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Expert perspectives on the wind plant of the future

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Abstract

Wind power technology has changed rapidly in recent years. Technology innovation, evolving power markets, and competing land and ocean uses continue to influence the design and operation of wind turbines and plants. Anticipating these trends and their impact on future facilities can inform commercial strategies and research priorities. Drawing from a recent survey of 140 of the world's foremost wind experts, we identify expectations of future wind plant design in 2035, both for onshore and offshore wind. Experts anticipate continued growth in turbine size, to 5.5 (onshore) and 17 MW (offshore), with plants located in increasingly less favorable wind and siting regimes. They expect plant sizes of 1,100 MW for fixed-bottom and 600 MW for floating offshore wind. Experts forecast enhanced grid-system value from wind through significant to widespread use of larger rotors, hybrid projects with batteries and hydrogen production, and more. To explain experts' perspectives on future plant design and operation, we identify five mechanisms: economies of unit, plant, and resource scale; grid-system value economies; and production efficiencies. We characterize learning effects as a moderating influence on the strength of these mechanisms. In combination, experts predict that these design choices support levelized cost of energy reductions of 27% (onshore) and 17%–35% (floating and fixed-bottom offshore) by 2035 compared to today, while enhancing wind energy's grid service offerings. Our findings provide a much-needed benchmark for representing future wind technologies in power sector models and address a critical research gap by explaining the economics behind wind energy design choices.

KEYWORDS

cost drivers, expert elicitation, optimization, technology foresight, value drivers, wind, wind farm design

1 | INTRODUCTION

Wind energy is increasingly among the least-cost technology choices in many energy markets, growing by an average of 55 GW in annually installed global capacity over the past 5 years.[1] A changing generation mix, policy drivers, competing land and ocean uses, and technology innovation present a dynamic environment for wind energy today and into the future. Technology and plant design need to evolve for wind energy to continue expanding its role in a sustainable, least cost, and reliable power system. Our understanding of prospective wind plant design and operation is limited, yet anticipating key design features a decade or more ahead of their deployment can improve today's investment, research and development (R&D), and energy system planning decisions.

A large body of literature is concerned with technology foresight of wind energy. Most discuss future wind technology and plant design in the context of the levelized cost of energy (LCOE).[2] LCOE forecasts can employ multiple tools, including historical extrapolation via learning curves,[3,4] expert assessments via elicitations,[5] or engineering studies.[6,7] Beyond LCOE, a growing literature takes a more holistic approach by also considering other factors. Research has increasingly focused on the power system value of energy and energy services and specifically on wind plant design and operation choices that can enhance that value.[8–11] Other research has emphasized land and ocean use constraints on wind potential and technology and plant design.[12–14] Public acceptance and other societal concerns have also been highlighted as possible wind plant design and operations drivers.[15–19] Within these different streams of research, the literature has tended to focus on individual technology innovations. Holistic conceptualizations of future wind plant design are rare.[20,21] Moreover, although well established in broader economic theory and often tackled individually, relatively few efforts in wind energy science have systematically assessed the exact mechanisms that drive wind plant design.

Here, we (1) describe key features of wind plants in 2035 by drawing from a large survey of the world's foremost experts and (2) explain the causal mechanisms between design features and their effects on cost and value by discussing the relevant literature. Our assessment spans onshore, fixed-bottom offshore, and floating offshore wind applications. We derive results for this article from an expert elicitation described by Wiser et al., which we describe further in Section 2.[5] This survey, conducted during 2020, focused on potential changes in LCOE for wind plants with commercial operation dates between 2019 and 2050 (with intermediate steps in 2025 and 2035). The survey also asked respondents to illuminate key features and attributes of future wind energy facilities in 2035. These expected wind plant and operational attributes in 2035 are the focus of our analysis. They include expected site (annual average wind speed at 100 m and—for offshore—distance to shore, water depth, and project size) and technology (nameplate turbine capacity, rotor diameter, hub height) characteristics and the relative impact of design, materials, logistical, transportation, and siting constraints that could limit turbine size growth. For onshore wind, the survey asked respondents about the influence of different factors that drive turbine choice for specific sites. For the two offshore technologies, the survey explored the least-cost substructure choice depending on water depth. The survey also included questions about design and operational strategies to enhance the grid-system value of wind energy. From each respondent, the survey elicited data on geographic region and organizational type.

The conventional paradigm that has guided wind turbine and plant design and operations focuses on maximizing energy production and minimizing LCOE. But maximizing grid-system value and managing competing logistical, regulatory, and social constraints have become more important. Growing interest in these factors coincides with the phase-out of revenue support such as feed in tariffs, the growth of wind's share of electricity generation, and increasing scarcity of easily developable wind sites. Accordingly, the last several years have seen a great deal more industry focus on the potential of these issues to alter or limit wind turbine and plant design and operations in a manner and at a level not previously observed. Our focus on these elements as well as design aspects that impact LCOE extends our earlier summary of the portions of the expert survey that emphasized LCOE expectations.[5]

Our work elaborates an updated picture of future wind energy technology and plants. We translate the responses of global experts on these topics into future wind plant characteristics (Section 3) that can be used by energy analysts and modelers in future research and can inform R&D decision making. We also illuminate critical drivers and constraints and identify potential sensitivities that might alter the insights extracted from our survey (Section 4). While some of the causal mechanisms discussed in this section are well-established (e.g., economies of plant size and learning effects), they often appear fragmented or poorly defined when applied to wind energy. We close this research gap by applying those mechanisms in a systematic and holistic fashion to wind energy and develop an explanation of why our survey respondents might prefer a particular design choice (over another) for future wind plants and their operation.

Anticipating future wind plant and technology designs can inform the needs of regulatory authorities as they seek to understand how deployment might affect the resources (e.g., wildlife) they oversee. Moreover, the data presented herein on technology, siting conditions, deployment constraints, and the extent of grid-system value offerings (e.g., higher sensitivity to electricity pricing, balancing services, etc.) from wind energy provide a benchmark for use in electricity sector scenario analysis. Lastly, in our conclusions (Section 5) we discuss the design features expected by the survey respondents in the context of deep de-carbonization scenarios when wind might assume a central role in the transition to a fully sustainable, reliable, and least-cost energy future. Importantly, we did not ask survey respondents to consider such a scenario and focused their answers on a median scenario only. Therefore, the results presented herein might be more reflective of a "business-as-usual" scenario, and we consider it helpful to discuss in the conclusions the degree to which responses might have been different for a future that is drastically different from today's power system.

2 | METHOD

Insight into future wind plant design and operations can be derived using a variety of methods. Technology foresight methods can broadly be classified as quantitative, semiquantitative, and qualitative.[22] Each of these methods has been used for future wind technology and plants. For instance, research often investigates innovations through quantitative modeling and simulation[23] or the extrapolation of historical trends to identify viable wind technology pathways. Expert elicitations[2,20,24] and patent analysis[25] of technologies provide a semiquantitative assessment of future plant design and operations. Qualitative methods such as expert panels are used widely at industry and research conferences.

We analyze data from a recently completed elicitation survey of 140 global wind experts. Future wind plant design and operations will be driven by complex interactions among multiple drivers, at times by conflicting conceptual motivations,[*] and is often informed by limited data. Expert elicitations are typically considered well-suited for such a setting.[26] An expert elicitation is broadly understood as "a structured procedure designed to gather knowledge from individuals considered human experts in that domain"[27] and is often used to solicit judgments of uncertain quantities and their probability distributions.[28,29] As a method, expert elicitation provides a convenient way of characterizing the future of wind technology and plants at the system level. The accuracy of expert elicitations varies. Comparing the survey sample analyzed here with an earlier expert elicitation conducted in 2015, Wiser et al.[5] find that experts have considerably underpredicted the decline of wind energy costs in the past. Alternative forecasting approaches, such as detailed engineering assessments, tend to be more narrowly focused and are more labor and cost-intensive, without necessarily reducing uncertainty because of the number of required assumptions.

