Title

Expert elicitation survey on future wind energy costs

Permalink

https://escholarship.org/uc/item/3kk1j7sg

Journal

Nature Energy, 1(10)

ISSN

2058-7546

Authors

Wiser, Ryan
Jenni, Karen
Seel, Joachim
et al.

Publication Date

2016

DOI

10.1038/nenergy.2016.135

Peer reviewed

Expert elicitation survey on future wind energy costs

Authors:

Ryan Wiser,[1] Karen Jenni, [2] Joachim Seel,[1] Erin Baker,[3] Maureen Hand,[4] Eric Lantz,[4] Aaron Smith[4]

[1] Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, California 94720, USA

[2] Insight Decisions, LLC, 2200 Quitman Street, Denver, Colorado 80212, USA

[3] University of Massachusetts—Amherst, 160 Governors Drive, Amherst, Massachusetts 01003, USA

[4] National Renewable Energy Laboratory, 15013 Denver West Parkway, Golden, Colorado 80401, USA

Energy Analysis and Environmental Impacts Division
Lawrence Berkeley National Laboratory

Pre-print accepted version published in Nature Energy

http://dx.doi.org/10.1038/nenergy.2016.135

September 2016

This work was supported by the the IEA Wind Implementing Agreement for Cooperation in the Research, Development, and Deployment of Wind Energy Systems (IEA Wind). It would not have been possible without the funding of the U.S. Department of Energy (DOE) under Contract Nos. DE-AC02-05CH11231 (LBNL) and DE-AC36-09GO28308 (NREL), and the support of the NSF-sponsored IGERT: Offshore Wind Energy Engineering, Environmental Science, and Policy (Grant Number 1068864)

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor The Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or The Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof, or The Regents of the University of California.

Ernest Orlando Lawrence Berkeley National Laboratory is an equal opportunity employer.

COPYRIGHT NOTICE

This manuscript has been authored by an author at Lawrence Berkeley National Laboratory under Contract No. DE-AC02-05CH11231 with the U.S. Department of Energy. The U.S. Government retains, and the publisher, by accepting the article for publication, acknowledges, that the U.S. Government retains a non-exclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this manuscript, or allow others to do so, for U.S. Government purposes.

Expert elicitation survey on future wind energy costs

Ryan Wiser,[1]* Karen Jenni,[2] Joachim Seel,[1] Erin Baker,[3] Maureen Hand,[4] Eric Lantz,[4] Aaron Smith[4]

[1] Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, California 94720, USA
[2] Insight Decisions, LLC, 2200 Quitman Street, Denver, Colorado 80212, USA
[3] University of Massachusetts—Amherst, 160 Governors Drive, Amherst, Massachusetts 01003, USA
[4] National Renewable Energy Laboratory, 15013 Denver West Parkway, Golden, Colorado 80401, USA

*corresponding author; email: rhwiser@lbl.gov

Abstract

Wind energy supply has grown rapidly over the last decade. However, the long-term contribution of wind to future energy supply, and the degree to which policy support is necessary to motivate higher levels of deployment, depends—in part—on the future costs of both onshore and offshore wind. Here, we summarize the results of an expert elicitation survey of 163 of the world's foremost wind experts, aimed at better understanding future costs and technology advancement possibilities. Results suggest significant opportunities for cost reductions, but also underlying uncertainties. Under the median scenario, experts anticipate 24%–30% reductions by 2030 and 35%–41% reductions by 2050 across the three wind applications studied. Costs could be even lower: experts predict a 10% chance that reductions will be more than 40% by 2030 and more than 50% by 2050. Insights gained through expert elicitation complement other tools for evaluating cost-reduction potential, and help inform policy and planning, R&D, and industry strategy.

Main Text

As of the end of 2014, wind power capacity installed globally was capable of meeting roughly 3.7% of electricity demand, up from 0.9% at the end of 2006 [1]. This growth has been supported by energy policies and facilitated by technology advancements and related cost reductions [2-3]. Though the majority of deployed capacity is onshore (>97%), offshore wind deployment is increasing, especially in Europe [3]. The increasing maturity of wind technology, as well as the scale of the global resource [4], suggests that wind energy might play a significant future role in electricity supply, especially in the context of efforts to reduce greenhouse gas emissions [5-8]. That role, however, is uncertain. A review of 150 long-term energy scenarios by the Intergovernmental Panel on Climate Change (IPCC) shows wind's global contribution to electricity supply in 2050 reaching 13-14% in the median climate change mitigation scenario, but with a range of less than 5% to over 50% [2]. Recent scenarios published by the International Energy Agency [9] and Global Wind Energy Council [10] have ranges of 6-15% (2040) and 17%-31% (2050), respectively.

Part of the uncertainty in the contribution of wind to the future energy mix comes from uncertainty in its costs [8, 11]. Past studies of wind energy costs have used a variety of approaches. *Learning curves* have a long history within the wind sector as a means of understanding past cost trends and as a tool to forecast future outcomes [2, 12-13], but they have been criticized for largely focusing only on capital costs [13-14], and for simplifying the many causal mechanisms that lead to cost reduction [14-19]. In addition, using historical data to generate learning rates that are then extrapolated into the future implicitly assumes that future trends will replicate past ones [14, 20-21]. *Engineering assessments* provide a bottom-up, technology-rich complement to learning analyses [15]. They involve detailed modelling of specific technology advancements [22-26] and often consider both cost and performance, providing better insights into trends in levelized cost of energy (LCOE). But they also generally require sophisticated design and cost models, often emphasize more-incremental advances, and rarely provide insight into the probability of different outcomes.

This study summarizes the results of a global expert elicitation survey on future wind energy costs and related technology advancements. The research relies on expert knowledge to gain insight into the possible magnitude of future wind energy cost reductions and to identify the sources of and enabling conditions for those reductions. In so doing, we complement learning curve and engineering assessments as well as less-formal means of synthesizing expert knowledge [23, 25, 27-31] by seeking a more detailed understanding of how cost reductions might be realized and by clarifying the important uncertainties in these estimates. The online elicitation survey is global in scope and covers both onshore and offshore technology. It emphasizes costs in 2030, but with additional markers in 2020 and 2050. With 163 respondents, it is the largest known elicitation ever performed on an energy technology in terms of expert participation [32].

Expert Elicitation Survey

Expert elicitation is a tool used to develop estimates of unknown or uncertain quantities based on careful assessment of the knowledge and beliefs of experts about those quantities [33]. It is often considered the best way to develop credible estimates when data are sparse or lacking, or when projections are sought for future conditions that are different from past conditions [34-35]. Several formal protocols for conducting elicitations have been developed [36] and a rich literature provides guidance on question design, the importance of clarity in what is being asked, how to minimize the effects of motivational and cognitive biases, and the importance of providing feedback and opportunities to update assessments [33, 37-38]. Expert elicitation has been widely used to support decision making in the private and public sectors. Its use was explicitly called for in a review of the IPCC [39] and by a National Academies review of the U.S. Department of Energy [40]. Expert elicitation is increasingly common as a tool for making estimates of the future costs of energy technologies [32, 41]. However, formal elicitation procedures have not yet been widely applied to understand wind energy costs [42-43].

Expert elicitation is not without weaknesses. Most notably, it is impossible to entirely eliminate—or even to fully test for—the possibility of motivational or cognitive biases. Those individuals who are considered subject-matter experts on wind energy, for example, might have a tendency to be optimistic about the future of the sector. On the other hand, experts sometimes underestimate the possibility of technological change, as has been the case with solar energy [32, 44]. Nonetheless, when implemented well, the method can provide valuable insights on the views of subject-matter experts, supplementing other forecasting approaches.

