Expert Elicitation for Wave Energy LCOE Futures

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1 National Renewable Energy Laboratory
2 U.S. Department of Energy Water Power Technologies Office

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Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-5700-82375
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Suggested Citation
Baca, Elena, Ritu Treisa Philip, David Greene, and Hoyt Battey. 2022. *Expert Elicitation for Wave Energy LCOE Futures*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5700-82375. https://www.nrel.gov/docs/fy22osti/82375.pdf.

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Golden, CO 80401
303-275-3000 • www.nrel.gov

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Acknowledgments

The National Renewable Energy Laboratory appreciates the significant investment of time and thought offered by the Marine Energy Levelized Cost of Energy (LCOE) Expert Elicitation participants. The United States Marine Energy Council also provided critical in-kind support of this effort through communication with its membership.

List of Acronyms

CapEx	capital expenditures
CF	capacity factor
DOE	U.S. Department of Energy
GW	gigawatt
kW	kilowatt
kWh	kilowatt-hour
LCOE	levelized cost of energy
MW	megawatt
OpEx	operational expenditures
R&D	research and development
TRL	technology readiness level
WPTO	Water Power Technologies Office
yr	year

Executive Summary

As the world faces increasing threats from climate change, the importance of developing renewable energy technologies and reducing their costs has similarly increased. Marine energy technologies (which include wave, tidal, ocean current, ocean thermal, and salinity gradient resources) are a nascent suite of renewable technologies. There are vast marine energy resources available around the world and within U.S. territorial waters, and as the technologies have continued to develop, the long-term trajectory of cost reductions and performance improvements is of particular interest. This study specifically investigates the long-term cost reduction potential for commercial wave energy technologies, as wave energy represents the largest marine energy resource available to the continental United States. Similar studies focused on other resources and technologies may follow in the future.

Through its Water Power Technologies Office, the U.S. Department of Energy (DOE) supports research and development to advance wave energy technologies and other marine energy systems. DOE was interested in collecting information to better understand present-day status and long-term potential for cost reductions and performance improvements within the wave energy industry. As a result, an expert elicitation study was conducted by the National Renewable Energy Laboratory, the results of which have been summarized in this report. Technical experts from the United States and other countries were asked for their input on the industry's current and future trends regarding the levelized cost of energy (LCOE) and on important factors that would drive performance improvements and cost reductions.

The expert elicitation process consisted of in-person workshops, webinars, and quantitative data collection. The methodology was modeled on a previous elicitation study on the progress and cost-reduction drivers of offshore and land-based wind energy technologies (Wiser et al. 2016). An initial workshop was held in October 2019, followed by a webinar in April 2020 to introduce the elicitation process to a targeted list of experts. Each of the participants was later asked to provide data reflecting their best assessment of a baseline LCOE for the year 2020,[1] ranges regarding the year when LCOE could reach 30 cents per kilowatt-hour (kWh) under both conservative and optimistic scenarios, and further LCOE estimates for the year 2050 (again, following conservative and optimistic scenarios).

Based on their responses, estimates for 2020 LCOE ranged between \$0.35/kWh and \$0.85/kWh with a mean value of \$0.57/kWh (±\$0.18/kWh).[2] On average, the respondents believed that LCOE could reach \$0.30/kWh by 2033 (±8 years) under conservative assumptions and 2029 (±6 years) under an optimistic scenario. Results for LCOE in the year 2050 under the conservative and optimistic scenarios were \$0.13/kWh ± \$0.06/kWh and \$0.07/kWh ± \$0.03/kWh, respectively. The analysis of the elicitation results demonstrates that among the surveyed experts there is weak agreement on existing LCOE values but strong agreement on the possibility for future LCOE cost reductions and performance improvements.

[1] Given the lack of deployed commercial wave energy projects to base real-world costs on, participants were instructed to consider costs assuming presently available technology was deployed at scale. Further details on the assumptions given to elicitation participants can be found below.

[2] In this report, the standard deviation is represented as a ± range.

Most of the participants ranked structural assembly costs as the highest contributor to LCOE for the 2020 baseline case. Operations; power take-off; mooring, foundation and substructure; and maintenance costs were other major cost drivers identified by participants. The respondents also thought that capacity factor could gradually increase from 2020 to 2050, and that wave devices like oscillating surge wave energy converters and hybrid systems along with oscillating water columns could gain popularity in future years.

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1 Introduction

Wave energy conversion is a type of marine renewable energy that converts the kinetic and potential energy of ocean waves to useful mechanical energy. The theoretical potential of wave energy to provide electricity is significant on both the national and global scale (Kilcher, Fogarty, and Lawson 2021). Despite the large potential, progress in developing the industry has thus far been limited to a number of pilot projects and in-water tests around the world, and the industry as a whole has not yet demonstrated sustained operations or commercial competitiveness. Though the global marine energy industry has expanded significantly in the past decade, wave energy technologies for commercial energy production are still in relatively early stages of development,[3] with little convergence on device designs and few deployments.

The U.S. Department of Energy (DOE) Water Power Technologies Office (WPTO) strategically supports research and other initiatives to advance the state of wave energy technologies (along with other marine energy technologies). Wave energy is a reliable and carbon-free energy source that could contribute to national clean energy and climate goals.

This report summarizes the findings of an expert elicitation conducted by the National Renewable Energy Laboratory, funded by WPTO. The purpose of the elicitation was to collect and analyze expert technical views about the current state and future possible trajectories of wave energy technological advancement. Experts were asked to provide opinions about current and future levelized cost of energy (LCOE) for commercial-scale wave energy systems, and to share their thoughts on which factors may drive LCOE reductions. LCOE is an industry standard for comparing the performance of energy converters both within and across sectors (Mai, Mowers, and Eurek 2021).

The research goals of this study are both quantitative and qualitative. Quantitatively, DOE hopes to utilize data obtained in this study to inform research and development (R&D) performance goals required under the Government Performance and Results Act. Qualitatively, the opinions expressed on which factors may have the largest contributions to LCOE reduction—and why or how—could also inform WPTO's strategic planning as it seeks to continually make impactful investments.

[3] In addition to commercial-scale energy production, technology developers are also designing smaller wave energy systems that can serve other purposes, like powering ocean-observing equipment or desalinating water; these systems are likely much closer to commercial readiness. For more discussion on these opportunities, see the DOE website on Powering the Blue Economy™.

2 Background

The United States and other countries around the world are currently investing significant resources to increase the speed of innovation for a wide variety of clean energy technologies. These technologies aim to reduce the impacts of climate change, lower local air pollution, and enhance energy access and security. Wave energy is a clean energy technology still in the early stages of development; it has yet to demonstrate consistent and cost-competitive performance.

Technology innovation studies have developed a number of tools for estimating future costs and identifying areas for performance improvement. The tools cover a range of precision and technology readiness levels (TRLs). Among other types of analyses, expert elicitation studies are an important way to improve the collective understanding of future possible trends in technology cost and performance, especially for technologies that have limited commercial deployment data available. Similar elicitation studies have been conducted by Wiser et al. (2016; 2021) for wind technologies, from which the fundamental elicitation study framework has been adopted.

