Assessing Wind Power Operating Costs in the United States:

Results from a Survey of Wind Industry Experts

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Abstract

This paper draws on a survey of wind industry professionals to clarify trends in the operational expenditures (OpEx) of U.S. land-based wind power plants. We find that average all-in lifetime OpEx has declined from approximately $80/kW-yr (~$35/MWh) for projects built in the late 1990s to a level approaching $40/kW-yr (~$11/MWh) for projects built in 2018. Turbine operations and maintenance costs represent the single largest component of overall OpEx and the primary source of cost reductions. We observe wide ranges of OpEx over time; respondents cite a range in average expected costs for recently commissioned projects from $33/kW-yr to $59/kW-yr. We also use historical OpEx learning rates, showing a 9% OpEx reduction for each doubling of global wind capacity, to project a further $5–$8/kW-yr reduction from 2018 to 2040. These findings suggest that continued OpEx reductions may contribute 10% or more of the expected reductions in land-based wind's levelized cost of energy. Moreover, these estimates understate the importance of OpEx owing to the multiplicative effects through which operational advancements influence not only operations and maintenance costs but also component reliability, performance, and plant-level availability—thereby also affecting levelized costs by enhancing annual energy production and plant lifetimes. Given the limited quantity and comparability of previously available OpEx data, the trends reported here may inform OpEx assumptions used by electric planners, analysts, and modelers. The results may also provide useful benchmarks to the wind industry, helping developers and asset owners compare their expectations with historical experience and other industry projections.

Keywords

wind power; operations & maintenance; levelized cost of energy; operational expenditures; learning curves

1. Introduction

The levelized cost of energy (LCOE) of wind power plants is driven by five primary parameters: upfront capital expenditures (CapEx), operational expenditures (OpEx), project performance, financing and tax assumptions, and project life. Among these factors, long-term OpEx has been understudied. While a robust and growing literature on turbine and component reliability exists[1-5] data on OpEx trends are limited.

More specifically, extensive literature on land-based wind CapEx has tracked trends over time and across countries[6-8] established data-driven cost-reduction trajectories based on learning curves,[9-12] and developed engineering models to understand past and possible future cost-reduction options.[13] A growing literature also emphasizes improvements in wind project performance, especially as turbine rotor diameters and hub heights have increased.[6-7]

Project-level data on land-based wind plant OpEx, on the other hand, are not widely available,[6-7,14] owing to the proprietary nature of the data and the fact that lifetime OpEx data are only available after the full life of plants, which can be 20 years or more. Few plants have been operating for 20 years, and those that have are using turbine technology of vastly different scale and sophistication compared with modern projects. As a result, OpEx for early plants may not be relevant for estimating OpEx for newer plants.[6-7, 15] A lack of standardization in both intra- and inter-firm data collection and management (e.g., limited tracking of specific costs that result from specific maintenance issues) has further hindered the development of OpEx datasets and intelligence.[16]

Even when wind OpEx data are available, they can be hard to interpret. In some cases, data are reported as actual realized costs; in other cases, as long-term cost expectations. The number of years covered by the data, relative to expected wind project life, may vary. Costs are often reported in $/kW-yr terms, but also as $/MWh, $/turbine, or $/project. Costs may vary by project size, location, and other factors. Turbine operations and maintenance (O&M) is sometimes contracted out to the turbine manufacturer or an independent service provider with varying servicing terms and durations. In other cases, O&M is self-provided by the wind plant owner. Turbines are typically under manufacturer warranty during the first years of operations, so costs due to unscheduled maintenance may be embedded in turbine purchase agreements, thereby reducing annual O&M costs for the project owner. Finally, a wide and diverse set of costs can be embedded within the OpEx category: turbine O&M (scheduled and unscheduled), balance of plant (BOP) O&M, land costs, property or other local taxes or payments, grid and electrical use, insurance, asset management and administration, and others. Less mature turbines have sometimes required extensive in-field retrofits (e.g., gearboxes) due to premature component failures, which may or may not be considered part of OpEx. Absent clarity on what costs are included, establishing clean comparisons across various sources of OpEx data is impossible.

The result is not only a wide array of OpEx estimates in the literature but, more importantly, a general lack of fidelity and confidence in those estimates. At the same time, understanding past and current land-based wind plant OpEx is important for several reasons.

First, OpEx represents a sizable and potentially growing share of LCOE, especially as wind's LCOE declines owing to lower upfront costs and better performance. Ten years ago, analysts often attributed up to 20%–25% of land-based wind LCOE to OpEx[17-19] associating approximately half of OpEx directly with turbine O&M.[16-17] Recent data suggest that OpEx accounts for 25% to more than 35% of overall LCOE.[8,20]

Second, operational practices and OpEx have important connections to other parameters that influence wind's LCOE. Specifically, turbine O&M practices directly influence turbine component reliability and related downtime, turbine performance, and overall wind plant availability[1-3, 5, 16, 21-22] thereby affecting annual production and project lifetime. CapEx and OpEx are also related, because higher-cost, more reliable turbines may yield lower long-term OpEx, and vice versa.

Third, OpEx represents an important lever for wind plant LCOE reductions. One study, for example, found that OpEx reductions accounted for 9%–11% of overall land-based wind LCOE reductions from 2008 to 2016 in Norway, Germany, and Denmark, 17% in Sweden, and 0% in Ireland.[8] Another study reported on a survey of wind experts, who collectively anticipated that OpEx would decline 9%, on average, by 2030; the experts expected that the lower OpEx would account for 11% of the overall decline in land-based wind LCOE from 2014 to 2030, with plant lifetime extensions (related to OpEx, as noted above) accounting for another 14%.[23] And another study forecasted a 25% reduction in OpEx for plants built in 2030, contributing to 13% of the projected overall LCOE reduction from 2015 to 2030, with expected project lifetime extensions accounting for another 22% of the LCOE reduction.[24]

Finally, OpEx for older plants can dictate the economics and timing of plant refurbishment and repowering, which are increasingly important as the wind fleet ages.[25-27] Though past work has generally found OpEx decreasing over time—with new generations of wind technology—and with increasing turbine size, studies also show that OpEx can increase as projects age.[7-8, 17-18, 28-34]

Recognizing that wind plant OpEx is an important but sometimes overlooked driver of overall LCOE trends for land-based wind, this paper draws from a survey of senior members of the U.S. wind industry to clarify past and current trends in land-based wind OpEx as well as key drivers of those trends.[*] We supplement the survey with a review of literature containing empirical OpEx data for U.S. wind plants. We compare our resulting estimates for average OpEx with other U.S. and global OpEx assessments. Finally, we extrapolate historical data to estimate future land-based wind OpEx, and we compare those estimates of potential cost reductions with other recent assessments.

Our core contributions to the broader literature are twofold. First, using an industry survey methodology, we seek consistent historical and recent data on OpEx and clarity on the drivers of OpEx. Given the limited quantity and comparability of previously available data, the data and trends reported here may usefully inform OpEx input assumptions used by electric system

[*] Note that this paper focuses on land-based wind. Offshore wind faces higher OpEx given the uniquely challenging environmental in which offshore projects operate.[6, 20, 23]

planners, analysts, and modelers. The results may also provide useful benchmarks to the wind industry, helping developers and asset owners compare their OpEx expectations with historical experience and other industry projections. Second, we project future OpEx based on historical learning rates. To our knowledge, ours is the first attempt to document a learning rate for OpEx, and to use those findings to forecast a future range in OpEx. These results too may help inform planners, analysts, modelers, research and development managers, and others—and can be compared to and inform other attempts to project future wind power OpEx.

2. Survey Methods

We conducted the wind industry survey in mid-2018 via email and phone correspondence. We sought historical and recent quantitative data on all-in (i.e., total) OpEx for land-based wind projects in the United States, encompassing costs related to scheduled and unscheduled maintenance, operations personnel, land leases, property taxes, and other operations activities. We also sought qualitative insights into OpEx drivers. We received responses from 11 wind developers/owners/financiers (out of 19 asked), two wind turbine manufacturers (out of five asked), and three consultants (out of five asked)—for an overall response rate of 55%, though some respondents offered only limited qualitative insight.

Recognizing that OpEx data are considered confidential and are not widely and consistently compiled, we sought—in effect—whatever data and insight we could obtain. By implication, we did not require respondents to fill out a standardized formal survey instrument. Instead, we sought quantitative and qualitative insight by starting with an informal contact that was then used to frame further interactions and discussion. In some cases, respondents provided a record of average OpEx for plants built historically up to the present. In other cases, they provided a single point-in-time estimate. Most responded in terms of fixed annual costs ($/kW-year), but others used $/MWh, which we converted to $/kW-yr based on capacity factors for projects built in various years as reported in Wiser and Bolinger (2018).[7] While we primarily focused on all-in OpEx, some respondents broke out all-in OpEx into its constituent parts in various ways. Some respondents assessed only a portion of OpEx (solely turbine O&M, for example, or all costs except for property taxes); we sometimes supplement those respondent-provided data with averages of other data to *estimate* respondent-specific all-in OpEx. Finally, some respondents did not report lifetime values, but instead values for some subset of years less than plant lifetimes; in some of those cases, we estimate lifetime values based on the available data.

