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The co-benefits of California offshore wind electricity

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ABSTRACT

California has set forth an ambitious goal of generating all its electricity from carbon-free technologies by 2045. Offshore wind (OSW) presents several attractive system, economic, and environmental attributes to help the state achieve these goals. Inclusion of OSW into the clean electricity generation portfolio could contribute significantly to total resource cost savings. In addition, OSW offers several major co-benefits. Its high and consistent capacity factor and generation time profile complements that of solar and helps enhance renewable electricity generation reliability. OSW could also be instrumental in early retirement of costly and pollution-heavy natural gas plants and lead to substantial job creations. Moreover, California could reap additional economic co-benefits from the development of a local wind energy industry. Additionally, OSW has the potential to advance environmental justice through reduction of ordinary air pollutants in urban areas and by bringing economic opportunities to lagging areas. At the same time, there are multiple challenges that must be addressed for OSW to reach its full potential. Our analysis is intended also to serve as a template for studies elsewhere by providing a comprehensive framework for estimating co-benefits, taking account of important local conditions, and identification of challenges and how they might be overcome.

1. Introduction

California has set forth an ambitious goal of generating all of its electricity from clean and carbon-free technologies by the year 2045. The state had been planning for this target to be met primarily by several renewable sources like solar, land-based wind, geothermal and biomass, along with other zero-carbon technologies. Offshore wind (OSW) energy has more recently proven to be a technologically feasible and economically viable option in other locations. Therefore, momentum has increased to include California's OSW energy as a complement to its current renewable energy and storage resources.

Given the long time-horizon of California's electricity planning, it is prudent to be flexible about the range of technological options. OSW has several relative advantages and can complement other renewable alternatives. Currently, OSW is being included in California's 2019–2020 Integrated Resource Plan (IRP) modeling for the first time by the California Public Utility Commission (CPUC, 2020). The CPUC has also directed the California Independent System Operator (CAISO) to assess the transmission capacity and requirements for large-scale OSW as part of a policy analysis of the Transmission Planning Process (TPP).

The current U.S. presidential administration has formally expressed its support for speeding up the development of OSW to the level of 30 GW nationally by the year 2030, including committing sizable funding for loans to the industry and for increases in seaport capacity to accommodate the shipment of the necessary large equipment components. This commitment to OSW appears staunch as well, given that the U.S. Departments of the Interior and Commerce recently approved construction of the Massachusetts Vineyard Wind Project, the first utility-scale OSW farm in the United States (BOEM, 2021). Furthermore, the Biden administration announced on May 25, 2021, an initiative to accelerate California OSW development. Specifically, the Departments of the Interior and Defense have delineated a central coast development area known as the "Morro Bay 399 Area". The Interior Department has also stated that it will engage in efforts to advance a potential OSW area on the northern coast of California adjacent to Humboldt County (White House, 2021).

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California has recently made tremendous strides in the effort to make Pacific OSW a reality. On September 23rd, 2021, California Governor Gavin Newsom signed into law AB 525, which creates a directive for state agencies to deliver plans for the establishment of OSW in the state's coastal waters (Bulijan, 2021). This state bill is contained within a much broader climate package as part of the California Comeback Plan (Office of Governor Gavin Newsom, 2021). It mandates the California Energy Commission (CEC) to set OSW energy production targets for 2030 and 2045 and determine the maximum feasible capacity of OSW before June 1, 2022. The legislation also outlines the needed infrastructure improvements (such as port space and transmission lines) to allow for OSW generation and distribution. The bill, moreover, requires the CEC to coordinate with the other relevant state and federal agencies, and other stakeholders, to identity suitable sea space, develop a permitting roadmap, and assess potential impacts on coastal resources and groups of peoples (California Legislative Information, 2021). The passing of this bill comes as the nation as a whole is preparing for an imminent OSW future (Davenport, 2021).

The California Energy Commission (CEC) recently recognized the potential of OSW and worked with the federal Bureau of Ocean Energy Management (BOEM) to identify the best sites in the state, as identified in the President's May 25th announcement. A recent draft report by a Joint Agency group composed of the CEC, CPUC, and California Air Resources Board (CARB) indicated that, under several scenarios including the "core study scenario," 10 GW of OSW is required to meet the 100% clean energy goal in the state by 2045 (CEC/CPUC/CARB, 2021). The report estimates that this addition of OSW would contribute toward total resource cost savings of $1 billion. At the same time, the 10 GW represents only about 5% of the estimated OSW potential capacity in the state.

In addition to providing economic gains to ratepayers, OSW in California can offer several major co-benefits (Rose et al., 2021). The purpose of this paper is to estimate these additional gains. A large number of direct net job gains will accompany OSW development, even after accounting for displacement of other sources of electricity. Moreover, these construction and operation/maintenance jobs on-site have multiplier effects on the rest of the state's economy. Furthermore, many of the direct job gains would likely be in areas of the state that are lagging economically, thereby promoting income equity. OSW promises reductions in ordinary air pollution and greenhouse gas emissions when accomplished through the displacement of fossil-fuel installations in urban areas, which would also yield environmental justice co-benefits. OSW represents a valuable complement to other renewable energy sources in terms of electricity reliability as well. Also, an early start on OSW development could help California become a leader in OSW technology and support industries up the supply chain, as well as allow the state to become an important transshipment point for trade in this technology with other Pacific Rim countries.

All of this is not to deny that issues still need to be resolved relating to planning, including the permitting process and environmental compliance, the need for a significant amount of investment in transmission lines, and the need to address a diverse set of stakeholder concerns. We also address these concerns and note the progress underway in addressing them.

Offshore wind development will need to consider many localized features, including wind speed, water depth, solar radiation competitiveness, transmission line accessibility, proximity of support industries, availability of nearby specialized ports, and especially state and local government regulations. Our analysis, however, is intended to be of broader interest by serving as a template for studies elsewhere by providing a comprehensive framework for the analysis of co-benefits, specification of how these are affected by important local conditions, and identification of challenges and how they might be overcome.

Section 2 presents the analytical framework used to evaluate electricity generation technologies, including both the consideration of the "value proposition" relating to delivering electricity and other broader co-benefits. OSW development potentials in California and operating experiences in other states/countries are introduced in Section 3. Section 4 summarizes the important role of OSW in providing flexible and reliable clean electricity resources. The direct benefits and co-benefits of OSW are evaluated in Sections 5 and 6. More detailed job creation potentials of a 10 GW OSW build-out in California and the development of in-state wind energy manufacturing cluster are presented in Section 7. Section 8 discusses major challenges of OSW development. Sections 9 and 10 conclude the paper by providing a summary of our findings.

2. Analytical framework and methodology

Many factors are typically considered in evaluating electricity generation technologies. The major one is the "value proposition," which is the cost of generating electricity without a given technology minus the cost of generating it with the technology. In other words, it is the cost savings to the system from adopting the technology. This is an example of cost-effectiveness analysis (CEA), which essentially compares the new candidate to the current or projected mix of technologies to determine whether it is competitive in delivering a given amount of electricity. CEA is a special case of benefit-cost analysis (BCA), because it does not require consideration of any benefits beyond delivering a target level of electricity. If the revenues from producing electricity are juxtaposed to the costs, it would also be analogous to the private-sector profitability criterion.

This narrow characterization of the value proposition, however, has evolved to include other considerations relating to delivery of electricity. One of these is "reliability," which differs across energy resources and technologies in terms of variations in daily or seasonal input flows and the prevalence of scheduled and unscheduled downtimes of the technology that transforms the raw energy into electricity. In this case, the value proposition becomes even simpler because the candidate technology need only be compared to the cost and reliability of the next one or two resources/technologies it is intended to replace and not the entirety of the electricity production mix. Still another basic extension is to cast the analysis in "portfolio theory," where diversification is a key risk reduction strategy, and any new candidate technology can contribute to this apart from a narrower value proposition or the reliability consideration.

Public policy decisions, on the other hand, are based on many other considerations. Beyond the narrow benefit of delivering electricity, these have come to be known as "co-benefits." One of the first examples of this concept was that of "joint-product" production, as in the case of multiple-purpose river development, which factored in the value of flood control and recreational services in evaluating hydroelectric dam projects (Krutilla, 1958). More recently, there has been a focus on the co-benefits of reducing greenhouse gases and ordinary pollutants with the use of clean energy technologies. One way of factoring this into the basic CEA or BCA criteria is to value the social costs (health, property, ecological) of the pollutants and add them to the cost of the technology that generates the pollutants in making the comparison of energy alternatives. An alternative approach is to consider the reduction of these broader *societal cost* of pollution as a direct *social benefit* of the candidate renewable/clean energy technology. Other co-benefits include: job creation and its multiplier effects on the overall economy, improvements in equity/justice, enhanced national security, technological innovation, and attainment of broader economic development goals.