Expert elicitations are a structured method for gathering information from developers, engineers, and other researchers who are well-informed about the technologies and factors at hand (Verdolini et al. 2018). These studies can be conducted in person, online, by mail, or through a combination of those modes, and may or may not involve interactions directly between the experts. Some of the challenges associated with the application of expert elicitation studies include (1) minimizing participants' biases, which could influence their responses, (2) identifying and engaging a highly qualified and diverse pool of experts (to minimize the possibility of experts who rely on common information sources), and (3) identifying inaccuracies due to the underestimation of or overconfidence in technological advancement rates assumed by the experts (Wiser et al. 2021; Verdolini et al. 2018). Those challenges aside, an elicitation approach has the potential to provide insights that supplement other approaches for assessing possible pathways for technological advancements and performance improvements, and they aid policy and planning, R&D, and industry strategy.

There are several additional ways to assess possible future costs and performance improvements for emerging energy technologies. The application of learning curves is one such method; it uses historical data to extrapolate future trends based on the observed learning rates for similar technologies and industries as deployments accumulate. The issue with this approach is that it assumes that future trends would resemble those of the past. Also, it does not explicitly capture the effect of intermediate processes like R&D or economies of scale on technology cost reductions (Meng et al. 2021). Bottom-up engineering assessments are another approach used for investigating technology costs. This method, however, requires very detailed design and cost modeling and makes numerous uncertain assumptions. Meng et al. (2021) conducted a study in which they compared technology cost forecasts obtained by the elicitation method against model-based methods (based on Wright's law and Moore's law), concluding that in most cases all those methods tend to underestimate possible technological advancements, while elicitation studies have narrower uncertainty ranges in comparison. Expert group elicitation studies are more evidence-driven and yield relatively greater consistency of estimates.

LCOE is one of the most prevalent ways to represent the cost and performance characteristics of energy generation technologies and is especially useful in tracking long-term trends (where, for instance, costs of components or materials may increase, but performance increases by a much greater amount, thereby decreasing LCOE). There are also many other useful metrics for assessing the performance of marine energy technologies, but LCOE is the preferred measure for similar energy technology elicitations on long-term trends. LCOE represents the average revenue per unit of electricity generated that would be required to recover the costs of building and operating a generating plant during an assumed financial life and duty cycle. It is a common performance metric that normalizes the cost of a marine energy project, whether a single device or multiple devices in an array, with the amount of electricity it can generate annually over the project lifetime.

As previously mentioned, a 2021 wind technology elicitation study was used as a reference to develop the basic framework of the elicitation study conducted for wave technologies. The 2021Wiser et al. study asked respondents to estimate the LCOE of a typical wind project in a baseline year (2019) followed by years 2025, 2035, and 2050 for three wind technology types: land-based, fixed-bottom offshore, and floating offshore (Wiser et al. 2021). The survey asked the respondents to provide five core LCOE inputs: (1) capital expenditures (CapEx, in U.S. dollars per kilowatt [$/kW]), (2) operational expenditures (OpEx, in U.S. dollars per kilowatt per year [$/kW/yr]), (3) energy output (capacity factor, %), (4) project life (yr), and (5) financing costs (after-tax, nominal weighted-average cost of capital, %), for specific years. It was observed that wind technologies have a larger pool of expert respondents—the majority of whom were from North America and Europe—that have deeper experience with actual deployments. By contrast, because wave energy technologies are in earlier stages of development than wind technologies, an expert elicitation for wave energy is expected to be more limited with respect to participant experience. The quantitative accuracy of these elicitation efforts can vary over the years due to unforeseen variability of associated parameters. For example, wind energy technologies saw substantial cost reductions due to a variety of technological advancements over the course of 5 years. As a result, the 2021 Wiser et al. elicitation study was conducted to update the qualitative and quantitative results obtained from the 2015 study (Wiser et al. 2016; 2021). Owing to the limited experience of marine energy technologies with commercial deployment, we expected a balance of qualitative and quantitative insights from this elicitation study.

3 Methodology

Preparation for the elicitation involved a review of literature and interviews with practitioners of recent expert elicitations from the offshore wind energy sector, as discussed in Section 2. The expert elicitation used a multistage approach consisting of in-person workshops, webinars, and guided-response forms.

An initial workshop was held in October 2019 with a small group of industry representatives who were attending a related industry meeting. The workshop explained the goals of the elicitation and used small groups to foster discussion on marine energy LCOE futures and factors driving those futures. The small groups reported out a summary of their discussions, and attendees were then asked to provide some preliminary LCOE estimates and information on contributing factors. This initial round of data collection and comments on the methods of collection informed the next steps in the elicitation.

Plans for a second dedicated in-person workshop in Spring 2020 were delayed by the COVID-19 pandemic. The elicitation thus pivoted to a remote format using a guided-response form that could be sent to a targeted list of experts. The spreadsheet response form comprised both default values and blank cells for experts to input their assessment of LCOE and near- and long-term contributing factors.

A first webinar was held in April 2020 to introduce the elicitation process to a targeted list of experts. Based on feedback about the length and format of the elicitation from this and subsequent webinars (held in July 2020, August 2020, and January 2021), a revised response form and corresponding explanatory user guide video were designed.

The response form asked users to estimate a baseline LCOE for the year 2020, to estimate the year when LCOE could reach $0.30 per kilowatt-hour (kWh) for both conservative and optimistic scenarios, and to estimate LCOE for the year 2050 for both conservative and optimistic scenarios. For the 2020 baseline scenario, users were directed to assume that the highest performing technology that was presently available would be produced and deployed in an array, and that it would perform consistently with present-day assumptions about reliability (given that there are not active commercial wave energy projects from which to capture baseline cost and performance assumptions). In all cases, the users provided estimates for LCOE percent contribution for CapEx, OpEx, and the associated cost categories[4] of CapEx and OpEx. In addition to LCOE, the users estimated capacity factor (CF) and total cumulative installed capacity for all cases.

For the baseline 2020 and conservative scenarios, users were instructed to assume the following conditions:

- LCOE is based on a 100-megawatt (MW) array.
- Annual energy production is based on the CF input from the user and 8,760 hours per year.

[4] The CapEx and OpEx cost breakdown follows the MHK Cost Breakdown Structure available here: https://mhkdr.openei.org/submissions/361.

- LCOE is calculated using the fixed-charge-rate method assuming a fixed charge rate of 10.8% that is based on a real discount rate of 7% and a 20-year project life.

For the optimistic scenarios, users were to assume the following conditions:

- LCOE is based on a 100-MW array.
- Annual energy production is based on the CF input from the user and 8,760 hours per year.
- LCOE is calculated using the fixed-charge-rate method assuming a fixed charge rate of 8.95% that is based on a real discount rate of 6% and a 25-year project life.