There is a distinction between actual realized costs and cost expectations. For wind plants built far in the past (i.e., the late 1990s to late 2000s), we asked for and primarily report actual realized costs wherever possible, in part because these costs have often been higher than the expected costs when the plants were commissioned. We levelize the values and, where necessary, extend them to estimate lifetime levelized figures (see the table in the appendix for additional details). For the most-recent projects, however, actual lifetime costs can only be known in the future, so we primarily report their expected lifetime costs at time of plant commissioning. Finally, for plants built in intermediate timeframes (e.g., between 2010 and 2015), we often report a combination of the two—actual costs when those costs are available, and estimated costs when necessary because actual costs were not provided or not available. Survey respondents generally reported a convergence between actual and expected OpEx occurring around 2010, which lends credence to our approach in this regard. In all cases, after adjustments, we seek to estimate levelized OpEx over plant lifetimes—using actual data where possible, and estimated data where necessary

To increase the quantity of data and the robustness of results, we combine the survey-derived data with empirical OpEx data for U.S. wind plants from the broader literature.[7,16,21,28,35] Specifically, where possible, all quantitative results presented in this paper include relevant data from both the survey and—to a lesser extent—from the other available data sources noted above; these other sources tend to fill some holes in the survey-derived OpEx data, especially for projects built from the late 1990s through the mid- to late-2000s.

To facilitate comparisons, we convert all survey and literature data to real 2017 U.S. dollars, with adjustments and assumptions required in some cases to place OpEx estimates on equal footings. All OpEx data are reported on a levelized basis, with a 5% real discount rate used, as needed to levelize annual values. Levelized costs are most-often reported over the expected lifetime of the wind plants, which as highlighted by survey respondents increased from roughly 20 years in the earlier phases of wind development to 25 to 30 years in more recent times.

Though confidentiality provisions prohibit sharing the full resulting dataset, the appendix to this paper provides a tabular summary of the type of quantitative data provided by each respondent and secondary source. That table also highlights some of the key adjustments required to create a reasonably comparable dataset of levelized lifetime OpEx values across the myriad sources.

3. Land-Based Wind Power OpEx Trends and Drivers

This section describes estimates of OpEx reductions over time, expected versus actual OpEx over time, turbine O&M costs over time, recent estimates of all-in OpEx and OpEx components, and drivers of the range of OpEx estimates observed.

3.1 All-in OpEx Reductions Over Time

All-in (i.e., total) levelized lifetime OpEx for land-based wind projects in the United States are summarized in Figure 1, over time by year of plant commissioning. Each data point represents a different levelized lifetime OpEx figure for projects constructed in the year noted on the x-axis—most come from the industry survey but some from the broader literature as highlighted earlier. Data points joined by horizontal lines reflect single data sources (e.g., survey respondents) that provided OpEx estimates for plants with different commissioning dates. Data points joined by vertical lines reflect the range of OpEx in any specific commercial operation year as revealed by a single data source. Different colors are used to signify different types of data sources.

As indicated earlier, these data reflect a mix of actual OpEx (for the oldest projects, especially prior to 2010), estimated future OpEx (for the newest projects, especially those built after 2014), and combinations of the two (for those projects built in intermediate years). As there is general agreement that convergence between estimated and actual OpEx occurred in roughly the year

2010, the use of both sets of data in this figure is appropriate. In all cases, the resulting data points presented in the figure intend to reflect all-in levelized lifetime values, inclusive of all operational expenditures and for the specified plant commissioning dates.

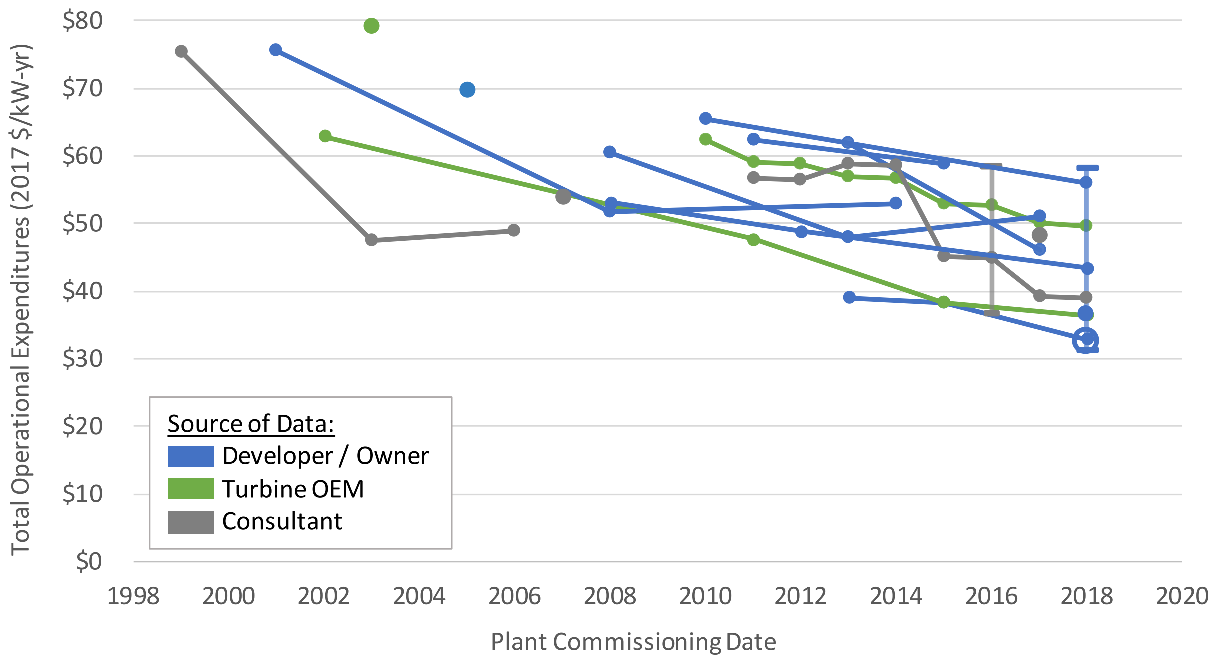

Figure 1. All-in Operational Expenditures, Based on Plant Commissioning Date

Though there is considerable data spread, a consistent and sizable downward trend in OpEx is observed over the entire period. All-in levelized lifetime OpEx is reported to have averaged approximately $80/kW-yr for projects built in the late 1990s, dropping to an average *anticipated* lifetime OpEx in the low- to mid-$40s/kW-yr for recent projects. The trends do not appear to vary by the source of estimates (wind developers/owners, turbine OEMs, consultants). Given the notable increase in wind capacity factors over this period, the decline in OpEx is even greater in $/MWh terms, from approximately $35/MWh for projects built in the late 1990s to ~$11/MWh for the more-recent projects constructed in 2018.

Survey respondents attribute this reduction in OpEx to several factors. Wind turbines, wind plants, and owner-fleets have all increased in size, and each increase has reduced costs through economies of scale—spreading fixed costs over more capacity, reducing required labor per unit of output, enabling optimization of spare parts supply, reducing the cost of component repair and retrofit, and more. In addition, wind technology and operational practices have matured, which has made components more reliable, made widespread the use of automated 24/7 monitoring and condition-based monitoring equipment, and improved predictive and preventative maintenance. Competitive forces and learning have also come into play, with a diversity of improved and more highly optimized OEM service offerings competing with a growing market for third-party service providers and owner self-provision of O&M services.

Results associated with evolving wind project lifetimes also emerged from the survey. A number of respondents suggested that improved technology, O&M practices, and competitive pressures have increased assumed economic lifetimes to 25 or 30 years, making the previously standard 20-year assumption obsolete. Facilitating this development has been the introduction of life-extension programs by OEMs and analyses that show that actual site-specific accumulated fatigue damage is in many cases lower than design-certification fatigue damage.

3.2 OpEx Expectations vs. Reality

For wind plants built in the more distant past (i.e., prior to 2010), Figure 1 tends to report actual realized costs because survey respondents acknowledged that actual costs diverged from expectations over this pre-2010 period. In fact, survey respondents consistently indicated that actual OpEx for plants built from the late 1990s through about 2010 have been substantially higher than expected OpEx at the time of plant commissioning. They identified premature component failures, especially of gearboxes, as a notable cause of these discrepancies during this period of time. Competitive pressure to attract purchasers and financiers also often resulted in overly optimistic OpEx forecasts during this timeframe. As a result, though actual OpEx declined for projects built from 1998 to 2010 due to economies of scale, improved component reliability and other advancements (Figure 1), expectations for lifetime OpEx actually increased (not shown in the figure). One developer, for example, reported an increase in OpEx expectations from $59/kW-yr in 2006 to $66/kW-yr in 2010. Another reported an increase in expectations from $38/kW-yr in the 2001–2005 period to $61/kW-yr in the 2006–2010 timeframe.