Many of these co-benefits are not always fully appreciated by those who interpret CEA or BCA in a narrow sense. However, their acceptance has been increasing over the years. The societal cost of pollutants has resulted in the inclusion of price "adders" in electric utility rate-making (see, e.g., Burtraw et al., 1995; Akin-Olçum et al., 2021). More recently, there has been a renewed push to include "economy-wide" (multiplier or multi-market) effects (EPA, 2017; Farrow and Rose, 2018). Also, recently, there has been a move to analyze disaster risk reduction, including long-term disruption of utility infrastructure, in terms of a "resilience triple-dividend." In addition to including the direct benefits of lowering potential losses, it adds two general categories of co-benefits— reduction of uncertainty, which improves the business climate, and inclusion of externalities and joint products (Surminski and Tanner, 2016; Rose, 2016).

Employment impacts from the potential development of OSW represent a major category of co-benefits of climate action plans including specific energy technologies (Rose and Wei, 2012; Wei and Rose, 2014; Wei and Rose, 2016; Mamkhezri et al., 2021). This is sometimes a controversial topic characterized by extreme claims that rushing renewables will be a panacea or will bankrupt the economy.

Yet another co-benefit is the potential to attract OSW-related industrial clusters to California. These would further reduce production costs through agglomeration effects and increase the size of multipliers of the supply chain by displacing imported sources of OSW equipment with local production.

Finally, we consider regulatory obstacles and supportive measures and inducements relating to a range of stakeholders, including electricity generators, electricity grid system operators, investors, developers, trade unions, the general population, and governments at all levels. Along the way, we examine positive and negative aspects of OSW development in California, and identify ways to enhance the positive and reduce the negative ones, mainly through the fostering of development of wind energy manufacturing capacities and clusters within the state.

3. Background

California has implemented a number of policy goals intended to transition the state into a green economy, notably including Senate Bill (SB) 100, which aims at achieving a 100% clean electric grid by 2045. The target in California SB 100 is expected to be met primarily by renewable generation sources like onshore wind, onshore solar, and geothermal, along with other zero-carbon technologies like existing hydroelectric and energy storage (see SB 100, 2018). Wind energy has a potentially strong presence in California, as it has proven to be a technologically feasible and economically viable resource elsewhere. Moreover, formal steps have been taken and public and private sector support has been increasing to include OSW as a complement to the state's current renewable energy portfolio standard (RPS) (CPUC, 2020; SB 100 Joint Agency, 2021).[1]

California is on track to meet its goal of 60% renewables by 2030. However, under the SB 100 Core scenario, which factors in high electrification demand, California will need to install around 50 GW of cumulative renewable capacity to meet the 2030 goal, and greater than 150 cumulative GW to satisfy the 2045 goal of complete carbon neutrality (CEC et al., 2021). Additionally, California is expected to require two to six times current renewable generation capacity by 2050 in order to meet the state's separate GHG emission reduction goals outlined in AB 32, which indicates the potential need for 100–150 GW of new capacity (Hull et al., 2019; Mahone et al., 2018). Meeting these decarbonization goals will necessitate a large overhaul of the current electric system and a diversified energy mix in California.

OSW is an attractive alternative for several reasons, as evaluated by Wang et al. (2019), Collier (2020), and Brightline Defense (2020), and as included in policy discussions by the SB- 100 (2018), CEC (2021), CPUC (2020), Amul et al. (2020), and Chiu (2021). In California, there is an extensive coastal wind resource base. OSW in five potential OSW development areas in California has the potential to generate up to 21 GW of electricity in perpetuity (Collier, 2020). This could contribute up to 12% of California's anticipated renewable electricity growth by 2045. Total OSW technical potential in California is considered to be approximately 200 GW; therefore, the state could possibly accommodate even larger net capacities than what these studied sites would offer (Optis et al., 2020).

Appendix A provides a summary of the OSW operations in other states and countries.

4. Role of OSW in meeting the need for flexible clean resources in California

4.1. Extent of the resource base

Studies to date have focused on five potential areas totaling 21 GW of viable OSW resource in California, capable of providing around 25% of state electricity needs in perpetuity (CPUC, 2020; Beiter et al., 2020c; Collier et al., 2019).[2] The total space potentially available for the first round of offshore wind development, according to the recent White House announcement, would enable roughly 4.6 GW.

In the 2019–2020 Integrated Resource Planning (IRP) process in California, OSW was included as a candidate resource available starting in 2030. Modeling conducted by the CPUC selected OSW as part of a least-cost 2030 energy portfolio, but only under the strictest GHG target of 30 million-metric-tons (MMT). Specifically, 1.6 GW is selected (primarily from the Morro Bay call area) under the assumption that no new out-of-state onshore wind (OOS) is available. If 3 GW of OOS wind resources in Wyoming and New Mexico are made available, selected OSW capacity falls to only around 6 MW. Still, these figures are only a fraction of the technically viable OSW resources across the five sites listed above (CPUC, 2019). It is important to note, however, that the CPUC and the CAISO are currently working to update the cost and resource assumptions for OSW by incorporating the latest projections from NREL and transmission cost information that will be available in early 2022 with completion of the OSW sensitivity in the TPP. These updates will potentially improve the performance of OSW in future cycles of the IRP.

4.2. Niche role based on some superior qualities

OSW energy generation has several superior qualities that warrant its further evaluation by California's energy planning agencies. Winds off the coast of California are steady and generally blow throughout the day, offering the potential for consistent electricity generation. OSW also experiences higher and more stable capacity factors than terrestrial wind sources (Hull et al., 2019). Additionally, offshore wind shows a tendency to peak between 6 PM and 9 PM, and this daily peak coincides with the hours when net energy demand ramps up quickly. In contrast, solar generation typically peaks around noon, and onshore wind peaks around midnight (Wang et al., 2019; Hull et al., 2019). There is a daily challenge of balancing the electricity grid, and this issue is exacerbated by vanishing solar generation in the evenings as power consumption rises (Collier, 2017). The evening "ramp" is typically met by natural gas plants either powering back on or increasing generation, thereby increasing GHG and local air pollutants.

[1] Offshore wind was made available as an optional "candidate" resource for the first time in the state's 2019–2020 IRP process, which helps to coordinate the expansion of carbon-free energy by load-serving entities (Amul et al., 2020). Since the release of the 2019–2020 (IRP) report, the CPUC has been collaborating with the BOEM and the National Renewable Energy Laboratory (NREL) to further explore offshore wind's potential in California's resource portfolio. OSW has also been included in core modeling scenarios in the 2021 SB 100 joint agency report, and the modeling has determined that offshore wind (up to 10 GW) is selected for resource planning purposes when made available.

[2] The total resource potentials for the three BOEM designated call areas, Humboldt, Morro Bay, and Diablo Canyon, are estimated to be 1.6 GW, 2.4 GW, and 4.3 GW, respectively. The other two major study areas, Cape Mendocino and Del Norte, have total resource potentials of 6.2 GW and 6.6 GW, respectively (Amul et al., 2020; Beiter et al., 2020c).

OSW generation has the potential to eliminate this energy imbalance. OSW is also more suitable to operate in tandem with solar than onshore wind resources due to its capacity factor and stability advantages (the fact that OSW capacity factors are less volatile than other renewables). These advantages may also help reduce the state's future reliance on costly grid scale lithium-ion battery storage (Hull et al., 2019). The desirable generation attributes of OSW can therefore help in providing energy diversification for a high-electrification future.

OSW turbines can thus also be expected to operate at greater capacity for a larger percentage of time than onshore wind, which can offset relatively higher installation costs. The reliability of wind speed also reduces wear on the turbine and limits plant downtime, reducing the need for backup generation (BOEM, 2017). Furthermore, unlike solar PV, OSW maintains a similar levelized avoided cost of energy (LACE) at increased scale because generation is spread more evenly throughout the day. All of these positive characteristics of OSW power will be increasingly valuable to the grid, especially given the upcoming decommissioning of currently operational energy resources like the Diablo Canyon nuclear power plant (American Jobs Project, 2019).

4.3. Potential of OSW to replace other generation

OSW could further reduce the need for back-up gas generation to balance variable renewables. Offshore wind's capacity value may also offset the need for the CAISO or load-serving entities to maintain Resource Adequacy (RA) contracts with gas plants, enabling quicker retirement of peaking plants than otherwise would be retained for reliability needs. Furthermore, Collier et al. (2019) postulates that the addition of 8 GW of offshore wind would replace the need for approximately 7 GW of battery storage and 14 GW of solar, as well as precipitate the retirement of an additional 5 GW of combined-cycle (NGCC) gas plants by 2045.