In addition to the assumptions, users answered a series of questions that provided supplemental context to responses. The questions sought a mixture of quantitative and qualitative responses. The following is a list of the additional questions requested in the feedback form:

1. Define your assumptions for the LCOE scenario outlined above. These inputs do not impact the reverse LCOE calculations and are solely for informational purposes.
2. What is the device or technology type that you envision for the hypothetical 100-MW array?
3. What is your assumed rated power, in megawatts, of a single device in the hypothetical 100-MW array?
4. What is your assumed water depth, in meters, for the hypothetical 100-MW array?
5. What is your assumed distance to shore, in kilometers, for the hypothetical 100-MW array?
6. What is the total cumulative installed capacity for the wave energy industry when this hypothetical array is installed?
7. How many open-water demonstrations or prototypes have been deployed prior to this hypothetical array?

4 Analysis

4.1 Feedback Form Results

4.1.1 Levelized Cost of Energy

The elicitation effort received eight completed feedback forms. While more experts were initially engaged, there were a number who indicated they did not have the time to continue participating given challenging circumstances during 2021. The 2020 LCOE estimates have a minimum, maximum, and mean of \$0.35/kWh, \$0.85/kWh, and \$0.57/kWh ± \$0.18/kWh, respectively. On average, the respondents believed that LCOE could reach \$0.30/kWh by 2033 ± 8 years for the conservative case and 2029 ± 6 years for the optimistic case. The average estimates for LCOE in the year 2050 under conservative and optimistic scenarios are \$0.13/kWh ± \$0.06/kWh and \$0.07/kWh ± \$0.03/kWh, respectively. LCOE results by respondent are shown in Table 1.

Table 1. LCOE Estimates by Respondent and Scenario

	LCOE 2020 (\$/kWh)	Year LCOE Reaches \$0.30/kWh Conservative	Year LCOE Reaches \$0.30/kWh Optimistic	LCOE 2050 Conservative (\$/kWh)	LCOE 2050 Optimistic (\$/kWh)
Respondent 1	0.75	2045	2040	0.25	0.15
Respondent 2	0.47	2027	2023	0.06	0.06
Respondent 3	0.85	2042	2032	0.11	0.06
Respondent 4	0.55	2035	2028	0.14	0.08
Respondent 5	0.35	2021	2021	0.07	0.04
Respondent 6	0.60	2035	2030	0.19	0.05
Respondent 7	0.60	2030	2030	0.10	0.06
Respondent 8	0.35	2030	2024	0.12	0.05
Min	0.35	2021	2021	0.06	0.04
Max	0.85	2045	2040	0.25	0.15
Mean	0.57 ± 0.18	2033 ± 8	2029 ± 6	0.13 ± 0.06	0.07 ± 0.03

Trendlines representing LCOE over time for each respondent for the conservative and optimistic cases and a best-fit line of all responses in each scenario are shown in Figure 1 and Figure 2, respectively.

