# Forecasting Wind Energy Costs and Cost Drivers – The Views of the World's Leading Experts

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## Summary

The largest expert survey in terms of expert participation ever conducted on future cost of wind energy worldwide was led by Dr. Ryan Wiser from Lawrence Berkeley Lab in cooperation with IEAwind Task 26 covering the levelized cost of energy (LCOE) for onshore, offshore fixed-bottom and floating technology in the years 2020, 2030 and 2050. The survey reached out to 482 participants from the wind industry with 163 experts responding. The results of the survey are intended to inform policymakers, researchers and industrial professionals on the LCOE outlook and to improve the treatment of wind in energy-sector planning models.

LCOE reduction in the range of 24% to 30% are being expected by the respondents for every sector by the year 2030 and in the long term to 2050 cost cuts of 35% to 41% are being projected compared to 2014 baseline values. Onshore wind will remain cheaper than both offshore technologies with fixed-bottom and floating narrowing in after significant progress in floating from 2020 to 2030.

Rotor dimensions are expected to further increase. For 2030 diameters of 130 m onshore and 190 m offshore result as median values. For offshore wind turbines capacity will rise as high as 11 MW whereas capacity onshore will slightly increase to 3.75 MW subsequently leading to much lower specific power turbines with increased capacity factors. Advancements in rotor design are thus the most influential impact factor for onshore LCOE while upscaling and reduced financing cost are the main driver for fixed-bottom cost reductions.

## Introduction

This paper summarizes the results of an expert elicitation survey of 163 of the world's foremost wind energy experts, aimed at better understanding future wind energy costs and technology advancement possibilities. We specifically sought to gain insight on the possible magnitude of future cost reductions, the sources of those reductions, and the enabling conditions needed to realize continued innovation and lower costs. In implementing what may be the largest single elicitation ever performed on an energy technology in terms of expert participation, we sought to complement other tools for evaluating cost-reduction potential, including learning curves, engineering assessments, and other means of synthesizing expert knowledge. Wind applications covered by the survey include onshore, fixed-bottom offshore, and floating offshore wind. Ultimately, the study is intended to inform policy and planning decisions, research and development decisions, and industry investment and strategy development while also improving the representation of wind energy in energy-sector planning models. Some key findings are summarized in Figure 1and discussed below.

Note: All dates are based on the year in which a new wind project is commissioned. LCOE and LCOE drivers are shown relative to 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 seek a 2014 baseline estimate for floating offshore wind; floating offshore wind changes are therefore compared to expert-specific 2014 baselines for fixed-bottom offshore wind.