The focus of the wind elicitation survey was twofold: (1) to glean insight on LCOE and its components (reported separately in Wiser et al.[5]) and (2) to elicit critical data points on wind technology and plant evolution that can inform a better understanding of future wind plant design and operations (reported in the present article). To our knowledge, this survey provides the most comprehensive and recent assessment of global wind energy experts. It builds on a similar expert elicitation conducted in 2015[2] (hereafter referred to as the "2015 survey"). The survey was conducted online in mid to late 2020 and covers onshore, fixed-bottom offshore, and floating offshore wind. Further details about the sample selection, the identification of "leading experts" (i.e., those we identified as having the greatest level of experience and insight), and survey response rate can be found in Wiser et al.[5] Our respondent sample features considerable variation across organizational types and types of expertise (e.g., onshore vs. offshore). The regional affiliation of our respondents is skewed towards Europe and North America, with only 6% of responses reporting expertise in Asia or Central and South America.

In the survey, we provided definitions of key terms and baseline data. Respondents were then asked for their assessment of wind costs at four distinct points in time: 2019, 2025, 2035, and 2050. Elicitation of wind plant and technology characteristics was limited to 2035. For 2035, we asked respondents to forecast turbine, site, and project characteristics; turbine size constraints; and grid-system value enhancement options. For offshore wind, we asked about expectations of future substructure preferences (i.e., fixed-bottom vs. floating). For onshore wind, we asked about turbine selection factors. Respondents chose values either on a sliding scale (with an alternative input field) for some questions or selected from predefined answer categories (e.g., large, medium, small, or no expected impact) for others. As part of characterizing three future LCOE scenarios (low, mid, and high), respondents also had the option to provide descriptions in a text field.

Elicitation surveys rely on human experts. Judgments made by experts are necessarily subjective "but should be made as carefully, as objectively and as scientifically as possible."[29] The main challenge of any elicitation survey is its reliance on individuals who are subject to motivational and cognitive biases and heuristics.[30] Common biases and heuristics include anchoring, desirability, overconfidence, and the recallability trap (among many others). As described in Wiser et al., [5] we employed a number of recognized techniques to reduce the impact of bias and heuristics. Further detail on the survey methodology is described in Wiser et al., [5] building on the 2015 survey.[2] The full survey instrument can also be found in Wiser et al.,[5] as can additional analysis of the respondents' characteristics and their LCOE expectations.

We recognize that no survey instrument can eliminate all possible biases and that no method can alone result in accurate predictions about future wind plant and turbine design and operations. We supplemented the survey findings by conducting a literature review on drivers for wind plant design and operation. This review was conducted using a combination of keyword search (see the Supporting Information) and our own records of the relevant literature.

3 | RESULTS

Survey respondents expect considerable reductions in LCOE over the next three decades for all studied wind applications (Figure 1). Here, we analyze the survey responses to explore the type of wind plant design and operational strategies that can enable such cost reductions. In addition, we assess the extent to which power system value and constraints in siting and logistics influence wind project design.

In this section, we describe the expected site characteristics (wind speeds, distance to shore, and water depth) and technology characteristics (turbine capacity, hub height, rotor diameter, and plant size) in 2035 for each wind application and world region. We contextualize these characteristics with data for 2019 where available and summarize barriers to turbine growth and grid-value enhancement options. Key characteristics of typical future wind energy plants are depicted in Figure 2, which we refer to and discuss throughout this section.

In the subsequent Section 4, we explain why respondents might have chosen specific design features. To do so, we introduce a theoretical framework of the causal mechanisms between wind plant design features and their effects on cost and value. Additional data (e.g., on regional differences and respondent demographics) and details on our method are included in the Supporting Information.

*Wind plant design is motivated by different and at times conflicting motivations. For instance, motivations guided by maximizing the energy production (i.e., longer blades) versus minimizing the visual and noise impacts (i.e., shorter blades) can result in significantly different plant designs.

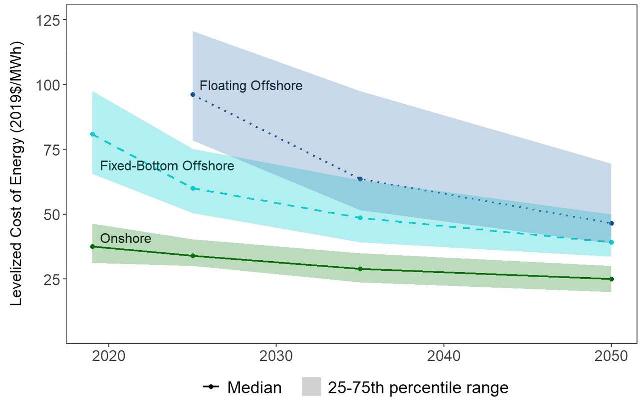

FIGURE 1 Levelized cost of energy survey estimates (median scenario) for onshore and offshore wind applications, 2019–2050 (adapted from Wiser et al.[5])

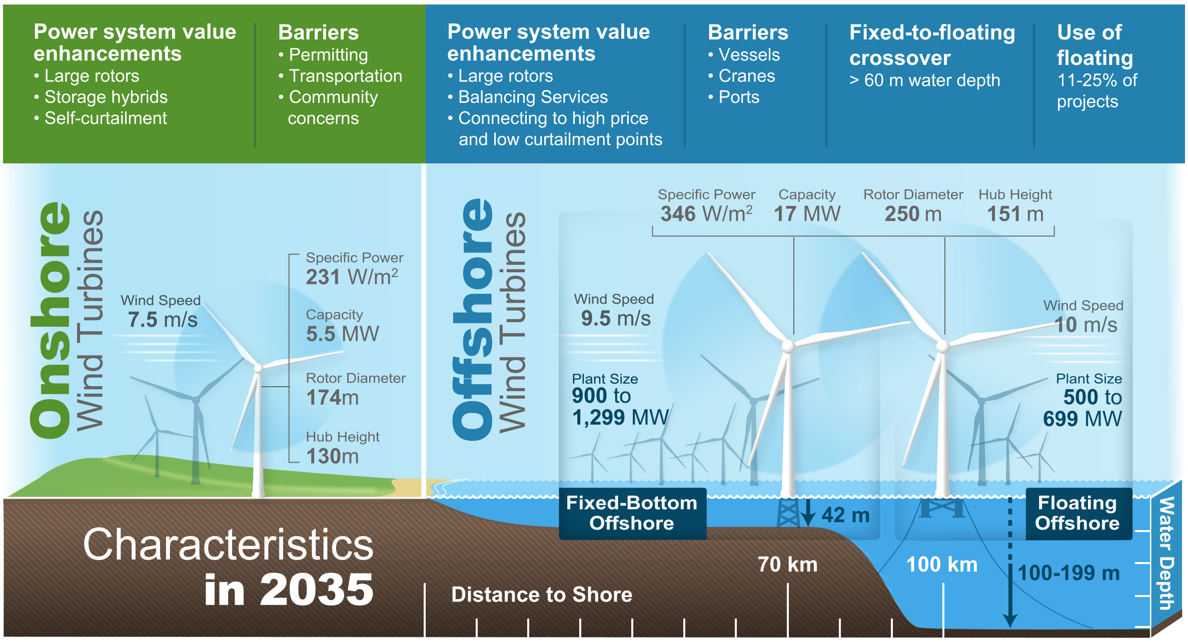

FIGURE 2 Experts' expectations of the key characteristics of the wind plant of the future. *Note*. Attributes shown represent the median-scenario expert prediction. Only those attributes are shown here that were elicited in the expert survey and can easily be visualized. Others are discussed in text or amended in the discussion below from a literature review. Plant size was only elicited for offshore applications

3.1 | Typical sites

Both turbine and site characteristics influence LCOE. Starting with site characterization, the surveyed experts expect LCOE reductions despite a predicted trend towards less-attractive wind sites over time. For onshore wind, experts forecast the median global annual average wind speed (at 100 m above ground) for new projects to decline slightly from 7.9 m/s in 2019 to 7.5 m/s in 2035. For fixed-bottom offshore wind, experts anticipate the median project in 2035 to be located farther from shore (70 km [2035] vs. 40 km [2019]) and in deeper water (42 m [2035] vs. 30 m [2019]) but expect average wind speed to remain steady at 9.5 m/s (at 100 m above water).