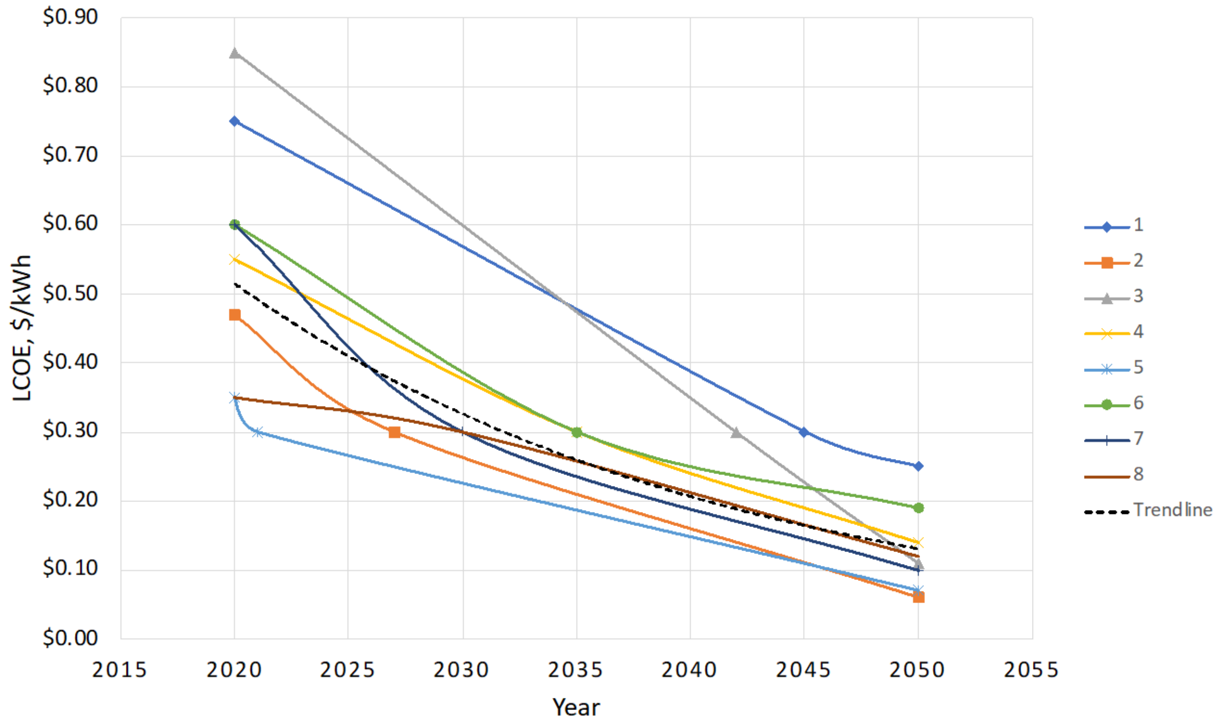

Figure 1. Conservative LCOE estimates over time by respondent

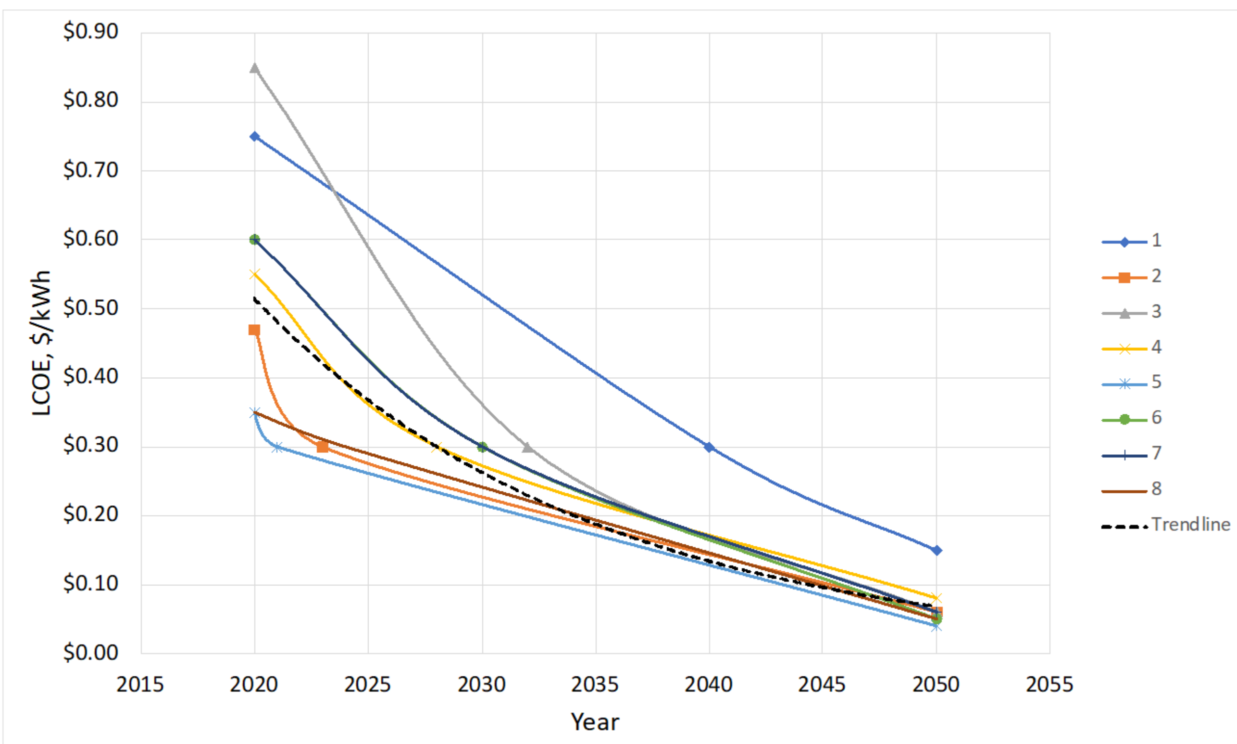

Figure 2. Optimistic LCOE estimates over time by respondent

The average 2050 LCOE estimate decreased for both the conservative and optimistic scenarios in comparison to the 2020 baseline case, as shown in Figure 3 and Figure 4, where the mean is represented by an x and the whisker shows extreme data points. The 2050 optimistic scenario has the tightest distribution of LCOE estimates with the lowest standard deviation.

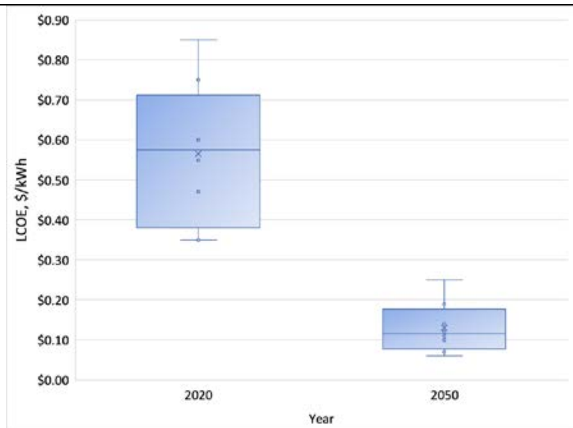

Figure 3. 2020 LCOE versus 2050 LCOE conservative scenario

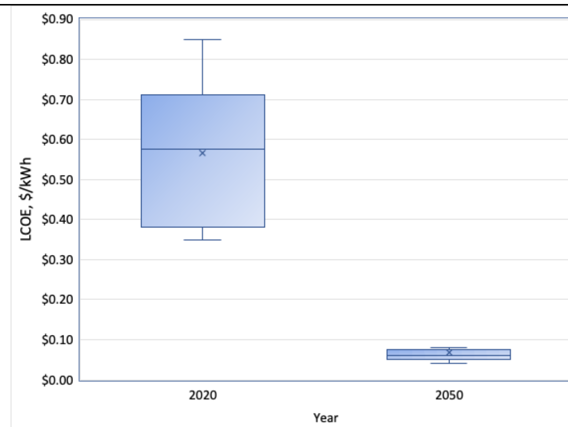

Figure 4. 2020 LCOE versus 2050 LCOE optimistic scenario

In addition to LCOE, respondents provided estimates for the percent contribution of LCOE for cost categories associated with CapEx and OpEx. For the 2020 baseline case, responses indicated the following categories to be the greatest cost contributors to LCOE:

- Structural assembly
- Operations
- Power take-off system
- Mooring, foundation, and substructure
- Maintenance
- Electrical infrastructure.

Most participants ranked structural assembly costs as the highest contributor to LCOE for the 2020 baseline case. The top six cost categories with the greatest contribution to LCOE for the 2020 baseline, 2050 conservative, and 2050 optimistic case are shown in Figure 5. Based on the responses for each scenario, the average percent contribution of LCOE for each cost category changes very little over time. Some respondents thought the contribution to LCOE from device-related costs would decrease over time and the contribution to LCOE from balance of systems and OpEx costs would increase over time, whereas others believed the opposite. Alternatively, some respondents estimated a constant LCOE contribution for all cost categories over time.