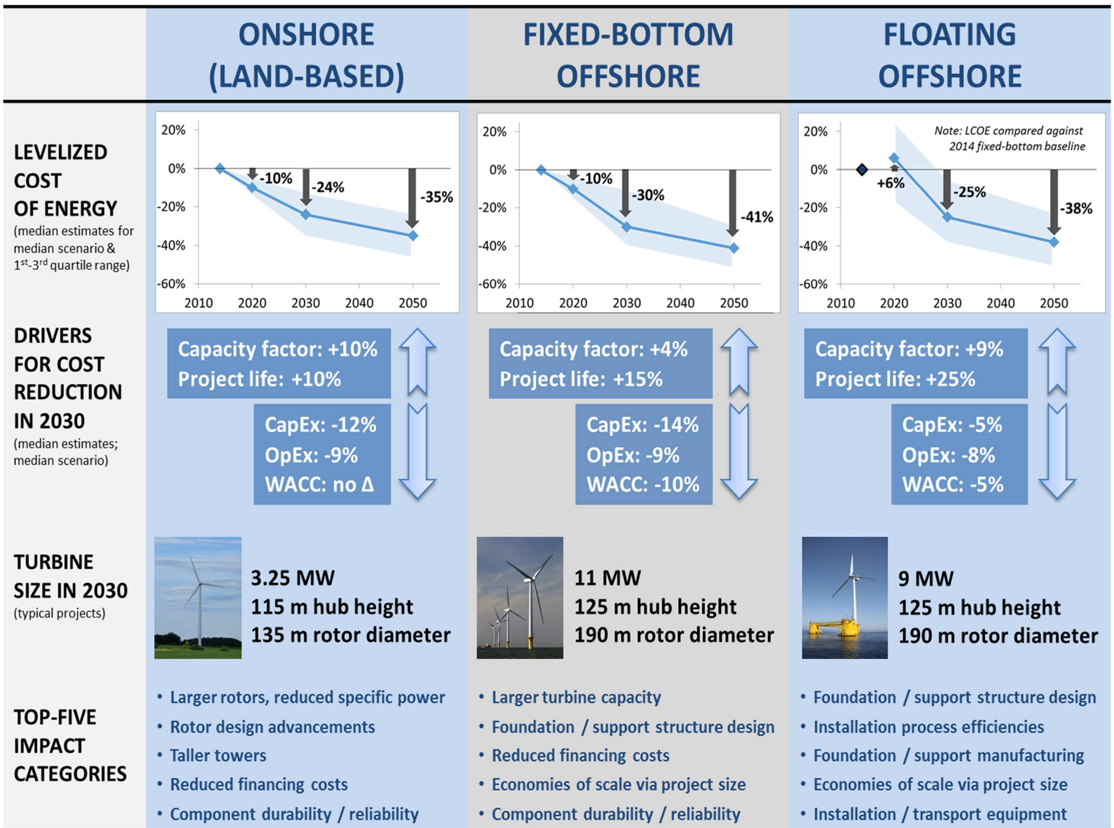


**Figure 1: Summary of Expert Survey Findings**

***Significant Cost Reductions Are Anticipated:*** The modern wind industry has matured substantially since its beginnings in the 1970s. Expert survey results show an expectation of continued reductions in the levelized cost of wind energy (LCOE). Figure 1 summarizes LCOE-reduction expectations for the median (50th percentile, or "best guess") scenario, focusing on the median value of expert responses.

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 baseline are the most broadly applicable approach to presenting survey findings because each region and expert might have different baseline values, depicting the relative 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 anticipated reductions in the LCOE of floating offshore wind between 2020 and 2030.

Note: Emphasis should be placed on the relative positioning of and changes in LCOE, not on absolute magnitudes. Because the 2014 baselines shown in the figure are the median of expert responses, they do not represent any specific region of the world. For any specific region, the 2014 baselines and future absolute LCOE values would vary. Additionally, because roughly 80% of experts chose to use the default 2014 baseline values for onshore and fixed-bottom offshore, the 1st and 3rd quartile as well and the median expert response for 2014 are all equivalent to those default baseline values.

