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Floating offshore wind on the U.S. West Coast: an expert elicitation

Nils Angliviel de La Beaumelle¹ , Kamran Tehranchi¹ , Matteo Simoncini², Ekundayo Shittu³
and Inês M L Azevedo^{1,4,5,6,7,*} ¹ Department of Civil and Environmental Engineering, Stanford University, Stanford, CA, United States of America² Terna, Rome, Italy³ Department of Engineering Management and Systems Engineering, George Washington University, Washington, DC, United States of America⁴ Department of Energy Science & Engineering, Stanford University, Stanford, CA, United States of America⁵ Senior Fellow, Precourt Institute for Energy, Stanford University, Stanford, CA, United States of America⁶ Senior Fellow, Woods Institute for the Environment, Stanford University, Stanford, CA, United States of America⁷ Visiting Professor, Nova School of Business and Economics, Carcavelos, Portugal

* Author to whom any correspondence should be addressed.

E-mail: iazevedo@stanford.edu**Keywords:** floating offshore wind, expert elicitation, costs, probability of failure, transmission configurationsSupplementary material for this article is available [online](#)

Abstract

California has ambitious offshore wind goals of 2–5 GW by 2030 and 25 GW by 2045. The coastline deep ocean floor calls for floating offshore wind (FOSW), a new technology whose application has yet to be built to scale. Given the novelty, deep uncertainty, and lack of data regarding FOSW, we fielded an expert elicitation regarding the costs, probability and duration of failure, and likely potential system architectures. We find that there is significant disagreement among experts: cost estimates vary by a factor of at least 3. Probabilities of failure range from 0.01% to 20% for most parts of the system. Experts diverged on likely transmission configurations that are likely to be used with FOSW projects, though most agreed DC technologies will be used in the future. Overall, experts believe California's 2030 FOSW targets will not be met but could be achieved by 2035, and 2045 targets could be realized with faster buildout of future lease areas.

1. Introduction

Floating offshore wind (FOSW) is an early-stage renewable technology that holds promise for significantly expanding wind energy harvesting capabilities along the world's coastlines [1]. FOSW system's architecture includes a turbine mounted on a floating foundation, secured to the seafloor via anchors and moorings, enabling operation in waters up to 1300 m deep [2]—in contrast with fixed-bottom offshore wind technologies, which are only feasible up to a seafloor bed depth of ~60 m [2].

However, FOSW has yet to be built to scale. Indeed, to date, the world's total installed capacity for FOSW amounts to a modest figure of 211 MW [2]. In the U.S., no floating capacity is operating, though some is under development [3]. On the West Coast, a demonstration project (CADEMO) awaits permitting [3]. In 2022, the Bureau of Ocean Energy Management auctioned five commercial lease areas

along California's coast—two in Humboldt Bay and three in Morro Bay, with total farm potential capacities exceeding 1.6 GW and 3 GW, respectively [3]. California has a goal of having 2–5 GW installed by 2030 and 25 GW by 2045 [4]. The landscape may be poised for rapid change, driven by DOE's FOSW Shot⁸ [5] and California's Senate Bill 100 [6]. At the federal level, we observe different levels of prioritization for FOSW across administrations, with the Biden administration establishing the FOSW Shot [5], whereas the current administration has issued a Presidential Action on 'Temporary Withdrawal of All Areas on the Outer Continental Shelf from Offshore Wind Leasing and Review of the Federal Government's leasing and Permitting Practices for Wind Projects' [ref].

⁸ DOE's Floating Offshore Wind Shot aims to decrease the cost of floating OSW by 70% by 2035.

Recent efforts have used expert elicitation to estimate the future costs of offshore and onshore wind technologies, demonstrating the value of structured expert judgment in the absence of long-term empirical data. Wiser *et al* conducted one of the first large-scale expert elicitations on wind energy costs, finding that experts anticipated significant declines in cost driven by larger turbines, higher capacity factors, and lower financing costs [7]. A follow-up study by Wiser *et al* [8] confirmed and refined these projections, predicting a 37%–49% decline in onshore and fixed-bottom offshore wind costs by 2050 under median scenarios, and highlighting the role of innovation in turbine technology and plant design [8]. However, both studies focused on aggregate cost trajectories and did not address component-level costs or operational characteristics. More recently, Hughes and Longden [9] applied expert elicitation to offshore wind in the Asia-Pacific, incorporating policy dimensions, but did not isolate floating technologies or evaluate technical specifications such as transmission architecture or component reliability [9]. Given the novelty of FOSW, the lack of detailed empirical data, and the deep uncertainties surrounding component-level costs and system configurations, this study conducts an expert elicitation focused specifically on FOSW. We gather estimates on component costs, failure probability and duration, likely transmission configurations and outages (figure 1), and technical characteristics such as turbine rating, power density, and component capacities⁹.

2. Methods

In this expert elicitation, participants were asked to consider two time-horizons (10 and 20 years) and to provide a low, best, and high estimate for the different quantities being elicited as to capture the uncertainty of FOSW in the West Coast of the U.S. in terms of timescale, but also because FOSW has not yet been deployed on a commercial scale, or some of the data inquired for does not yet exist. The 10 year and 20 year horizon were chosen to broadly represent the beginning of operation of FOSW on the West Coast, and more particularly California, and 20 years from now is almost 2045, the year for which California is trying to reach net zero emissions [6].