The scope of our assessment comprises three wind power applications: onshore wind, fixed-bottom offshore wind, and floating offshore wind. Onshore (i.e., land-based) wind is relatively mature and already makes a significant contribution to energy supply in many countries. Fixed-bottom offshore wind is less mature than onshore wind, but is already being deployed at scale in Europe. Floating offshore wind (e.g., spar buoy, semi-submersible platform, tension-leg platform) is not yet commercialized, but has been deployed in full scale demonstration projects.

Our analysis centres on potential changes in the LCOE of wind, in real 2014 US dollars or euros per megawatt-hour ($/MWh or €/MWh). The LCOE is the levelized cost per unit of generated electricity from a specific source over its project life that allows recovery of all project expenses and meets investor return expectations. Though LCOE should not be the only metric used when comparing electric generation assets [45-47], it is regularly and appropriately used to assess the unit costs of electric-generation technologies, and minimizing LCOE is a primary goal of the wind industry and of wind energy R&D. In exploring future LCOE trends, we asked respondents to provide probabilistic estimates for the LCOE of a "typical" project, defined as the median project in a future scenario. We distinguish between three such scenarios: a low LCOE scenario (10th percentile), a high LCOE scenario (90th percentile), and a median LCOE scenario (50th percentile). In considering the differences in LCOE among those scenarios, experts were asked to consider only broad, non-project-specific factors that affect the industry as a whole, e.g., changes in wind technologies, markets, and policies.

In addition to LCOE we requested details on five core input components of LCOE: (1) total upfront capital costs to build the project (CapEx, $ or €/kW); (2) levelized total annual operating expenditures over the project design life (OpEx, $ or €/kW-yr); (3) average annual energy output (capacity factor, %); (4) project design life considered by investors (years); and (5) costs of financing, in terms of the after-tax, nominal weighted-average cost of capital (WACC, %). We asked about these five detailed components only for a 2014 baseline year and our focus year of 2030. For capacity factors, respondents had to judge the possible positive influence of technological advancements on capacity factors, but also the possible offsetting influence of resource depletion over time if the best wind sites are used first. For the focus year of 2030, we also asked about the market and technology characteristics and drivers most likely to impact LCOE trends. Many survey results are presented as changes from 2014 baseline values. Rather than assume that all experts have the same internal 2014 baselines, we offered a default option but allowed experts to provide their own estimates for onshore and fixed-bottom offshore wind. Roughly 80% of experts opted to use the default baseline values. We did not provide or seek a baseline estimate for floating offshore wind, given the nascent state of that technology and lack of current commercial applications. Floating offshore wind changes are therefore compared to expert-specific 2014 baselines for fixed-bottom offshore wind. The Supplementary Methods describes the survey design and approach in more detail. The key findings from the elicitation are summarized in Figure 1.

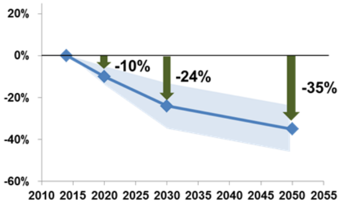
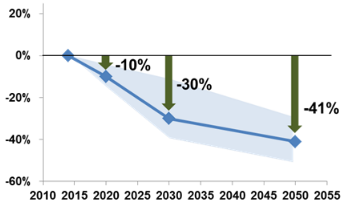
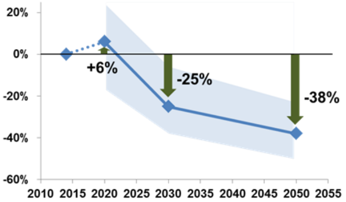
	ONSHORE (LAND-BASED)	FIXED-BOTTOM OFFSHORE	FLOATING OFFSHORE
a) LEVELIZED COST OF ENERGY			
b) DRIVERS FOR COST REDUCTION IN 2030	Capacity factor: +10% Project life: +10% CapEx: -12% OpEx: -9% WACC: no Δ	Capacity factor: +4% Project life: +15% CapEx: -14% OpEx: -9% WACC: -10%	Capacity factor: +9% Project life: +25% CapEx: -5% OpEx: -8% WACC: -5%
c) TURBINE SIZE IN 2030	**3.25 MW rated capacity 115 m hub height 135 m rotor diameter**	**11 MW rated capacity 125 m hub height 190 m rotor diameter**	**9 MW rated capacity 125 m hub height 190 m rotor diameter**
d) TOP-FIVE IMPACT CATEGORIES	• Larger rotors, reduced specific power • Rotor design advancements • Taller towers • Reduced financing costs • Component durability / reliability	• Larger turbine capacity • Foundation / support structure design • Reduced financing costs • Economies of scale via project size • Component durability / reliability	• Foundation / support structure design • Installation process efficiencies • Foundation / support manufacturing • Economies of scale via project size • Installation / transport equipment

Figure 1. Summary of expert elicitation findings. Top panel (a) depicts expected LCOE changes in the median scenario in percentage terms relative to 2014 baseline values. The median of expert responses in terms of percentage LCOE reductions are shown by the lines/markers, whereas the shaded areas represent the 1st to 3rd quartile of all responses. Floating offshore wind changes are compared to expert-specific 2014 baselines for fixed-bottom offshore wind. The second panel (b) presents the median of expert responses for changes in five factors that impact LCOE, from 2014 to 2030 in the median scenario. Floating offshore wind changes are again compared to 2014 baselines for fixed-bottom offshore wind. The third panel (c) presents the median of expert responses for typical turbine size in 2030. The bottom panel (d) lists the top-5 advancements (out of 28 rated items) identified by experts as having the largest expected impacts on lowering LCOE by 2030.

Expected Reduction in Wind Costs in Median Scenario

Experts anticipate sizable reductions in the LCOE between now and 2050. Figure 1 summarizes LCOE-reduction expectations for the median (50th percentile) scenario. Across all three wind applications, the LCOE is anticipated to decline by 24%–30% in 2030 and by 35%–41% in 2050, relative to 2014 baseline values. Though percentage changes from the 2014 baselines are the most broadly applicable approach to presenting survey findings because experts could specify their own baseline values and because baselines might vary by geography, depicting the absolute value for expert-specified LCOE is also relevant (Figure 2). In these terms, onshore wind is expected to remain less expensive than offshore—and fixed-bottom offshore less expensive than floating. However, there are greater absolute reductions (and more uncertainty) in the LCOE of offshore wind compared with onshore wind, and a narrowing gap between fixed-bottom and floating offshore, with especially sizable expected reductions in the LCOE of floating offshore wind between 2020 and 2030.