As already noted, respondents generally portrayed a convergence between actual and expected OpEx occurring around 2010. Reported reasons for that convergence include industry growth/maturation and an associated increase in component failure and O&M cost data. Additionally, the growing market for long-term "full-wrap" (i.e., O&M contracts that provide full coverage for scheduled and unscheduled maintenance and repair) O&M contracts with availability guarantees offered by turbine OEMs and third-party service providers encouraged a level of sophistication, knowledge, and risk internalization not previously present in the industry. The estimates included in Figure 1 after 2010 significantly derive from lifetime OpEx expectations, informed by early-year actual realized OpEx since commercial operations.

These conclusions from the survey are consistent with the broader literature. Wind Energy Update reported that actual O&M costs were coming in at double or triple the figures originally projected during this period.[36] Debt ratings associated with FPL's (now NextEra's) wind portfolio over time illustrate multiple successive revisions towards higher OpEx expectations as actual costs came in.[37-41] DNV KEMA and GL Garrad Hassan noted the prevalence and cost of serial gearbox failures before 2010, which contributed to unexpectedly high OpEx for some projects and increased overall fleet-wide average OpEx expenditures; series gearbox failures have decreased since 2010.[16,21] Notably, during this period and absent better data, analysts and modelers regularly used OpEx estimates that were lower than the OpEx subsequently realized in practice.[42-44]

3.3 Turbine O&M Costs Over Time

Turbine O&M costs—inclusive of scheduled and unscheduled maintenance of turbines, but excluding all other operational expenditures—represent the single largest component of overall wind plant OpEx as well as the primary source of OpEx reductions over the last decade.

Figure 2 depicts a range of data on turbine O&M, from the late 2000s to the present by year of plant commissioning. Comments made earlier surrounding Figure 1 related to the differences between actual and expected costs apply equally well here—data on plants with early commissioning dates primarily reflect levelized actual costs, whereas plants commissioned most recently primarily reflect lifetime estimates. Most data points reflect levelized lifetime turbine O&M costs for wind plants that enter commercial operations in the year specified, though some of the data points reflect shorter terms, often based on the duration of a signed O&M contract (5-years, 10-years, or variable terms with no average reported).

Overall, though considerable variability exists in the data, levelized turbine O&M cost reductions of around $10/kW-yr are apparent. This reduction is consistent with public information provided by the largest wind-project fleet owner in the North America—NextEra Energy, which owned 14 GW of wind through mid-2018. NextEra highlights a 25% reduction in wind O&M costs from 2014 to 2018, enabled by NextEra's portfolio scale and purchasing power.[45]

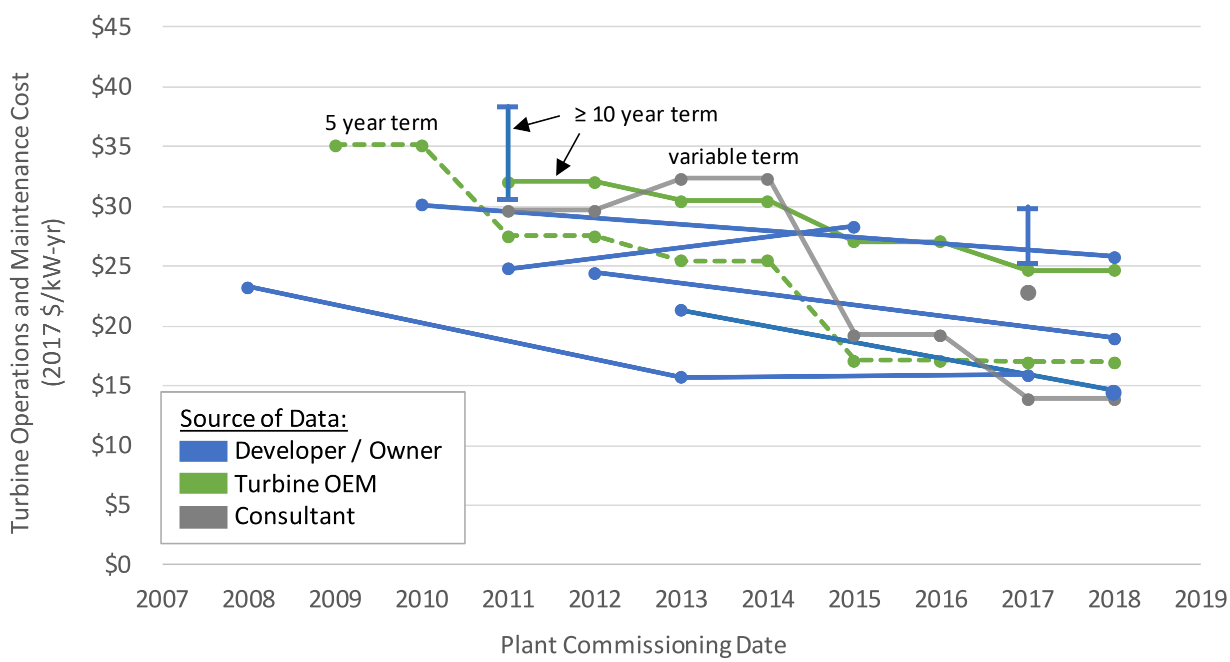

Figure 2. Turbine O&M Costs, Based on Plant Commissioning Date

3.4 Non-Turbine OpEx Over Time

Respondents indicated that reductions in the non-turbine components of OpEx were less significant during this period, with some indicating possible cost increases. For example, U.S. land lease payments are often calculated as a percentage of gross revenue, so declining wind energy prices will have reduced average land lease costs, all else being equal. However, such land contracts often embed a minimum per-MW payment, and minimum payments have been triggered more frequently as wind prices have declined, thus limiting overall cost reductions.

Additionally, in some areas of the country, increased competition for attractive wind sites over time has tended to boost required lease payments. Other costs—such as insurance, BOP maintenance, and property tax—have not declined much over this period, if at all, with some costs even increasing in some instances.

3.5 Recent All-in OpEx Estimates

Based on the data gathered and presented so far, all-in levelized lifetime OpEx appears to have declined over time, though the data show a wide range of OpEx at each point in time (Figure 1). Figure 3 shows the range of expected levelized lifetime all-in OpEx for projects commissioned between 2015 and 2018. In this case, data are almost exclusively based on expectations, as projects of this vintage have little operating history. Levelized expected all-in lifetime OpEx varies by data source, with a range of $33/kW-yr ($9/MWh) to $59/kW-yr ($16/MWh). Across all sources, the average for these 2015-2018 projects is $44/kW-yr ($12/MWh).

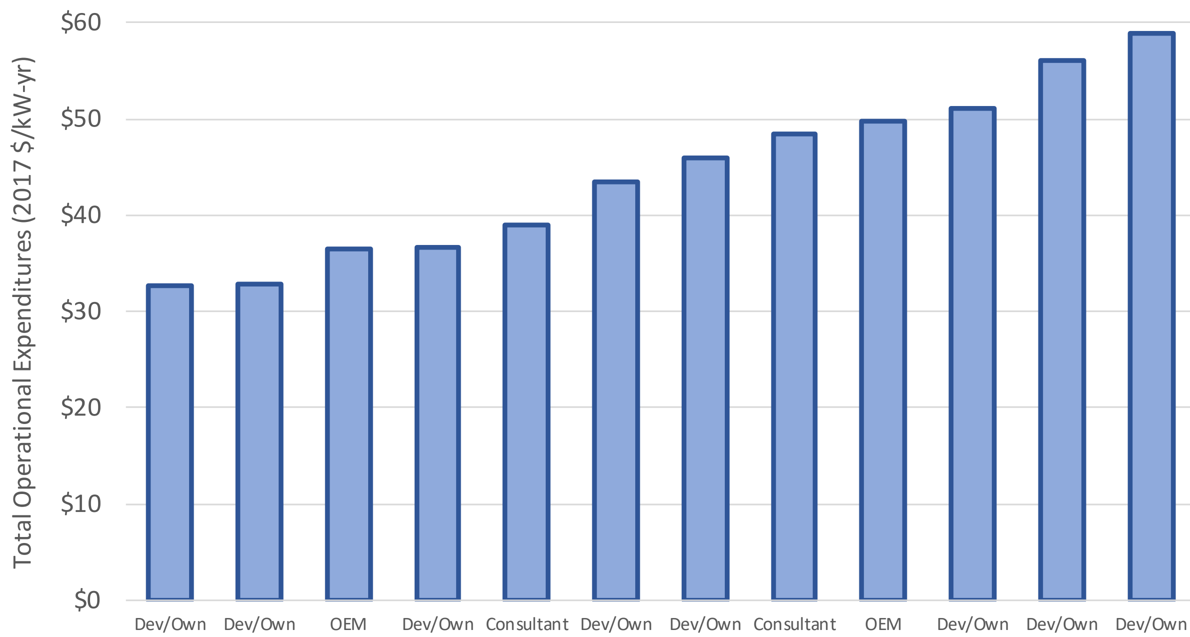

Figure 3. All-in OpEx Expectations for Projects Commissioned 2015–2018, by Respondent Type

Because respondents provided data on average costs, often for large wind project fleets, the costs reported here are a range across fleets of projects; the range across individual projects would be larger still.