This expert elicitation obtained Internal Review Board (IRB) approval for human subject study, which can be found at the end of SM, and experts

consented to participate using the IRB consent form. It was conducted in the form of recorded interviews over video conferencing software (Zoom Communications Inc.), with most interviews lasting between one and two hours. During these calls, experts went over the protocol and justified their reasoning and answers in the form of a conversation. The authors refrained from steering the discussion, instead permitting the experts to elaborate on their perspectives, intervening solely with clarifying inquiries. The experts were aware that all results would be anonymized, and only answered questions for which they felt comfortable giving data. In total, twenty-one experts participated in the study, some of them answering all questions, while others answering subsets. Two interviews occurred with two complementary experts with knowledge on different aspects of the industry, which means there are only 19 experts in the results, even though 21 persons participated, out of the 63 experts contacted. This number of participants in the study is consistent with expert elicitation practices [10–19]. Experts were selected based on meetings at FOSW-specific conferences, published research and reports, and through contacts and suggestions from other experts. Overall, people working in the industry, especially developers, were quite reticent to the idea of sharing data in such an emerging area with lots of competition. Most experts were based in the U.S., while a few were in Europe. Table S1 in supplementary materials (SMs) presents the general statistics of the population that participated in the study.

The results presented in the main paper include component-specific costs and probability and duration of failure, as well as expert opinions on the likelihood of different transmission design configuration. Transmission systems are one of the key design considerations for FOSW deployment [20]; and thus, we considered five potential options: 1) an AC system with offshore substations and 230 kV export cables, and overhead transmission lines between the shore and a demand center. 2) Same as 1, but DC lines are built onshore. 3) Same as 1 but with submarine 525 kV DC cables between an onshore substation and a load center. 4) DC offshore substations and 525 kV DC export cables (which involve a dynamic section). 5) No offshore substation but instead 132 kV array cables directly from the farm to shore (and the installed capacity sustained by this design would be around hundreds of MWs). All these scenarios are illustrated in figure 1.

Experts were first asked about the costs of each component in the different transmission designs. The costs estimates represent the overnight capital cost, meaning the cost from conception and engineering to the beginning of operation. These costs do not reflect

⁹ Transmission system potential forced outage rates, turbine and floating foundation specifications, operation and maintenance (O&M) conditions, and component capacities were also elicited, and results for these sections can be found in SM.