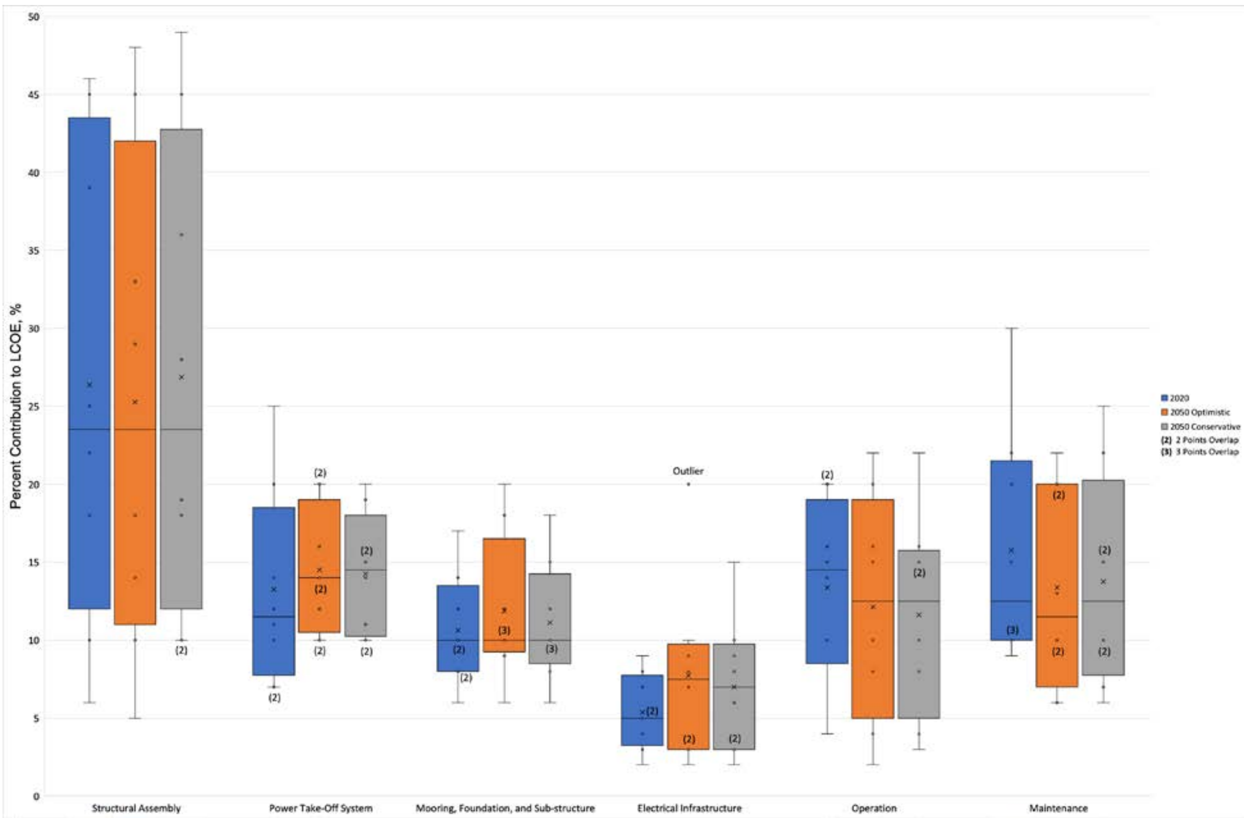

Figure 5. Percent contribution to LCOE by cost category for the 2020 and 2050 conservative and optimistic scenarios

4.1.2 Capacity Factor

The respondents also estimated capacity factor for all five scenarios. The CF estimates differed from LCOE, as there was a broader range for estimated possible future CF values than present values. Table 2 shows CF estimates for each respondent and scenario. Figure 6 and Figure 7 show the potential variation of CF over time for each respondent.

Table 2: Capacity Factor (CF) Estimates by Respondent and Scenario

	CF 2020	CF for Year LCOE Reaches $0.30/kWh Conservative	CF for Year LCOE Reaches $0.30/kWh Optimistic	CF 2050 Conservative	CF 2050 Optimistic
Respondent 1	20%	30%	35%	35%	40%
Respondent 2	30%	30%	30%	30%	70%
Respondent 3	21%	24%	26%	26%	28%
Respondent 4	35%	40%	42%	45%	50%
Respondent 5	35%	35%	40%	45%	60%
Respondent 6	30%	30%	30%	42%	50%
Respondent 7	20%	25%	30%	35%	45%
Respondent 8	30%	30%	35%	33%	40%
Min	20%	24%	26%	26%	28%
Max	35%	40%	60%	45%	70%
Mean	28% ± 6%	32% ± 5%	34% ± 6%	36% ± 7%	48% ± 13%