As no commercial-scale floating offshore wind projects had been deployed at the time of the survey, respondents did not provide a baseline for the year 2019. However, relative to fixed-bottom offshore installations in the year 2035, experts forecast the median floating offshore project to be farther from shore (100 km), in much deeper water (100–199 m), and located at sites with slightly higher wind speeds of 10 m/s (at 100 m above water). Respondents expect floating offshore to become the least-cost choice (rather than fixed-bottom) at increasingly shallower water depths (>60 m [2035] vs. >80 m [2019]).

Experts anticipate regional differences to persist through 2035. For onshore projects, experts expect average wind speeds to decline moderately in all markets, with North America retaining the highest average 100-m speeds at 8 m/s. For offshore, experts predict that Europe will continue deploying fixed-bottom offshore wind projects farthest from shore (80 km), in the deepest waters (45 m), and with the strongest wind speeds (10 m/s). This trend is especially pronounced for floating installations (150 m water depth in Europe vs. 75 m in North America). A small ($n = 5$) sample of experts expect Asian fixed-bottom installations to remain closest to shore (25 km) and to be cheaper than floating installations in deeper waters (>100 m), compared to shallower cost crossovers in Europe and North America (>60 m).

Some perspectives also vary by respondent demographics. Globally, equipment manufacturers and developers expect the greatest median distance from shore for fixed-bottom installations in 2035 (the latter predicting 106 km), whereas government and nongovernmental organization officials expect the shortest distance (41 km).

3.2 | Technology characterization

Surveyed experts anticipate continued growth in turbine capacity ratings, hub heights, and rotor diameters. Compared to today's wind turbines, the typical, newly installed onshore wind turbine is projected to have a greater capacity (5.5 MW [2035] vs. 2.5 MW [2018]), higher hub height (130 m [2035] vs. 100 m [2018]), and larger rotor diameter (175 m [2035] vs. 117 m [2018]). The surveyed experts also predict larger turbine dimensions than in the 2015 survey, when they forecasted turbine sizes of only 3.25 MW, hub heights of 115 m, and rotor diameters of 135 m for 2030.[2]

Experts expect offshore wind turbines to continue to dwarf onshore turbines, with stronger growth in turbine capacity (17 MW [2035] vs. 4.4 MW [2018]), hub height (151 m [2035] vs. 90 m [2018]), and rotor diameter (250 m [2035] vs. 132 m [2018]). Notably, roughly 40% of respondents anticipate the typical offshore turbine installed in 2035 to be ≥20 MW (Figure 3). These predictions have also increased from the 2015 survey, when respondents anticipated 11 MW offshore turbines with a hub height of 125 m and a rotor diameter of 190 m for 2030. Experts believe that along with turbine growth, plant sizes will double for fixed-bottom offshore installations (1,100 MW [2035] vs. 500 MW [2019]). Floating offshore plant sizes are expected to average 600 MW in 2035. Despite the increases in turbine dimensions, experts anticipate specific power (the ratio of turbine capacity to rotor swept area) in 2035 to remain stable both for onshore turbines (231 W/m^2) and offshore turbines (346 W/m^2) compared to 2019, though 35% of respondents predict declines to a median of 206 W/m^2 (onshore) and even 198 W/m^2 (offshore). In the 2015 survey, experts believed that specific power would remain at higher levels (260 W/m^2 for onshore and 388 W/m^2 for offshore) in 2030.

We find modest differences by region. For onshore turbines, experts anticipate lower specific power and larger rotors in North America (224 W/m^2, 178 m rotor) than in Europe (249 W/m^2, 160 m rotor), similar to historical trends. Experts expect continued higher hub heights in Europe (130 m vs. 123 m in North America), but North America to take the lead in rated capacity (5.6 MW vs. 5.0 MW in Europe). For offshore installations, experts predict that Europe will continue to have the highest turbine capacity ratings of 17.1 MW (relative to 15.6 MW in North

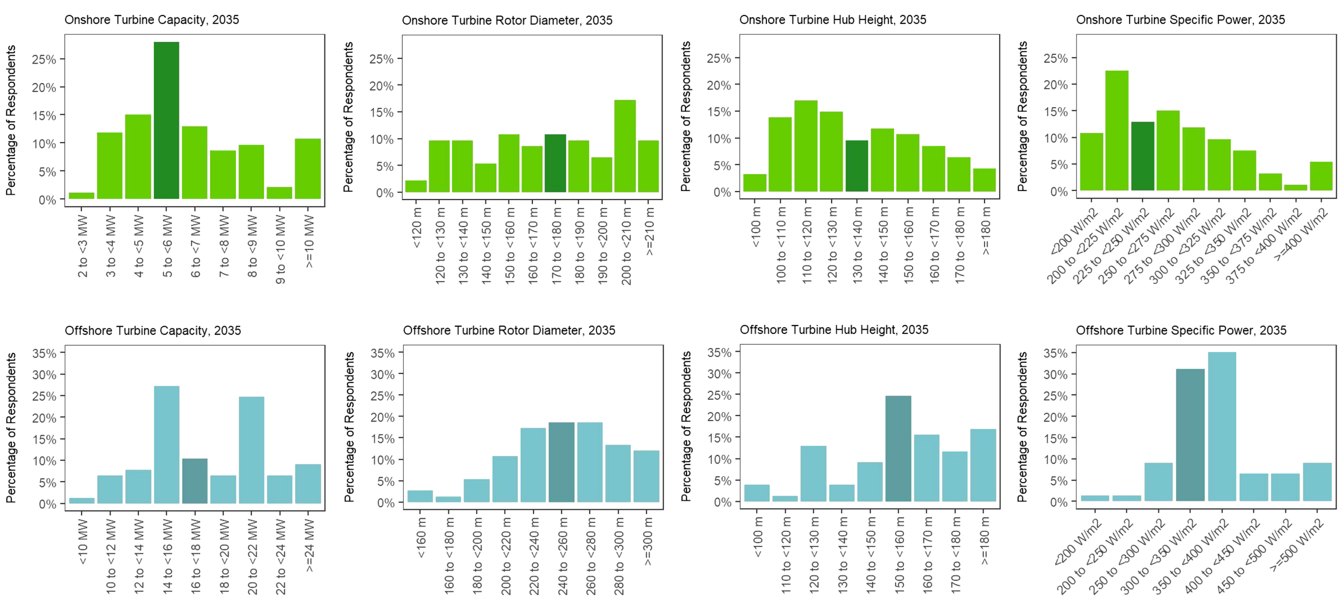

FIGURE 3 Distribution of experts' expectations for onshore and offshore turbine characteristics, 2035