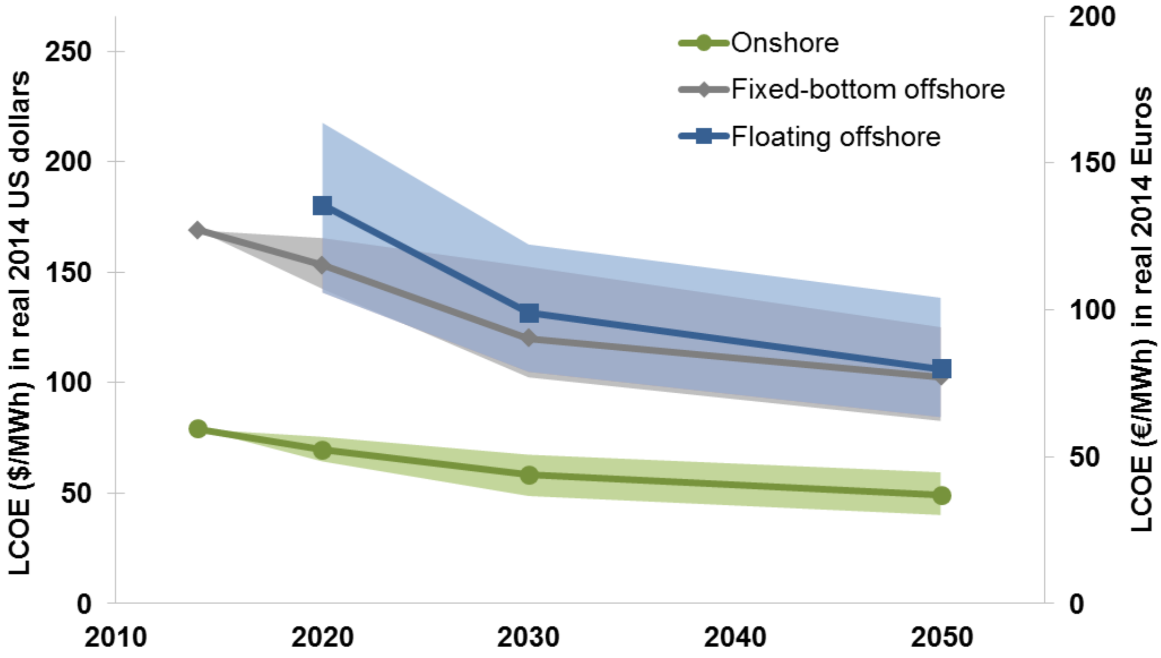


Figure 2. Expert estimates of median-scenario LCOE. Lines/markers indicate the median expert response for the median LCOE scenario. Shaded areas show the 1st to 3rd quartiles of expert responses. A review of expert responses for the low and high LCOE scenarios is included in the Supplementary Discussion.

Figure 1 also summarizes expert views on how the median scenario LCOE reductions between 2014 and 2030 might be achieved, in terms of CapEx, OpEx, capacity factors, project design life, and cost of finance. Figure 3, in contrast, highlights the *relative* impact of the changes in each driver in achieving the median scenario LCOE in 2030. Specifically, we use each expert's 2014 baseline and 2030 values for each of the five factors to calculate what the change in LCOE would be for that expert if only one of the five factors changed, relative to that expert's overall change in LCOE. We repeat this for each of the five factors and for each expert and present the median of expert responses in Figure 3.

For *onshore wind*, CapEx and capacity factor improvements constitute the largest drivers of LCOE reduction in the median scenario. The importance of higher capacity factors is consistent with expert views on turbine characteristics (see Supplementary Discussion), with scaling expected not only in turbine capacity ratings but also in two factors related to increased capacity factors—rotor diameters and hub heights. For *fixed-bottom offshore wind*, CapEx reductions and improvements in financing costs are the largest contributors to LCOE reduction. The higher importance of CapEx and lower importance of capacity factors is consistent with expert opinions on future turbine size (see Supplementary Discussion): expected turbine capacity ratings (and hub heights) grow significantly, but ratios of rotor swept area to nameplate capacity remain roughly constant. Capacity factor improvements play a larger role for *floating offshore wind* (relative to the 2014 baseline for fixed-bottom), perhaps reflecting a belief that floating technology will tend to be deployed in windier sites as enabled by the ability to access deeper water locations. Financing cost reductions are more important for offshore than for onshore wind, presumably due to its lower level of market maturity.

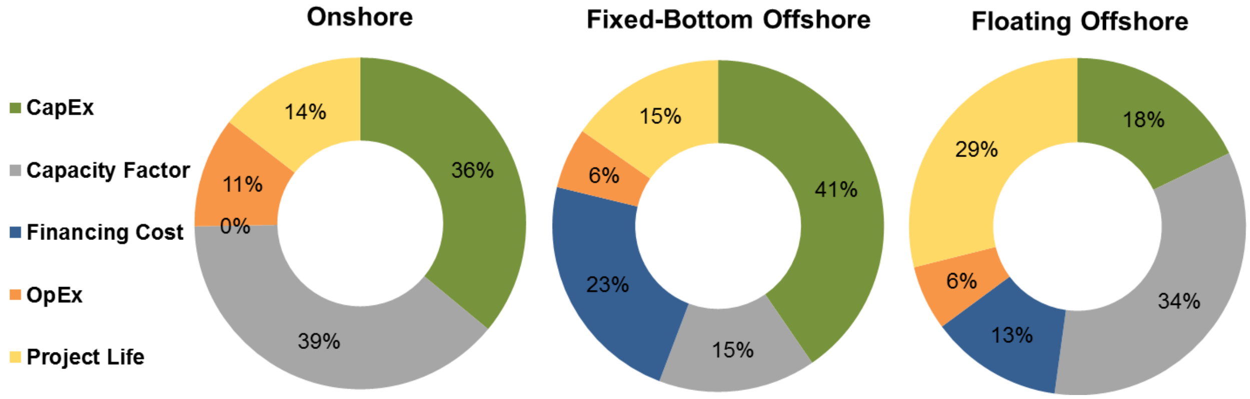


Figure 3. Relative impact of drivers for median-scenario LCOE reduction in 2030. The figure covers onshore, fixed-bottom offshore, and floating offshore wind. Floating offshore wind is compared to 2014 baselines for fixed-bottom offshore wind. The Supplementary Discussion explores the relative impact of drivers in more depth not only for the median LCOE scenario but also the low LCOE scenario.

Opportunity Space for and Uncertainty in Cost Reductions

Figure 4 presents median-expert LCOE expectations for all three LCOE scenarios. The resulting range in expert-specified LCOEs suggests significant uncertainty in the degree and timing of future advancements even among wind experts. The low-cost scenario represents what might be possible through aggressive research, development, and deployment. Under that scenario and across all three wind applications, experts predict LCOE percentage reductions of more than 40% by 2030 and more than 50% by 2050. The Supplementary Discussion highlights how survey respondents believe that such LCOE reductions might be achieved, and also shows that greater “learning with market growth” and “research and development” are the two most-significant broad enablers for the low LCOE scenario.