A recent NREL study (Beiter et al., 2020a) has also indicated that under 2 GW and 7 GW hypothetical offshore wind rollout scenarios on the east coast, OSW capacities can primarily displace NGCC generations, providing 4% and 13.5% of total energy consumption in ISO-NE, and 1.4% and 5.1% in NYISO. However, the increased variability in the net load of OSW generation does cause NGCC plants to experience increased starts and decreased hours on-line. The variability can also lead to more frequent starts, and at higher costs, for natural gas combustion-turbine plants.

In CPUC SB 100 2045 framing study scenarios (CPUC, 2019), three scenarios were explored that reflect varying decarbonization strategies: high electrification, high biofuels, and high hydrogen. All scenarios assume the GHG policy constraint of 86 MMT by 2050. In considering the high electrification scenario, the sensitivity that includes OSW as a candidate resource enables the largest retirement of gas-fired power plants (5.2 GW), equal to around one-eighth of California's current natural gas generation capacity.

5. The basic value proposition – direct benefits

We begin with the evaluation of OSW cost-effectiveness. Total OSW System Value is defined as the cost of generating electricity without a given technology minus the cost of generating it with the technology. In other words, it is the cost savings to the system from adopting the technology. Appendix B summarizes basic electricity generation and transmission considerations.

While California's state utility and energy agencies have not until very recently begun to model OSW in integrated resource planning portfolios (IRPs) (CPUC, 2020), empirical studies of the technology in the wake of the erection of OSW farms around the globe have provided evidence of this technology's potential for transforming California's power grid.

One key component of OSW's value proposition involves the more traditional benefit of integrating the technology into the state power grid. A recent estimate by the CEC/CPUC/CARB (2021) in a joint agency report estimates that the inclusion of OSW into the state's portfolio of clean electricity generation could contribute up to $1 billion in annual total resource cost savings. Another estimate places this contribution at up to a net present value of $2 billion between 2030 and 2040 for 7–9 GW of installed capacity (Energy and Environmental Economics, 2019). The majority of the savings stem from the displacement of higher-cost energy alternatives. Resource portfolio diversity can thus generally lower system-wide costs.

6. Co-benefits

6.1. Reliability Co-benefits

The first area of analysis in determining the efficacy of OSW in California concerns grid-system benefits. One significant reason for the difficulty in integrating renewable energy into electric grids is that the energy generation profiles of existing technologies do not always adjust for system reliability (Wang et al., 2019).[3] In order to match energy supply and demand during peak hours, California often deploys costly and carbon-intensive natural gas peaking plants. This mix of energy generation may be adequate in the short-term, but as the state's share of renewable power purchases increases, this grid incompatibility will not be sustainable and could lead to rolling blackouts, as witnessed recently (Smith et al., 2015). The hourly generation profile of OSW could potentially address the grid balancing problem, as Pacific winds generally blow 24 hours a day and peak around 6–9 PM, when energy demand is highest (Wang et al., 2019; Hull et al., 2019). By bridging the late-afternoon gap between diminishing solar radiation and rising electricity consumption, OSW could also reduce the need to import power from other Western states, and, moreover, allow California to develop additional renewable capacity without destabilizing the grid. Additionally, OSW is typically stronger and more consistent than land-based wind, and this reliability can provide more constant power to the grid, further reducing the need for backup gas generation (AECOM, 2017). Development of OSW close to coastal load centers (or connected to coastal load centers via subsea transmission) may also decrease the need for transmission system upgrades and can provide greater flexibility to independent system operators by helping to decentralize the system (AECOM, 2017).

6.2. Job creation

The suitability of OSW for California's power grid must also take into consideration economic ramifications in terms of impacts on regional economies as well as net energy costs. Recent studies have estimated that a California OSW industry could support about 185,000 job-years between now and 2045 with the buildout of 18 GW of offshore energy capacity (American Jobs Project, 2019). OSW is also projected to bring new investment via the creation of industrial clusters; a study focusing on the East Coast OSW rollout estimated that every $1 invested into a project will result in $1.83 in regional economic GDP (American Jobs Project, 2019). A 2016 NREL study on the OSW development scenarios of 10 GW and 16 GW in California by 2050 estimated job impacts of 135, 000 to 327,000 job-years between 2020 and 2050 (Speer et al., 2016). Our estimates, to be presented in more detail in Section 7 below, indicate that a 10 GW installed OSW capacity in California by 2040 can stimulate a total of 97,000 to 195,000 job-years between 2020 and 2040 for the construction of the wind facilities and another 4,000 to 4,500

[3] "Reliability" is used here in the narrow sense of continuous supply of electricity in relation to renewable energy input. This differs from more general definitions of the term that relate to any cause of electricity system disruption as defined by the North American Electric Reliability Corporation (NERC, 2020).

annual operation jobs starting in the Year 2040. The job impacts are very comparable when we adjust for the differences in capacity in these studies.

Our estimates also project that construction and operation of the OSW facilities provide good opportunities of high-paying jobs. For example, the wage rate for construction-related labors (including foundation, erection, electrical workers) is about $50 per hour. The salary for O&M labor is around $40/hour for technicians and environmental scientists & specialists, and nearly $60/hour for managers and supervisors (American Jobs Project, 2019; Musial et al., 2020b).

6.3. Environmental benefits

Environmental benefits relate to the role OSW could play in preserving California's natural resources and achieving GHG reduction goals. Meeting the targets outlined in SB 100 will require tremendous build-outs of onshore wind and solar power plants; specifically, under the high electrification scenario in the recent Joint Agency Report, an average of 2.7 GW of solar and 0.9 GW of wind must be constructed each year to remain aligned with SB 100 objectives. Commensurately, approximately 36,500 acres and 22,100 acres of land will be needed for land-based wind and solar per year, respectively, for the next 25 years (Defenders of Wildlife and the Nature Conservancy, 2020). OSW requires sea-space area, but the footprint of a project in the ocean and its impacts to wildlife and habitats may be relatively low. California must therefore make sure that its clean energy goals do not compromise its natural resource and climate goals. Land-based wind and solar are both increasingly valuable generation sources; however, land-use constraints could threaCEten California's ability to achieve 100% clean energy without OSW. California has also suffered from drought for several years, and the OSW farms do not consume any of California's freshwater supply (Musial et al. 2016a).

Furthermore, as mentioned previously, the integration of OSW into the state grid can lead to substantial displacement of fossil-fuel electricity (CPUC, 2019; Collier et al., 2019). For example, if the development of 10 GW OSW would enable a displacement of 5 GW gas-peaker power plants, it would result in a reduction of 4.73 million metric tons of carbon dioxide equivalents in the year 2040. Given the latest estimate of the societal cost of carbon (GAO, 2020), this translates into a savings of $42.56 million to $340.45 million (depending on whether domestic vs. global climate change damages are considered).

Although California has seldom been hit by hurricanes, there has been an increasing threat of earthquakes. Companies have begun to design their turbine to better withstand the strikes from both of these threats. The well-designed OSW turbines are required to be able to continue stable electricity generation under high magnitude earthquake strikes, as well as strong winds, hitting the California coastline.

6.4. Equity and environmental justice

Port revitalization to accommodate shipment of OSW component parts is a major co-benefit of OSW development, especially when it is implemented in economically lagging areas, such as Humboldt County. It offers an opportunity to promote socioeconomic equity for small businesses, low-income residents and disadvantaged minorities (Brightline Defense, 2020). However, it is necessary to consider only the incremental gains from this development vis-à-vis its potential displacement of other renewable and non-renewable energy sources.

In addition to the promotion of socioeconomic equity, OSW can also aid in securing environmental justice for minority and low-income communities by displacing fossil fuel generators. The retirement of natural gas plants is especially important from an environmental justice standpoint, since many gas-fired peaking plants are located in areas with economically disadvantaged populations,[4] such as in the City of Los Angeles. Given California's coastal resource base, the potential to develop 10 GW of OSW by 2040 would go a long way in achieving environmental justice goals.

7. Details of job creation potential of OSW in California

We summarize our analysis of the impacts of OSW development in California on the state's economy. The impacts are evaluated in terms of major macroeconomic indicators of employment, gross domestic product (GDP), and personal income. We quantify not only the direct impacts of construction and operation of the OSW plants and associated transmission line improvements, but also various indirect impact indicators as the direct expenditures ripple throughout the economy. Our analysis is based on the use of input-output (I-O) modeling, the standard approach to estimating regional economic impacts of energy development utilized previously by the authors (see, e.g., Rose and Wei, 2012; Wei and Rose, 2016) and others (Speer et al., 2016; Bae and Dall'erba, 2016; American Jobs Project, 2019; Hackett and Anderson, 2020; Faturay et al., 2020).