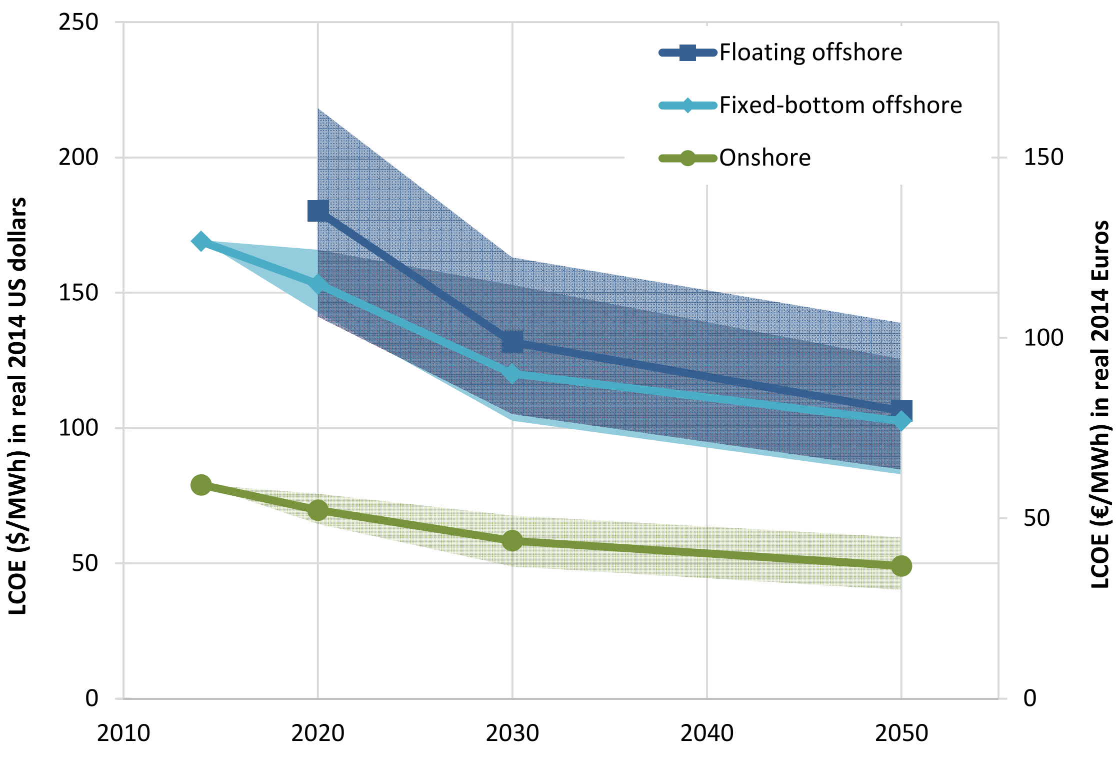


**Figure 2: Expert Estimates of Median-Scenario LCOE for All Three Wind Applications**

***Drivers of Cost Reduction Are Diverse:*** Figure 1 summarizes expert views on how the median scenario LCOE reductions between 2014 and 2030 might be achieved, in terms of upfront capital costs (CapEx), operating costs (OpEx), capacity factors, project design life, and cost of finance (weighted average cost of capital, WACC). Figure 3, meanwhile, highlights the *relative* impact of the changes in each driver in achieving the median scenario LCOE in 2030, while Figure 4 summarizes expected turbine characteristics in 2030 for typical projects in Europe, relative to 2014 baseline values from German market.

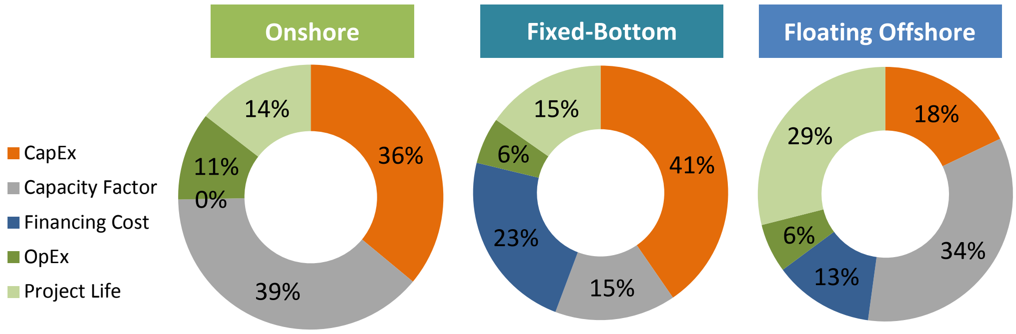


**Figure 3: Relative Impact of Drivers for Median-Scenario LCOE Reduction in 2030**

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, with scaling expected not only in turbine capacity ratings but also rotor diameters and hub heights. Higher hub heights result in higher wind speeds, and therefore capacity factors. Experts also predict greater scaling in rotor swept area than in turbine capacity (leading to a reduction in specific power, defined as turbine capacity divided by rotor swept area), at least globally, also yielding higher capacity factors. For *fixed-bottom offshore wind*, CapEx and financing cost improvements are the largest contributors to LCOE reduction. The relatively higher importance of CapEx and lower importance of capacity factor is consistent with expert opinions on future offshore turbine size: expected turbine capacity ratings (and hub heights) grow significantly in order to minimize CapEx, but specific power is expected to remain roughly at recent levels. 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.