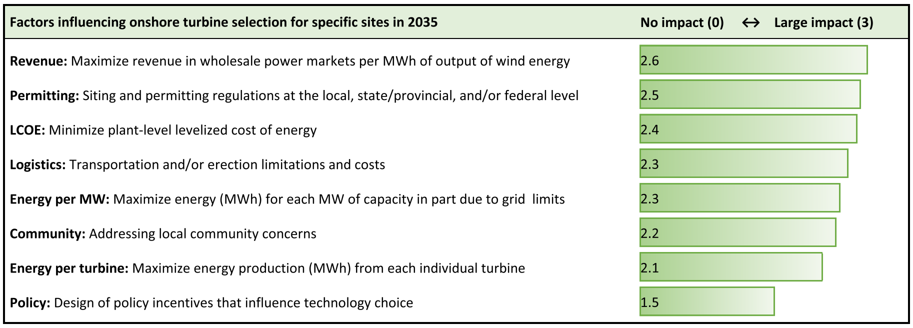

FIGURE 4 Factors influencing onshore turbine selection

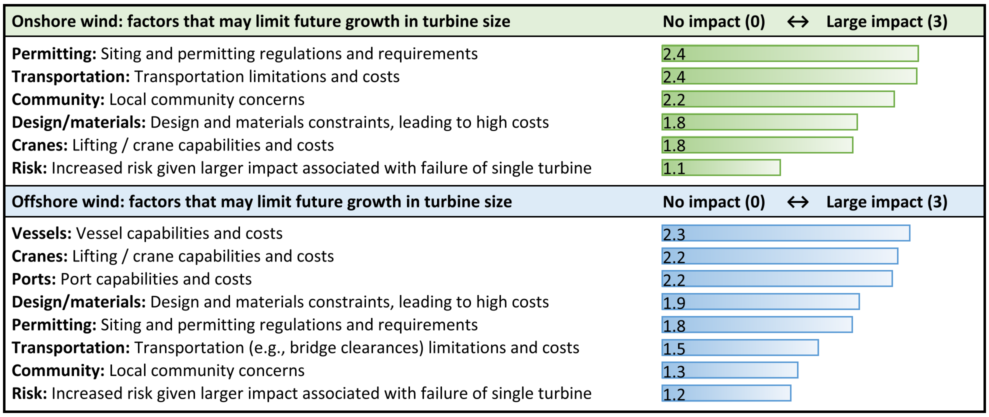

FIGURE 5 Turbine size constraints for onshore and offshore applications

America) paired with hub heights and rotor diameters similar to those in North America, leading to a greater specific power of 348 W/m^2 relative to North America's 324 W/m^2. Our small sample of Asian experts forecast a 15-MW turbine capacity coupled with a relatively small rotor of only 220 m, and, consequently, a higher specific power of nearly 400 W/m^2.

Views differ by expert demographics. The leading experts anticipate larger turbines (a 5.8-MW turbine with 183-m rotors for onshore and 18 MW with 266 m for offshore) and lower specific power. For onshore, manufacturers (e.g., original equipment manufacturers) predict lower specific power (down to 212 W/m^2) and higher hub heights (up to 145 m) than developers. For offshore, manufacturers and developers predict larger turbines than other respondents (20.2 MW turbines with 162-m hub height and 275-m rotor diameter). Leading experts predict larger offshore project sizes than the full sample for both fixed-bottom (1,100 MW vs. 800 MW) and floating (800 MW vs. 600 MW) installations.[†] The full distribution of turbine specification responses is shown in Figure 3.

The survey also provides insights on the factors and constraints that may influence onshore turbine selection, and these insights illustrate the growing role of factors beyond LCOE. For instance, when asked about the factors most likely to influence onshore turbine selection in 2035, respondents rated many factors from different domains as nearly equal in influence. These include wholesale market revenue, permitting, LCOE, logistics, and energy production (Figure 4). Regional differences are also apparent; logistics are expected to be a larger driver in North America, while permitting and energy per turbine are somewhat larger drivers in Europe. Community concerns are less of a factor in Asia.

Additionally, the survey asked about the primary constraints to further upscaling of turbine size. For onshore wind, the primary listed constraints are permitting, transportation, and community acceptance. For offshore wind, the primary limits include the capabilities and costs of vessels, cranes, and ports (Figure 5). We found some regional differences in these constraints. Transportation, vessels, cranes, and ports were identified as more challenging in North America than in Europe; community acceptance was a greater constraint in Europe for onshore, less so in Asia. Interestingly, design and materials constraints were not among the top three listed by experts, either for onshore or offshore wind. This again illustrates the growing importance of factors beyond the science and engineering of turbines in defining the wind plant of the future; logistics, transportation, community acceptance, and permitting were all deemed greater barriers to turbine upscaling.

[†]Expected plant size was only elicited for offshore applications in the survey.

3.3 | Grid-system value enhancement options

Experts anticipate that a variety of measures to enhance wind's grid value will become more prevalent in the future. Specifically, for onshore wind, a substantial percentage of experts anticipate significant use (more than 10% of projects) or even widespread use (more than 50% of projects) of many grid-system value-enhancement options (Figure 6): large rotors, hybridization with storage, curtailment for revenue maximization and life extension, and more. Large rotors represent a value-enhancing strategy because they enable generation even during times of lower wind speeds when wholesale electricity prices tend to be higher.[9] For offshore wind, top-rated value enhancement options include larger rotors, provision of balancing services, interconnection to increase grid value, and hybridization with storage and hydrogen production.

Except for larger rotors for onshore wind, there is not a single dominant value-enhancing measure that is expected to be used for most projects. Rather, a wide variety of methods is expected to be employed to maximize the value of wind, with the specific options dependent on the context of individual sites.

For onshore wind, developers predict higher use of curtailment, hybrids, interconnection, and overplanting; public research organizations and universities expect higher use of life extension, curtailment, and balancing services than the private sector; and leading experts are generally more optimistic about all value-enhancing options except hybrids (Figure S14). For offshore wind, manufacturers expect greater use of hydrogen and storage hybrids; and public research organizations and universities are more optimistic about life extension and curtailment than is the private sector (Figure S15).

4 | DISCUSSION

Our survey focused on eliciting characteristics of future wind plants and their impacts on cost. From these answers, we were able to infer several features of a wind plant of the future. In this section, we introduce a theoretical framework to explain why respondents might have chosen these design features (and not others). To identify these fundamental economic mechanisms, we draw on literature and apply them to principal design choices in wind energy.

4.1 | Design features and their effect on cost and value

We extracted information on possible explanations from the survey responses on turbine selection, turbine size constraints, and the use of grid-value enhancement options as well as from text fields in which respondents had the option to characterize the "low," "high," and "mid" LCOE scenario. We hypothesize that the surveyed design features affect the cost and value offering of a wind plant through five mechanisms—economies of unit, plant, and resource scale; grid-system value economies; and production efficiencies. We identified these mechanisms through reviewing the broader literature on industrial economics (see Section S2 for a list of search words used to identify these mechanisms). Although these mechanisms are well established in broader economic theory (e.g., Pindyck and Rubinfeld),[31] they have not been assessed comprehensively as they relate to wind plant design features. Möller et al.[32] and Samadi[33] discuss economies of scale broadly for the wind sector; others have focused on

Onshore Wind: frequency of use of grid-value enchancement options by 2035	Widespread use: *over 50% of projects*	Significant use: *over 10% of projects*
Large rotors: Employing larger rotors and/or taller towers to increase production when wholesale prices are higher	77%	95%
Storage hybrids: Co-locating wind projects with storage at the plant site or point of interconnection	46%	83%
Curtailment: Self-curtailment when wholesale prices are low or negative to avoid financial losses during those times	45%	79%
Life extension: Operating to reduce mechanical stress when wholesale prices are low, in part to extend project life	38%	71%
Interconnection: Interconnecting projects to locations with higher wholesale prices and/or lower levels of curtailment	30%	70%
Balancing services: Using wind plants to provide balancing reserves and/or other essential reliability services	29%	81%
Generator hybrids: Co-locating wind projects with other generating sources at the plant site or point of interconnection	26%	80%
Hydrogen: Using wind energy to produce fuels, such as hydrogen, at the plant site or point of interconnection	22%	56%
Overplanting: Building more wind power capacity than transmission interconnection capacity	17%	65%