7.1. Study areas and development scenarios

Our major source of data on the projected capital expenditures and O&M costs of commercial-scale offshore wind projects in California is a recent study conducted by NREL (Beiter et al., 2020c). This study analyzes the cost of large-scale OSW deployment along the central and northern coast on the Outer Continental Shelf in California. The water depth of the analysis domain ranges from 40 m to 1300 m. Floating offshore wind technology is well-suited to this water depth.[5] We analyze the economic impacts of a hypothetical deployment scenario of a cumulative 10 GW of offshore wind capacity by 2040 across five selected study sites in California consistent with the latest NREL study (see Table 1).

7.2. Basic construction impacts

Table 2 presents the results for the development of 3 GW and 7 GW OSW between 2020 and 2030 and between 2030 and 2040, respectively. In both cases, lower- and upper-bound locally produced content (RPC)[6] adapted from Speer et al. (2016) are used. The table presents the results for both wind farm construction and transmission system upgrades separately, and the total impacts combined.

The hypothetical deployment of 3 GW offshore wind between 2020 and 2030 in California is estimated to increase employment by 31,691 and 63,656 job-years for the lower and higher RPC scenarios, respectively. The estimated impacts on GDP and personal income are $4.0 billion and $3.7 billion for the lower RPC scenario, and $7.9 billion and $7.4 billion in the higher RPC scenario (all nearly doubled compared to the lower RPC scenario).

The deployment of the additional 7 GW offshore wind between 2030 and 2040 is estimated to increase employment by 65,279 and 131,615 job-years for the lower and higher RPC scenarios, respectively. The estimated impacts on GDP and personal income are $8.2 billion and $7.7 billion for the lower RPC scenario, and $16.2 billion and $15.3 billion in

[4] Seventy percent of current gas-fired peaker plants are in communities with environmental justice concerns (Brightline Defense, 2020).

[5] The energy production and associated costs presented in Beiter et al. (2020c) are adapted based on the assumption of a wind power plant size of 1000-MW at each possible site in the analysis domain.

[6] Regional Purchase Coefficient (RPC) represents the proportion of in-state demand of certain types of goods and services that is fulfilled by in-state production.

Table 1
Hypothetical offshore wind deployment scenarios in California between 2020 and 2040.

	Morro Bay	Diablo Canyon	Humboldt	Cape Mendocino	Del Norte	Total
Capacity Potential (MW)	2419	4324	1607	6216	6605	21,171
Hypothetical Deployment Scenario						
Between 2020 and 2030 (MW)	1000	1000	1000			3000
Between 2030 and 2040 (MW)	1000	2000		2000	2000	7000
Cumulative by 2040 (MW)	2000	3000	1000	2000	2000	10,000

Table 2
Economic impacts of capital expenditures for the deployment of 3 GW of OSW in 2020–2030 and 7 GW of OSW in 2030–2040 in California.

Impact Indicator	Category	3 GW OSW (2020–2030)		7 GW OSW (2030–2040)	
		Lower RPC	Higher RPC	Lower RPC	Higher RPC
Employment (job-years)	**Wind farms**	22,049	42,923	42,709	83,082
	Transmission upgrades	9642	20,733	22,570	48,533
	Total	31,691	63,656	65,279	131,615
GDP (million 2019$)	**Wind farms**	2818	5391	5466	10,449
	Transmission upgrades	1153	2477	2699	5799
	Total	3971	7869	8166	16,248
Personal Income (million 2019$)	**Wind farms**	2642	5062	5124	9810
	Transmission upgrades	1100	2364	2575	5534
	Total	3742	7426	7699	15,344

the higher RPC scenario (again all about doubled compared to the lower RPC scenario). The stimulus effects of wind farm construction are slightly more than two times of the stimulus effects of transmission upgrades.

7.3. Operating impacts

Table 3 presents the annual economic impacts associated with the operation and maintenance of the OSW plants. The results are presented for Year 2030 (the year in which we assume that the total cumulative offshore wind capacity reaches to 3 GW in California) and for Year 2040 (when the cumulative capacity reaches 10 GW). In 2040, the annual employment impacts are estimated to be 3979 jobs and 4513 jobs[7] in for the lower and higher RPC scenarios, respectively. The average annual GDP and personal income impacts are estimated to be $463 million and $429 million, respectively, for the lower RPC scenario, and $530 million and $492 million respectively, for the higher RPC scenario.

Sectors that are directly stimulated by the capital expenditures include Construction, Ship Building and Repairing (including offshore floating platforms manufacturing), Turbine Manufacturing, and Professional, Scientific & Technical Services. Sectors most directly stimulated by the O&M expenditures include Water Transportation and Professional, Scientific & Technical Services. Sectors that are stimulated by the indirect effect (supply-chain effect) and induced effect (spending effect of wages and salaries of the construction and O&M workers) include Retail, Food Services & Drinking Places, Health Services, Retail and Wholesale Trade, and Real Estate.

In general, the results are in line with recent estimates found in other studies. The construction of wind farms and associated transmission lines can stimulate 97,000 to 195,000 job-years of employment and

Table 3
Economic impacts of operation and maintenance of OSW projects in California.

Impact Indicator	2030		2040	
	Lower RPC	Higher RPC	Lower RPC	Higher RPC
Employment (jobs)	1375	1560	3979	4513
GDP (million 2019$)	160	183	463	530
Personal Income (million 2019$)	148	170	429	492

about 4000 to 4500 annual operation and maintenance jobs in totality for all facilities built by 2040 throughout their operational life-cycles (see the summary of these studies in Appendix C).

7.4. Prospects for developing a wind energy manufacturing cluster

OSW has the potential to attract new investment and production both directly and indirectly via the creation of industrial clusters or agglomerations. Although there are no current instances, studies point to this promising opportunity (see, e.g., Navigant, 2013; Rigas, n.d.). There are, however, examples of clusters elsewhere for ocean wind and related technologies. The experiences of Denmark and Germany show that sustained government direction and support for port development can contribute to highly competitive regional industrial clusters (Collier et al., 2019). Moreover, investment into the U.S. OSW industry may be facilitated rather soon, as one of the largest turbine suppliers in the world, Siemens Gamesa, is considering a manufacturing facility in the states (Huxley-Reicher and Read, 2021).

We adapt our economic impact modeling to estimate the potential of industrial clusters specifically, and increased production of OSW components in California more generally to further stimulate California's economy. This involves modifying major parameters in the model based on estimates by NREL (Speer et al., 2016) of a potential increase of in-state production of OSW-related equipment, which leads to higher local (in-state) content shares of supplies of equipment and professional/technical services relating to the construction and operation of the wind farms. This results in estimates of about 90,000 more job-years

[7] We note that the concept of "job-years" is used for the employment impacts associated with the capital expenditures presented in Table VIIIB. This is because the employment impacts only occur in the year(s) of the construction of the new offshore wind facilities. One job-year refers to a worker working full time for that year. However, we use "jobs" in Table VIIIC for the employment impacts associated with the annual operation and maintenance activities of the wind farms. These jobs are of longer-term nature, which are expected to last for the entire life of the offshore wind generation facility.

than the scenario with assumptions of lower local content shares.

We also conducted a separate analysis to estimate the extent to which the in-state higher production capacity of wind turbine components could stimulate the state's economy by supplying the OSW facilities in California and exporting OSW components to other areas of the country for the buildout of OSW capacities between 2020 and 2040 in the U.S. In the lower-bound case, we assume the in-state supply of wind turbine tower and rotor nacelle assembly is increased to 50% and 25%, respectively; while in the upper-bound case, this is increased to 100% for wind turbine tower and 50% for rotor nacelle. The estimated employment impacts are between 9000 and 18,000 job-years, and the GSP impacts are between $1.5 billion to $3.0 billion. In the simulation of the increased export of wind turbine components to other regions in the U.S., we assume that 29 GW of OSW capacity will be installed in the rest of the country by 2040 (OWC, 2021; Zhang et al., 2020; AWEA, 2020). We further assume that the total domestic share of turbine components for OSW is between 40% and 60% (Zhang et al., 2020; AWEA, 2020), and the development of wind energy manufacturing clusters in California would enable California to obtain 25–50% domestic market share. The estimated employment impacts are 16,000–48,000job-years, and the increased GSP is between $2.3 billion and $7.0 billion in the lower-bound and upper-bound cases, respectively. Such outcomes would represent a sizable increase in the economic impacts presented in the previous section.[8]

8. Key challenges

There are a variety of challenges concerning OSW that need to be addressed before policy-makers and industry move forward to make Californian OSW energy a reality.