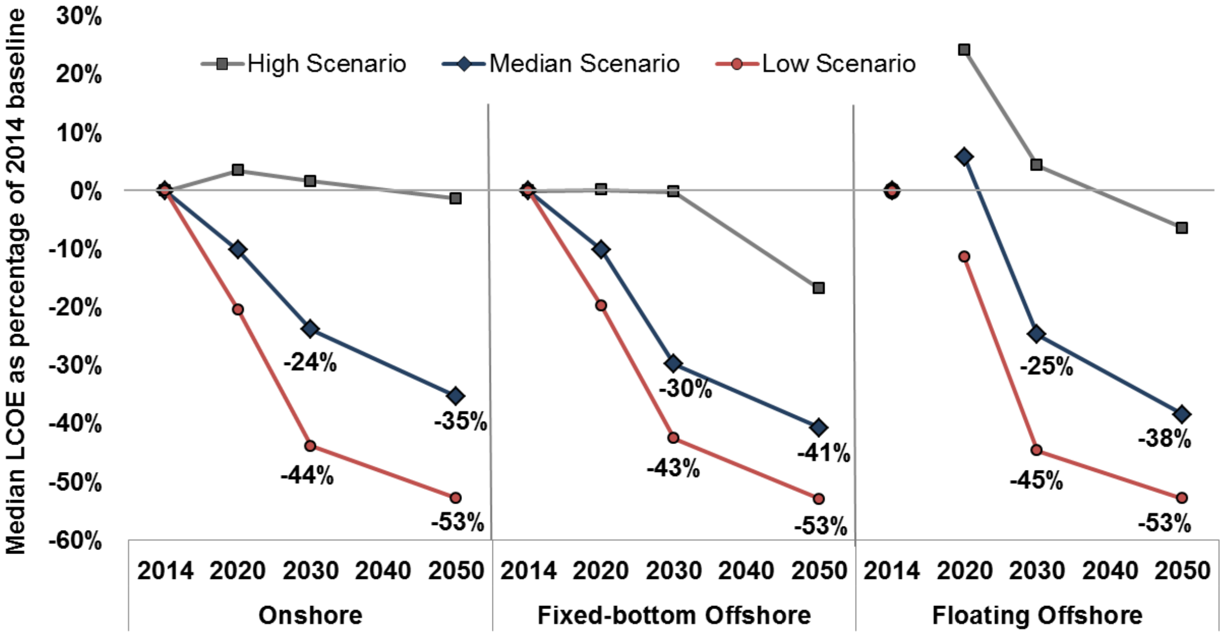


Figure 4. Estimated change in LCOE over time across all three scenarios. Depicts the median of expert responses for expected LCOE reductions in the median (50th percentile) scenario as well as the low scenario (10th percentile) and high scenario (90th percentile) in percentage terms relative to 2014 baseline values. Floating offshore wind is compared against the 2014 baseline for fixed-bottom offshore. See Supplementary Discussion for full results.

A variety of development, technology, design, manufacturing, construction, operational, and market changes might contribute to reducing LCOE. Respondents rated 28 different drivers based on their expected impact on LCOE. The top-5 responses for each wind application are listed in Figure 1 (see Supplementary Tables 3-5 for the full set of results). That the two leading drivers for LCOE reduction for onshore wind are related to rotors confirms earlier survey results highlighting capacity factor improvements, as does the third ranked item, increased hub heights. For fixed-bottom offshore wind, the most highly rated advancements include increased turbine capacity ratings, design advancements for foundations and support structures, and reduced financing costs and project contingencies. Some of the same items rate highly for floating offshore wind, with an even greater emphasis on foundations and support structures as well as installation processes.

Considerable uncertainty exists across all of these variables and factors, partly reflected in the range between the low, median, and high scenarios shown in Figure 4. Differences are also found when reviewing the range in expert-specific responses, as shown by the 25th to 75th percentile expert ranges depicted in Figures 1 and 2 (as well as Supplementary Figures 1-5, 12-14). Some of the variation in expert-specific responses can be explained by segmenting respondents into various categories. For example, as shown in the Supplementary Discussion, a smaller group identified as “leading-experts” generally expects more-aggressive wind energy cost reductions (27% reductions for onshore wind by 2030 in the median case, 35% for fixed-bottom offshore, and 38% for floating offshore) than the larger set of other survey respondents less that “leading-experts” group (24% for onshore, 29% for fixed-bottom, 15% for floating). Wind equipment manufacturers, on the other hand, are more cautious about nearer-term advancement possibilities, especially for fixed-bottom offshore wind, though those differences narrow by 2050. Though the differences identified here are notable, it is also important that the results from most respondent groups—by organization, by region, and by expertise type—vary only to a small degree, suggesting that any biases in the survey results are either (a) limited or (b) apply broadly and similarly across most of the wind expert respondent groupings.

Comparison with Past Trends and Other Forecasts

A substantial literature has sought to estimate historical learning rates for onshore wind. Estimated learning rates span an enormous range, from a 33% cost decline with each doubling of cumulative production (LR = 33%) to a cost increase of 11% for each doubling (LR = -11%) [2, 12-13]. The wide variation can be partly explained by differences in learning model specification, assumed geographic scope of learning, and the period of the analysis. Learning rates have typically been estimated based on turbine- or project-level CapEx, and have rarely focused on the more decision-relevant metric of LCOE. Recent CapEx learning rates have been estimated at 6-9% [1, 48-49].

To compare expert elicitation results with historical LCOE and LCOE learning rates, Figure 5 depicts four published estimates of historical onshore wind LCOE and the associated single-factor learning rates based on historical growth in cumulative global wind capacity. The absolute values of the LCOE estimates span a considerable range, with effective learning rates ranging from 10.5% to 18.6%. The figure also depicts the expert survey results relative to a single forecast of future wind capacity. Future wind deployment, however, is uncertain. Combining the median-scenario LCOE reduction from 2014 to 2030 with a range of wind deployment projections for cumulative global wind capacity ("New Policies" in [9]; "Base Scenario" in [50]; and "Moderate Scenario" in [10]) yields an implicit elicitation-based onshore LCOE learning rate of 14%–18%; 2050 learning rate estimates for the median LCOE scenario are consistent with this range. As indicated earlier, learning rates are an imperfect tool for understanding the drivers of past cost reduction or forecasting future costs. Moreover, elicitation results show that both deployment growth and R&D are expected to exert downward pressure on LCOE, implying that a two-factor learning curve would be a more appropriate specification. Nonetheless, the implicit single-factor learning rate embedded in the median-scenario LCOE forecast from our experts is highly consistent with past learning trends for onshore LCOE.

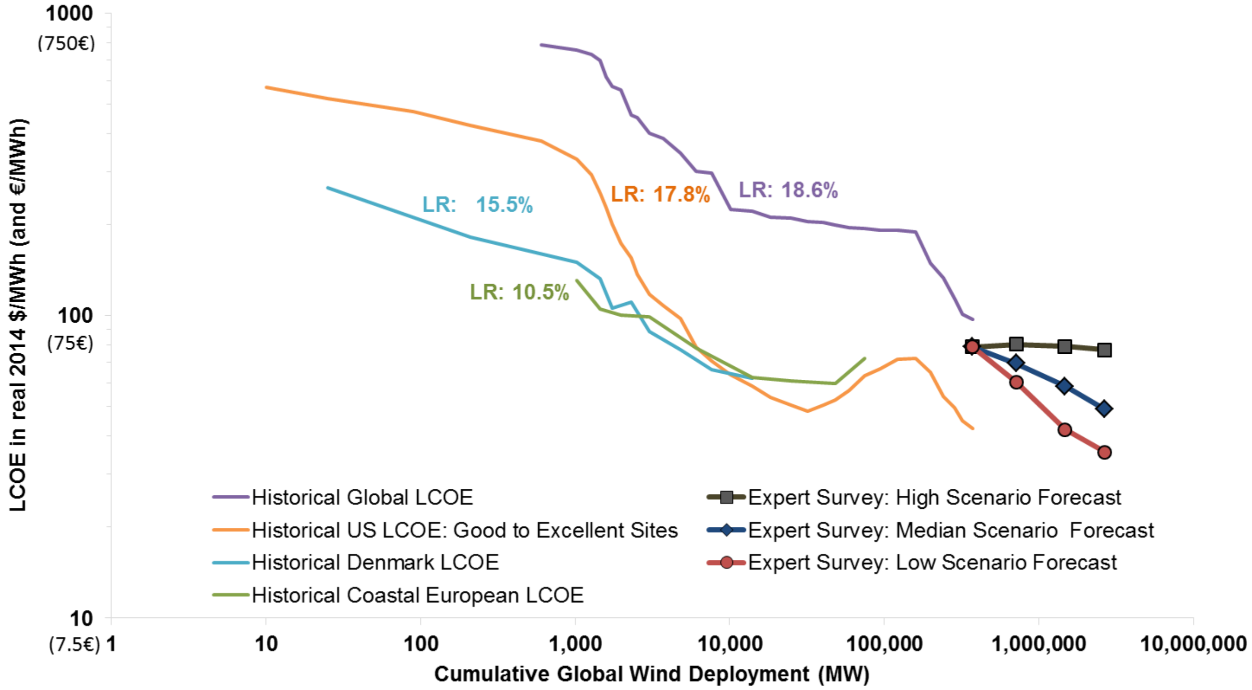


Figure 5. Historical and forecasted onshore wind LCOE and learning rates. Historical LCOE estimates and derived single-factor learning rates (LRs) come from four sources (Global: [48]; US: [51]; Denmark: [52]; European Coastal: [53]; each of these LCOE estimates is derived differently, and each covers distinct geographies. To depict expert survey results on this figure, we rely on the “Moderate Scenario” in [10] as the global wind deployment forecast from 2014 to 2050. Note that graphic is presented in log-log form.