3.6 Recent Estimates of OpEx Components

Once a wind project emerges from its warranty phase, maintenance costs can become substantial, and uncertainty in major component lifetimes can increase the difficulty of estimating maintenance costs accurately. Because of this, uncertainty in turbine O&M costs might be expected to be the primary driver of the range in recent all-in OpEx estimates. Other costs—such as those related to insurance, land payments, and routine maintenance—are often easier to predict, so greater convergence in those costs might be expected.

However, based on the industry survey, we find that turbine O&M and non-turbine OpEx represent nearly equal drivers of the range in recent all-in levelized OpEx estimates. As shown in Figure 4, recent turbine O&M cost expectations range from $14–$28/kW-yr ($20/kW-yr average) on a levelized basis, whereas all other costs range from $18–$35/kW-yr ($25/kW-yr average).

Non-turbine OpEx includes costs related to BOP O&M, land leases, property or other local taxes or payments, grid and electrical use, insurance, asset management and administration, and other activities. Though the survey did not seek detailed cost breakdowns, a subset of wind developers and asset owners who responded to the survey provided relevant data (summarized, on a levelized basis, in Figure 5). Lifetime levelized turbine O&M (inclusive of scheduled and unscheduled maintenance) is clearly the largest single element, with property taxes, land lease payments, and BOP O&M representing the next tier of cost elements, followed by a larger number of less-significant factors.

Figure 4. Wind OpEx Expectations for Projects Commissioned 2015–2018: Turbine O&M (top), and Non-Turbine OpEx (bottom)

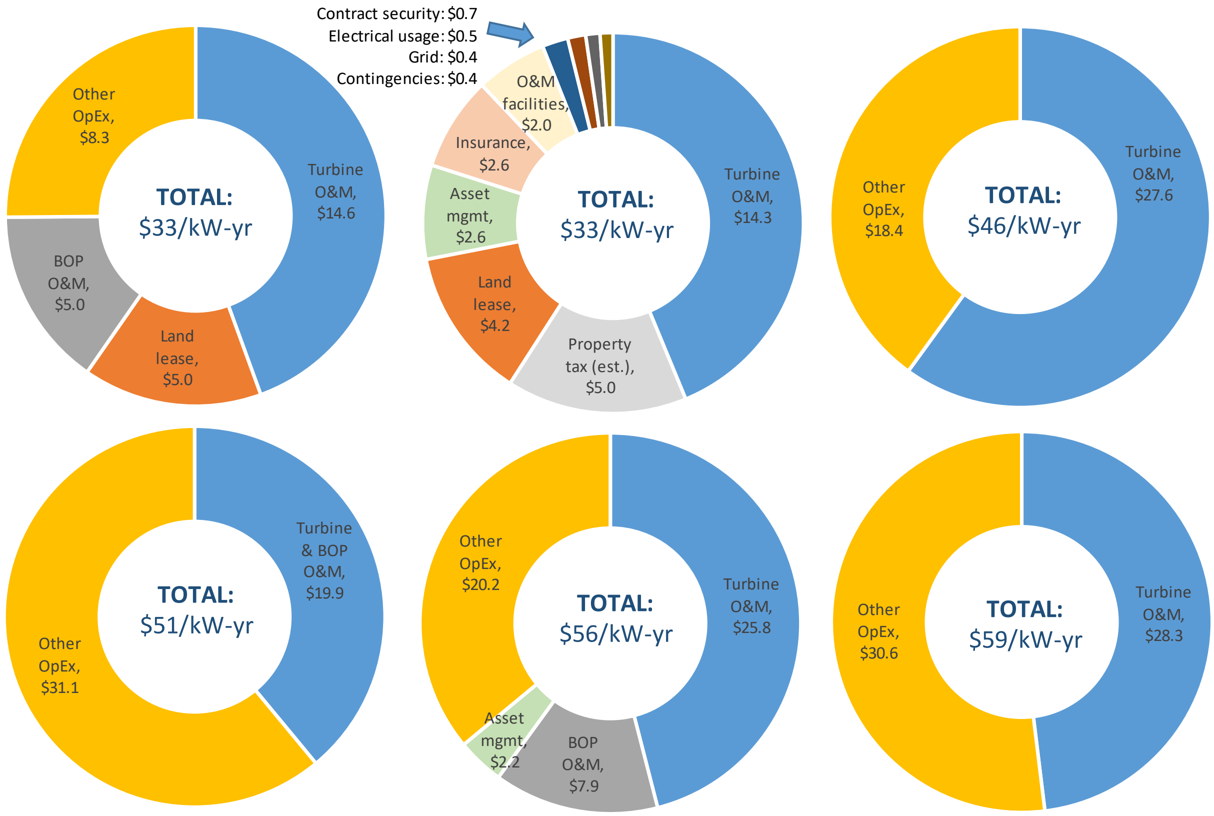

Figure 5. Wind OpEx Expectations for Projects Commissioned 2015–2018 by Component, for various Respondents

3.7 Drivers for Range in OpEx Estimates

Though reporting inconsistencies might account for some of the wide range in all-in OpEx estimates summarized above, survey respondents noted various substantive explanations for the OpEx trends and variability. Some of these are more technical in nature, whereas others are strategic. Here the focus is on explaining variability in OpEx estimates at any given point in time; however, some of these same drivers have also impacted trends in OpEx over time.

Technical factors impacting OpEx:

- **Project Size:** Some costs are fixed, regardless of project size, or consist of fixed and variable components—spare parts and labor, crane mobilization, infrastructure for predictive maintenance, insurance, asset management, etc. Such costs will not scale linearly with size on a $/kW-yr basis, but will instead offer economies of scale, a fact confirmed by BNEF, Briggs, and IHS Markit.[28-29,34] One developer noted a spread in costs from $75/kW-yr (for plants of about 40 MW in size) to $45/kW-yr (for plants of about 250 MW in size).
- **Turbine Size:** Some costs are fixed, regardless of turbine size. Moreover, as turbines have grown, the number of parts per MW has declined, often reducing replacement costs even as

crane mobilization expenses increase. That turbine size impacts OpEx has been widely reported for decades.[15,18,28,30,32-33]

- **Owner Fleet Size:** Wind project owners with larger fleets may choose to self-perform turbine O&M, opening one important route to lower OpEx as described in the "strategic factors" list below. Even those who choose not to self-perform O&M can benefit from larger fleet sizes, as fixed turbine O&M costs and non-turbine OpEx may be spread across more capacity (enabling labor and spare parts optimization, as two examples) and larger fleet sizes may also enable a degree of purchasing power for services and parts, resulting in lower costs.[45-46]
- **Turbine Maturity:** More-mature turbines have generally experienced lower OpEx than less-mature turbine models, as the latter have sometimes been subject to greater risk of serial component failure. One respondent noted a realized OpEx twice as high for a less-mature turbine deployed in the mid-2000s than for more-mature turbines available at the time, due in large measure to serial component failures and resultant retrofit activity.
- **Failure Rates and Project Life:** Regardless of turbine maturity, there remains endemic uncertainty in component reliability and failure. In effect, the wind industry is trying to predict 20 to 30 years of failure rates for newer equipment for which past historical failure rates may not apply. And, while assumed project lifetimes have increased from the previous 20-year standard to 25-30 years today, the timing and degree of this shift varies across the industry. As such, some of the variability in estimated OpEx simply reflects varied assumptions about future component failure and project life.
- **Location:** Regions with greater concentrations of wind projects can benefit from ready access to service infrastructure, whereas regions with lower concentrations present longer service distances and transport times. Regions that feature cold weather, winter storms, lightning, dust, corrosion, and challenging terrain can also push up costs.
- **Wind Resource:** Higher wind speeds and capacity factors, as well as shear and turbulence, tend to increase wear-and-tear and turbine O&M costs in $/kW-yr terms. This is one reason why some participants strongly prefer to think of OpEx in $/MWh terms, noting that maintenance would naturally be expected to scale more so with production than capacity.
- **Property Tax:** Property tax rates and rules vary broadly by jurisdiction, yielding one of the more variable elements in overall wind project OpEx.