8.1. Need for new transmission infrastructure

In the case of a build-out on the North Coast, infrastructure currently in place in the Humboldt region is designed to serve only local load. New investments would need to be made, such as upgrades or new construction of cables or substations that serve as connecting points. For example, a utility-scale wind farm along the Humboldt coast would require either an undersea cable that connects to a major Northern California load center, or overland transmission lines, which would almost certainly get bogged down by permitting and inaccessible terrains (Severy and Jacobson, 2020). These overland routes may also encroach upon federally protected lands and could also potentially pose wildfire risks (Amul et al., 2020). Moreover, new transmission could cost in excess of $1 billion (Collier, 2020).

8.2. Seaport capacity

Few ports in California could serve as importation, manufacturing, or assembly hubs. The size of the OSW turbines will be significantly larger than those that are used for onshore wind power, and thus the final assembly cannot be accomplished at ports with tall seaward bridges. This requirement eliminates all ports in the San Francisco Bay Area and Delta, as well as Los Angeles, Long Beach, and San Diego. The ideal characteristics of suitable ports would ultimately require deep and sheltered harbors with high-quality port infrastructure and facilities, large areas of vacant land for manufacturing and assembly purposes, and no restrictions for ship access (Porter and Phillips, 2019).

Many studies have identified the Port of Humboldt Bay as a promising site for the final assembly of OSW turbines. The port has vast vacant industrial land at a deep-water harbor with limited access constraints, and the Humboldt Bay Harbor District (HBHD) has been active in the development of the port area into an offshore wind manufacturing hub (Hackett, 2020).[9]

Other reports, such as Hamilton et al. (2021), have studied the potential for a specialized OSW port along California's Central Coast. A specialized Central Coast port facility with several staging areas, possibly situated in San Luis Obispo, would be instrumental for final component assembly, as well as O&M and decommissioning-related activities.

8.3. Environmental and wildlife concerns

The North Coast Offshore Wind Feasibility Project has assessed two potential OSW scenarios along California's northern coast with multiple build-out scenarios. All scenarios would entail construction, operations, and decommissioning activities that could have adverse effects on both terrestrial and marine environments. H.T. Harvey & Associates (2020) found that effects from the build-out of both the onshore and offshore components necessary to support OSW integration will primarily be short-term and will mostly affect the immediate regions. Offshore wind-related operations and maintenance activities will present some long-term concerns, however, such as potential adverse interactions with wildlife and ship interactions and collisions with blades. Lastly, improvements to overland transmission infrastructure would also present long-term challenges for both terrestrial and marine habitats. Many of the potentially affected plant and animal species are subject to state and federal protections.

8.4. Military concerns

The U.S. Navy initially expressed significant concerns with OSW areas in the central coast of California following BOEM's call for interest and nominations in 2018. During the Trump administration, federal legislators from California sought to make progress in resolving these concerns, but did not reach a successful resolution. California state legislators have held talks with the Secretary of the Navy regarding the viability of OSW (Braithwaite, 2020). On May 25th 2021, the Biden-Harris Administration and the Governor of California announced plans to move forward with OSW leasing for 399 square miles in Morro Bay (the site of the major US naval base) and the original Humboldt Call Area. While there will likely be on-going discussions between Department of Defense, Department of Interior, and State of California on mitigation to protect DOD's long-term interests in the region, as well as to determine the space and timing for additional phases of OSW leasing, this announcement represents a major step forward in the establishment of an OSW industry in the state (DOI, 2021).

8.5. Fishing industry concerns

Impacts on marine wildlife could potentially adversely affect California's $183 million fishing industry. Industry groups have stated that not enough research has been done on how OSW could affect commercial fish harvests (Collier, 2020). The Diablo Canyon and Morro Bay call areas overlap with essential fish habitats and designated conservation areas. OSW development near these coastal regions proposes potential challenges for commercial fisheries, through both active fishing

[8] Strictly speaking this is not a direct comparison because the economic impacts presented in Section VIIB do not include the exports impact, though include the impacts of all components of OSW buildout, not only turbine components. However, the bottom-line statement still holds.

[9] However, the current challenges of this port include the lack of highway and rail transport access, grid interconnection, and the need for extensive upgrades to the supporting port facilities. Another potential concern is sediment deposits from the Eel River, making vessel transit to offshore sites only possible during part of the year (Amul et al., 2020). Port improvements may also prove to be extremely costly, with Collier (2020) estimating that renovations could cost in the neighborhood of $100 million for this location.

activities and the movement of marine vessels (Natural Resources Defense Council (NRDC) et al., 2019). At the same time, wind farms themselves may serve as marine protected areas for fish, or could create reef-effects which attract increased numbers or greater diversity of species (Dauterive, 2000; Hooper and Austen, 2013).

8.6. Cargo vessel availability

Specialized vessels with heavy lifting and specific stability characteristics are required to perform the decommissioning operations. However, the vessels also need to satisfy the requirement based on the site conditions. The number of turbines, the foundation type, the water depth, the distance to the operating ports and the seabed type need to be considered. Meanwhile, vessel operations are impacted by other uncertainties, such as the equipment used, the weather, and the market (Topham et al., 2019). However, the vessel availability challenges and Jones Act compliance for fixed-bottom OSW are expected to be much less of an issue for floating OSW.

8.7. Lack of wind power supply chain

Currently, California has minimal to no manufacturing of large-size turbine, rotor blades, nacelles, tower and other major components (Collier et al., 2019).[10] Therefore, the state may need to import major components from other states or countries. Many developers view shipping cost as a main issue compared to the manufacturing cost of the various components.[11] However, the development of an in-state supply-chain would be much preferable from the economic standpoint, as the establishment of new hubs of wind manufacturing industry would bring well-paid jobs and other benefits to the host region. California's decision on the scale of OSW development in the next two decades would affect the market demand of wind generation equipment in the state, and the potential for major turbine manufacturers to invest and establish production sites in California (Collier et al., 2019; Burke et al., 2021).

Developing a California supply-chain for essential turbine components will also help lead to commercial-scale and therefore cost-competitive wind farms. Clear long-term state goals of OSW development and aligned market acceleration targets will facilitate the strategic establishment of an in-state wind manufacturing supply-chain. Other state policies, such as adopting financing mechanisms, building channels of knowledge exchange, attracting capital investment opportunities, establishing training capacity to prepare a skilled OSW workforce, and encouraging development of specialized wind port infrastructure, will also drive the establishment of local wind industry and supply chains in the state (American Jobs Project, 2019; DOE, 2021).

8.8. Decommissioning of offshore wind project

The final challenge of OSW projects is the decommissioning phase. While the U.S. is still in the initial stage of OSW development, many wind farms in Europe will be entering the lifetime extension, repowering, or decommissioning decision-making process. The decommissioning plans should ideally be integrated in the design phase of an OSW project. According to European experience, major challenges of OSW project decommissioning include: 1) limited and unclear guidelines and lack of specific regulations, 2) planning of the decommissioning process, 3) availability and cost of vessels to conduct the decommissioning activities; 4) the potential impacts to marine environment (Topham et al., 2019).

8.9. Short-term and unpredictable tax credits

The short-term nature of relevant subsidies and congressional pattern of not committing to consistent OSW tax credits makes it challenging for OSW developers to plan projects. These credits include both a production tax credit (PTC) and an investment tax credit (ITC). The PTC was extended by congress at 60% of its per-kilowatt value for one year in late 2020, and the ITC was set at 30% of the cost of a project that begins construction prior to 2026. As a result of their short-term nature, development drops when the credits expire and then increases again once the credits are reinstated. These incentives, while important for project financing, can create much uncertainty for OSW developers (Huxley-Reicher and Read, 2021). However, it should also be mentioned that, at the very end of 2020, the Internal Revenue Service (IRS) issued Notice 2021–05, which effectively extended the continuity safe harbor credits for qualifying offshore energy projects to ten years, meaning that any OSW project that begins construction prior to 2026 may delay operation for ten calendar years and still be eligible for the 30% ITC (IRS, 2020).

9. Benefit and co-benefit summary

Overall, offshore wind presents a number of attractive system, economic, and environmental attributes for California's electric grid and may help to achieve the goals outlined in SB 100. Its value proposition is attractive, as it is increasingly competitive with gas-peaker plants and solar/storage. In terms of reliability co-benefits, OSW has a generation profile complementary with solar, is a consistent generation source with high capacity factors, and, with proper transmission resources, can inject power directly into heavily populated coastal load centers. In terms of environmental co-benefits, it could also be instrumental in the early retirement of costly and pollution-heavy natural gas plants. There is also the potential to avoid degradation of important land that would otherwise be harmed by the construction of solar and onshore wind resources. OSW promises substantial job creation co-benefits. Moreover, California could reap additional economic co-benefits from the development of a local OSW industry, boosting manufacturing and creating still additional jobs. Additionally, OSW has the potential to advance environmental justice through its reduction of ordinary air pollutants in urban areas and can bring economic opportunities to lagging areas of the state.