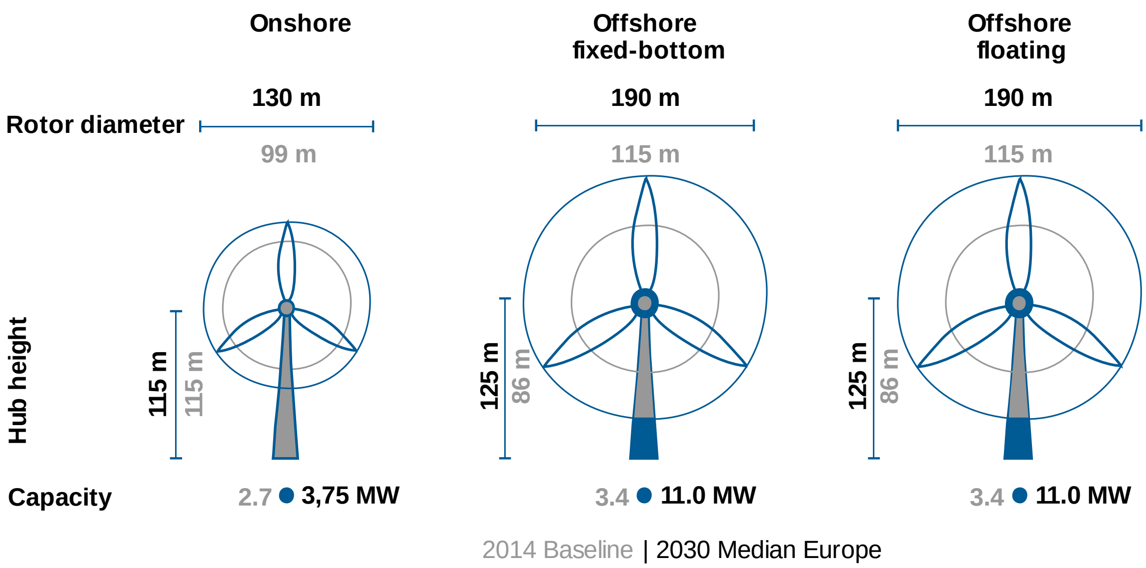


**Figure 4: Wind Turbine Characteristics in 2030 for typical onshore, fixed-bottom offshore and floating projects in Europe compared to 2014 baseline Germany.**

***Opportunity Space for Greater Cost Reductions Is Sizable:*** We sought expert insight not only on the median (50th percentile) LCOE scenario, but also on less-likely scenarios for high and low future LCOEs. The sizable resulting range in expert-specified LCOEs (Figure 5) suggests significant uncertainty in the degree and timing of future advancements. On the other hand, managing this uncertainty is—at least partially—within the control of public and private decision makers; the low scenario, in particular, represents what might be possible through aggressive research, development, and deployment. Under the low 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 full report highlights how survey respondents believe that such LCOE reductions might be achieved. Those results further show that "learning with market growth" and "research and development" are the two most-significant broad enablers for the low LCOE scenario for both onshore and offshore wind.

Note: Floating offshore wind is compared against the 2014 baseline for fixed-bottom offshore.