Turning to offshore wind, historical cost trends are mixed, with an initial reduction in costs for the first fixed-bottom offshore wind installations in the 1990s, following by steeply increasing costs in the 2000s and, most recently, some indication of cost reductions [54]. Given this history—and the limited amount of total deployment—there have been few recent attempts to fit a learning curve to offshore data. One study [55] finds a learning rate of 3%–5% when focused on CapEx, whereas [56] find little evidence of learning thus far. Another study [57] suggests that expectations for future cost reductions should be tempered given historical trends and the complexity of offshore wind. Others conclude that a simple learning curve cannot readily be used to explain historical cost developments, especially given the early state of deployment [54]. It is also unclear what learning specification might best be used to understand past trends or to forecast future ones, as offshore wind costs might decline as a result of both onshore and offshore experience.

When applying an *offshore-only* capacity forecast of cumulative wind deployment [57], an implicit fixed-bottom offshore learning rate of 8% is estimated for our median scenario 2030 LCOE results, lower than the range estimated previously for onshore wind. In contrast, a range of cumulative *total (onshore and offshore)* wind capacity projections yield implicit LCOE learning rates of about 16%–20%, somewhat higher than but closer to the range for onshore wind. These results suggest that experts either anticipate lower offshore-only learning or expect learning spill overs from onshore to offshore. Even in the high-cost scenario, though, experts anticipate fixed-bottom offshore wind LCOE reductions in the long run, following a flat learning curve for the next 15 years. Experts apparently believe that the recent history of rising costs is likely to be reversed eventually as the market matures. Whether these views are prescient or are instead overly optimistic, influenced by motivational or other biases, will only be known in hindsight.

Finally, Figure 6 compares survey results for onshore and fixed-bottom offshore wind with a variety of other recent wind energy cost forecasts. Though elicitation results are generally within the range of other forecasts, the elicitation tends to show greater expectations for LCOE reductions for onshore wind in the median scenario than much of the broader literature. The opposite is true for offshore wind, where elicitation results are more conservative than much of the other recent literature. The reasons for the more aggressive set of onshore estimates from wind energy experts is not known, but the broader onshore literature might be conservatively biased when those forecasts are informed by lower historical CapEx-based learning rates rather than higher LCOE-based learning estimates [19, 49]. The reviewed offshore literature, in contrast, often considers not just CapEx but also capacity factors, OpEx, and cost of finance. The reasons for the more-conservative views of the experts in comparison to the broader literature for offshore wind are unclear but, as indicated earlier, offshore wind energy costs have not experienced the sizable historical reductions witnessed onshore. Those historical data points may be encouraging some conservatism among the experts, at least relative to the broader literature.

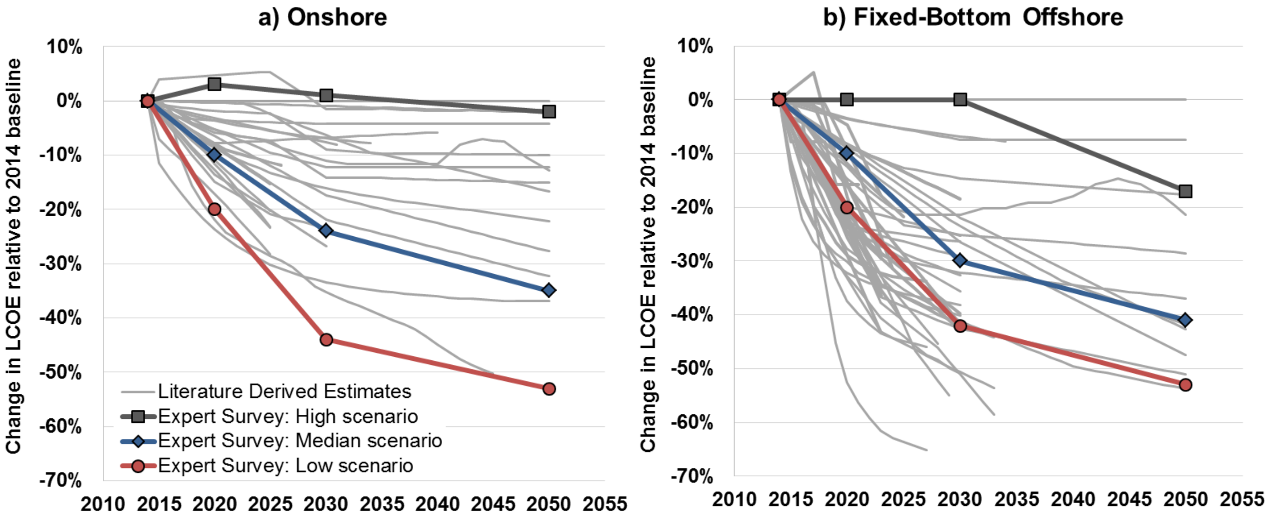


Figure 6. Estimated change in LCOE comparing expert survey results to other forecasts. Depicts the median of expert responses for expected LCOE reductions in the median (50th percentile) scenario as well as the low scenario (10th percentile) and high scenario (90th percentile) in percentage terms relative to 2014 baseline values for onshore (panel a) and fixed-bottom offshore (panel b) wind. Other forecasts are included for comparison; see Supplementary References for the listing of studies included.

Conclusions and Implications

The wind industry has matured substantially since its beginnings in the 1970s. Sizable reductions in the cost of onshore wind energy have accompanied that maturation, with the hope that those reductions will also be witnessed offshore. But how much additional cost reduction is possible? What technological and market factors are the most likely contributors to those reductions? And what broad trends may drive even greater technological advancements and cost reductions? This study provides some insight to these questions, leveraging the largest single expert elicitation ever performed on an energy technology. Results can inform policy and planning decisions, R&D decisions, and industry investment and strategy development while improving the representation of wind energy in energy-sector and integrated-assessment models. Three prominent implications deserve special attention.

First, notwithstanding the growing maturity of onshore wind and the limited evidence of historical cost reductions for offshore wind, experts anticipate significant additional reductions in the levelized cost of wind energy across all three applications in the median scenario. Elicitation results for onshore wind are consistent with historical LCOE learning, suggesting that properly constructed learning rates may be reasonably used to forecast future costs in more mature applications. The consistency among respondent-specific answers across our survey questions provides additional confidence in the results. The elicitation findings for offshore wind, on the other hand, are at odds with historical trends that show little evidence of cost reductions so far; using historical learning rates to forecast future costs would therefore result in values different from the expert-specified views.