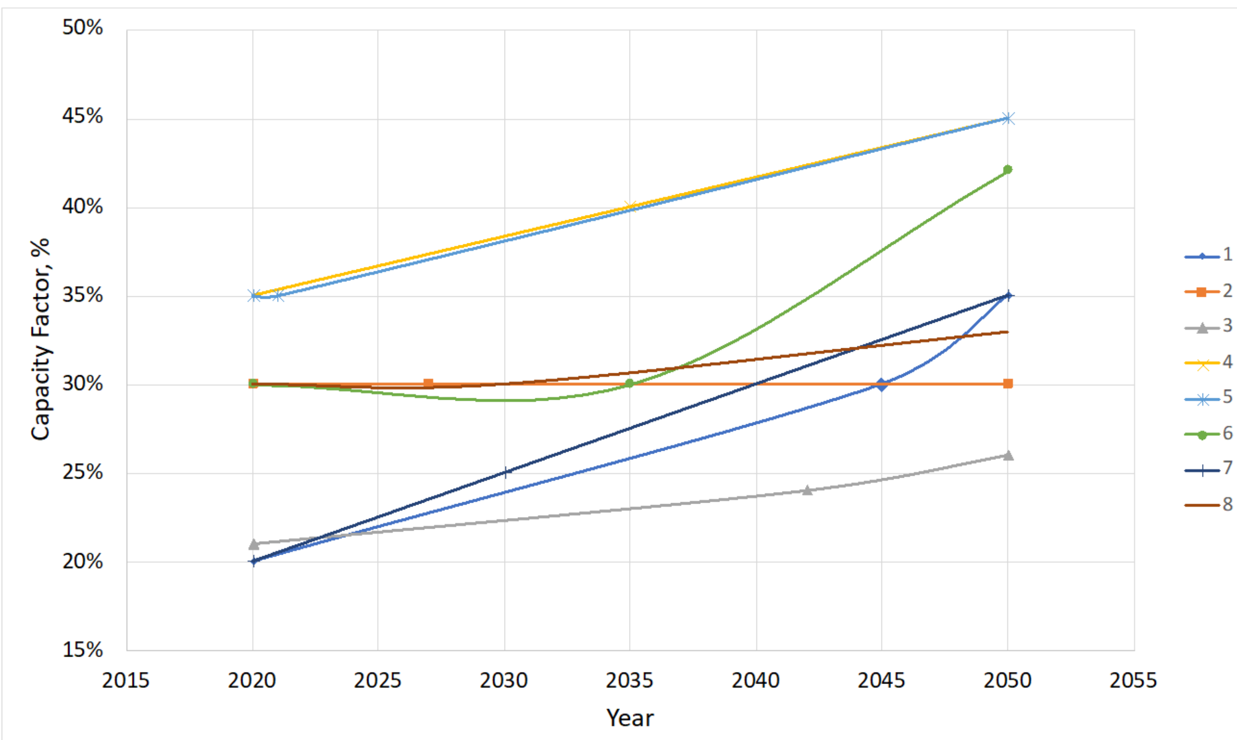

Figure 6. Capacity factor over time by respondent for the conservative scenario

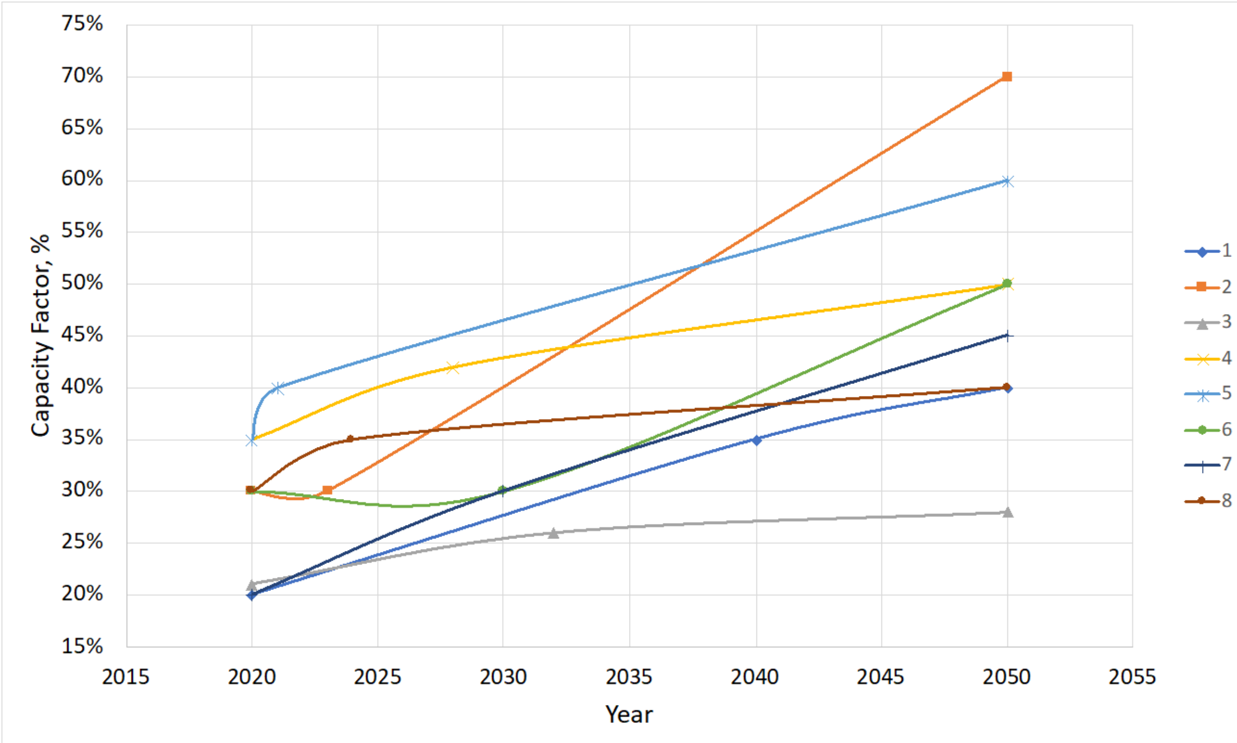

Figure 7. Capacity over time by respondent for the optimistic scenario

4.1.3 Cumulative Global Installed Capacity

For each scenario, respondents also provided an approximation for the total cumulative global installed capacity across different time periods and scenarios. This relationship is important to investigate, as deployments and cumulative "learning-through-doing" effects themselves can drive performance improvements and technology cost reductions. Respondents' projections for LCOE paired with assumed worldwide capacity deployment for the conservative and optimistic scenarios are shown in Figure 8 and Figure 9, respectively. For the conservative case, respondents suggested that 196 MW of installed capacity is likely needed prior to reaching LCOE values below $0.30/kWh, whereas for the optimistic case, respondents suggest 131 MW of installed capacity is needed to reach the same target. For both scenarios, estimates for reaching 1 gigawatt (GW) of installed capacity are between the years 2035 and 2040. The elicitation results indicated that in the year 2050 under the conservative and optimistic scenarios, the estimated global installed capacity of 9 GW and 25 GW corresponded to the average estimates for LCOE of $0.13/kWh ± $0.06/kWh and $0.07/kWh ± $0.03/kWh, respectively.

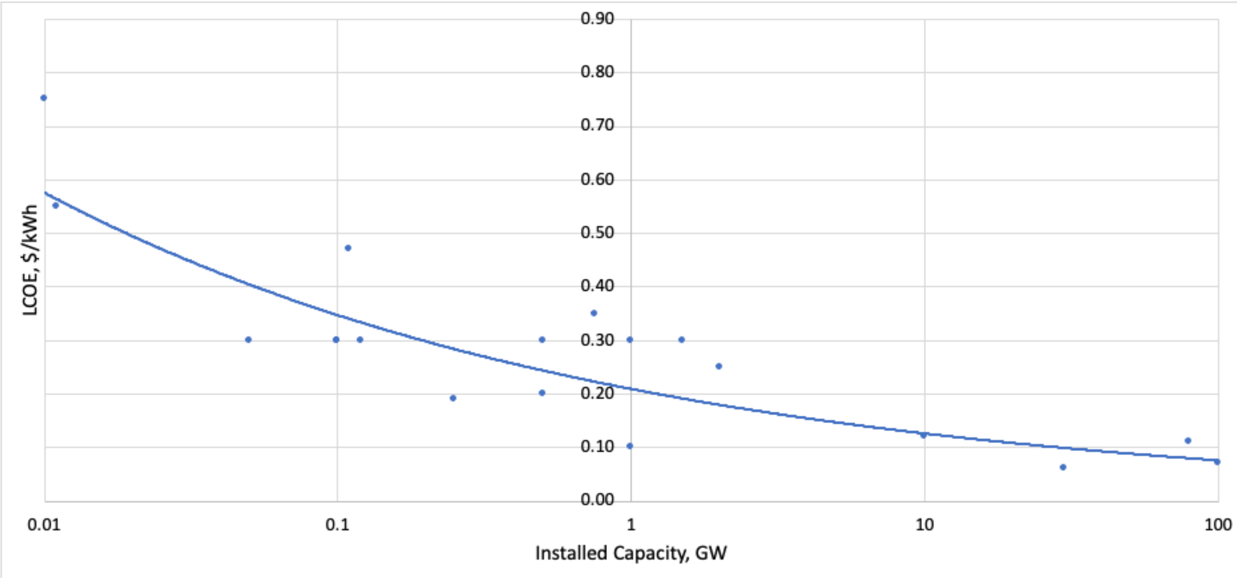

Figure 8. Projection for LCOE and cumulative installed capacity for the conservative case

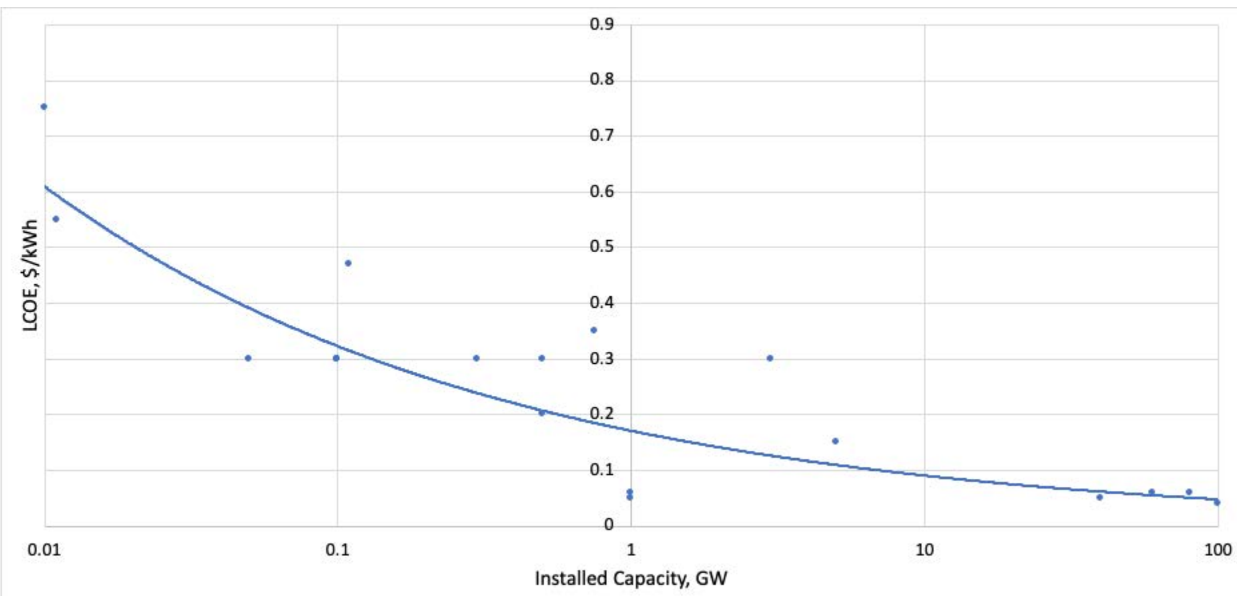

Figure 9. Projection for LCOE and cumulative installed capacity for the optimistic case