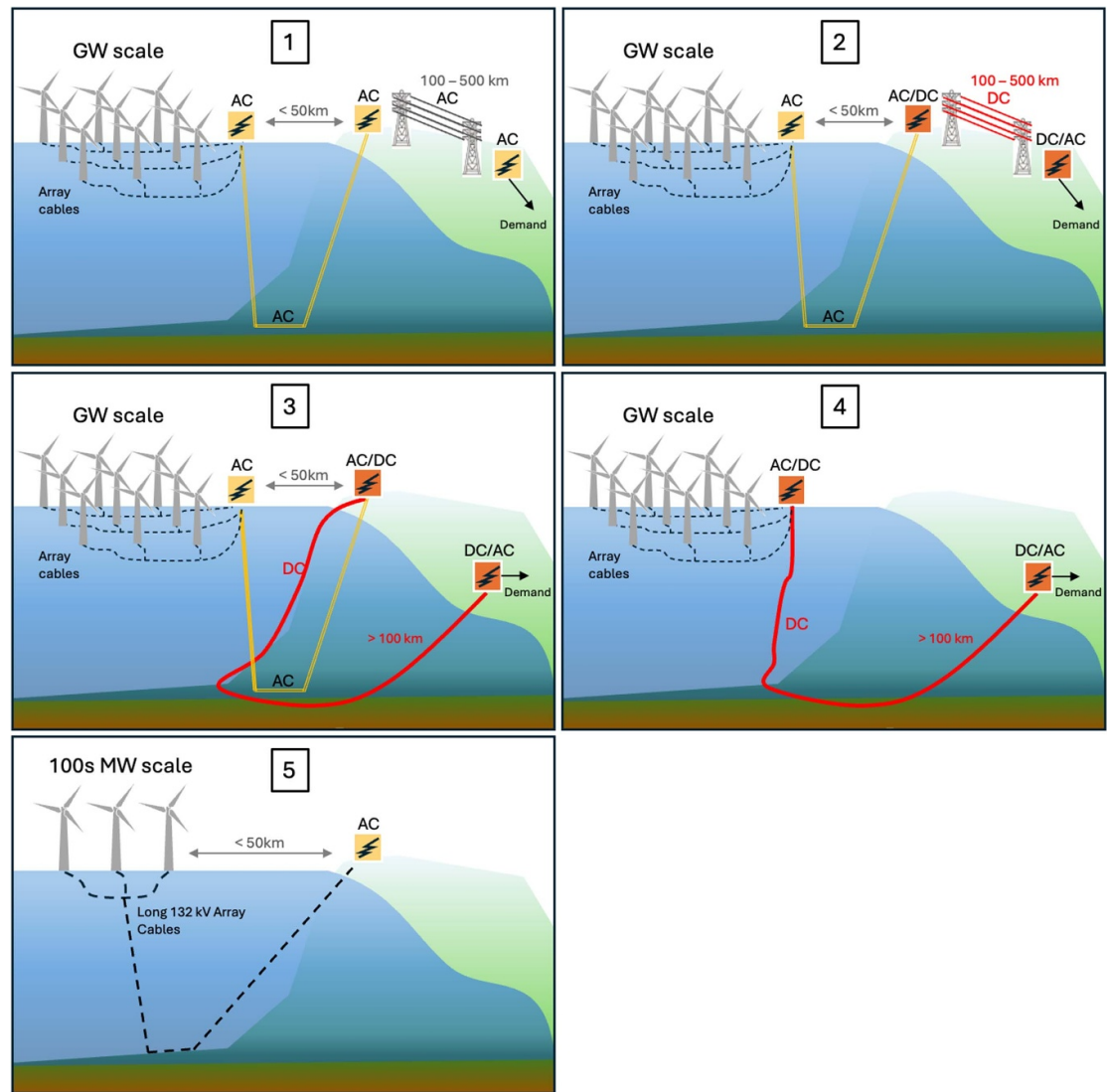


Figure 1. Illustration of transmission designs considered. (1) AC system with offshore substations, 230 kV export cables, and overhead transmission lines between the shore and a demand center. (2) Same as 1, but DC lines are built onshore. (3) Same as 1, but submarine 525 kV DC cables between an onshore substation and a load center. (4) DC offshore substations and 525 kV DC export cables, which involve a dynamic section. (5) No offshore substation but instead 132 kV array cables directly from the farm to shore. These figures are slightly different than the ones showed to experts in the elicitation (see SM).

the potential subsidies and corresponds to the price developers would pay. The components for which costs were inquired are turbines, floating foundations, 66 kV array cables, AC offshore substations, 230 kV AC export cables, 525 kV DC submarine cables, DC offshore substations, DC dynamic cable sections, and finally 132 kV long array cables.

For almost all components, participants answered questions on the probability and duration of catastrophic failure and capacities. For costs and probability and duration of failure, no differentiation was made between different designs of floating foundations (semi-submersible, tension-leg, etc.), though some designs are cheaper than others. Additionally, many components have not yet been commercially developed, such as 132 kV AC array cables and 525 kV DC submarine cables, AC and DC dynamic

export cable sections, and AC and DC offshore substations, highlighting the uncertainty surrounding these components.

During interviews, Nils Angliviél de La Beaumelle would share his screen where the protocol could be seen, and experts and Nils would go along together as interviewees would answer questions and explain their reasoning. This format of live interviews was preferred over asking experts to fill out a survey so that experts could provide feedback, discuss their opinions, and overall share their views. This allows authors to understand and discuss the data more accurately and input it in the results correctly. This kind of detailed explanations would not have been possible without the live interview process, and this kind of relevant information was recorded and is discussed in this paper appropriately.

While we conducted 19 full expert interviews, not all participants responded to every question. Experts were encouraged to answer only the questions within their domain of expertise—for instance, a cable manufacturer responded only to cable-related items. As a result, the number of responses varies across questions. This partial-response structure is common in expert elicitation and reflects the method's goal: to capture informed judgment from domain specialists where empirical data are limited, rather than to produce statistically representative estimates.

The protocol and all data were recorded using a survey service software (Qualtrics). The full elicitation protocol can be found at the end of the SM.

3. Results

3.1. Costs

Experts provided estimates for the overnight capital cost (in \$2024) of the different components in project architectures shown in figure 1: turbines, floating foundations, anchors and moorings, cables (AC array cables at 66 kV and 132 kV, 230 kV AC and 525 kV DC export cables), and offshore substations. Overnight capital cost includes all costs from conception and engineering to the first day of operation. Figure 2 displays each component median cost, with a comparison to other values found in literature [1, 21, 22] when available, discussed in the SM. We display the number of respondents in the title of each cost-component section in parenthesis. They are also visible in figure 2.

Turbines (5), foundations (7), and anchors and moorings (3): experts' median turbine costs are \$1400 kW and \$1170 kW for a 10- and 20 year time horizon, respectively, and tended to provide cost estimates that are lower than current costs found in the literature [1, 21, 22]. Median floating foundation costs are \$20.0 M/foundation in 10 years and \$18.4 M/foundation in 20 years. Anchors and moorings are highly uncertain (and only three experts responded to this question, limiting the robustness of our findings), with a median \$8 M/foundation in 10 years and \$6 M/foundation in 20 years.

Cables (5–6): experts suggest that 66 kV array cables will have a median cost of \$0.55 M km⁻¹ cable (10 years) and \$0.44 M km⁻¹ cable (20 years), with a maximum of \$2.48 M km⁻¹ cable in 20 years, reflecting supply shortages in the future. Few experts provided the cost of a 132 kV long array cable, and thus we refer the reader to figure S3 (A and B) in SMs for the results regarding this component. During the live interviews, experts stated that 132 kV array cables are unlikely to be used as export cables but could be deployed within the farm instead of 66 kV array cables.

Experts in the live elicitations stated that installation of export cables at the depths on the California shoreline have yet to be deployed to scale, and that cables laid above 700 m depth require protection from anchors and other collisions. However, cables laid deeper than 700 m necessitate a more complicated installation process, but do not need protection, which has a counterbalancing effect on cost. Therefore, export cable costs were differentiated between shallow and deep cables, but results are extremely similar across both depths and are combined here. We find that the median for 230 kV AC cables across experts is \$1.70 M km⁻¹ cable in 10 years and \$1.50 M km⁻¹ cable in 20 years. These values include the floating section of the export cable.

Regarding the 525 kV DC submarine cable, the median cost is \$2.00 M km⁻¹ cable in 10 years and \$1.47 M km⁻¹ cable in 20 years. These values do not include the floating section. Though some experts predict an increase in cable prices due to large future demand (especially for DC cables), supply chain shortages, and metal scarcity, participants mostly indicate a reduction in cost due to advancements in installation practices, technology, and industry maturity over time. Experts noted that increased manufacturing within the US could help address some of these issues.

The additional cost for the floating section of a 525 kV DC export cable has a median of \$8.40 M in 10 years and \$6.68 M in 20 years. Such technology is still in development and unproven.