Second, the majority of the literature assessing historical learning rates for wind have emphasized only upfront capital costs, and some energy-sector and integrated-assessment models rely on those learning estimates when forecasting future costs [19, 49, 58]. However, expert elicitation findings demonstrate that capital-cost improvements are only one means of achieving LCOE reductions, and not always the dominant one. Extrapolation of past capital-cost-based learning models therefore likely understates the opportunities for future LCOE reduction by ignoring major drivers for that reduction. This is illustrated by the fact that the elicitation-based forward-looking LCOE learning rates are twice as high as recently estimated CapEx-based learning rates for onshore wind of 6-9%, and may explain why the onshore cost reduction estimates from wind experts are more aggressive than many past forecasts.

Third, survey results reveal significant uncertainty in future cost expectations but also a sizable opportunity space for cost reductions, implying a substantial potential upside to wind energy technology policies that might push costs lower and lead to widespread deployment; but a potential downside if poorly crafted policies encourage aggressive deployment even under high costs. High levels of uncertainty also suggest that there is value in policies and efforts that increase future flexibility by, for example, reducing the lead-time needed to deploy large amounts of wind in the case that low costs are realized [59]. Overall, the elicitation results will enable energy-system and integrated-assessment models to better explore these options and to thereby better understand the long-term role of wind energy under varying scenarios by explicitly representing the significant uncertainty in future costs.

Methods

Online survey. We gathered data through an online elicitation survey (via the Near Zero platform, http://www.nearzero.org/) under the auspices of IEA Wind Task 26 on the "Cost of Wind Energy." The survey was carefully designed over a number of months, including numerous rounds of review, testing, and revision. Reviewers included the core survey design team, IEA Wind Task 26 members, and a select group of external wind energy experts. An expert workshop was held early in the process to discuss the goals of the survey and to pilot test an early draft. A version of the final survey can be found as Supplementary Note 3 and as an addendum to our published technical report [60].The survey was launched in October 2015 and closed in December 2015. We first "pre-announced" the survey to possible respondents, and we invited participation in a webinar during which we discussed the purpose, structure, and details of the elicitation. The online survey was distributed with personalized web links, and six separate waves of reminders were sent before the survey finally closed—including personalized and less-personalized reminders. In some cases, several individuals within an organization collaborated on a single, collective survey response.

Expert respondents. The success of an expert elicitation depends on the expertise and commitment of the contributing experts. Given the focus of our elicitation on LCOE, our ideal respondents included strategic, system-level thought leaders with wind technology, cost, and/or market expertise. Many expert elicitations feature detailed and sometimes lengthy in-person interviews with fewer than 20 experts. In contrast, we sought a relatively large number of respondents, in part reflecting the need for a greater number of respondents to address two key goals of our effort: to assess three different wind applications and, following other research [61-63], to enable comparison of responses across a diverse set of respondent groups. The Supplementary Methods provides further details on the trade-offs involved with an online elicitation, including the need for a shorter, more focused survey than would be common in an in-person setting, with less follow-up and in-depth exploration of responses.

Though the survey was global in scope, we focused on identifying experts from North America and Europe. We received considerable assistance in identifying possible respondents from IEA Wind Task 26 members and their affiliated institutions, and we reached out to many other experts and organizations to ensure broad coverage. In addition to the full survey sample, we identified a smaller group of "leading experts." These individuals were selected through an iterative, deliberative process by a core group of IEA Wind Task 26 members and several leading external wind experts. The survey team believed this small group was uniquely qualified to complete the survey, and the group was created in part to enable comparison of survey results between the smaller sub-sample (paralleling a more traditional elicitation) and the larger group of other respondents.

We ultimately distributed surveys to 482 experts, including 42 in the leading-expert group. The total number of returned surveys was 163, of which 22 came from the leading-expert group. This reflects a response rate of 34% across the full set and 52% among the smaller group. The Supplementary Methods summarizes the characteristics of the 163 respondents by wind application area addressed (134 onshore, 110 fixed-bottom offshore, 44 floating offshore), regions of the world with which experts are most familiar (104 North America; 110 Europe; 27 Asia; 24 Latin America; 7 Middle East and Africa), organizational type (32 involved in wind development, ownership, finance, operations, construction, and/or installation; 25 wind equipment manufacturers; 46 others in the private sector wind industry; 43 in academia and/or public R&D; and 16 others including government and non-profits not included in the other categories), and type of expertise (116 wind energy markets and/or cost analysis; 87 systems-level wind technologies; and 41 sub-systems level wind technologies). Supplementary Table 20 identifies the 163 respondents by name and organization. The median respondent dedicated 49 minutes to completing the survey, with the 25th-to-75th percentile range from 29 to 99 minutes.

Elicitation methods. In an expert elicitation, responses may be affected by the design of the data-collection instrument, by the individuals selected to submit their views, by the behaviour of the interviewers, and/or by features of the questionnaire or web-based instrument. We applied the basic concepts, tools, and guidelines of a well-designed expert elicitation in order to minimize biases. Best elicitation practices include clearly defining the quantities that are being assessed, minimizing extra cognitive burden on the expert by asking questions using familiar terminology and units, and minimizing the need for "side" calculations. In addition, we sought to minimize the effects of anchoring and overconfidence biases [64] by asking for low- and high-scenario estimates *before* asking for a mid-point estimate, and providing experts with feedback and the opportunity to review and modify their responses [38]. Our online survey format created challenges (e.g., we had a limited ability to tailor questions to respondent preferences) but also provided benefits over traditional interview-based elicitations in terms of easily accessible calculation and graphical display tools that gave experts immediate feedback and context for their assessments. The Supplementary Methods provides further details on our application of expert elicitation principles, highlights unique aspects of our assessment, and describes in detail the types of questions and definitions included in the elicitation protocol. Notwithstanding the fact that we followed the basic protocols for a well-designed expert elicitation, as with any survey effort, it is impossible to entirely eliminate—or even to fully test for—motivational or cognitive biases. As such, one might consider expert elicitations as a means of revealing the views of subject-matter experts, not necessary a means of revealing the "truth."

Scope of assessment. As briefly covered earlier, the survey focused on potential changes in the LCOE of projects that use each of the three wind applications. The LCOE estimate equates to the minimum power price a project must obtain to cover all project costs, service debt, pay expected returns to equity shareholders, and cover income tax. LCOE is calculated at the plant boundary and excludes the valuation of public benefits (e.g., carbon reduction) as well as ratepayer, taxpayer, or other forms of project-level government support (e.g., investment and production tax credits, feed-in-tariff premiums, renewable energy certificates). The formula used to calculate LCOE and more details on its use in the survey can be found at: http://rincon.lbl.gov/lcoe_v2/background.html.

In surveying experts, we sought insight on the LCOE of the three wind applications at four time points: a recent-cost baseline in 2014 (for which respondents could accept a predefined baseline or create their own) and then in 2020, 2030, and 2050. Inclusion of a 2014 baseline allows for any changes over time to be characterized in absolute ($ or €) and relative terms (% increase or decrease). We did not seek a baseline estimate for floating offshore wind, given the nascent present state of that technology and lack of current commercial applications. For the baseline year, and for our focus year of 2030, we further requested details on five core input components of LCOE as noted earlier: CapEx, OpEx, capacity factor, design life, and WACC. The WACC represents the average return required by the combination of equity and debt investors to make a project an attractive investment opportunity, where each category of capital is proportionately weighted. In calculating the LCOE, we use standardized taxation and inflation assumptions: standardized income tax rate (25%), depreciation schedule (20-year straight-line), and long-term inflation rate (2%); 100% of capital costs are assumed depreciable. For 2020 and 2050, we solicited only estimates of the LCOE and not the five input components.