4.2 Webinar Discussion Synthesis

The goal of this elicitation study was to acquire a sense of possible future wave energy technology cost and performance trends as well as to get an understanding of what experts believe to be the primary cost contributors. To make wave energy technologies more economically viable, there is an urgent need to study the major cost drivers and the most promising areas for innovation. The responses provided by the participants in this study were also used to analyze data in a qualitative manner. The primary objective behind this analysis was to understand and identify the potential factors that could result in technology cost reductions and performance improvements. The following are some insights that were drawn from a discussion with the participants of the elicitation study:

- Based on responses obtained from the participants, it was noted that an LCOE of $0.30/kWh for wave energy technologies could be achievable within the next 10 years.
- The respondents also felt that if wave farms could be realistically and cost-effectively planned at smaller array sizes (around 50 MW, for instance), an opportune market space would be created, considering that most offshore wind projects are being planned at 100 MW or greater due to economies of scale.
- As respondents were comparing the growth of wind and wave technologies, it was observed that significant financial incentives and tax credits bolstered the growth of land-based wind installed capacity, which accelerated cost reductions associated with economies of scale and learning.
    - This observation highlighted the assumptions underpinning the estimates of LCOE for installed capacity vs. wave energy technology. The two variables are related, and opportunities will need to exist for wave energy technologies to be deployed at increasing rates for certain portions of cost reductions and performance improvements to be realized through economies of scale and deployment-focused learning.
    - Currently, the lack of deployment incentives and uncertainties/risks associated with offshore projects were identified as obstacles that need to be addressed to promote the commercial implementation of wave technologies in the future (and as one of the major differences in assumptions between the conservative and optimistic scenarios).

The inputs provided by the participants on the elicitation survey showed that the following were major contributors to wave LCOE:

- Structural costs
- Power take-off system
- Mooring costs
- Operations
- Maintenance.

There were broadly agreed-upon views that more investment in R&D is needed to develop more efficient installation and operation and maintenance processes. One of the participants suggested developing and reusing decommissioned offshore wind farms or oil platforms for marine renewable applications closer to 2050, as this could result in significant reductions in electrical infrastructural costs.

The reduction of LCOE could be further driven by increased capacity factors or due to increased device rated power. Most participants think that the capacity factor will increase over time. Some participants also assumed that there could be similar CapEx and OpEx trends to those of offshore wind farms. Unlike offshore wind, wave energy technologies may not have extensive infrastructural needs.

Table 3. Summary of Devices Used in Different Scenarios

Device Type	2020 Baseline	Year LCOE Reaches $0.30/kWh Conservative	Year LCOE Reaches $0.30/kWh Optimistic	2050 Conservative	2050 Optimistic
Point Absorber	4	3	2	2	1
Oscillating Water Column	3	3	3	3	3
Submerged Pressure Differential	1	1	1	1	1
Oscillating Surge Wave Energy Converter		1	1	1	1
Hybrid Devices[a]			1	1	2

[a]Hybrid devices consist of devices like point absorber hybrids and novel hybrid body load-shedding devices, which have characteristic properties like variable geometry/novel flexible materials (such as elastomers piezoelectric properties) in the device structure.

The wave energy sector, being in an era of ferment, has not yet converged on a specific archetype, and this was reflected even in the small sample of our respondents. Table 3 illustrates a summary and count of the different device types chosen by the different participants. The respondents specified three different archetypes for the 2020 baseline (point absorber, oscillating water column, and submerged pressure differential). Two additional archetypes emerged for the future categories: oscillating surge wave energy converter and hybrid devices were assumed by three experts for the 2050 optimistic scenario values. The point absorber archetype received reduced support in the future among the experts: four people assumed its use for their 2020 baseline values while only one assumed its use for the 2050 optimistic scenario value.

4.3 Literature Review

To compare published LCOE projections with the elicitation results obtained, a literature review was conducted. The literature review focused on sources that provided present-day estimates and future projections for wave energy LCOE. The assumptions taken for the reported LCOE values in the literature are unclear (International Renewable Energy Agency 2020; European Commission 2016; Magagna, Monfardini, and Uihlein 2016; Ocean Energy Systems 2019; Ocean Energy Systems 2020; Magagna 2019; SI Ocean 2013; Carlsson et al. 2014). Due to the potential differences in assumptions for LCOE inputs such as fixed charge rate and project lifetime, comparing the results of the elicitation with published results is not a fair comparison. However, respondents' LCOE estimates may have been influenced by previously published LCOE trends, and the data are compared to look for general similarities. Figure 10 illustrates a comparison of LCOE data (converted to 2021 U.S. dollars) collected from the literature review with elicitation LCOE estimates obtained from participants for both the conservative and optimistic scenarios.