Strategic factors impacting OpEx:

- **Self-Provision vs. OEM Full Wrap:** OEMs have historically dominated the service market, benefiting from experience, scale, technical knowledge, and access to spare parts; OEMs earn relatively high margins in that business, but can deliver quality service and quick turn-around times when unplanned maintenance needs arise. Experienced wind plant owners with larger fleets, however, have progressively moved towards self-provision of turbine O&M. Many survey respondents noted that self-provision will increase with time, offering an opportunity for significant OpEx reductions, and also enabling asset owners to more easily make tradeoffs between OpEx, plant performance, and profitability. Recent literature supports these views,[47] with Briggs finding a 30% potential reduction in turbine O&M cost due to self-provision,[29] and IHS Markit showing a 19% cost reduction.[48] It is important to recognize, however, that lower costs enabled by self-provision come with increased risk.[29,48] Another respondent indicated that their company prefers OEM-provided full-wrap contracts because the extra costs incurred are more than offset (in their case) by increased asset performance, backed by liquidated damages if availability performance guarantees are not achieved.

- **Plant Profitability:** Wind projects that offer high operating profits from power sales or production tax incentives tend to warrant more intensive O&M activities, resulting in higher O&M costs compared with lower-profit projects. One survey respondent, for example, noted that they tend to overstaff their profitable sites with technicians and employ extensive monitoring, striving to return malfunctioning turbines to service quickly. This has resulted in high availability, with the additional costs overshadowed by the higher revenue from power sales and production tax credits. The same developer does not apply the same operational rigor to less-profitable projects. One fully merchant project that sells power into the local wholesale power market and not under a lucrative sales agreement, for example, is only covered with a day shift and does not receive overly proactive efforts on large corrective maintenance issues. The energy-based availability for this site is considerable lower and the O&M costs needed to increase that availability are not justified in the current market. Another asset owner indicated that some of its focus on O&M trails off after the 10th year of project operations as the 10-year federal production tax credit rolls off, and the focus on maximizing the value of that tax incentive therefore disappears.
- **OEM Service Provision:** OEMs that sell turbines and enter into service contracts simultaneously in a bundled fashion may, at times, embed some ongoing turbine O&M costs in upfront turbine prices, which reduces apparent ongoing OpEx; alternatively, the opposite may also be true, with some turbine costs embedded in the O&M contract. In addition, an OEM that believes its turbine is the most desirable for any specific site or period may be able to boost the price of full-wrap service contracts.
- **Buyer vs. Seller:** Those seeking to sell wind development assets tend to present OpEx estimates that are more optimistic, assuming lower levels of component failure over time, whereas potential asset buyers often choose a more-conservative stance.

4. Comparisons with Other Recent Assessments

As reported earlier, all-in levelized lifetime OpEx expectations for U.S. land-based wind have recently averaged $33/kW-yr to $59/kW-yr, with an average across respondents of $44/kW-yr for projects entering commercial operations from 2015 through 2018. These values can be compared to other recent U.S. and global estimates (Table 1), not all of which have transparent methodologies or substantial data underpinnings.

Table 1. Other Recent U.S. and Global Land-Based Wind Operational Expenditure Estimates

Geographic Scope	Commercial Operation Data	All-in OpEx ($/kW-yr)	Source
United States	2017	30–40	Lazard[49]
United States	2016	51	NREL,[50] Stehly[20]
United States	2020	47	EIA[51]
United States	2014	44	IEA,[52] new policies
United States	2020	49	IEA/NEA[53]
United States & Europe	2014	60	Wiser et al.[23]
Global: 18 countries	2020	22 (China) 40–64 (12 countries) > 70 (5 countries)	IEA/NEA[53]
Global: 9 regions	2015	30 (China) 34–54 (7 regions) 56 (Japan)	IEA,[52] new policies
Europe: 5 countries	2016	37–60	IEA Wind[8]
Europe: low to high wind speed	2014	42–48	Valpy and English[54]
China & Central/South America	2008–2016	35	IRENA[6]

As shown, notwithstanding the limitations of many of the other assessments, the estimates presented in this paper often fall within the range of other estimates, in which case our findings may bolster confidence in the previously available literature. In other cases, our results diverge from the broader literature, in which case our findings may inform upward or downward adjustments to these other estimates, especially where limited data are otherwise used.

Figure 6 compares the average reduction in U.S. wind lifetime levelized OpEx from 2008 to 2016 reported in this paper (see the later text around Figure 7 describing those values) with the reduction observed in five European countries and reported in IEA Wind.[8] The U.S. data fall within the range of other countries shown in both 2008 and 2016, and the percentage cost reduction in the United States over this period (17%) is consistent with that shown for Germany, Norway, and Denmark. Overall, these comparisons provide support for the U.S. OpEx data presented earlier.

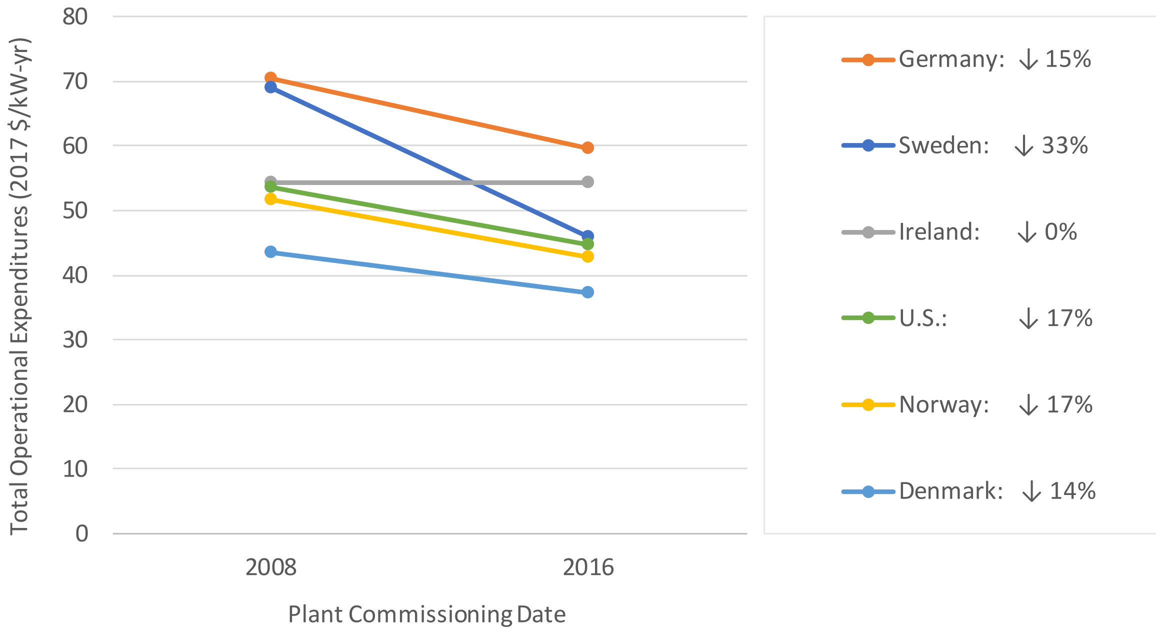

Figure 6. Comparison of Country-Level All-in Wind OpEx Reductions from 2008 to 2016

5. Estimating Future OpEx for Land-Based Wind

Historical cost data are sometimes used to estimate learning rates, which trace the relationship between the cost of wind, for example, and cumulative installed wind capacity. These historical learning rates are then commonly extrapolated to forecast possible future costs.[55-56]

The use of learning rates to project future costs has—at times—been critiqued. In part this is because learning rates do not often seek to provide deep insight into the myriad causal mechanisms that result in cost reduction.[57] Additionally, there is no inherent reason that future costs should fall at the same pace as in the past, an argument that applies not only to learning rates but to any use of historical data to forecast future outcomes.[58-59] Moreover, the use of learning rates to understand wind costs has primarily focused on understanding trends in CapEx.[9-12] Wiser et al. and Williams et al.,[23,56] however, argue that applying learning rates to wind LCOE is more appropriate, because LCOE has been the principal criterion for assessing industry progress and technological advancements, and because reducing CapEx is only one way to reduce wind's LCOE.

Notwithstanding these critiques, the application of learning rates to wind energy remains common,[9-12] and represents a useful, simple means of estimating future wind costs or reinforcing estimates derived through other methods. In the end, all methods to forecast future costs have advantages and disadvantages, some of which overlap with the critiques sometimes leveled at learning rates. Recent analyses suggest historical global learning rates of 6%–9% for land-based wind CapEx, meaning the CapEx has declined by 6%–9% for each doubling of cumulative global installed wind capacity.[6,23] LCOE-based learning rates have recently been shown to be higher, typically ranging from slightly below 10% to nearly 20%.[6,23,56]

All-in OpEx reductions have contributed to LCOE-based learning. From the survey results and empirical data we have collected for this study, Figure 7 depicts average lifetime (levelized) OpEx for U.S. land-based wind, by project commissioning date. The historical average depicted in the figure is, in effect, a smoothed version of the average of the data reported in Figure 1. Additionally, to represent the broad range of data presented earlier, the figure also depicts an illustrative range in OpEx over time that spans the majority of data reported earlier in Figure 1.