For the 2014 and 2030 CapEx estimates, respondents were asked to include only costs within the plant boundary, which include costs for electrical cabling within the plant but exclude costs for any needed substations, transmission lines, or grid interconnection costs. As applied to offshore wind, this means that CapEx includes costs for within-plant array cabling but excludes the costs for offshore substations, any high-voltage direct-current collector stations and associated cables, and grid connection to land (e.g., subsea export cables, onshore substations, and onshore transmission cables). As defined in the survey, OpEx excludes any costs associated with grid interconnection, substations, or transmission use; for offshore wind, transmission system use charges are also excluded.

The survey emphasized the “typical” LCOE of wind projects in each respondent’s primary region of expertise. We defined “typical” as the median project in terms of costs in a future scenario (Supplementary Figure 1). Future wind LCOEs are uncertain. They can be affected by project-specific factors, such as the quality of the wind resource at a particular site, as well as by factors that affect the entire wind sector, such as changes in wind turbine technologies, markets, and policies. Technological changes may be induced by direct R&D or other advances. Market changes comprise, for example, systemic changes in the average wind speed of sites that remain for development as well as the amount of competition in the wind supply chain. Policy changes may directly or indirectly support or impede wind energy development and deployment. In exploring future LCOE trends, we asked respondents to provide estimates for a low LCOE scenario (10th percentile), a high LCOE scenario (90th percentile), and a median LCOE scenario (50th percentile), considering only the broader, non-project-specific factors. We asked experts specifically to focus on changes in the typical LCOE (i.e., to ignore project-to-project variation) that might result from changes in factors that affect the industry as a whole (i.e., changes in wind energy technologies, markets, and policies). We also asked respondents to assume no changes in macroeconomic conditions (such as interest rates, inflation, and currency fluctuations), materials and commodity prices, and other factors not directly related to the wind energy business.

In addition to asking about LCOE and the five core LCOE inputs, we asked about the market and technology characteristics and drivers most likely to impact LCOE trends in 2030. Specifically, we sought information on: (1) expected typical turbine characteristics for projects installed in 2030—nameplate capacity, hub height, and rotor diameter for all three wind applications; (2) the expected impact of each of a list of specific changes in wind development, technology, design, manufacturing, construction, operations, and markets on achieving reduced LCOE by 2030 for all three wind applications; and (3) broad drivers most likely to facilitate achieving “low” estimates of LCOE in 2030 as opposed to “median” estimates in that year, separately for onshore and fixed-bottom offshore wind.

References

[1] Wiser, R. & Bolinger, M. *2014 Wind Technologies Market Report.* (U.S. Department of Energy, 2015).

[2] Wiser, R. *et al.* Wind Energy. In Edenhofer, O. *et al.* (eds). *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation.* (Cambridge University Press, 2011).

[3] *Global Wind Report: Annual Market Update 2015*. (Global Wind Energy Council, 2016).

[4] Marvel, K., Kravitz, B. & Caleira, K. Geophysical limits to global wind power. *Nature Climate Change* **3**, 118-121 (2012).

[5] Barthelmie, R.J. & Pryor, S.C. Potential contribution of wind energy to climate change mitigation. *Nature Climate Change* **4**, 684-688 (2014).

[6] Cochran, J., Mai, T. & Bazilian, M. Meta-analysis of high-penetration renewable energy scenarios. *Renewable and Sustainable Energy Reviews* **29,** 246-253 (2014).

[7] IPCC. *Climate Change 2014: Mitigation of Climate Change* [Edenhofer, O. Pichs-Madruga, R. & Sokona, Y. (eds)]. (Cambridge University Press, 2014).

[8] Luderer, G. *et al*. The role of renewable energy in climate stabilization: results from the EMF27 scenarios. *Climatic Change* **123**, 427-441 (2014).

[9] *World Energy Outlook 2015.* (International Energy Agency, 2015).

[10] *Global Wind Energy Outlook 2014.* (Global Wind Energy Council, 2014).

[11] MacDonald, A. *et al*. Future cost-competitive electricity systems and their impact on US CO_2 emissions. *Nature Climate Change*. **6,** 526-531 (2016).

[12] Lindman, Å. & Söderholm, P. Wind power learning rates: a conceptual review and meta-analysis. *Energy Economics* **34,** 754-761 (2012).

[13] Rubin, E.S., Azevedo, I., Jaramillo, P. & Yeh, S. A review of learning rates for electricity supply technologies. *Energy Policy* **86**,198-218 (2015).

[14] Ferioli, F., Schoots, K. & Van der Zwaan, B.C.C. Use and limitations of learning curves for energy technology policy: A component-learning hypothesis. *Energy Policy* **37,** 2525- 2535 (2009).

[15] Mukora A., Winskel, M. Jeffrey, H.F. & Mueller, M. Learning curves for emerging energy technologies. *Proceedings of the Institution of Civil Engineers – Energy* **162**, 151-159 (2009).

[16] Ek, K. & Söderholm, P. Technology learning in the presence of public R&D: The case of European wind power. *Ecological Economics* **69***,* 2356-2362 (2010).

[17] Junginger, M., Sark, W.V. & Faaij, A. (eds). *Technological Learning in the Energy Sector: Lessons for Policy, Industry and Science.* (Edward Elgar, 2010).

[18] Yeh, S. & Rubin, E.S. A review of uncertainties in technology experience curves. *Energy Economics* **34,** 762-771 (2012).

[19] Witajewski-Baltvilks, J., Verdolini, E. & Tavoni, M. Bending the learning curve. *Energy Economics* **52,** S86-S99 (2015).

[20] Arrow, K.J. The economic implications of learning by doing. *The Review of Economic Studies* **29**, 155-173 (1962).

[21] Nordhaus, W.D. *The Perils of the Learning Model for Modeling Endogenous Technological Change.* (National Bureau of Economic Research, 2009).

[22] Fingersh, L., Hand, M. & Laxson, A. *Wind Turbine Design Cost and Scaling Model*. (National Renewable Energy Laboratory, 2006).

[23] *Offshore Wind Cost Reduction Pathways Study.* (The Crown Estate, 2012).

[24] 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* **15**, 3-17 (2010).

[25] Hobohm, J. *et al. Cost Reduction Potentials of Offshore Wind Power in Germany.* Prepared for the German Offshore Wind Energy Foundation. (Fitchner-Prognos, 2013).

[26] Valpy, B. & English, P. *Future Renewable Energy Costs: Offshore Wind.* (BVG Associates and KIC InnoEnergy, 2014).

[27] Junginger M., Faaij, A. & Turkenburg, W.C. Cost reduction prospects for offshore wind farms. *Wind Engineering* **28**, 97-118 (2004).

[28] *Cost Reduction Options for Offshore Wind in the Netherlands FID 2010-2020.* (TKI Wind op Zee, 2015).

[29] Cohen, J. *et al. Technology Improvement Opportunities for Low Wind Speed Turbines and Implications for Cost of Energy Reduction*. (National Renewable Energy Laboratory, 2008).

[30] Neij, L. Cost development of future technologies for power generation – A study based on experience curves and complementary bottom-up assessments. *Energy Policy* **36**, 2200-2211 (2008).

[31] Wüstemeyer, C., Madlener, R. & Bunn, D.W. A stakeholder analysis of divergent supply-chain trends for the European onshore and offshore wind installations. *Energy Policy* **80,** 36-44 (2015).

[32] Verdolini, E., Anadon, L.D., Baker, E. Bosetti, V. & Reis, L.A. *The Future Prospects of Energy Technologies: Insights from Expert Elicitations*. (Fondazione Eni Enrico Mattei, 2016). http://www.feem.it/userfiles/attach/2016751147214NDL2016-047.pdf

[33] Morgan, M.G. Use (and abuse) of expert elicitation in support of decision making for public policy. *Proceedings of the National Academy of Sciences (PNAS)* **111,** 7176-7184 (2014).