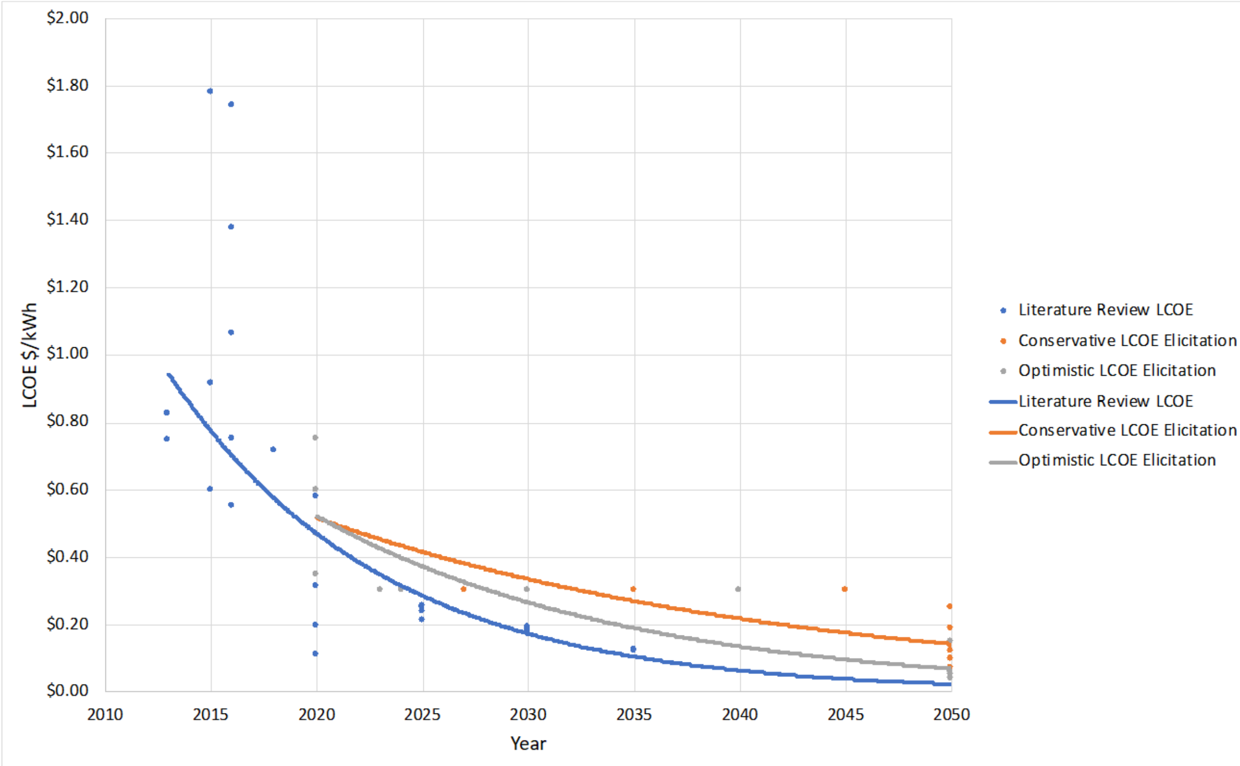

Figure 10. Trendlines and LCOE data for the elicitation conservative and optimistic cases compared to published LCOE estimates

Similar to the elicitation results, LCOE estimates reported in literature show a greater range for the current year (year of publication) than for future years. The best-fit line for the literature review data was extended past the last data point in the data set to 2050. The trendlines show LCOE estimates as reported in published literature are more aggressive than the elicitation results. The optimistic LCOE scenario from the elicitation results aligns most closely with the data from the literature review.

5 Discussion and Synthesis

The elicitation results demonstrate that among the surveyed experts there is a broad range of and weak agreement on existing LCOE values but strong agreement on future potential LCOE reductions. Comparing data from the LCOE elicitation to previously published LCOE estimates shows similar trends. The feedback suggests that respondents generally agreed on the cost categories that are the greatest contributors to LCOE while the overall ranking varied by respondent. The respondents generally expected capacity factor to gradually increase from 2020 to 2050. For the 2020 baseline scenario, four respondents assumed point absorbers, three assumed oscillating water column devices, and one assumed a submerged pressure differential device as the most common devices in use. However, respondents did not appear to expect point absorbers to be the dominant archetype in the future; instead, they predicted a growth in other types of systems like oscillating surge wave energy converters and hybrid systems, along with oscillating water columns. As technologies continue to advance over time, further analyses of the realized innovations compared to these estimates will be useful to gauge where progress has been made and how future possible trends could change.

References

Carlsson, Johan, Roberto Lacal Arantegui, Arnulf Jager-Waldau, Andrei Bocin-Dumitriu, Bergur Sigfusson, Ghassan Zubi, Davide Magagna, et al. 2014. *2013 Technology Map of the European Strategic Energy Technology Plan*. Luxembourg: European Commission Joint Research Centre. http://dx.doi.org/10.2790/99812.

European Commission. 2016. "SET Plan – Declaration of Intent on Strategic Targets in the Context of an Initiative for Global Leadership in Ocean Energy." Accessed Nov. 2, 2021. https://setis.ec.europa.eu/system/files/2021-04/declaration_of_intent_ocean_0.pdf.

International Renewable Energy Agency (IRENA). 2020. *Innovation Outlook: Ocean Energy Technologies*. Abu Dhabi: IRENA. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Innovation_Outlook_Ocean_Energy_2020.pdf.

Kilcher, Levi, Michelle Fogarty, and Michael Lawson. 2021. *Marine Energy in the United States: An Overview of Opportunities*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5700-78773. https://www.nrel.gov/docs/fy21osti/78773.pdf.

Magagna, Davide. 2019. *Ocean Energy Technology Development Report*. Luxembourg: European Commission, Joint Research Centre. JRC118296. https://data.europa.eu/doi/10.2760/158132.

Magagna, Davide, Riccardo Monfardini, and Andreas Uihlein. 2016. *JRC Ocean Energy Status Report – 2016 Edition*. Luxembourg: European Commission, Joint Research Centre. JRC104799. https://data.europa.eu/doi/10.2760/509876.

Mai, Trieu, Matthew Mowers, and Kelly Eurek. 2021. *Competitiveness Metrics for Electricity System Technologies*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-72549. https://www.nrel.gov/docs/fy21osti/72549.pdf.

Meng, Jing, Rupert Way, Elena Verdolini, and Laura Díaz Anadón. 2021. "Comparing Expert Elicitation and Model-Based Probabilistic Technology Cost Forecasts for the Energy Transition." *Proceedings of the National Academy of Sciences* 118(27): e1917165118. https://doi.org/10.1073/pnas.1917165118.

SI Ocean. 2013. *Ocean Energy: Cost of Energy and Cost Reduction Opportunities*. https://oceanenergy-sweden.se/wp-content/uploads/2018/03/130501-si-ocean-cost-of-energy-report.pdf.

Ocean Energy Systems. 2019. *Annual Report: An Overview of Ocean Energy Activities in 2018*. https://tethys.pnnl.gov/sites/default/files/publications/oes2018_0.pdf.

Ocean Energy Systems. 2020. *Annual Report: An Overview of Ocean Energy Activities in 2020*. https://tethys-engineering.pnnl.gov/sites/default/files/publications/oes-annual-report-2020.pdf.

Verdolini, Elena, Laura Díaz Anadón, Erin Baker, Valentina Bosetti, and Lara Aleluia Reis. 2018. "Future Prospects for Energy Technologies: Insights From Expert Elicitations." *Review of Environmental Economics and Policy* 12(1): 133–153. Available at: https://www.journals.uchicago.edu/doi/full/10.1093/reep/rex028.

Wiser, Ryan, Karen Jenni, Joachim Seel, Erin Baker, Maureen Hand, Eric Lantz, and Aaron Smith. 2016. "Expert Elicitation Survey on Future Wind Energy Costs." *Nature Energy* 1: 16135. https://doi.org/10.1038/nenergy.2016.135.

Wiser, Ryan, Joseph Rand, Joachim Seel, Philipp Beiter, Erin Baker, Eric Lantz, and Patrick Gilman. 2021. "Expert Elicitation Survey Predicts 37% to 49% Declines in Wind Energy Costs by 2050." *Nature Energy* 6: 555–565. https://doi.org/10.1038/s41560-021-00810-z.