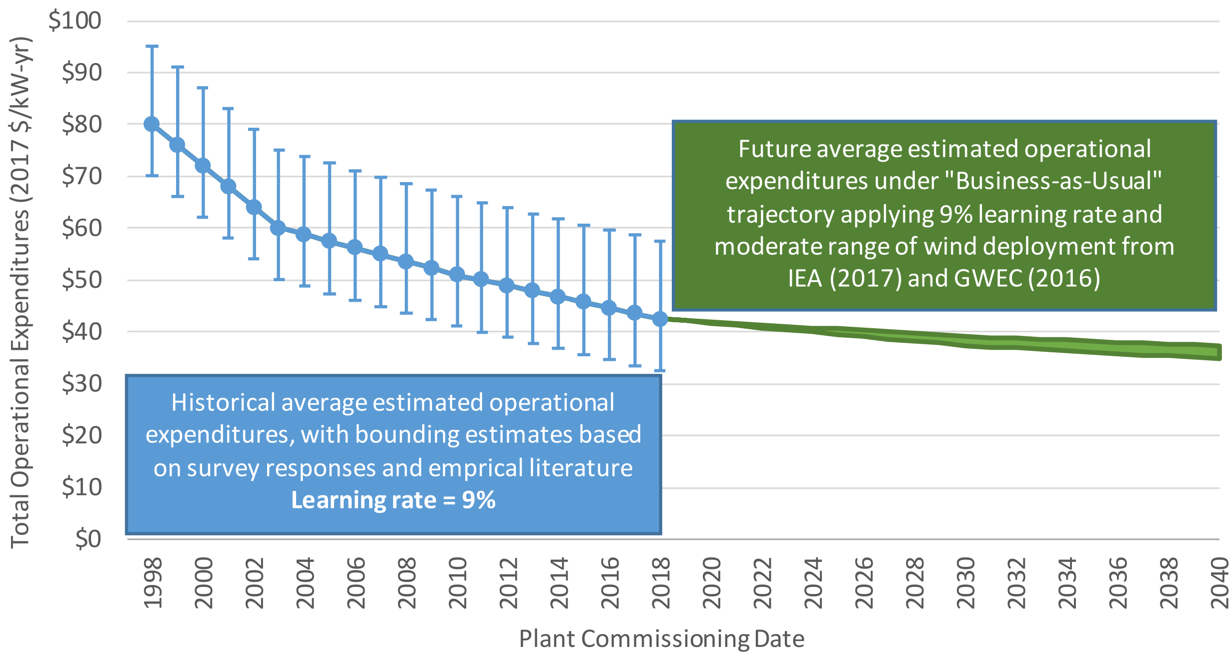

Figure 7. Average All-in Wind OpEx Over Time, with Future Projections

Pairing these data (the blue line in Figure 7) with historical global cumulative installed wind capacity from GWEC,† we estimate an OpEx-based learning rate of 9% over the 1998–2018 period, meaning that all-in OpEx in the United States has historically declined by 9% for each doubling of cumulative global installed wind capacity. Though OpEx reductions may be due to a variety of forces unrelated to cumulative global wind installations (e.g., many of the non-turbine O&M cost categories, some of which may have increasing costs over time), we find that this simple learning model performs very well ($R^2 = 0.978$). This OpEx learning rate is at the high end of the CapEx learning rate range (6%–9%), suggesting that historical advancements to reduce all-in OpEx have been "doing their share" to reduce the LCOE of wind energy.

We then apply the 9% historical learning rate to estimate future land-based wind OpEx reductions through 2040 under "business as usual" conditions (assuming the learning rate

† Because the wind industry is global in scope, we assume that OpEx-based learning primarily accrues through global wind capacity additions, not solely U.S. additions. While this thesis may be true for technical advancements such as condition monitoring, component reliability, and turbine size, learning may be driven by U.S. capacity additions for other components of OpEx such as those affected by the overall size of wind project fleets. To test whether the learning rate would differ substantially were learning assumed to be primarily domestic in nature, we also estimate a learning rate based on cumulative U.S. installed wind capacity—resulting in an estimate of 9%, the same as the global learning rate cited in the text above, albeit with a slightly lower R^2 value of 0.960.

remains steady, and applies to all-in OpEx considering all OpEx categories in sum), using a representative range of future projections for global installed capacity from IEA and GWEC of 1,700 to 2,770 GW.[52,60,‡] Based on this method, all-in levelized lifetime OpEx for newly installed U.S. wind projects is projected to *average* $35–$37/kW-yr by 2040. This represents a $5–$8/kW-yr (12%–18%) reduction from the 2018 average depicted in the figure ($42.5/kW-yr [$11/MWh], slightly lower than the average over the 2015–2018 period highlighted earlier due to an assumed continued reduction in OpEx over this period). If achieved, this OpEx reduction would reduce the LCOE of land-based wind by as much as $2/MWh.

Our approach of using an historical learning curve to project future OpEx has limitations, but may nonetheless inform other estimates by providing a simple transparent reference point. We compare the learning-based reductions in land-based wind lifetime levelized OpEx to other recent forecasts of OpEx developments through 2025, 2030, and/or 2040 (Table 2). These other forecasts use a range of methods, but in many cases are based on expert intuition. Our learning-based estimates are broadly consistent with these projections, with notable exceptions. For example, EIA assumes no further advancements in OpEx,[51] which seems overly conservative given historical developments. On the other end of the spectrum, Dykes et al. as well as Wiser et al. present more aggressive R&D scenarios with effective rates of OpEx reductions that are considerably higher than past rates.[23-24]

Table 2. Comparing Land-Based Wind Operational Expenditure Projections through 2040

Source	Future All-in OpEx Reduction
Current Work: *Business as usual scenario*	$3.4–$5.2/kW-yr (8%–12%; $0.9–$1.3/MWh) from 2018 to 2030 $5.2–$7.7/kW-yr (12%–18%; $1.3–$1.9/MWh) from 2018 to 2040
Wiser et al.[23]	Mid case: $5.3/kW-yr (9%) from 2014 to 2030 Low case: $14.8/kW-yr (25%) from 2014 to 2030
Dykes et al.[24]	Low case: $13/kW-yr (25%) from 2015 to 2030
DOE[61]	Mid case: $4/kW-yr (8%) from 2014 to 2030 Low case $8/kW-yr (16%) from 2014 to 2030
EIA[51]	Mid-case: No OpEx cost reduction through 2040
IEA[52]	Mid-case: $4/kW-yr (9%) from 2015 to 2030
Valpy and English[54]	Mid-case: $2.5–$2.9/kW-yr (6%) from 2015 to 2025
BNEF[28]	Mid-case: $5.2/kW-yr from 2018 to 2025 considering only turbine O&M
BNEF[14]	Mid-case: $1.7/MWh (14%) from 2015 to 2025
IRENA[62]	Mid-case: $3/MWh from 2015 to 2025

Future OpEx-reduction mechanisms likely include continuations and enhancements of past mechanisms. Also consistent with past trends, greater opportunities for future cost reduction likely exist within the turbine O&M category than within the many components of non-turbine OpEx. Specifically, economies of scale may offer further reduction opportunities as both turbines and turbine fleets continue to grow. Moreover, additional research and experience is expected to yield better component reliability. Increased competition among O&M service providers and O&M self-provision could also yield OpEx reductions. Finally, further standardization and application of advanced condition monitoring, drones, and data analytics (‘digitization’) for

‡ The IEA “New Policies” scenario estimates 1,700 GW of wind by 2040,[52] whereas the GWEC “Moderate” scenario forecasts 2,770 GW.[60]

predictive maintenance, facilitated by the growing amount of available data and experience, are anticipated. As noted by survey respondents, the wind industry is somewhat unique for its high degree of unplanned O&M, and a move from reactive to prognostic and proactive maintenance enabled by condition-based monitoring and data analytics is an area of particular focus.

The future LCOE of land-based wind is uncertain, with a range of estimates available in the literature (for a summary, see Wiser et al.[23]). Overall, however, the learning-based OpEx estimates reported above suggest that continued OpEx reductions may contribute 10% or more of the overall land-based wind LCOE reductions expected through 2030.[14,23-24,62]

6. Conclusions

Wind plant OpEx is an important but sometimes overlooked driver of overall LCOE trends for land-based wind. This paper draws primarily from a survey of senior members of the U.S. wind industry to describe historical and current trends in land-based wind OpEx and to provide insights into drivers of those trends. We compare the resulting estimates for average OpEx with other U.S. and global OpEx assessments, and we extrapolate the historical data to estimate future land-based wind OpEx, comparing the resulting estimates with other recent assessments.

We find that average all-in levelized lifetime OpEx in the United States has declined from roughly $80/kW-yr (~$35/MWh) for projects built in the late 1990s to levels approaching $40/kW-yr (~$11/MWh) for projects under construction in 2018. Turbine O&M costs represent not only the single largest component of overall OpEx, but also the primary source of OpEx reductions.