Table 4 presents a summary of these findings. The first numerical column presents the best estimates and the second column presents a range for these estimates, given the uncertainties. In places where we did not perform the calculations ourselves, we present summaries of the findings of others. Final column of the table provides some comments to clarify the presentation.

Below we summarize important implications of our analysis results for the implementation of the OSW technology in other coastal states in the U.S. and other countries:

- Our framework for identifying and analyzing co-benefits of OSW has general applicability to all other locations.
- California's OSW resources are of equal magnitude and other desirable features as in many locations already implementing this technology and those not yet doing so, especially in developing countries, thereby providing an indication of the likely competitiveness of this electricity technology more broadly.

[10] Around the world, major manufacturers of wind turbines are located in Europe (e.g., UK, Germany, Denmark, France) and East Asia (e.g., China, Japan, and South Korea). According to the 2018 market assessment report by NREL, major wind turbine manufacturing facilities in the U.S. are concentrated in Ohio, Texas, Illinois, Wisconsin, and Colorado (Energy.gov, 2020).

[11] For example, the Block Island OSW project located in Rhode Island largely relied on sourcing of key components from out-of-state and foreign suppliers. This project used turbines and blades imported from France, and the foundations were constructed by an oil rig manufacturing firm in Louisiana (Musial et al., 2020a).

Table 4
Summary of benefits and co-benefits of offshore wind energy.

Benefit or Co-Benefit	Best Estimate	Estimate Range	Comment
Cost Saving	$1 billion (CEC, 2021)	up to $2 billion NPV (2030–40) (E3, 2019)	does not include transmission cost
Reliability	Improvement (complement to other renewables)	n.a.	complementary daily timing
Jobs – Construction	146,120 job-years (2020–2040);	96,970 to 195,271 job-years (2020–2040);	includes both direct and indirect jobs
Jobs – Operation	4246 annual jobs in 2040	3979 to 4513 annual jobs in 2040	includes both direct and indirect jobs
Jobs – Industrial Cluster[a]	45,578 job-years	25,057–66,908 job-years	in-state and exports to rest of U.S.
Environmental – Basic	$191.5 million	$42.56 to $340.45 million[b]	societal cost of carbon impact savings only
Environmental – Other	moderate reduction for ordinary pollutants; moderate reduction for land preservation (general literature)	n.a.	does not include all environmental impacts
Environmental Justice	improved health by race/income; economic stimulus for lagging regions (general literature)	n.a.	does not include all environmental justice attributes

[a] This analysis is only conducted for potential higher in-state production capacities of wind turbine components.
[b] Calculation assumes the development of 10 GW OSW in California would displace 5 GW gas-peaking power plants. The social cost of carbon data is for Year 2040 emissions. This estimate is based on an average of $9/ton for domestic climate change damages and $72/ton for global climate change damages (GAO, 2020).

- Reduction in greenhouse gas emissions will be the case for nearly all other sites, given the likelihood that OSW will displace fossil fuels.
- The displacement of fossil-fuel electricity generation is likely to take place in urban areas, thereby reducing concentrated local air pollutants, generally helping to improve environmental justice for local, more socially and economically vulnerable residents that typically live near such sites in industrialized countries.
- The need for additional transmission capacity to serve OSW generation, given its geographic remoteness, is likely to be the case for a great many prime resource sites.
- Most of the challenges confronting OSW in California are present universally, including environmental concerns, seaport capacity, complexity of permitting processes, and decommissioning.
- California provides examples of how government can positively support OSW development.
- Our analysis indicates how employment impacts can be increased significantly by the presence of more local OSW support industries, no matter what country is implementing this technology.

10. Conclusion and policy implications

We have analyzed the major benefit and co-benefits of offshore wind development in California. Although there are likely to be some negative side-effects and some details in relation to considerations, such as transmission lines and various externalities, still need to be worked out, we conclude that OSW is an attractive electricity alternative for the state's electricity generation mix.

Some specific examples of the various benefits and co-benefits of OSW include:

- Resource cost savings of at least $1 billion in providing clean electricity.
- Improved reliability of electricity services due to its higher and more stable capacity factors and the timing of its peak electricity generation.
- Job gains of the development of 10 GW OSW estimated to be a total of 97,000 to 195,000 job-years through 2040 for the construction of the wind facilities and another 4000 to 4500 annual operation and maintenance jobs, which translates into an additional 120,000 to 180,000 job-years of employment.
- Potential reduction of 4.73 million metric tons of carbon dioxide equivalents in the year 2040 if 5 GW gas-peaking capacity can be replaced under the scenario of 10 GW OSW deployment, translating into the prevention of up to $340.45 million of global climate change damages.
- Minimization/reduction of environmental impacts associated with the construction of land-based energy infrastructures such as onshore wind and solar.
- Improvements in environmental justice through the reduction of ordinary air pollution in socioeconomically disadvantaged urban areas of the state and construction of OSW facilities in some of its lagging regions.

At the same time, there are multiple challenges that must be addressed in order for OSW to reach its full potential in California. The first is affordability; floating OSW LCOE is currently more than double that of both solar-PV and land-based wind, and the technology is not expected to become cost competitive with these renewables until at least 2030 (Hull et al., 2019). In the case of a build-out on the North Coast, the state would also need to invest heavily in new transmission infrastructure (Severy and Jacobson, 2020). All candidate ports in California are also expected to require upgrades to enable OSW, and concerns have also arisen from the military, fishing industry, and conservationists worried about effects on the ocean environment. Despite these hurdles, offshore wind has the potential to play a pivotal role in meeting the goals set by SB 100, as well as turning California into a global hub for OSW development.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Operating experiences with OSW in other states and countries

Global fixed-bottom OSW LCOE has dropped 67.5% to $84/MWh since 2012 and is expected to achieve $58/MWh by 2025 due to larger utility-scale projects, bigger turbines, and reduced cost of capital, which makes it comparable to or even cheaper than new gas and nuclear power (Lee and Zhao, 2020). OSW also has a high capacity factor (yielding more energy per unit of installed capacity). For instance, the Hywind floating OSW farm demonstrated a capacity factor of 65%, which is two to three times that of solar, nearly twice that of land-based wind, and even greater than that of coal (American Jobs Project, 2019).

Floating OSW is expected to account for 6% of neNw installations internationally in 2030 (Lee and Zhao, 2020). As of the end of 2020, there were around fifteen floating offshore wind projects in demonstration and trial phases. 2020 was actually a surprisingly prosperous year for OSW, in spite of the COVID-19 pandemic; in fact, the level of OSW capacity with a signed offtake agreement more than tripled between March 2019 and March 2020 (Huxley-Reicher and Read, 2021). There are also many floating projects in pre-commercial phases, with 1100 MW under construction and planned to be built by 2025. The scale of floating offshore farms is expected to increase significantly over the next ten years, with other projects recently announced to approach 2 GW by around 2030 (Lee and Zhao, 2020). Moreover, the Global Wind Energy Council projects that more than 70 GW of OSW capacity will be installed globally between 2021 and 2025 (Lee and Zhao, 2021). The International Energy Agency also anticipates that an annual development of around 80 GW of OSW will be installed worldwide in 2030, slowing to 70 GW annually by 2050 (Bouckaert et al., 2021).

The majority of OSW projects have thus far required government financial support, as the initial high-costs would otherwise make the resource uncompetitive with other renewables. In the U.S. east coast, OSW development has been promoted through a mix of capacity targets, investment tax credits, and research support. New projects are in various stages of development across the eastern seaboard, with total capacity commitments in eight states at a minimum of 29 GW by 2035 (OWC, 2021). Other initiatives to support an OSW rollout have been announced by New York and New Jersey, which have committed to upgrading ports for the purposes of OSW development (Huxley-Reicher and Read, 2021).