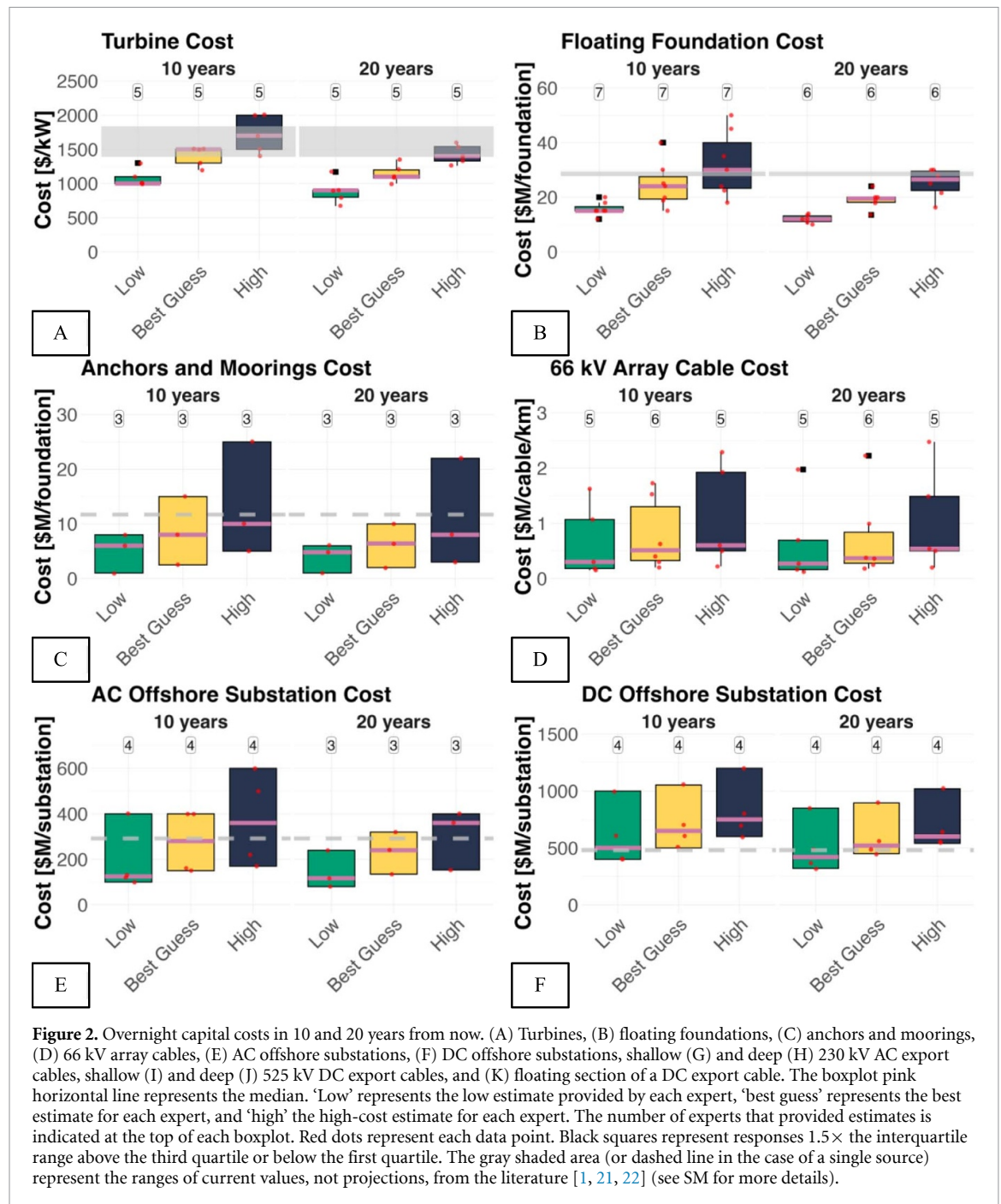
Offshore substations (4): some participants mentioned offshore substations might be subsea rather than floating, but we did not differentiate these two technologies in terms of cost or probability of failure. Though fewer experts responded to our questions about substation costs, the median cost is \$195 M/substation in 10 years and \$240 M/substation in 20 years. This increase in median price is explained by the fact that one expert who estimated costs 10 years from now and had estimates on the lower end did not predict expenses 20 years from now.

For DC offshore substations, the median cost is projected to be \$650 M/substation in 10 years and \$550 M/substation in 20 years.

Other Costs (3–6): given the importance of O&M and insurance costs, we also elicited these quantities from the experts. Most experts believed that the O&M would represent 45% of the total project overnight capital cost, and the insurance loan would be 8%. Figure S4 shows results, and a more detailed discussion can be found in SMs section Costs.

3.2. Probability and duration of catastrophic failures

Experts estimated the probability and duration of catastrophic failure (or 'large corrective') during the



first five years of operation for each of the offshore components, with the exceptions of the turbines, for which reliable failure rates can be found in literature [23–26]. In this study, catastrophic failure encompasses any failure requiring unanticipated maintenance (short or long-term, at sea or in port) or component replacement that results in production stoppage.

Catastrophic failure is estimated for each element on its own, meaning, for instance, that the probability of catastrophic failure of a floating foundation corresponds to the probability of catastrophic failure of each floating foundation in the farm on its own, not the probability that at least one of them over the whole

farm will fail. The duration of failure was defined as the time between the catastrophic event and the resumption of system operation. Figure 3 displays both probability and duration of failure for the different components. No data was collected on the probability and duration of catastrophic failure for DC offshore substations since this technology's deployment is particularly distant in the future. Similarly to the Costs section, we note the number of respondents for each component in parenthesis, in the following format: (probability of failure respondents; duration of failure respondents).