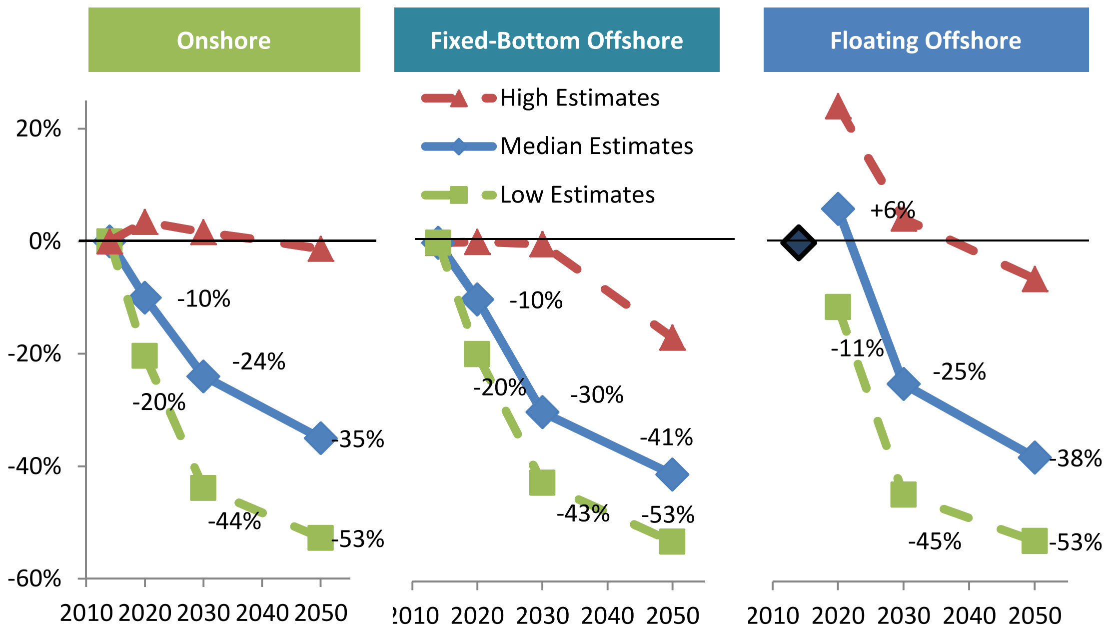


**Figure 5: Estimated Change in LCOE over Time for All Three Wind Applications**

***Many Advancement Opportunities Exist:*** 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, and a general summary of the findings is shown in Figure 6. That the two leading drivers for LCOE reduction for onshore wind are related to rotors—increased rotor diameters and lower specific power, and rotor design advancements—confirms earlier survey results highlighting capacity factor improvements as a major contributor to LCOE reduction. Increased hub heights, coming in at number three on the ranked list, are also consistent with this theme. The relative ranking differs for offshore wind. For fixed-bottom offshore, 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.

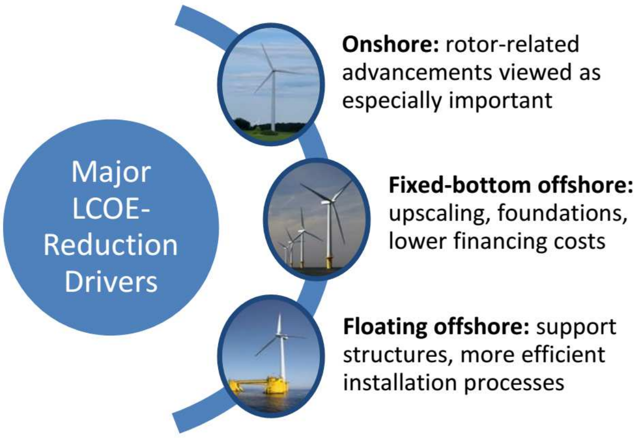


**Figure 6: Top Advancement Opportunities**

***Cost Reductions Are Uncertain, Differ by Respondent Demographics:*** 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 5. Differences are also found when reviewing the range in expert specific responses, as shown in the 25th to 75th percentile expert ranges depicted in Figure 1 and Figure 2. Some of the variation in expert-specific responses can be explained by segmenting respondents into various categories. For example, we find that a smaller "leading-expert" group generally expects more aggressive wind energy cost reductions than the larger set of other survey respondents, whereas equipment manufacturers are more cautious about nearer-term advancement possibilities.

***What's special about Europe? Regional differences:*** Though the responses are cohesive across all regions that participants declared their familiarity with, there are a few differences between US and European results in detail. Respondents with familiarity with the US market have shown slightly stronger focus on capacity factor increases for cost reduction whereas experts from European background have put more emphasis on the extension of project life and increased durability and reliability as means for LCOE reductions onshore. Besides, increasing competition and lower risks have higher ratings as impact factor in Europe. For offshore wind US experts expect smaller turbine dimensions in 2030 with 9 MW in contrast to 11 MW for European sites with smaller rotor and hub height. Again, also for offshore, project life receives higher attention from participants with European perspectives.