[34] Kotra, J.P., Lee, M.P. Eisenberg, N.A. & DeWispelare, A.R. *Branch Technical Position on the Use of Expert Elicitation in the High-Level Radioactive Waste Program*. (Nuclear Regulatory Commission, 1996).

[35] Meyer, M.A & Booker, J.M. *Eliciting and Analyzing Expert Judgment: A Practical Guide.* (Society for Industrial and Applied Mathematics, 2001).

[36] Knol, A.B., Slottje, P.E., van der Sluijs, J.P. & Lebret, E. The use of expert elicitation in environmental health impact assessment: a seven step procedure. *Environmental Health* **9**(19) (2010).

[37] Hora, S. Assessing Probabilities from Experts. In Edwards, W., Miles, R.F. & von Winterfeldt, D. (eds). *Advances in Decision Analysis: From Foundations to Applications*. (Cambridge University Press, 2007).

[38] Coppersmith, K.J., Jenni, K.E., Perman, R.C. & Youngs, R.R. Formal expert assessment in probabilistic seismic and volcanic hazard analysis. In Connor, C.B., Chapman, N.A. & Connor, L.J. (eds). *Volcanic and Tectonic Hazard Assessment for Nuclear Facilities*. (Cambridge University Press, 2009).

[39] *Climate Change Assessments: Review of the Processes and Procedures of the IPCC.* (InterAcademy Council, 2010).

[40] NRC. *Prospective Evaluation of Applied Energy Research and Development at DOE (Phase Two).* (The National Academies Press, 2007).

[41] Baker, E., Bosetti, V., Anadon, L.D., Henrion, M. & Reis, L.A. Future costs key low-carbon energy technologies: Harmonization and aggregation of energy technology expert elicitation data. *Energy Policy* **80**, 219-232 (2015).

[42] Gillenwater, M. 2013. Probabilistic decision model of wind power investment and influence of green power market. *Energy Policy* **63**, 1111-1125.

[43] Kempton, W., McClellan, S. & Ozkan, D. *Massachusetts Offshore Wind Future Cost Study.* (University of Delaware Special Initiative on Offshore Wind, 2016).

[44] Curtright, A.E., Morgan, M.G. & Keith, D. Expert assessment of future photovoltaic technology, *Environmental Science & Technology* **42**, 9031-9038 (2008).

[45] Joskow P.L. Comparing the costs of intermittent and dispatchable electricity generating technologies. *American Economic Review: Papers & Proceedings* **100**, 238–241 (2011).

[46] Edenhofer, O. *et al*. On the economics of renewable energy sources. *Energy Economics* **40,** S12-S23 (2013).

[47] Mills A. & Wiser, R. Changes in the economic value of wind energy and flexible resources at increasing penetration levels in the Rocky Mountain Power Area. *Wind Energy* **16**, 1711-1726 (2013).

[48] *The Future Cost of Onshore Wind – An Accelerating Rate of Progress.* Wind Insight. (Bloomberg New Energy Finance, 2015).

[49] Criqui, P., Mima, S., Menanteau, P. & Kitous, A. Mitigation strategies and energy technology learning: An assessment with the POLES model. *Technology Forecasting & Social Change* **90**, 119-136 (2015).

[50] *New Energy Outlook 2015.* Wind Insight. (Bloomberg New Energy Finance, 2015).

[51] *Revolution Now. The Future Arrives for Five Clean Energy Technologies - 2015 Update.* (U.S. Department of Energy, 2015).

[52] *Wind Power in Denmark: Technologies, Policies, and Results.* (Danish Energy Agency, 1999).

[53] Lemming, J.K., Morthorst, P.E., Clausen, N.E. & Jensen, P.H. *Contribution to the Chapter on Wind Power in Energy Technology Perspectives 2008.* (Risø National Laboratory for Sustainable Energy, 2009).

[54] Voormolen, J.A., Junginger, H.M. & van Sark, W.G.J.H.M.. Unravelling historical cost developments of offshore wind energy in Europe. *Energy Policy* **88,** 435-444 (2016).

[55] van der Zwaan, B.C.C., Rivera-Tinoco, R., Lensink, S. & van den Oosterkamp, P. Cost reductions for offshore wind power: exploring the balance between scaling, learning and R&D. *Renewable Energy* **41**, 389-393 (2012).

[56] Dismukes, D.E. &. Upton Jr, G.B. Economies of scale, learning effects and offshore wind development costs. *Renewable Energy* **8**3, 61-66 (2015).

[57] *H1 2016 Offshore Wind Market Outlook*. Wind Insight. (Bloomberg New Energy Finance, 2016).

[58] Schwanitz, V.J. & Wierling, A. Offshore wind investments – Realism about cost developments is necessary. *Energy* **106**, 170-181 (2016)

[59] Dixit, A.K. & Pindyck, R.S. *Investment under Uncertainty.* (Princeton University Press, 1994).

[60] Wiser, R. *et al. Forecasting Wind Energy Costs and Cost Drivers: The Views of the World's Leading Experts*. (Lawrence Berkeley National Laboratory, 2016). https://empl.lbl.gov/iea-wind-expert-survey

[61] Anadón, L.D., Nemet, G. & Verdolini, E. The future cost of nuclear power using multiple expert elicitations: effects of RD&D and elicitation design*. Environmental Research Letters* **8,** 1-10 (2013).

[62] Verdolini, E., Anadon, L.D., Lu, J. & Nemet, G. The effects of expert selection, elicitation design, and R&D assumptions on experts' estimates of the future cost of photovoltaics. *Energy Policy* **80**, 233-243 (2015).

[63] Nemet, G.F., Anadon, L.D. & Verdolini, E. Quantifying the effects of expert selection and elicitation design on experts' confidence in their judgements about future energy technologies. *Risk Analysis,* advance online publication (2016).

[64] Kahneman D., Slovic, P. & Tversky, A. *Judgment under Uncertainty: Heuristics and Biases*. (Cambridge University Press, 1982).

Acknowledgements

This study was conducted under the auspices of the IEA Wind Implementing Agreement for Cooperation in the Research, Development, and Deployment of Wind Energy Systems (IEA Wind). It would not have been possible without the funding of the U.S. Department of Energy (DOE) under Contract Nos. DE-AC02-05CH11231 (LBNL) and DE-AC36-09GO28308 (NREL), and the support of the NSF-sponsored IGERT: Offshore Wind Energy Engineering, Environmental Science, and Policy (Grant Number 1068864). While the number of individuals providing critical contributions to this work are too numerous to list here, we especially thank our IEA Wind collaborators: Volker Berkhout, Aidan Duffy, Brendan Cleary, Roberto Lacal-Arántegui, Leif Husabø, Jørgen Lemming, Silke Lüers, Arjan Mast, Walt Musial, Bob Prinsen, Klaus Skytte, Gavin Smart, Brian Smith, Iver Bakken Sperstad, Paul Veers, Aisma

Vitina, David Weir.

Author contributions

All authors contributed to the formulation of the research, construction of the survey, and to editing and discussing the paper. R.W. led the overall effort, and wrote the paper. K.J. and J.S. helped lead the implementation and execution of the online survey, as well as the subsequent analysis of the results. E.B. provided insight on expert elicitation design, while M.H., E.L., and A.S. contributed wind expertise.

Additional information

Supplementary information is available online. Correspondence and requests for materials should be addressed to R.W.

Competing interests

The authors declare no competing financial interests.