Offshore Wind: frequency of use of grid-value enchancement options by 2035	Widespread use: *over 50% of projects*	Significant use: *over 10% of projects*
Large rotors: Employing larger rotors and/or taller towers to increase production when wholesale prices are higher	43%	78%
Balancing services: Using wind plants to provide balancing reserves and/or other essential reliability services	35%	87%
Interconnection: Interconnecting projects to locations with higher wholesale prices and/or lower levels of curtailment	30%	75%
Curtailment: Self-curtailment when wholesale prices are low or negative to avoid financial losses during those times	28%	56%
Storage hybrids: Co-locating wind projects with storage at the plant site or point of interconnection	26%	70%
Life extension: Operating to reduce mechanical stress when wholesale prices are low, in part to extend project life	26%	58%
Hydrogen: Using wind energy to produce fuels, such as hydrogen, at the plant site or point of interconnection	23%	73%
Overplanting: Building more wind power capacity than transmission interconnection capacity	21%	44%
Generator hybrids: Co-locating wind projects with other generating sources at the plant site or point of interconnection	11%	30%

FIGURE 6 Grid-value enhancement options for onshore and offshore wind

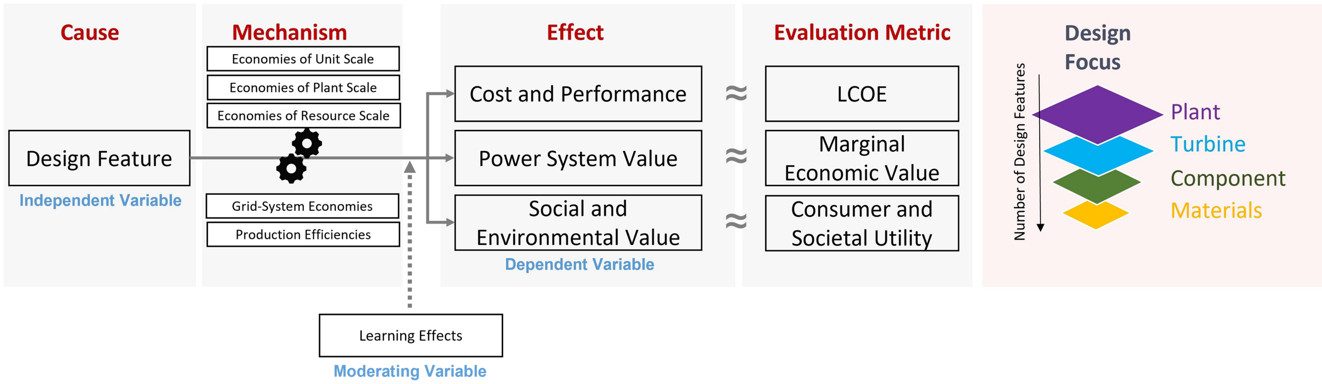

FIGURE 7 Conceptual mapping of design feature mechanisms, effects, and evaluation metrics (*left image*) and design focus (*right image*). *Note*. The listed evaluation metrics are examples that are commonly used. Different metrics exist to measure the effects (e.g., cost, performance, and value), depending on the intended use (e.g., rate of return)

TABLE 1 The effects of wind plant design features

Mechanism	Primary design features (examples)	Net effect[a]	Evaluation metric
Economies of unit scale	Larger and fewer turbines	Cost of the generating unit per kW decreases	LCOE
Economies of plant scale	More turbines (i.e., larger plants) Synergies with adjacent plants Greater manufacturing throughput	Fixed cost/kW decreases	LCOE
Resource economies of scale	Noise-reducing blade shapes Siting in higher quality resource areas	Generation (kWh) per kW increases or: Utility to society per kW increases	LCOE Social & environmental utility
Grid-system value economies	Advanced controls Siting Hybridization	System value per kW increases	System value
Production efficiencies	Substitution for lighter materials Blade aerodynamic design Airfoils Remote maintenance and faster installation strategies	Variable cost[b] per kW decreases or: Generation (kWh) per kW increases	LCOE

Note. The depicted design features are exemplary and not exhaustive.
[a]Holding all else constant.
[b]Variable costs are understood as those expenditures that vary with the level of output (in contrast to fixed costs).

offshore wind only.[34, ‡] Although these efforts generally acknowledge the significance of economies of scale for cost reductions, the exact mechanisms—for example, whether applied at the turbine or plant level—and their quantitative impacts remain unclear. Instead, economies of plant scale and economies of unit (i.e., turbine) scale are often used interchangeably,[35] even though these two mechanisms imply different conclusions for wind plant design.

In our theoretical framework, we distinguish conceptually between design features, mechanisms, effects, and evaluation metrics (Figure 7). Changing a *design feature* (e.g., the size of turbines) causes an *effect* on the cost and value of a wind plant. The magnitude and causal relationships between the design feature and its effect is governed by a *mechanism* (e.g., economies of unit scale). We conceptualize learning effects[36–38] as a moderating variable that influences the direction and strength of each of these economic mechanisms.[§] For instance, learning determines the extent to which turbines can be sized up (and at what cost), which is reflected in a series of individual and composite innovations, processes, and coordination activities (for further details, see Section S3). Evaluation metrics are used to measure the impact from a change in a design feature on costs, economic value, and utility to society or consumers. Further, when considering changes to a wind plant, the design focus often varies. We distinguish between focusing on plant, turbine, components, or materials.

Following the conceptual approach from Figure 7, we identified several key design features from the expert survey and combined those with the mechanisms that we hypothesize to be applicable (Table 1). The depicted design features are exemplary and not meant to be exhaustive. The

‡Economies of scale are also assessed generically for conventional power plants.[43,46]
§Dismukes and Upton[34] determine learning effects to exist when the "cumulative quantity of previously installed generating units is negatively related to the cost of producing the next unit" (i.e., the experience from past production allows for future production to occur more efficiently).

design focus of each mechanism can vary. For instance, economies of unit or plant scale are typically realized at the plant level, whereas resource and production efficiencies tend to appear at the turbine or subcomponent (e.g., materials) level.

We will now discuss each mechanism shown in Table 1 in turn, starting with a definition of each concept followed by a discussion of how the concept relates to our survey results. We distinguish between the various mechanisms by the quantity (i.e., Q in the denominator in Equations 1–6) that is varied. This quantity stands for the size of an individual turbine system (economies of unit scale), the number of turbine units (economies of plant scale), the three-dimensional space available to wind energy siting (resource economies of scale), the combination of input quantities (production efficiencies), and the time and location dependent electricity produced (MWh) (grid-system value economies). The first three are economies of scale because the quantity itself is changed, while for the other two mechanisms, either the make-up of the quantity changes (production efficiencies) or quantity covaries with electricity price (grid-system value economies). We consider moderating learning effects as an entirely different concept because they take effect over time and do not depend solely on physical dimensions (such as the number of turbines or input quantities). Although these concepts can be distinguished conceptually, they are interrelated in practice. For instance, learning mechanisms (e.g., technology innovations) are typically needed to enable economies of unit scale and economies of plant scale.

