0.04/kW-hr. Research and development continues to address logistical issues such as the transportation of blades and towers and reduced size and weight of state-of-the-art drivetrains.

• Since the early 2000s, technology development focused on offshore wind has enabled giant turbines between 10 MW and 15 MW in nameplate capacity with many currently in the prototype testing phase. A typical cost breakdown for offshore wind turbines includes roughly 70% balance of system costs versus 30% for onshore turbine installations. Consequently, offshore wind installations require very large turbines to be economically viable and generate sufficient electricity to absorb the higher costs associated with the BOS requirements such as offshore transmission cable installations, increased cost of installing wind turbine systems in harsh offshore environments, land leases and the very costly regulatory approvals necessary to proceed. These giant turbines, combined with large planned wind farms exceeding 1,000 MW in capacity, portend to future LCOEs in the $0.07/kW-hr to $0.08/kW-hr range.

• Economies of scale generally have an optimum followed by diseconomies of scale and reduced economic benefits. One recent 2021
research analysis (Key et al. 2021) concluded that a 3.5 MW onshore turbine represented the optimum size associated with a minimum LCOE for a typical installation. Scaling beyond 3.5 MW resulted in LCOE increases as foundation costs outpaced the AEP benefits of larger wind turbines. Potential future issues leading to wind turbine installation diseconomies of scale include disproportionate component cost increases associated with turbine nameplate rating scaling, reduced wind turbine system life and reliability as well as higher O&M costs due to a substantial increase in the fatigue of blades, hubs, bearings, drive shafts and towers. Longer blades could eventually pose component life and reliability risks due to higher levels of centrifugal and gravity forces and differences in bending moments across the swept area. For the behemoth turbines currently undergoing prototype testing, reliability and life issues could take years of actual operational experience to draw conclusions.

- Economies of scale for many industries has involved maximizing asset utilization and use of automation in order to increase production volumes and drive down production costs. The U.S. wind industry grew significantly between 2000 and 2010 timeframe reaching nearly 10 GW in annual installations. Since then, annual installations have generally trended with the ebb and flow associated with the Federal Production Tax credit. While production and installations have been inconsistent since 2010, the industry optimized operations via learning curve effects to significantly impact CAPEX. One recent landmark study by (Elia and Rogan 2020) utilized a bottom-up analysis to estimate the impact of learning curve drivers on turbine price reductions between 2005 and 2017. It estimated a 31% reduction equivalent to $423/kW in 2016 turbine price (including foundation). Learning by deployment was deemed to be the largest driver contributing 50% to the cost reduction followed by learning by R&D, supply chain impacts and market dynamic effects.

- While there are many factors which have impacted the success of the U.S. wind industry including research and development efforts, policy decisions, and federal, state and local support, analysis completed as part of this paper determined that economies of scale significantly contributed to reduction in LCOE over the past four decades. In one simple analysis involving historical wind turbine data between 2010 and 2020, it was determined that 48% of LCOE cost reduction could be attributed to increased annual electric production via increased turbine and plant size, taller towers and a continuing trend to reduced specific power as blade lengths outpaced turbine nameplate rating. Just a 10% increase
in blade length on a 2.4 MW turbine was estimated to decrease LCOE by more than 17%. The remaining 52% of the LCOE cost reduction ($0.094/kW-hr to $0.043/kW-hr) over this decade was attributed to cost reductions including production, operation and installation learning curve effects. Besides increased annual electric production, larger and less numerous wind turbines for a given wind farm contributed to O&M cost reductions and an associated 16% LCOE reduction over the past two decades.

In conclusion, the importance of recognizing and exploiting potential economy of scale advantages of various technologies and products can be a critical factor in the ultimate successful development of new products and entire industries. This wind industry success story serves as an important case study and guide as entrepreneurs and technology developers undertake future efforts to develop and commercialize new, innovative and cost competitive renewable energy and high technology products.

**Acknowledgement**

The National Renewable Energy Laboratory provided input to this paper. Special thanks for Tyler Stehly, Eric Lantz and Owen Roberts.

**Acronyms**

- **AEP** Annual Electric Production
- **BOS** Balance of System
- **CAPEX** Capital expenditure
- **GW** Gigawatt
- **HAWT** Horizontal axis wind turbine
- **kW** kilowatt
- **LCOE** Levelized Cost of Electricity
- **MW** Megawatt
- **NPV** Net Present Value
- **OEM** Original equipment manufacturer
- **OPEX** Operational expenditure
- **O&M** Operational and maintenance
- **PV** Photovoltaics
- **SCADA** Supervisory control and data acquisition
References


Baraniuk C, Why Giant Turbines are Pushing the Limits of Possibility, BBC News, October 15, 2021.


Inconagello D. Large Turbine Blades have slashed wind energy costs. E& E News Scientific American. 3/5/20.

IRENA Renewable Cost Database.


Mariano, A. Wind Turbines are getting Bigger and Taller. Pager Power Urban and Renewables. October 17, 2019.
Steel Price Projections.
McGuinn J. More OEMs taking the direct drive approach for wind turbines. Gear Technology.com
Roberts D. These huge new wind turbines are a marvel, They’re also the future. VOX. May 20, 2019.


Siemens d6-offshore brochure. 2014.


Warburg P. An Introduction to the state of wind power in the U.S. *Yale Climate Connections*. October 7, 2019.


Biographies

Gary A. Nowakowski retired from the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, where he served in various management positions for 20 years. Prior to that, he was a Technology Manager for the Gas Research Institute, responsible for developing new and improved products for the natural gas industry. Gary has a BS and MS in Mechanical Engineering from the University of Wisconsin and a MBA from DePaul University.

David G. Loomis is Executive Director of the Institute for Regulatory Policy Studies and Professor of Economics at Illinois State University where he teaches in the Master’s Degree program in electricity, natural gas and telecommunications economics. He earned his Ph.D. in economics at Temple University.