For most components, catastrophic failure probability results display considerable variation, which

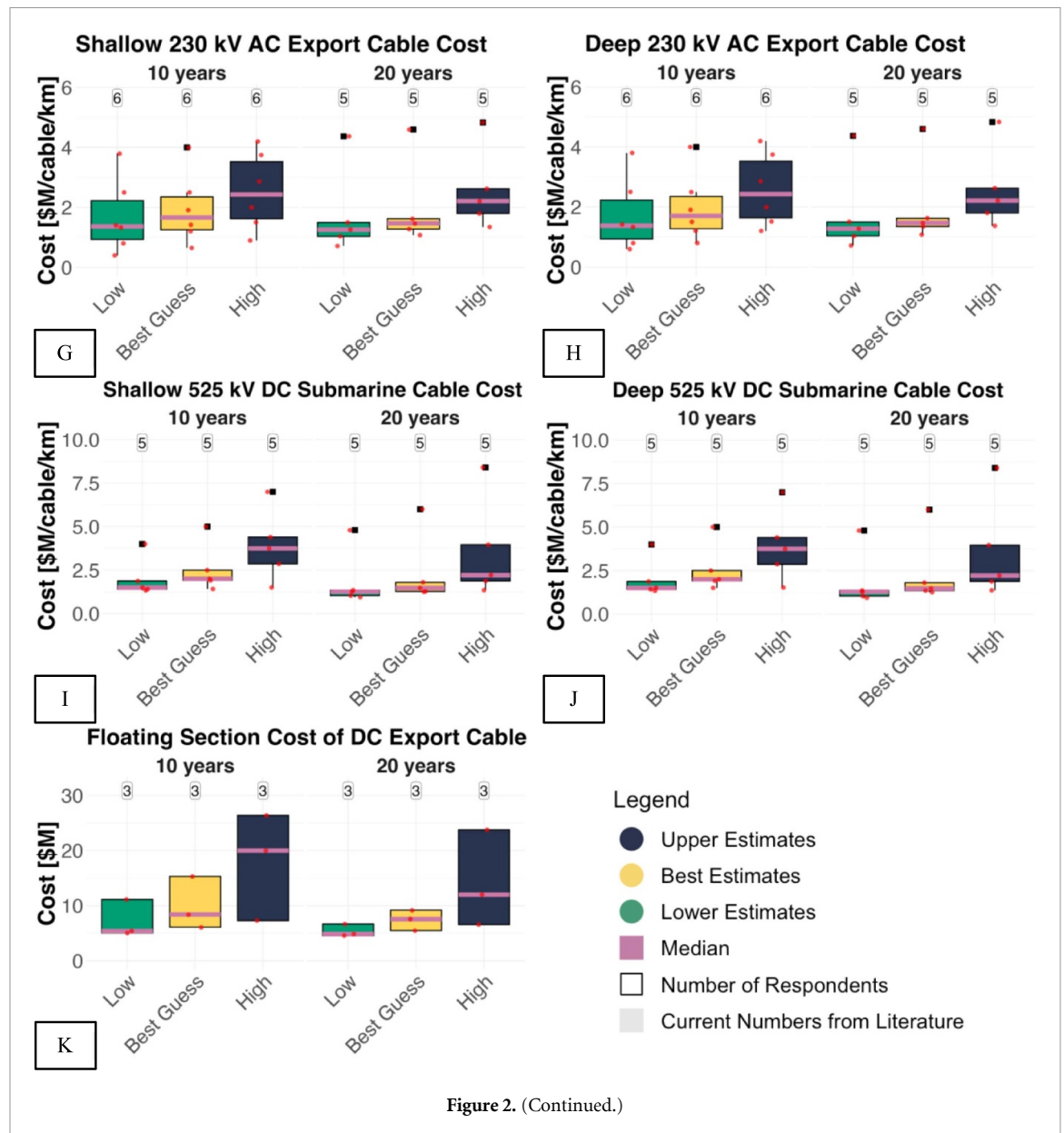


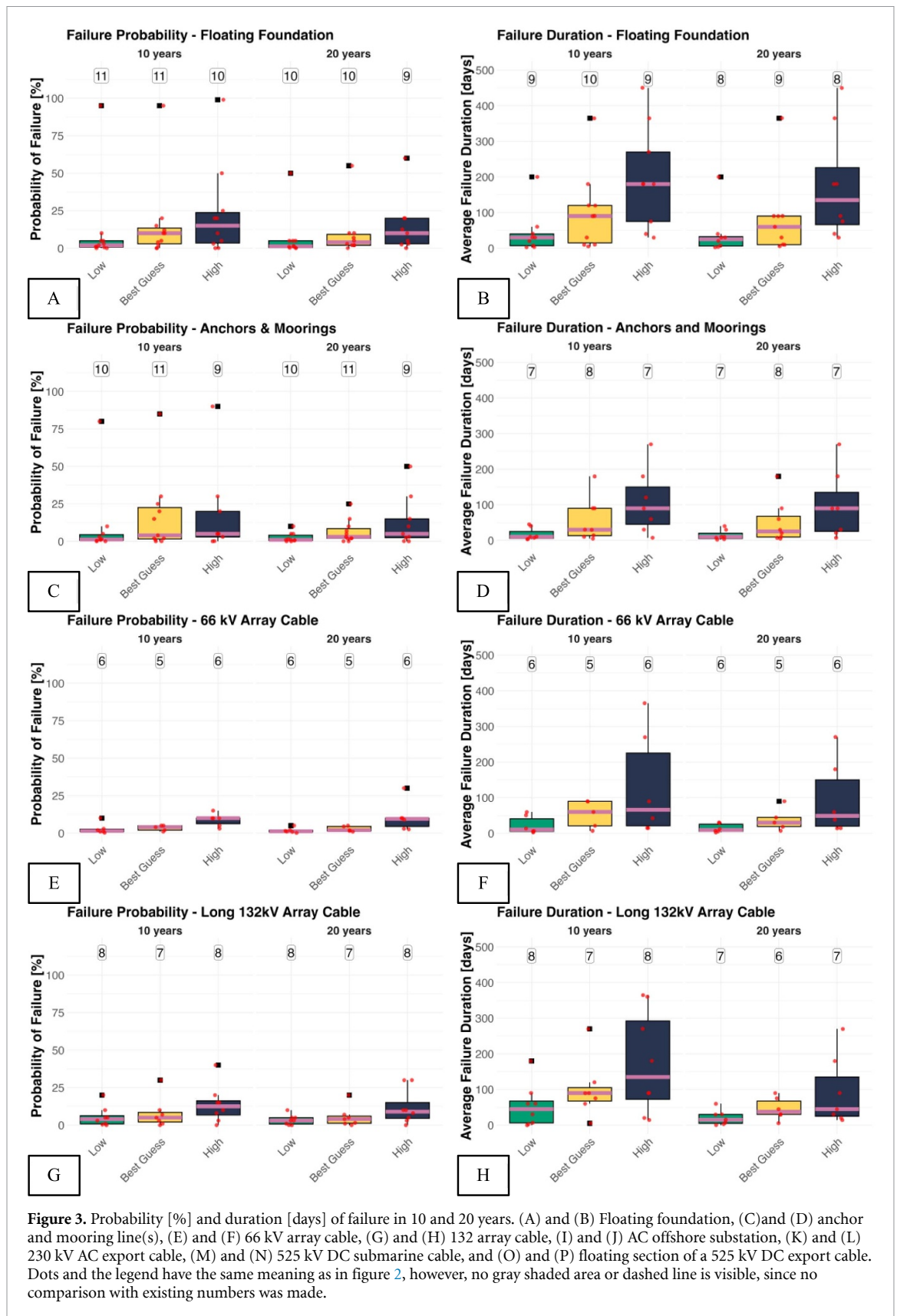
Figure 2. (Continued.)

can be attributed to differing expert perspectives: some assumed that engineering specifications and regulations would be precise, yielding failure probabilities around 0%–1%, while others anticipated that these novel technologies would encounter challenges during their initial five years of operation, with varying degrees of certainty. During the interviews, experts claiming extremely high probability of failure explained that these failures were minimal ones and could be fixed rapidly. High downtime values illustrate failures requiring towing to port, or potentially complete replacement of the component, which are often associated with lower failure probabilities. Notably, there is a consensus among experts that failure probabilities will decrease over time, owing to technological maturation, learning processes, and improvements in O&M practices. They

also indicate decrease in failure duration over time is associated to larger vessel availability due to a maturity and development of the vessel industry.

Floating foundations (11; 10): figure 3(A) displays a wide range of estimates for the failure of the floating foundation, ranging from 0.001% to 99% for project that would start operating 10 year from now, to between 0.01% and 60% 20 years from now, with median estimates remaining at 5%. Experts suggest that failure duration could be from a few days to more than 3 months, with the median duration being 68 (10 years) and 40 d (20 years).

Anchor and mooring lines (11; 8): Results range from 0.01% to 90% and 0.01% to 50% for projects that will be build 10 and 20 years from now, respectively. The median slightly decreases from 3.5% to 2.75% between time horizons, with most estimates



falling within the 0%–10% range. Some experts suggested higher failure probabilities of failure 20 years from now than 10 years, explaining that climate change might generate stronger currents and anchors and moorings might face more physical strain in the

future. Experts stated the failure of an anchor and mooring line could last between 3 and 270 d, with a median of 30 d (10 years) and 26 d (20 years).

Cables (6–8; 6–8): experts generally noted during the interviews that the dynamic section of an array