4.2 | Economies of unit scale

Economies of unit scale describe the effects from changing the size of a generating unit on the costs per unit.[33] For wind applications, we define "unit" as the turbine, tower, array cables, and—for offshore wind—the substructure. This relationship can be formalized as follows:

$$E(C,Q_u) = \frac{(\Delta C/C)}{(\Delta Q_u/Q_u)} < 1 \text{ for a given plant output } \overline{Q}_e, \tag{1}$$

where $E(C, Q_u)$ is the cost-quantity$_u$ elasticity, C is the capital ($/kW) and operations and maintenance (O&M) ($/kW/year) cost, $Q_u(s_u)$ is the number of generating units as a function of the unit size s_u (kW), and $\overline{Q}_e$ is a constant energy output (kwh). Economies of unit scale are present when a decrease of 1% in the number of generating units (by increasing the MW/unit) is associated with a decrease in total costs of more than 1%, while all else is constant.[¶] Wind exhibits economies of unit scale because as turbines increase in size, fewer generating units have to be installed, maintained, and decommissioned for the same power and services output. The primary effects from economies of unit scale are apparent in reduced capital (CapEx) and operational (OpEx) expenditures (i.e., a reduction in $/kW and $/kW/year). However, impacts on the grid value might also result if fewer generating units are present (see section on "grid-system value economies"). Economies of unit scale should be distinguished from economies of plant and manufacturing scale[33] because they result in different wind plant design characteristics.

Survey responses suggest that turbine upsizing is the most critical of all design drivers, in line with the 2015 survey findings.[2] This finding is echoed widely in the literature.[6,33,39–42] The fact that the LCOE trajectory predicted in 2015 was realized much earlier than anticipated could be the result of faster growth in turbine size during the last 5 years (see Section 3, and Wiser et al.[5]). Survey experts in 2020 again anticipate significant further growth in turbine size, attesting to economies of unit scale as a primary design driver for both onshore and offshore wind.

The relative increase in average turbine rating from 2018 to 2035 is anticipated to be considerably greater for offshore applications (+286%) compared to onshore applications (+120%). This could reflect the nature of marine logistics, which might lend itself better to turbine upsizing because larger components can potentially be transported and installed with greater ease than onshore. Permitting issues, transportation challenges, and community concerns were all highlighted as constraining growth in onshore turbine size (Figure 5).

Economies of unit scale are likely to diminish as turbine size increases because of technical (e.g., nonlinear component scaling, reliability, and resiliency) and logistical challenges. We did not gain any insight into this threshold from our survey responses. It remains to be seen at what turbine size threshold the diminishing returns might outweigh the costs to achieve them, which likely depends on several factors such as the wind application (e.g., onshore vs. offshore), logistical infrastructure, and siting and regulatory conditions.

4.3 | Economies of plant scale

Economies of plant scale are well established as drivers of cost reduction in production economics.[43–45] Economies of plant scale are present when "the percent increase in output is greater than the percent increase in costs needed to achieve the increase in output".[34, #] In other words, if economies of scale are present, then an increase of 1% of the produced energy (from more generating units) is associated with an increase in total costs of less than 1%, while holding the size of the generating units (i.e., MW/unit) constant:

¶Economies of unit scale have also been discussed for the nuclear generation and solar PV[33] and other infrastructure industries, such as aircraft and vessels.[66,67]

#That is, the average costs per unit of output decrease with the increase in the output.

$$E(C,Q_e) = \frac{(\Delta C/C)}{(\Delta Q_e/Q_e)} < 1 \text{ for a given size } \bar{s}_u \text{ of the generating units,} \quad (2)$$

where $E(C, Q_e)$ is the cost-quantity$_e$ elasticity, C is the capital ($/kW) and O&M ($/kW/year) cost, Q_e is the quantity of energy produced (kWh), and $\bar{s}_u$ is the constant size of the generating units (kW). Economies of plant scale are well established in the literature for energy technologies broadly[46] and relatively well established (though with contradictory results) for wind energy.[33,34,47,48] In wind energy, economies of plant scale are typically present when a fixed (or partially fixed) expenditure (e.g., port infrastructure, export cable system, access roads, and development costs) is spread over a larger amount of generating capacity (total MW). In this case, growth in the size of the plant results in a decline in per-unit CapEx (i.e., $/kW) or per unit OpEx ($/kW/year). With economies of plant scale, for example, additional units can leverage existing port and servicing infrastructure (i.e., a fixed cost) with relatively minor upgrades to accommodate additional generating units. Economies of scale are also realized through lower input prices from quantity discounts. For instance, suppliers might have lower expenses the higher the delivered amount, and the purchaser might have a stronger negotiation position that they can leverage. Broadly (and beyond the confines of the wind plant), economies of scale also extend to manufacturing when the fixed cost of manufacturing facilities can be spread across a greater output. These scaling effects generated in the manufacturing and supply chain are often referred to as "industrialization" of the sector, which also implies a high degree of standardization, as well as high and continuous production output. In our survey, we limited our question about plant size to offshore applications. Experts indicated an expected growth in offshore plant size, with a doubling for fixed-bottom offshore between 2018 and 2035. Presumably, this expectation is driven by the benefits of plant scale. The anticipated benefits from economies of plant scale are further illustrated by the relatively common mention by the survey respondents of O&M efficiencies and shared infrastructure when describing conditions that might drive low LCOE in the future (Figures S1 and S2). The survey did not reveal any insights about potential barriers to larger plant sizes, but limiting factors could include permitting issues due to competing uses (such as viewshed, wildlife, recreation) and detrimental wake and blockage effects.[49] In the survey responses, we found relatively little evidence for sector industrialization as a design driver, but industrialization might be implied in continued plant upsizing.

4.4 | Resource economies of scale

The siting of wind projects is governed by a number of factors—wind resource, market demand, transmission constraints, ecological impacts, competing uses, and social considerations.[17,50–54] Individually or collectively, these siting factors can affect the extent, rate, and cost of continued wind energy deployment.[53,55] Some of these constraints and adverse impacts might be mitigated through turbine technology[14] and wind plant design,[53] though doing so often imposes additional costs. With this as context, we define resource economies of scale to be present when an increase of 1% of the available wind resource is associated with an increase in total costs of less than 1%, while the total utility of the wind plant to society remains constant:

$$E(C,Q_r) = \frac{(\Delta C/C)}{(\Delta Q_r/Q_r)} < 1 \text{ for a given utility } \overline{U}_s, \quad (3)$$

where $E(C, Q_r)$ is the cost-quantity$_r$ elasticity, C is the overnight capital ($/kW) and O&M ($/kW/year) wind plant cost, $\overline{U}_s$ is the net social and environmental utility ($) of the wind project, and Q_r is the available wind energy resource (MWh, based on wind speed and profile) that can be accessed for wind project development and operation. In wind energy, increasing the "resource area" (i.e., the three-dimensional space available for wind energy siting) provides greater flexibility for turbine siting. We attest resource economies of scale to be present when a larger resource area available to wind development results in either higher energy production or reduced costs (or a combination of both), while the utility to society remains constant. For instance, serrated trailing edge blade treatments might mitigate some of the noise disturbance to nearby residents and therefore increase the number of (potentially higher yield) sites that are available for development. The (net) utility of a wind project can be understood as the sum of all social benefits (e.g., tax revenues, landowner payments, jobs, schools, and abated emissions) less its adverse impacts (e.g., nuisance or annoyances, property value reductions, or impacts to wildlife). Additional costs to access incremental wind energy resources might be incurred through solutions (such as trailing edge blade treatments) that mitigate the adverse impacts on society (e.g., annoyances and value loss). If this additional resource can be accessed without an offsetting equal increase in costs, while social utility is held constant, we attest that resource economies of scale are present.

The survey sheds some light on how experts regard resource economies of scale. The wind speed at typical new onshore wind sites in 2035 is expected to be lower than it was in 2019. For fixed-bottom offshore, the wind speed is expected to remain constant, perhaps a consequence of moving towards farther-from-shore sites. Yet for both onshore and fixed-bottom offshore, the experts expect improvements in capacity factors over the same time period and a coincident decline in LCOE. We attribute this, in part, to the use of taller towers. Taller towers are therefore enabling resource economies of scale despite an expectation of continued siting constraints (whether due to transmission, social, or environmental constraints).