Appendix B. Basic cost considerations

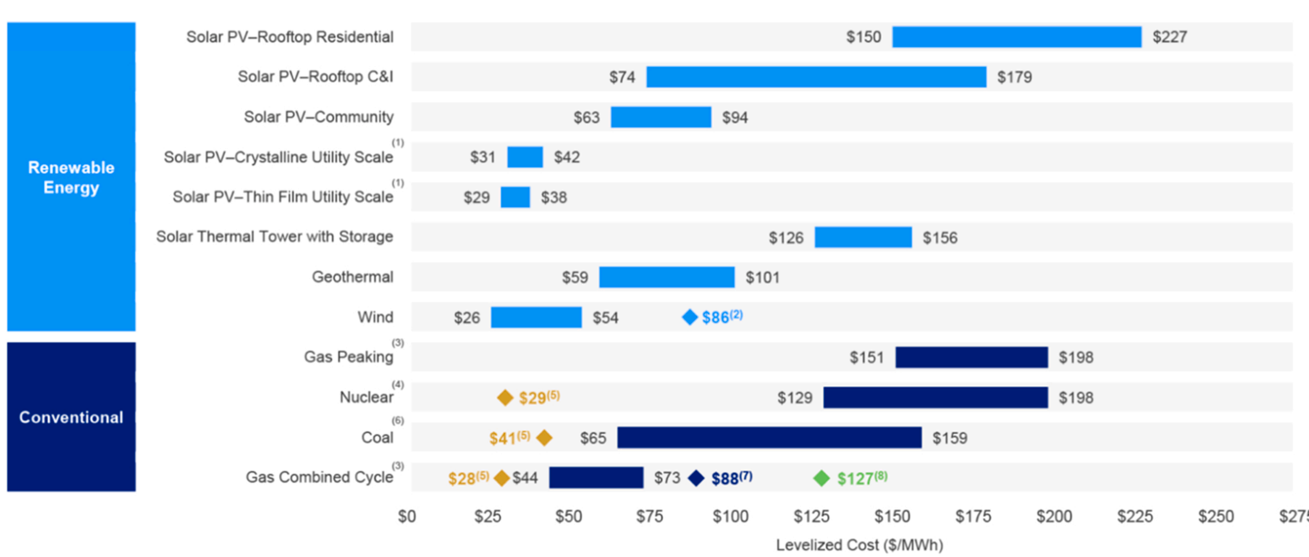
A. Electricity generation

The levelized cost of energy (LCOE) is the most widely used measure of the average cost of electricity generation over the entire lifetime of a facility. It provides a consistent basis to compare the cost of electricity generation using different energy sources and technologies. The LCOE includes both the capital cost expenditures (CapEx) and operational cost expenditures (OpEx). The former includes, for example, cost of the offshore wind turbine, platforms, electrical infrastructure, mooring and anchoring system, and installation costs. The OPEX cost can be divided into operation and maintenance cost, which consist primarily of labor cost and shipping cost (Maienza et al., 2020).

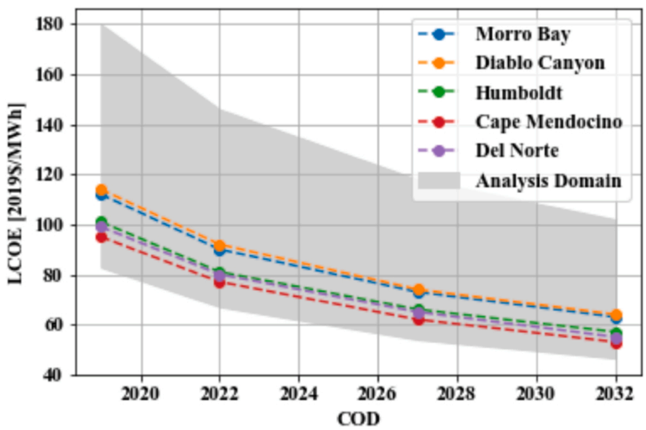
California offshore wind facilities would necessitate the use of floating turbines due to the state's deep coastal waters. Because of the nascent nature of this platform technology, the most recent NREL reports estimate that the current LCOE of floating OSW is about $113/MWh, and that the first offshore farms in California will arrive at an LCOE of about $92/MWh in the early-mid 2020 s. The LCOE is projected to decrease to $53-$64/MWh in 2032 (Beiter et al., 2020c). For comparison (see Appendix Fig. B1), solar-PV and onshore wind currently are at around $29–42/MWh and $26–54/MWh, respectively (Lazard, 2020). Natural gas combined-cycle generation has an LCOE range of about $44–73/MWh, and gas-peaking plants have an LCOE range of about $151–198/MWh. Floating wind farms are therefore at the moment only cost competitive with natural gas peaking plants, and still fall short of equalizing the energy costs of combined-cycle gas plants, as well as solar and onshore wind farms. However, it will become more economically viable in early 2030s

Despite the expectation of relatively high costs for floating OSW farms with CODs in the early-mid 2020s, by late this decade and early into the next, technological innovations in turbine size, as well as increased wind farm scale and industry standardization, could substantially reduce the cost differential between offshore wind and land-based renewables. This could help OSW play a large, complementary role in the state power mix (Collier et al., 2019).

Additionally, based on interviews with industry experts, floating offshore wind could actually become more economical than fixed-bottom offshore wind in certain locations, and could decrease in cost at a faster pace than fixed-bottom offshore wind, even at depths that



Appendix Fig. B1. Levelized Cost of Energy Comparison. Note: For wind generation, the estimate of $86/MWh represents implied midpoint of the LCOE of offshore wind, assuming a capital cost range of approximately $2,600-$3675/kW.
Source: Lazard (2020).



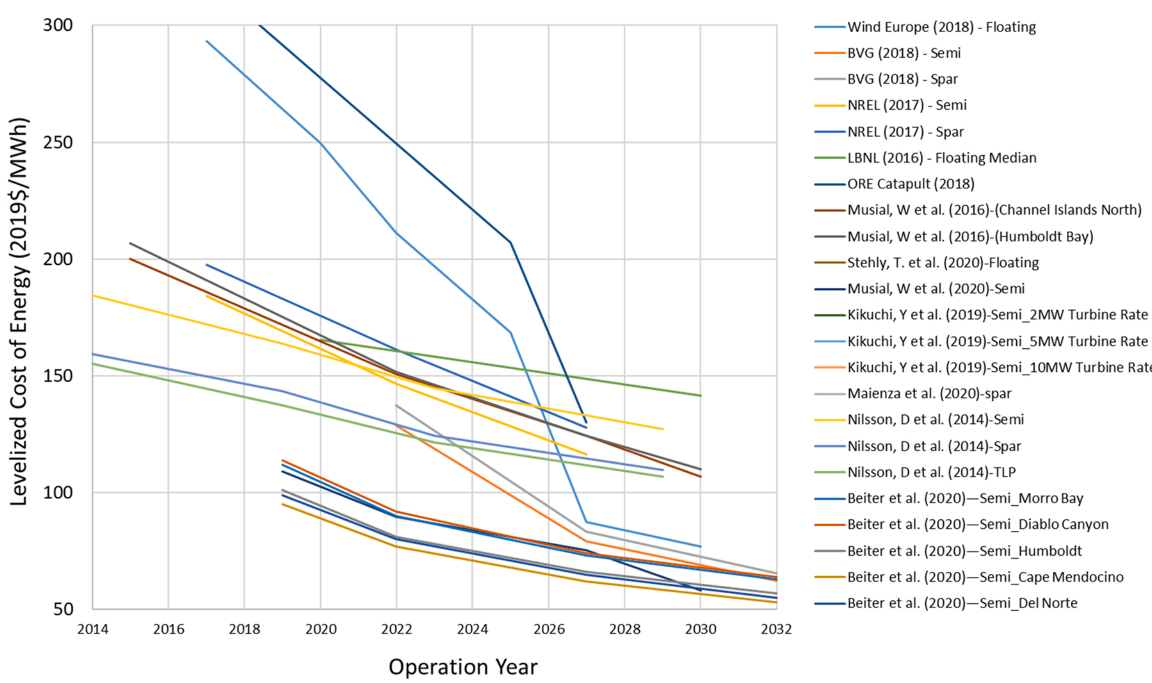
Appendix Fig. B2. Global LCOE Estimates for Floating Wind Farms.
Source: Beiter et al. (2020c).

would be feasible for both types of technologies. This potential cost advantage can be attributed with more portable components, scalable quayside manufacturing and assembly, and increasing ease of installation. These characteristics can allow floating platform components to scale using automated production in a way that would be more difficult for fixed-bottom components (Amul et al., 2020).

Accordingly, in the latest NREL estimation (Beiter et al., 2020c), the LCOE of floating OSW projects with a wind plant size of 1 GW at the five reference areas in California is projected to reduce from an average of $113/MWh in 2019 to $64/MWh in 2032, or a decline of 43% (see Appendix Fig. B2).