Though all-in OpEx has declined over time, each point in time contains a wide range of OpEx estimates. For projects commissioned between 2015 and 2018, average lifetime expected costs are reported (often for large fleets of projects) to range from $33/kW-yr to $59/kW-yr ($9–16/MWh). Some drivers of OpEx variability are more technical in nature, including turbine, project, and fleet size; wind project location; turbine maturity and assumed rates of component failure; wind resource; and local tax rules. Other drivers are strategic in nature, including the choice between OEM versus self-provision of O&M services as well as tradeoffs between the cost and value of enhanced O&M practices.

The all-in OpEx values presented in this paper are often within the range of other recent assessments, but they may also inform upward or downward adjustments to some of these estimates. We find a 9% reduction in U.S. wind plant OpEx for each doubling of cumulative global wind capacity—that is, a learning rate of 9%. This OpEx learning rate is at the high end of the CapEx learning rate range (6%–9%), suggesting that historical advancements to reduce OpEx have been "doing their share" to reduce the LCOE of wind energy.

We apply the 9% historical learning rate to estimate future land-based wind OpEx reductions under business as usual conditions, finding a possible $5–$8/kW-yr reduction in all-in OpEx from 2018 to 2040, which would reduce the LCOE of land-based wind by as much as $2/MWh. These findings suggest that continued OpEx reductions—primarily related to turbine O&M—

could contribute 10% or more of the overall land-based wind LCOE reductions expected in the future. Moreover, these estimates understate the importance of OpEx owing to the multiplicative effects through which operational advancements influence not only O&M costs but also component reliability, performance, and plant-level availability—thereby affecting levelized costs though OpEx reduction and by enhancing annual energy production and plant lifetimes

Given the limited quantity and comparability of previously available OpEx data, these findings can inform OpEx assumptions used by electric planners, analysts, modelers, and research and development managers. The results may also provide useful benchmarks to the wind industry, helping developers and asset owners compare their OpEx expectations with historical experience and other industry projections. That said, these estimates are not reliable or precise enough to enable detailed comparisons. Additional effort is clearly required to systematically collect standardized data on wind project OpEx to ensure the comparability of varying data sources and to better understand the differences that remain in OpEx expectations.

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References

1. Echavarria E, Hahn B, van Bussel GJW, Tomiyama T. Reliability of wind turbine technology through time. *Journal of Solar Energy Engineering*. 2008;130(3):031005.

2. Spinato F, Tavner P, Van Bussel GJW, Koutoulakos E. Reliability of wind turbine assemblies. *IET Renewable Power Generation*. 2009;3:387-401.

3. Keller J, Sheng S, Cotrell J, Greco A. *Wind Turbine Reliability Collaborative Workshop: A Recap*. Washington, DC: U.S. Department of Energy; 2016.

4. Sheng S. *Wind Turbine Gearbox Reliability Database, Operation and Maintenance Research Update*. Golden, CO: National Renewable Energy Laboratory; 2017

5. Artigao E, Martín-Martínez S, Honrubia-Escribano A, Gómez-Lázaro E. Wind turbine reliability: A comprehensive review towards effective condition monitoring. *Applied Energy*. 2018;228:1569-1583.

6. IRENA. *Renewable Power Generation Costs in 2017*. Abu Dhabi: International Renewable Energy Agency; 2018.

7. Wiser R, Bolinger M. *2017 Wind Technologies Market Report*. Berkeley, CA: Lawrence Berkeley National Laboratory; 2018.

8. IEA Wind. *IEA Wind TCP Task 26–Wind Technology, Cost, and Performance Trends in Denmark, the European Union, Germany, Ireland, Norway, Sweden, and the United States: 2008–2016*. Golden, CO: National Renewable Energy Laboratory; 2019.

9. Wiser R, Yang Z, Hand M, et al. Wind energy. In: Edenhofer O, Pichs-Madruga R, Sokona Y, et al, eds. *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation*. New York, NY: Cambridge University Press; 2011.

10. Lindman Å, Söderholm P. Wind power learning rates: a conceptual review and meta-analysis." *Energy Economics*. 2012;34:754-761.

11. Rubin ES, Azevedo I, Jaramillo P, Yeh S. A review of learning rates for electricity supply technologies. *Energy Policy*. 2015;86:198-218.

12. Samadi S. The experience curve theory and its application in the field of electricity generation technologies – a literature review. *Renewable and Sustainable Energy Reviews*. 2018;82:2346-2364.

13. Sieros G, Chaviaropoulos P, Sørensen J, Bulder B, Jamieson P. Upscaling wind turbines: theoretical and practical aspects and the impact on the cost of energy. *Wind Energy*. 2010;15:3-17.

14. BNEF. *The Future Cost of Onshore Wind – An Accelerating Rate of Progress*. Wind Insight. New York, NY: Bloomberg New Energy Finance; 2015.

15. Poore R, Walford C. *Development of an Operations and Maintenance Cost Model to Identify Cost of Energy Savings for Low Wind Speed Turbines*. Golden, CO: National Renewable Energy Laboratory; 2008.

16. DNV KEMA. *Historical Trends in Wind Energy Operations Costs and Project Availability: September 2012—July 2013*. Golden, CO: National Renewable Energy Laboratory; 2018.

17. Blanco MI. The economics of wind energy. *Renewable and Sustainable Energy Reviews*. 2009;13:1372-1382.

18. EWEA. *Wind Energy, the Facts*. Brussels, Belgium: European Wind Energy Association; 2009.

19. Walford C. *Wind Turbine Reliability: Understanding and Minimizing Wind Turbine Operation and Maintenance Costs*. Albuquerque, NM: Sandia National Laboratories; 2006.

20. Stehly T, Heimiller D, Scott G. *2016 Cost of Wind Energy Review*. Golden, CO: National Renewable Energy Laboratory; 2017.

21. Gil-Vazquez I, Mitchell R, Syme C. *Historical and Current Trends in Wind Energy Operations Costs and Project Availability: July 2012—July 2013*. Golden, CO: National Renewable Energy Laboratory; 2018.

22. van Kuik GAM, Peinke J, Nijssen R, et al. Long-term research challenges in wind energy – a research agenda by the European Academy of Wind Energy. *Wind Energy Science*. 2016;1:1-39.

23. Wiser R, Jenni K, Seel J, Baker E, Hand M, Lantz E, Smith A. Expert elicitation survey on future wind energy costs. *Nature Energy*. 2016;1:16135.

24. Dykes K, Hand M, Stehly T, Veers P, Robinson M, Lantz E. *Enabling the SMART Wind Power Plant of the Future Through Science-Based Innovation*. Golden, CO: National Renewable Energy Laboratory; 2017.

25. Ziegler L, Gonzalez E, Rubin T, Smolka U, Melero JJ. Lifetime extension of onshore wind turbines: a review covering Germany, Spain, Denmark, and the UK. *Renewable and Sustainable Energy Reviews*. 2018;82:1261-1271.

26. Mertes C, Milligan P. *Repowering Opportunities Aren't Gone with the Wind…Yet*. Fairfax, VA: ICF; 2018

27. Rubert T, McMillan D, Niewcas P. A decision support tool to assist with lifetime extension of wind turbines. *Renewable Energy*. 2018;120:423-433.

28. BNEF. *1H 2018 Wind Operations and Maintenance Index*. New York, NY: Bloomberg New Energy Finance; 2018.

29. Briggs K. Key drivers of O&M trends. Presentation to AWEA O&M and Safety Conference, San Diego, CA; 2017.

30. Lemming J, Morthorst PE, Hansen LH, Andersen PD, Jensen PH. O&M costs and economical life-time of wind turbines. In: *Proceedings of the 1999 European Wind Energy Conference.* Nice, France; 1999.

31. Rademakers LWMM, Braam H, Verbruggen TW. R&D needs for O&M of wind turbines. In: *Proceedings of the European Wind Energy Conference*. Madrid, Spain; 2003.

32. Vachon WA. Long-term O&M costs of wind turbines based on failure rates and repair costs. In: *Proceedings of American Wind Energy Association's Annual Conference WINDPOWER 2002*. Portland, OR; 2002.

33. Hahn B. Reliability assessment of wind turbines in Germany. In: *Proceedings of the 1999 European Wind Energy Conference*. Nice, France; 1999.

34. Lillian B. North American wind O&M costs could grow 40% by 2021: report. *North American Windpower*. September 11, 2018.

35. Infigen. Multiple public financial reports. Sydney, Australia: Infigen Energy; 2008–2014.

36. Wind Energy Update. *Wind Energy Operations & Maintenance Report*. Wind Energy Update; 2010.

37. Fitch. *FPL Energy National Wind, LLC*. New York, NY: Fitch Ratings; 2005.

38. Fitch. *Fitch Affirms FPL Energy National Wind Opco at 'BBB' and Holdco at 'BB'; Outlook Stable*. New York, NY: Fitch Ratings; 2008.

39. Fitch. *Fitch Affirms FPL Energy National Wind Opco Sr. Secured at 'BBB'; Holdco at 'BB'*. New York, NY: Fitch Ratings; 2010.