Yet in the case of taller towers, it remains unclear from our survey results whether the assumption of a constant utility can be upheld. Tall towers are not a panacea for achieving resource economies of scale, and in fact, turbine growth (in terms of both hub height and rotor diameter) has inherent trade-offs. Achieving higher hub heights typically places wind turbines into a better wind resource regime and can enhance the value of wind energy to the electricity system,[10,56] while larger rotors allow the turbine to capture more of the energy that passes by with relatively less impact on the rest of the system, boosting energy capture per dollar invested.[57] But each of those factors also makes turbines more conspicuous and influence sound, shadow flicker, and visual impacts at the local level. Although taller towers and larger rotors may open up new (i.e., lower wind speed) regions for wind development, they may simultaneously face new challenges with respect to local permitting.[16] Particularly for onshore wind, the experts expect that "permitting" and "community concerns" will have significant impacts on turbine growth and selection (Figures 4 and 5), suggesting that manufacturers will increasingly need to weigh social utility when designing new turbines and when turbines are selected by developers for specific sites.

4.5 | Grid-system value economies

The survey reveals that grid-system value considerations are of growing importance to project development. Grid-system value can be described as "the ability of any bulk-power system asset [such as wind energy] to contribute to meeting demand such that it avoids the cost of instead using other bulk-power system assets."[58] We consider grid-system value economies to be present when the marginal increase in grid-system value[**] exceeds the marginal cost of achieving it:

$$V(P_{t,l}, Q_{t,l}, C) = \frac{\Delta cov(C, Q_{t,l})/cov(C, Q_{t,l})}{\Delta cov(Q_{t,l}, P_{t,l})/cov(Q_{t,l}, P_{t,l})} < 1, \tag{4}$$

where $V(P_{t,l}, Q_{t,l}, C)$ is the cost-value elasticity; $V_{t,l}$ is the remunerated value services (e.g., energy, capacity, ancillary services) provided by the generator to the power market (in \$) at time t and in location l; C is the capital (\$/kW) and O&M (\$/kW/year) cost; $Q_{t,l}$ is the quantity of electricity produced (MWh) at time t and in location l; and $P_{t,l}$ is the price for value services (\$) at time t and in location l. The grid-system value of a wind power plant is determined in good part by the coincidence of provided wind energy services and wholesale power prices. The higher the covariance, the higher the revenue of the wind power plant, holding all else equal. This can be measured by the covariance between $Q_{t,l}$ and $P_{t,l}$. Any increases in their covariance typically necessitate an investment. Therefore, the amount of wind energy services $Q_{t,l}$ covary with the total costs C. Whenever the change in the covariance of electricity produced with price exceeds the covariance between electricity produced and costs, grid-system value economies are present. They also appear when the predictability of the wind energy services grows without a proportional increase in the total costs (not shown in Equation 4 for simplicity).

As wind penetrations increase, wind's marginal grid value tends to decrease (all else being equal). Yet several strategies exist to enhance the grid-system value of wind power.[59] In our survey responses, several grid-enhancing strategies were rated highly for significant and widespread use, perhaps suggesting that their relative importance will grow in the future (versus, e.g., cost minimization efforts). Some of the grid-enhancement options, such as the wind plant's location (i.e., next to interconnection points with higher realized wholesale prices), larger rotors, co-location with other generation, energy storage, or hydrogen infrastructure, and the number of turbines (i.e., overplanting) would impact wind plant design. Other value-enhancing measures are less visible but influence how the wind farm is operated, such as the provision of balancing services and self-curtailment.

The decision to make a value-enhancing design choice is ultimately a trade-off between the incremental value gain and the additional costs (or foregone revenue) required for its implementation. Further, uncertainty about the compensation rules for value services (such as ancillary services) might limit the future application of value-enhancing services, as might institutional rules that preclude wind from providing certain services. Larger rotors, meanwhile, might be limited by permitting regimes and competing uses (e.g., viewshed and noise impacts). In the case of hydrogen, which was rated more relevant for offshore than onshore applications, a limitation might be the availability of a pipeline infrastructure.

4.6 | Production efficiencies

Production efficiencies occur when less costly production techniques, materials, or operational strategies can be used to produce a given output. When production efficiencies are present, a change in the combination of input quantities (e.g., of steel, aluminum, and labor) is associated with a reduction in total costs for a constant output of wind services[††]:

[**]From wind energy services, such as energy, capacity, and ancillary services.

[††]Such as energy, capacity, and ancillary services.

$$E(C,Q_i) = \frac{(\Delta C/C)}{(\Delta Q_i/Q_i)} < 1 \text{ for a given output of wind energy services } \overline{Q}_{t,l}, \tag{5}$$

where $E(C, Q_i)$ is the cost-quantity$_i$ elasticity, C is the capital ($/kW) and O&M ($/kW/year) costs, Q_i is a vector of inputs (with specified quantities [e.g., kilograms or full-time equivalents] of steel, aluminum, labor, or operational strategies), and $\overline{Q}_{t,lt,l}$ is the quantity of energy services provided by a wind plant (as defined above). In wind energy, production efficiencies can be achieved by substituting with less costly or higher-yield materials (e.g., lighter or fewer materials), faster installation and maintenance strategies, standardizing processes, or enhancing coordination in the supply chain. When present, any of these would effectively reduce the per-unit cost (i.e., $/kW [CapEx] or $/kW/year [OpEx]).

We did not find much direct evidence for production efficiencies in the answers from survey respondents. However, we also did not specifically ask respondents to identify the fundamental drivers of cost reductions. That said, the presence of production efficiencies can be inferred from responses to questions related to turbine size and CapEx. Specifically, survey respondents anticipate significant growth in turbine size, but a decline in upfront capital expenditure. This may be due to unit economies of scale but could also be attributed to production efficiencies that come from lighter materials or lower relative materials usage due to engineering advancements. To enable larger turbines, the use of lightweight materials is often required.[60] Mention of improved or lighter weight materials appeared in the descriptions of the low LCOE scenario (Figures S1–S3), though relatively infrequently compared to other themes.[‡‡]

4.7 | Holistic design considerations

While we consider each economic mechanism to be relevant for design practice on its own, wind energy is perhaps unique in that systemic design considerations (i.e., plant-wide and in its interaction with the power system) matter greatly. In practice, wind plant design features are typically evaluated through co-optimization[§§] across different evaluation metrics (e.g., LCOE and grid-system value). In the survey, we find evidence for holistic design considerations in the multiple factors that were specified to influence onshore turbine selection (Figure 4). Only in rare cases does the change of one component not have consequences on the optimization of another. Co-optimizing across different evaluation metrics is not trivial because of data limitations, inconsistent units of comparison, and competing perspectives on how to weigh each factor. An academic and practice field has emerged that is concerned with "systems engineering,"[61] which attempts to develop protocols and data to allow for such co-optimization. Such co-optimization often takes the general form of:

$$\mathrm{Max}(U_{\mathrm{Wind}}) = w_1 * \max(-LCOE_{\mathrm{Wind}}) + w_2 * \max(U) + w_3 * \max\left(U_{\mathrm{Local\ Population}}\right), \tag{6}$$

where U_{Wind} is the utility of a wind plant to society, $LCOE_{\mathrm{Asset}} > 0$ represents the levelized cost of the wind plant, U_{System} is the utility (or value) of the wind plant to the power system, $U_{\mathrm{Local\ Population}}$ is the utility of the wind plant to the population that lives in proximity to the wind plant, and $w_i > 0$ is the weight that is assigned to individual utility components (per regulation, market, societal, or developer assessment). Alternatively, the utility$_{\mathrm{Local\ population}}$ could be rearranged as a constraint in the equation above, which might be more akin to the perspectives of a project developer or owner. Here, we take a broader perspective and include utility$_{\mathrm{Local\ Population}}$ as a metric to maximize. The lack of a metric with a common unit makes direct comparison challenging at best, and perhaps impossible in many cases.[¶¶] The weight w_i depends on the societal actor or group; for instance, a developer might weigh LCOE more heavily, while regulators might assign greater weight to environmental concerns.