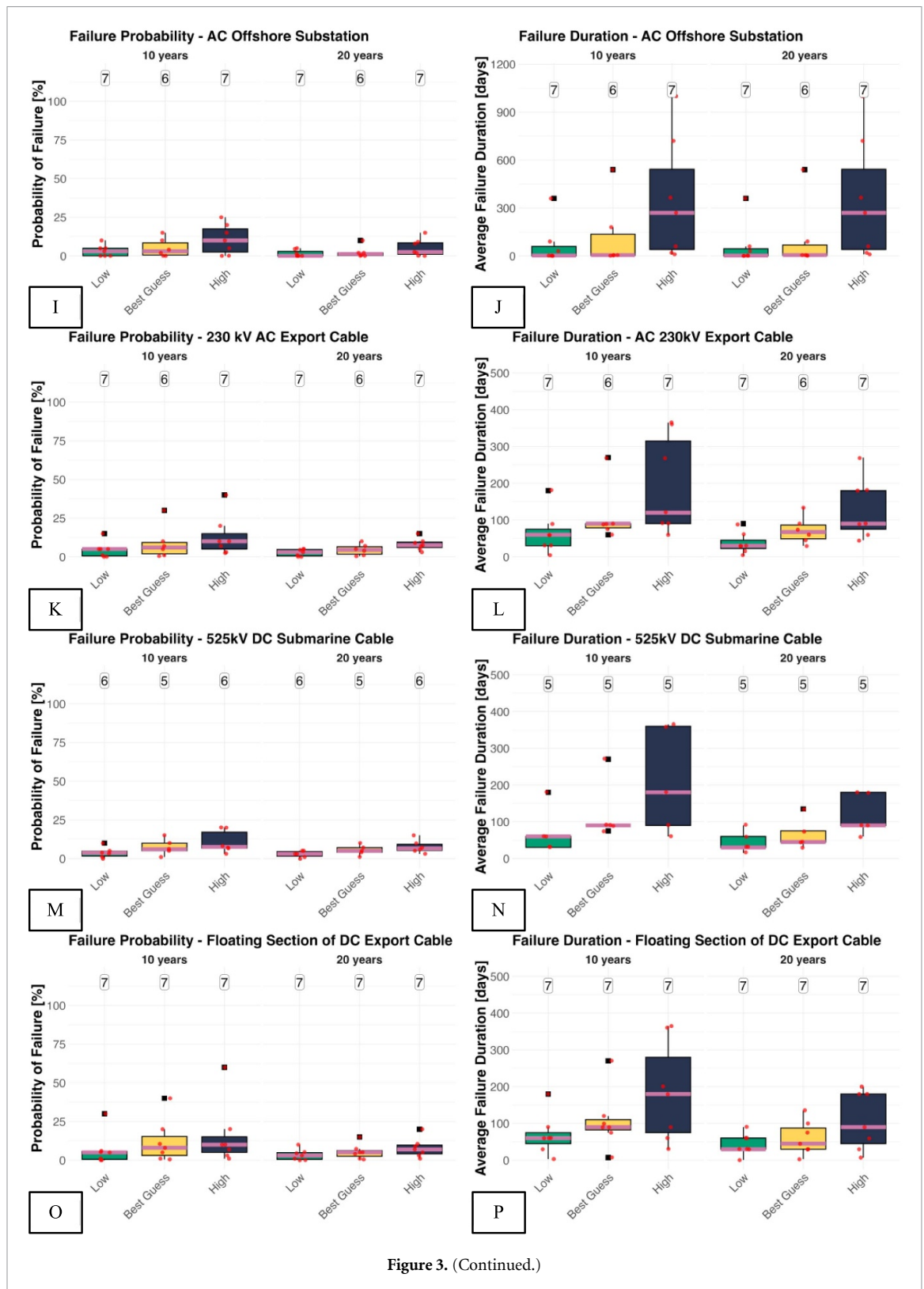


Figure 3. (Continued.)

or export cable is most prone to failure due to the novelty of the technology. The range of the probability of failure for 66 kV array cables is narrower than for previous components: 0.25%–15% (10 years) and 0.1% to 30% (20 years), with medians at 4% and 2.5%, respectively. Similarly to anchors and moorings, some participants mentioned that climate change will create harsher underwater conditions for

floating array cables. The estimates for 132 kV array cables have a median that remains constant at 5%. The median duration of a failure for a 66 kV array cable is 42 d and 30 d over the 10 and 20 year period, respectively. For 132 kV array cables, the median decreases from 90 to 30 d, because this technology is not yet developed, and will experience large maturity benefits between the two time-horizons.

For all export cables, no differentiation was made between shallow and deep for probability and duration of failure, as advised by experts. For AC export cables, the median is 5% for the two time-horizons. Experts provided a very wide range with the probability of failure spanning from 0% to 40% for the 10 year projection and 0% to 15% for the 20 year projection. The median duration for an AC export cable failure was 90 and 60 d for the two time-horizons, respectively, with a wide range for the duration, as shown in figure 3(J).

The responses regarding a 525 kV DC submarine cables were few, given the technology's novelty. The median response for the probability of failure is 6% (10 years) and 5% (20 years), and the duration of a catastrophic failure in DC submarine cables would most likely last 60–90 d.

As expected, the maximum probability value of the floating section of a 525 kV DC export cable is larger, with a range of 0.1%–60% (10 years). However, that range drastically decreases to 0.1%–20% in 20 years, illustrating important expected improvements. The duration of failure is similar to the other sections of the export cable.

AC offshore substations (7; 7): figure 3(G) indicates a narrower range of failure probabilities compared to most of the previous components, from 0.000 01% to 25% for the 10 year projection and 0%–15% for the 20 year projection. The median decreases from 4.5% to 1.75%, with most estimates falling within the 0%–5% range for both time horizons. These lower values compared to other components are partly due to the redundancy built into these substations that contain multiple transformers, which means that while the probability of some transformer failures might be higher, these failures would not be considered catastrophic as another transformer could take over, and only part of the production would be halted. The duration of these failures would reduce from 90 d (10 years) to 60 d (20 years).

3.3. Transmission configurations

Most of our interviews were conducted prior to CAISO's approval of new AC and DC overhead lines in Northern California [27]. The probability assigned to each transmission design represents the likelihood of its adoption in at least one location in California or the West Coast and are not cumulative across designs. Figure S5 (A, C, E, G, and I) in SMs show the distribution of estimates for the probability of deployment of each transmission design shown in figure 1 for California, and figure S5 (B, D, F, H, and J) display the same information for the West Coast of the U.S. This figure demonstrates a consensus in expert opinions regarding transmission designs for California

and the West Coast, allowing for a unified discussion of results.

We find that a short AC export cable combined with overhead AC lines is the most probable configuration within 10 years, but experts also predict that DC lines onshore are likely as well in 10 years, in alignment with the CAISO plan. However, some participants consider that overhead lines would be complicated since they require new, visible routes. Instead, they expect DC underground ones as they would avoid local opposition related to aesthetic and land use impacts.