40. Fitch. *Fitch Downgrades FPL Energy Nat'l Wind to 'BBB-' & FPL Energy Nat'l Wind Portfolio to 'B+'*. New York, NY: Fitch Ratings; 2011.

41. Fitch. *Fitch Downgrades FPL Energy National Wind OpCo Sr. Secured to 'BB+' & HoldCo to 'B'*. New York, NY: Fitch Ratings; 2012.

42. EIA. *Assumptions to the Annual Energy Outlook 2011*. Washington, DC: U.S. Energy Information Administration; 2011.

43. DOE. *20% Wind Energy by 2030: Increasing Wind Energy's Contribution to U.S. Electricity Supply*. Washington, DC: U.S. Department of Energy; 2008.

44. Chapman J, Wiese S. *Expanding Wind Power: Can Americans Afford It?* Washington, DC: Renewable Energy Policy Project; 1998.

45. NextEra. *September 2018 Investor Presentation*. Juno Beach, FL: NextEra Energy; 2018.

46. New Energy Update. *Renewables O&M, Asset Management and Energy Storage Market Outlook*. London: New Energy Update; 2018.

47. BNEF. *US Wind O&M Strategies in Transition*. New York, NY: Bloomberg New Energy Finance; 2015.

48. Ford N. *US Wind Study Warns of Cost Challenge from Rising Fleet Ages*. London: New Energy Update; 2018.

49. Lazard. *Lazard's Levelized Cost of Energy Analysis—Version 11.0*. New York, NY: Lazard; 2017.

50. NREL. *2018 Annual Technology Baseline*. Golden, CO: National Renewable Energy Laboratory; 2018.

51. EIA. *Cost and Performance Characteristics of New Generating Technologies, Annual Energy Outlook 2018*. Washington, DC: U.S. Energy Information Administration; 2018.

52. IEA. *World Energy Outlook 2017*. Paris: International Energy Agency; 2017.

53. IEA/NEA. *Projected Costs of Generating Electricity: 2015 Edition*. France: International Energy Agency and Nuclear Energy Agency; 2015.

54. Valpy B, English P. *Future Renewable Energy Costs: Onshore Wind*. Netherlands: KIC InnoEnergy; 2014.

55. Luderer G, Krey V, Calvin K, et al. The role of renewable energy in climate stabilization: results from the EMF27 scenarios. *Climatic Change*. 2014;123:427-441.

56. Williams E, Hittinger E, Carvalho R, Williams R. Wind power costs expected to decrease due to technological progress. *Energy Policy*. 2017;106:427-435.

57. Mukora A, Winskel M, Jeffrey HF, Mueller M. Learning curves for emerging energy technologies. *Proceedings of the Institution of Civil Engineers–Energy*. 2009;162:151-159.

58. Arrow KJ. The economic implications of learning by doing. *Review of Economic Studies*. 1962;29:155-173.

59. Ferioli F, Schoots K, Van der Zwaan BCC. Use and limitations of learning curves for energy technology policy: a component-learning hypothesis. *Energy Policy*. 2009;37:2525-2535.

60. GWEC. *Global Wind Energy Outlook 2016*. Brussels, Belgium: Global Wind Energy Council; 2016.

61. DOE. *Wind Vision: A New Era for Wind Power in the United States*. Washington, DC: U.S. Department of Energy; 2015.

62. IRENA. *The Power to Change: Solar and Wind Cost Reduction Potential to 2025*. Abu Dhabi: International Renewable Energy Agency; 2016.

Appendix: Tabular Summary of OpEx Data and Adjustments

Data Source	Data Obtained	Notable Ex-Post Adjustments
Survey: Developer/Owner	Lifetime levelized turbine O&M and non-turbine OpEx for plants built from 2013 to 2018 in $/MWh terms; reflective of actual historical costs and estimated data for operations after 2018	Converted to $/kW-yr based on average capacity factors appropriate to plant commissioning dates
Survey: Developer/Owner	All-in estimated OpEx by year over lifetime for 20 recent and in-development plants in $/kW-yr terms, excluding property tax but with extensive details on OpEx breakdown into various categories	Added average cost for property tax based on other survey responses to estimate all-in OpEx; levelized annual values with 5% real discount rate
Survey: Developer/Owner	All-in lifetime levelized OpEx for specific plants built from 2011 to 2017 in $/kW-yr terms, including breakdown in turbine O&M and other	Data provided in cohorts of 2011-2015, and 2016-present; for graphical purposes, assumed to reflect 2013 and 2017 costs, respectively
Survey: Developer/Owner	Lifetime levelized OpEx estimates for current projects for large assets owners and small asset owners in $/MWh terms, excluding property tax and land lease costs	Added property tax and land costs based on other survey responses to estimate all-in OpEx; weighted small and large assets owners to develop overall average; converted to $/kW-yr based on respondent-provided capacity factors
Survey: Developer/Owner	All-in estimated lifetime levelized OpEx for specific plants built from 2010 to 2018 in $/kW-yr terms, noting turbine O&M portion (expects actual costs to align with expected over this period; also provided historical estimated costs for plants built in 2006, noting that these do not align with actual)	None
Survey: Developer/Owner	All-in estimated lifetime levelized OpEx for plants built from 2006 to 2018 in $/kW-yr terms, noting plant O&M and other OpEx portions (expects actual costs to generally align with expected over this period; also provided historical estimated costs for plants built before 2006, noting that these do not align with actual)	Data provided in cohorts of 2006-2010, 2011-2015, and 2016-present; for graphical purposes, assumed to reflect 2008, 2013 and 2017, respectively; to estimate turbine O&M, reduced plant O&M by estimate of BOP O&M
Survey: Developer/Owner	All-in estimated OpEx for plants built from 2009 to 2017 in $/kW-yr terms, noting turbine O&M and other OpEx portions	Data provided in cohorts of 2009-2012 and 2012-2017; for graphical purposes, assumed to reflect 2011 and 2015, respectively; levelized annual values with 5% real discount rate
Survey: Developer/Owner	All-in actual OpEx by year for subset of years for plants built from 2005 to 2014 in $/kW-yr terms, noting turbine O&M portion; turbine O&M and non-turbine OpEx estimates for plants built in 2018	Data placed in cohorts and reported as averages for 2008 and 2012, as well as 2018; based on respondent, assume costs in years where data are not provided are similar to average of those provided to estimate lifetime levelized OpEx
Secondary Data: Developer/Owner	All-in actual OpEx by year for subset of years for plants built from 2003 to 2007 in $/kW-yr terms	Data reported as average for plants built in 2005; assume costs in years where data are not provided are similar to average of those provided to estimate lifetime levelized OpEx
Survey: Turbine OEM	All-in lifetime levelized OpEx for plants built from 2002 to 2018 in $/MWh terms; reflective of actual historical costs and, especially for more recent projects, estimated data (also provided historical estimated lifetime OpEx data for older projects)	Converted to $/kW-yr based on average capacity factors appropriate to plant commissioning dates

Survey: Turbine OEM	Data for actual and estimated turbine O&M cost for plants built in early-mid 2000s in $/kW-yr terms	Added non-turbine OpEx based on other data; averaged multiple turbine O&M data points provided by respondent
Survey: Turbine OEM	Average actual turbine O&M contract costs in $/kW-yr for contracts with < 5 year, 5 year, and > 10 year terms, with signature dates of 2005 to 2017	Added average cost for non-turbine OpEx based on other survey responses to turbine O&M for > 10-yr terms to estimate all-in lifetime levelized OpEx for points in time with adequate sample
Survey: Consultant	Lifetime levelized plant and turbine O&M for plants built in 2017, and low and high estimates for plant O&M for plants built in 2016; all estimated data in $/kW-yr terms; also provided global estimate of other OpEx	Added respondent-provided global 'other OpEx' figures to data on U.S. plant O&M to estimate all-in OpEx
Secondary Data: Consultant	Actual turbine O&M contract costs for plants built from 2011 to 2018 in $/kW-yr terms; derived from agreements with varied terms, with average unclear	Added average cost for non-turbine OpEx based on other survey responses to actual turbine contract costs
Secondary Data: Consultant	Actual plant O&M costs for plants built from 1998 to 2016 in $/kW-yr terms	Data provided in cohorts of 1998-2004, 2005-2010, and 2011-2016; for graphical purposes, assumed to reflect 2001, 2008 and 2014, respectively; actual plant O&M costs assumed to increase with inflation where data not available; added average cost for non-plant O&M based on other data
Secondary Data: Consultant	All-in actual OpEx in 2011 for large number of projects built in 2011 and earlier, in $/kW-yr terms	Average build date estimated at 2007, and used for graphing purposes; OpEx in 2011 assumed to be roughly equivalent to lifetime levelized estimates
Secondary Data: Consultant	All-in actual OpEx over up-to 13 years for plants built between 1999 and 2009, in $/kW-yr terms; also provides turbine O&M	Levelized lifetime OpEx in 1999, 2003, and 2006 assumed to be approximated by levelized OpEx over duration of data availability for each cohort