***Comparing Survey Results with Historical LCOE Estimates and Other Forecasts:*** Notwithstanding the sizable range in LCOE estimates reflected in the expert survey results, those results are found to be broadly consistent with historical LCOE trends—at least for onshore wind. Figure 7 depicts four separate estimates of historical onshore wind LCOE and associated single-factor learning rates (LRs =10.5%–18.6%, meaning that LCOE declines by this amount for each doubling of global cumulative wind capacity). Though learning rates are an imperfect tool for understanding the drivers of past cost reduction or forecasting future costs, the implicit learning rate embedded in the median-scenario LCOE forecast from our experts to 2030 (about 14%–18%, depending on the magnitude of future wind capacity deployment in that median scenario) is squarely within the range of these past, long-term learning trends for onshore LCOE. 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. Given this history, there have been few attempts to fit a learning curve to offshore data. 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. Overall, expert survey findings on offshore LCOE reductions suggest that experts either anticipate lower offshore-only learning (relative to learning for onshore wind) or expect learning spillovers from onshore to offshore.

Note: For the expert survey results, emphasis should be placed on the relative positioning of and changes in LCOE, not on absolute magnitudes. Because the 2014 baselines shown in the figure are the median of expert responses, they do not represent any specific region of the world. For any specific region, the 2014 baselines and future absolute LCOE values would vary. For similar reasons, it is not appropriate to compare expert-survey results in terms of absolute LCOE magnitudes with the historical LCOE estimates shown on the chart for specific regions. Finally, learning rates are calculated based on a log-log relationship between LCOE and cumulative wind installations; as such, while historical learning rates closely match expected future learning predicted by the expert elicitation, visual inspection of the figure does not immediately convey that result.