Experts believe that the probability of implementing submarine cables with two landing points is low for both horizons due to high costs and complex permitting and legal frameworks, though some consider it is more likely in 20 years. However, some experts consider it would be a successful option because it would avoid aesthetic and land use impacts, while not having to wait for DC offshore substation and DC dynamic cable technologies to be mature.

A design encompassing a dynamic DC export cable is deemed highly improbable within 10 years due to the anticipated unavailability of commercially viable dynamic DC cables. While most experts maintain this design's low likelihood even in the 20 year horizon, some project a significant increase in its feasibility.

The fifth design is considered a potential alternative if AC and DC offshore substations are not commercially available within 10 years. Experts conclude that this design would be unsuitable for GW-scale farms and economically unviable due to high electricity losses, but potentially suitable for projects of a few hundred MW. Overall, experts predict a low probability of deployment 10 years from now, and impossible for the 20 year horizon since offshore substation technologies will be mature by then.

Experts also asked about the likely operational date for windfarms of over 1.6 GW and 5 GW in Northern and Central California, regardless of transmission configuration options (see SM). Median results show experts consider 1.6 GW will be operating in Central California (Morro Bay) in 2033, before Northern California (Humboldt) in 2035, due to the currently limited transmission in the northern region. For an operating capacity of 5 GW in Northern and Central California, insinuating there would be more than the single Humboldt farm in the North, but Morro Bay could host 5 GW depending on power density used, the medians are 2040 and 2038, respectively. This shows that experts are not confident the state's goals [4] of 2–5 GW by 2030 will be met, but that large deployments of over 10 GW should be achievable by 2040. Participants considered that potentially the 2045 goal of 25 GW could be attained

if new call areas could be leased and developed at a faster pace than Humboldt and Morro Bay.

4. Conclusion

This comprehensive expert elicitation study provides crucial data for policymakers, developers, and researchers, offering a foundation for more accurate modeling and planning of future FOSW developments.

Overall, costs and probability and duration of failure are projected to decrease over time for all components, reflecting technology maturation, learning effects, and improvements in O&M practices. However, there are wide ranges in the expert estimates, reflecting significant uncertainty. Rather than diminishing the value of the findings, this variability highlights the diversity of expert perspectives—an important insight in itself when addressing complex, uncertain, and rapidly evolving challenges like those facing FOSW.

There is notable disagreement among experts regarding the probabilities of different transmission configuration designs. However, AC offshore substations with short AC export cables are considered more likely in the 10 year horizon, a preference that can be attributed to the anticipated lack of readiness of offshore DC technologies. Onshore, AC and DC overhead lines would connect FOSW to load centers, aligning with CAISO's recommendations for Humboldt [27]. Longer DC offshore designs are seen as much more feasible in 20 years, specially designs using offshore DC substations. Overall, DC options, both onshore and offshore, are expected to play an important role in 20 years.

There are important limitations to our approach: expert elicitations, while valuable, are inherently subject to potential biases. Although the protocol was designed to mitigate bias by requesting worst-, most expected, and best-scenarios, these are not completely unavoidable. Furthermore, forecasting for a nascent industry like FOSW, particularly for deployments decades in the future, inherently involves a large degree of uncertainty. Consequently, the results should be interpreted with caution and not considered definitive. Additionally, this analysis does not account for several critical factors that could impact overall costs and project viability, including supply chain development expenses, port infrastructure investments, and potential vessel failures. These omissions may result in an incomplete representation of the total cost and risk profile associated with FOSW projects.

While the number of responses varies across questions, this reflects the nature of expert elicitations, where participants contribute insights within their domain of expertise. The goal is not to generate statistically representative results, but to synthesize

informed judgments from practitioners with deep, specialized knowledge. This approach is particularly valuable in emerging fields like FOSW, where empirical data is limited and expert insight is critical to informing early-stage decisions.

Overall, experts believe that the California Senate goal of 2–5 GW of FOSW by 2030 will not be attained, but the 2045 goal of 25 GW might be if the industry accelerates its deployment in the West Coast of the U.S [4]. Continued research, capacity expansion and grid modeling, data collection, and expert elicitation will be crucial to refine these projections and support the industry's development on the West Coast of the United States, and elsewhere. Given the exploratory nature of this study, future work should build on these findings through broader data collection and mixed-methods approaches—including deeper qualitative analysis—to further contextualize expert judgments and capture evolving perspectives as the sector matures.

Data availability statement

Data resulting from our analysis that was used to create the figures, results, and code are available in the SMs. Individual responses from experts cannot be provided as to maintain deidentification of the data (we refer to the IRB approval letter and the study protocol which states that 'the study data will be stored securely, in compliance with Stanford University Standards, minimizing the risk of confidentiality breach' and 'The results of this research study may be presented at scientific or professional meetings or published in scientific journals. Your individual privacy will be maintained in all published and written data resulting from the study').

All data that support the findings of this study are included within the article (and any supplementary files). To obtain the specific data used for certain figures, please contact the authors.

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Engineering and the Precourt Institute for Energy at Stanford University.

Conflict of interest

MS worked for Terna at the time this study was performed and participated in the research as a visiting scholar at Stanford University.

ORCID iDs

Nils Angliviél de La Beaumelle  0000-0001-6052-2976

Kamran Tehrani  0009-0009-6186-6426

Ekundayo Shittu  0000-0003-3694-9034

Inês M L Azevedo  0000-0002-4755-8656

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