5 | CONCLUSION

In this article, we described key features of onshore and offshore wind plants in 2035, drawing on a survey of 140 global wind experts. Our findings suggest that a continued growth in turbine size can be expected in conjunction with the more frequent use of value-enhancing grid strategies. These design choices support reductions of LCOE by 27% (onshore) and 17%–35% (floating and fixed-bottom offshore)[##] compared to today's levels. This technology evolution and expansion of wind's service offerings is anticipated to take shape in an environment with increasingly less favorable siting conditions; onshore projects are expected to be located in slightly lower wind speed regimes compared to

[‡‡]In principle, economies of scale can also be described as a production efficiency. However, we separate these here because the implications for wind plant design and operation differ (i.e., the former yields more turbine units while the latter results, e.g., in the substitution of materials).

[§§]In this context, co-optimization refers to the simultaneous optimization of two or more different, yet related, design features within one optimization formulation (adapted from Olatujoye et al.[68]).

[¶¶]Efforts have been made in the cost–benefit literature to compare these across a common unit by monetizing all of them in currency.[2]

[##]An LCOE reduction of 17% is predicted for floating offshore wind; a reduction of 35% is predicted for fixed-bottom offshore wind. Note that floating offshore wind LCOE is compared with a fixed-bottom 2019 baseline (see Wiser et al.[5] for further details).

today and offshore projects are anticipated to be located farther from shore and in deeper waters. Specifically, survey respondents expect plant size to average 1,100 MW for fixed-bottom and 600 MW for floating offshore wind applications, a significant increase from today's levels. Compared to fixed-bottom in 2035, floating applications are expected to be even farther from shore and in much deeper waters; they are also anticipated to benefit from higher average wind speeds. At the same time, floating applications are expected to become increasingly cost competitive at shallower water depth. Anticipated, grid-system value enhancement options include larger rotors, hybrid projects with battery storage and hydrogen production, and siting strategies that maximize grid-system value. Operational strategies, such as using wind assets to provide grid services beyond energy and self-curtailment during periods of low wholesale prices, were also identified as likely to see significant use.

We identify several economic mechanisms that link these (and other) design choices to their effect on wind energy's cost and value offering. Economies of unit scale reduce the per-unit cost of turbines (and substructures) and result in turbine upsizing. Economies of plant scale spread a fixed cost over a larger number of turbines (holding all else constant), incentivizing a move towards larger plant sizes. Resource economies of scale are enabled by innovative technology solutions and siting strategies that lead to an incremental gain in the captured wind energy resource with a smaller relative increase in costs. Production efficiencies are created by less costly inputs for a given output by substituting existing materials with cheaper and lighter-weight ones. Further, we identify learning effects as a moderating variable that influence the strength of each of these economic mechanisms. We highlight that co-optimizing across the various cost and value components remains an important paradigm in wind plant design and operations, both in practice and in research. As LCOE is forecasted to decline, the influence of power system, social, and environmental value considerations is expected to grow.

With these survey findings in mind, some important questions remain. Namely, our survey answers suggest considerable technological evolution from the present day, but it is not clear whether additional, more drastic wind technology advances might be needed to support the power sector's transition to a deep de-carbonization and sustainable future, given the potential scale of infrastructure buildout needed. To achieve these types of de-carbonization scenarios, accelerated wind deployment (e.g., a doubling or tripling of average annual deployment rates in the United States alone[53,62]) and greater integration with other power system assets (e.g., with other variable renewable energy, demand, and storage devices) are likely necessary. A perspective one could draw from our results is that the turbine growth trajectory elicited in this survey is not too far removed from what is available as commercial offerings today. For instance, the onshore turbine parameters expected by our survey respondents are only about 10%–15% larger than what can be purchased today.[63] For offshore applications, the percent increase in size is somewhat greater, in the 15%–50% range.[64, ***] In contrast, one could also conclude that turbine growth alone—although it generates cost savings—is only one of several factors that make wind energy economically more attractive and can enhance deployment. As we found in the survey, revenue (i.e., system-grid value), logistical, competing use and social considerations, and others matter as well for turbine selection. From a deployability perspective, the use of a relatively stable turbine size and technology could suggest opportunities for standardizing supply chains, which might be hard to achieve if the technology continues to evolve rapidly. At the same time, enhanced standardization might limit the ability to tailor turbine and wind plant design to new or potentially more stringent social and environmental constraints. Deployment will likely have to find an optimal balance between standardization (i.e., wind energy costs) and highly customizable solutions that meet the requirements of local competing use and wildlife considerations and future work might better illuminate these tradeoffs and their appropriate balancing. Considering the sustainability of wind energy manufacturing and operations, we hypothesize that there might be risks to an incremental technology development approach relative to more drastic innovations. Reliance on concrete for wind turbine foundations and fiberglass for blades present carbon use and waste disposal challenges.[65] In addition, although not in widespread use, rare earth metals could introduce additional risks into the materials supply for wind energy.

Admittedly, we did not ask survey respondents specifically to consider a deep de-carbonization scenario when specifying wind plant design and operations, and most importantly, we focused their responses on a median scenario only. There is a good chance that our survey would have yielded more drastic changes to wind plant design and operations if we had asked respondents about a deep de-carbonization scenario or the full breadth of possibilities and scenarios. It is also possible that technology foresight is inherently limited with implications on the magnitude of the innovation challenge and R&D needs.

These various considerations suggest two specific future research directions. First, research should assess the extent to which additional innovation is needed for wind power to achieve a dominant role in a future power system. The wind plant design parameters presented in this article give energy modelers and analysts a helpful benchmark for scenario analysis of future wind and power system trajectories. But, under deep de-carbonization scenarios, an even broader set of wind plant design and operations considerations may come to the fore and could usefully be the focus of future elicitations. Second, research should continue to explore the accuracy and biases inherent in expert assessments relative to other forecasting methods. Past research has sometimes found that experts underestimate technological change or are overconfident in their assessments.[5] Validation efforts are needed to investigate the scope of the possible biases and to assess methodological options to increase predictive accuracy and insight.

***Note that a 15-MW rated turbine is in prototype development (Vestas V236-15.0 MW) but cannot be purchased yet commercially.[69]

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CONFLICT OF INTEREST

One author (p.G.) is employed by the U.S. Department of Energy, which provided funding to support research for this article. P.G. contributed to formulating the research, constructing the survey, and discussing, reviewing, and revising this article. The authors contend that this competing interest had no bearing on the results or findings of the work.

AUTHOR CONTRIBUTIONS

All authors contributed to formulating the research; constructing the survey; and discussing, reviewing, and revising the paper. P.B. led the conceptualization and completion of the initial draft of this article. P.B., J.S., J.R., and E.L. drafted most of the article. R.W. and P.G. edited the manuscript and provided guidance on the analysis. J.S., J.R., and P.B. led the analysis of the survey responses, with assistance from R.W. R.W. led the overall survey effort and completion of the companion article published in *Nature Energy* and titled "Experts predict 37% to 49% declines in wind energy costs by 2050"[5] to which all coauthors of this article also contributed.

PEER REVIEW

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DATA AVAILABILITY STATEMENT

Respondent-level data from the 2020 survey can be accessed at https://emp.lbl.gov/publications/expert-elicitation-survey-predicts-37. Answers to the small number of questions that were open-ended, inviting narrative responses, are not included in this data repository to help ensure the confidentiality of the respondents to the survey. Data underlying the figures will be provided with the published version of this article.

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