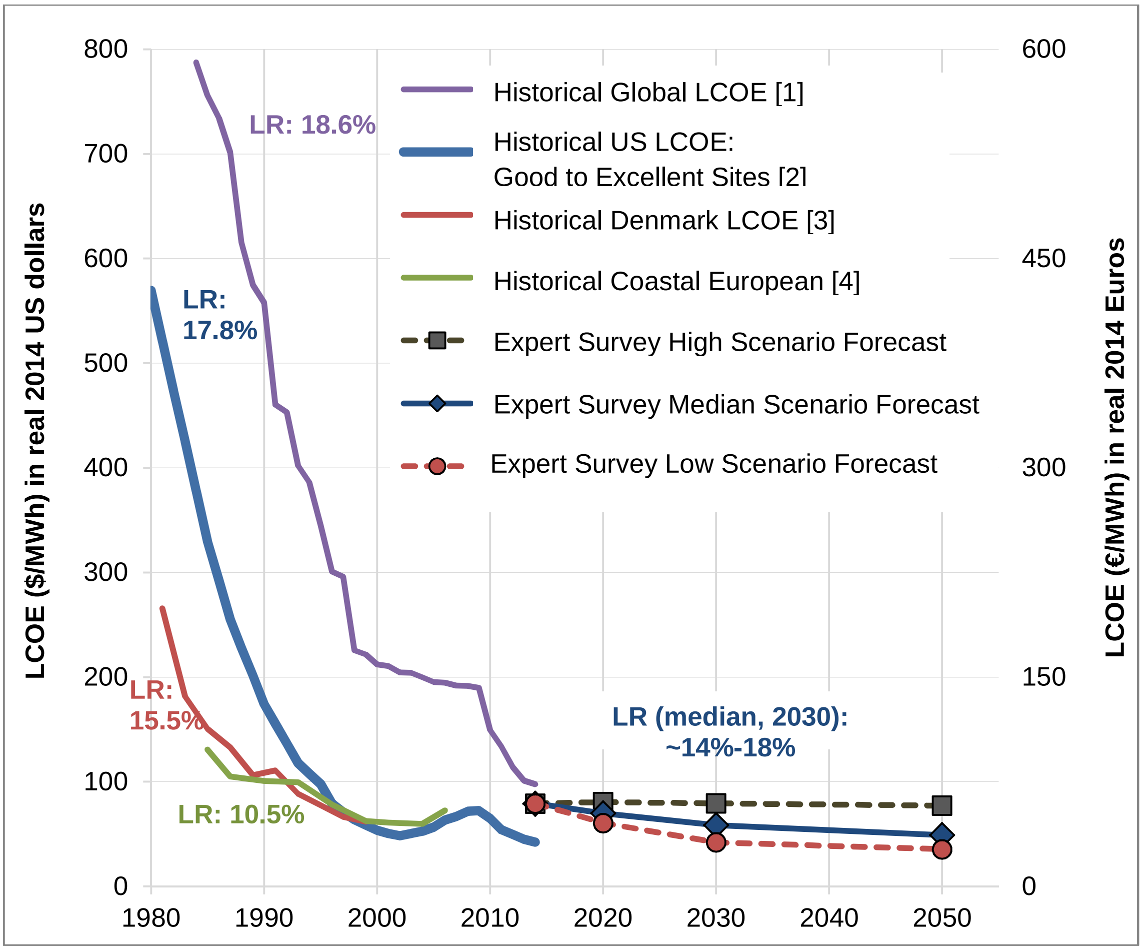


**Figure 7: Historical and Forecasted Onshore Wind LCOE and Learning Rates**

Expert elicitation results can also be compared to other forecasts of LCOE—whether derived from learning curves, engineering assessments, expert knowledge, or some combination of the three (Figure 8). As shown, expert survey results are broadly within the range of other forecasts, but the elicitation tends to show greater expectations for LCOE reductions for onshore wind in the median scenario than the majority of other forecasts. Survey results for offshore wind, on the other hand, tend to be more conservative than the broader literature, with a large number of the other forecasts showing steeper cost reductions than even the low-scenario expert survey results.

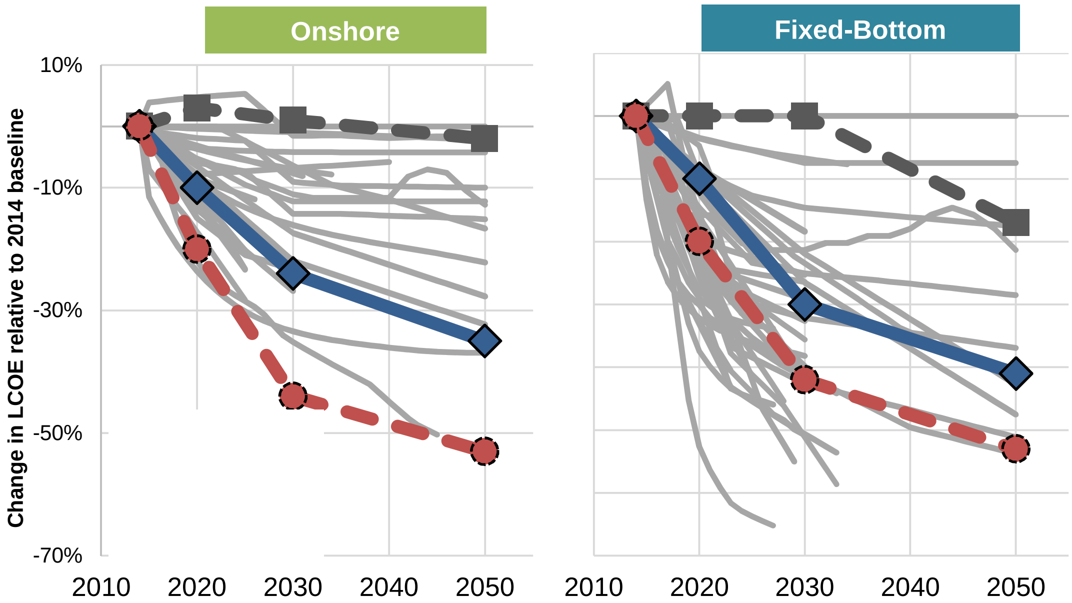


**Figure 8: Estimated Change in LCOE: Expert Survey Results vs. Other Forecasts**

***Learning Estimates: Getting it Right:*** As shown earlier in Figure 7, 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. However, the majority of the literature assessing historical learning rates for wind has emphasized only upfront capital costs, and some energy-sector and integrated-assessment models rely on those capital-cost-based learning estimates when forecasting future costs. Expert elicitation findings demonstrate that capital-cost improvements are only one means of achieving LCOE reductions, however, 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 onshore cost reduction estimates from wind experts are more aggressive than many past forecasts.

## Literature

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