In Appendix Fig. B3, we depict the estimated LCOE of floating OSW projects over time based on the data gathered from the literature. All studies project steady declines of LCOE of floating OSW over the next decade. Another observation is that given the rapid development of the OSW technology (such as the significant increase in turbine size and plant size) in recent years, the estimated LCOE of commercial-scale OSW has decreased significantly in the studies. The major difference in the cost estimates across the studies that were conducted in different years is the estimates of capital expenditures. For example, the projected capital cost of OSW in 2032 dropped from about $4900/KW in Musial et al. (2016a) to about $3050/KW in Beiter et al. (2020c).

Moreover, although OSW is more expensive than solar on an LCOE basis, the economic value of offshore wind may rest in its potential to offset future costs of solar-PV generators with battery storage. As a variable renewable energy (VRE) source, offshore wind also has relatively low operating and fuel expenses in comparison to thermal generators. OSW generation enters the merit-order bid stack at a marginal cost near zero and can thus decrease the wholesale electricity price (Beiter et al., 2020b). Furthermore, OSW is expected to remain cost-competitive in comparison with potential out-of-state (OOS) wind resources and is projected to remain cost-competitive with solar even if operational and storage costs for solar generation facilities fall faster than expected (Collier et al., 2019; Hull et al., 2019). Ultimately, OSW can bring immense value to California's energy portfolio, and in spite of its present relatively high costs compared to utility scale solar PV, onshore wind, and NGCC, technological innovations and industry maturity will allow this source of renewable power to compete



Appendix Fig. B3. Comparison of Floating OSW Cost Trends Estimated in Various Studies.
Source: Developed by the authors based on LCOE data collected from the literature.

effectively with other types of generation technologies in the near future.

B. Transmission

The costs associated with building transmission infrastructure to support OSW deployment must also be analyzed in order to understand the extent of necessary co-expenditures. The greatest investment in transmission capacity would be required by an OSW build-out on California's northern coast, in and around the Humboldt region. This is because the infrastructure currently operating in this area of California is only designed to serve local loads, as opposed to moving electricity to other areas in the state. Connecting OSW to the grid would therefore necessitate upgrading or constructing entirely new cables and substations. These costs would ultimately fall on the wind farm developer; however, California ratepayers could end up footing the bill as well due to the pass-through of transmission access charges paid out by load-serving entities (Severy and Jacobson, 2020).

Electric generation and distribution are the largest components of electric rates. Utility-owned generation and purchased power sources, plus distribution, collectively account for approximately 80% of electric rates from California's three largest investor-owned utilities (IOUs): Southern California Edison, Pacific Gas & Electric, and San Diego Gas & Electric (Hurd et al., 2019).

Severy and Jacobson (2020) examined three OSW deployment scenarios on the North Coast to assess potential transmission routes and their respective costs. These scenarios include a Pilot Scale OSW farm (48 MW), a Small Commercial Scale OSW farm (144 MW), and a Large Commercial Scale OSW farm (1836 MW). Both overland and subsea transmission routes are considered for a large commercial scale OSW project connecting to major transmission lines in California or large load centers. The state's largest load-serving entity, Pacific Gas & Electric, notes that this size of a generator far outpaces the capability of regional power lines (Severy and Jacobson, 2020). The cost estimates for the Pilot Scale, Small Commercial Scale, and Large Commercial Scale OSW farms are $540 million, $970 million, and $1.7 to $3.0 billion, respectively. For the large 1836-MW commercial-scale projects, the unit transmission costs are estimated to be $938/kW to $1090/kW for the on-land transmission option and $1313/kW to $1630/kW for the subsea transmission option.

One important qualification of these estimates is that they assume transmission improvements are completed in a way that avoids OSW curtailment entirely. This could impact transmission upgrade requirements and likely lead to higher overall transmission costs. The most cost-effective transmission option may also be associated with an installed OSW capacity much larger than 1.8 GW, which would indeed be feasible given the available technical resource. Strictly speaking, larger scale projects would result in declining transmission cost upgrades per unit of installed capacity.

Outside of California, transmission studies have similarly been conducted for the expansion of OSW energy in the eastern United States. A recent grid study for New York state estimates that transmission costs to connect an 8.5 GW OSW farm could approach as high as $793/kW; a prior analysis for New York state also estimated that transmission costs for a 7.2 GW OSW farm could range from $917/kW to $986/kW (Pfeifenberger et al., 2020; Pfeifenberger et al., 2021).

Regarding current transmission availability, it should be noted that the first California offshore wind farm could be in waters near Diablo Canyon nuclear plant, whose reactors are slated to close in 2025. Wind farms in these locations could connect with the transmission lines surrounding these nuclear power plants to lower the cost. It would be especially easy and inexpensive if the projects are built in waters near Santa Barbara County and San Luis Obispo County. Wind farms in this area could easily connect with the 2 GW transmission line at the Diablo Canyon nuclear power plant or the 600 MW interconnection at Morro Bay Power Plant (Collier, 2017). While analysis of North Coast transmission requirements has been completed, little study has been accomplished concerning transmission needs and/or costs on California's central coast. However, CAISO has indicated that it would be manageable to connect somewhere around 3–4 GW of OSW capacity to the grid along the Central Coast (CAISO, 2019). CPUC staff have also commented that 5 GW of transmission capacity is available in California's Central Coast (CPUC, 2020). Further evaluations will need to be finalized in the future for central coast wind farms to be considered, which is significant given the large potential for the Morro Bay and Diablo Canyon call areas. This type of assessment is expected to be accomplished as part of the OSW sensitivity in the CAISO 2021–2022 Transmission Planning Process (TPP).

Appendix C. Comparison with other studies

Speer et al. (2016) estimated the economic impacts of the construction and operations of two hypothetical offshore wind development scenarios (10 GW vs. 16 GW installed capacity) between 2020 and 2050 in California. The total employment impacts of the buildout of 10 GW offshore wind in California are estimated to be about 130,800 job-years between 2020 and 2050. Our lower RPC scenario uses similar assumptions of local content shares as in the 10 GW development scenario in Speer et al. (2016). Our impact estimates are lower compared to the results in Speer et al. (2016) primarily because of the considerably lower estimates of the capital cost of OSW capacity between the 2016 and 2020 NREL studies (Musial et al., 2016a, Beiter et al., 2020c).[12]

Hackett and Anderson (2020) estimated the economic iImpacts of offshore wind projects in Humboldt Bay and Cape Mendocino area. The estimated job impacts range from 2000 for a 48 MW pilot project to 13,000 for a 1836 MW commercial-scale project. The job estimates for the commercial-scale development are comparatively lower than the estimates in Wei et al. (2021) (even after the adjustment of the difference in total installed capacity). This difference is mainly a result of the relatively lower local (in-state) content shares assumed in Hackett and Anderson (2020).

The American Jobs Project (2019) estimated that the capital investment of 18 GW offshore wind capacities in California can create about 5500, 9000, and 13,000 jobs, respectively, in the last year of each of three phases of development over a 20-year period. This translates to about 185,000 job-years over the entire study period, which is close to our lower-bound estimate after adjustment for the difference in total buildout capacities.

Zhang et al. (2020) analyzed the potential economic impacts associated with the offshore wind investment activities as a result of lease auctions by BOEM between 2020 and 2022. In California, a total of 9 GW offshore wind capacity could be installed by 2040 in response to the anticipated auctions. It is estimated that an average of 38,000 jobs can be supported annually over a 5-year construction period. This translates to about 190,000 job-years, which comes close to our upper-bound estimate.

Hamilton et al. (2021) analyzed the regional economic impacts for a development of 3–7 GW OSW along the central coast of California. The Regional Economic Models, Inc. (REMI) Policy Insight Plus (PI+) model is used to estimate the economic impacts on San Luis Obispo County (assuming a specialized wind port is constructed in the County) and rest

[12] For example, the estimated per MW capital investment costs for OSW projects in the Central Coast area in Beiter et al. (2020c) are 33% lower in 2022 and 43% lower in 2032 compared to the cost estimates in Musial et al. (2016a) primarily because of the higher turbine rating and larger plant size assumed in the latter study. Note that lowered capital investment costs per MW of installed capacity of OSW, although increasing the cost competitiveness of the OSW technology compared to the other power generation technologies, are associated with lower economic impacts. This is because economic activities stimulated are primarily driven by the size of the total expenditures of projects.

of California. For the 7 GW OSW development scenario, the study estimated creation of 72,162 full-time equivalent (FTE) job-years. These include the jobs associated with the construction of the specialized wind port, assembly of OSW turbines at the port, and the maintenance and repair of the OSW turbines there. If the estimate in this study is scaled up to 10 GW, the job impacts would be closer to the lower-bound estimate in our study.

Finally, our estimated annual employment impacts in the operation phase of 10 GW offshore wind facilities are within the range of 2000 to 5000 jobs per year found in the other studies reviewed above.

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