USC Schwarzenegger
Institute for State and Global Policy

CALIFORNIA'S OFFSHORE WIND ELECTRICITY OPPORTUNITY

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Authors' Note

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Executive Summary

I. 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 is planning for this target, outlined in California Senate Bill 100, to be met primarily by several renewable sources like solar, land-based wind, geothermal, along with energy storage and other zero-carbon technologies. Wind energy has long been proven to be a technologically feasible and economically viable option. Moreover, momentum is increasing to include California's offshore wind (OSW) energy as a complement to the state's 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. The California Public Utility Commission (CPUC) has also directed the California Independent System Operator (CAISO) to assess the transmission capacity and requirements for large-scale offshore wind as part of a policy sensitivity of the Transmission Planning Process (TPP).

The Biden 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 Vineyard Wind Project, the first utility-scale OSW farm in the United States. Furthermore, the Biden administration announced on May 25, 2021, an initiative to accelerate California OSW development. Specifically, the Department of the Interior and Department of Defense have delineated a central coast development area known as the "Morro Bay 399 Area". The Department of the Interior has also stated that it will engage in efforts to advance a potential OSW area on the northern coast adjacent to Humboldt County (The White House, 2021). A robust OSW future appears imminent in the U.S., given that there are 29 coastal and Great Lakes states that could accommodate the resource, and these states have the technical resource potential of over 2,000 GW, equivalent to 7200 terra-watt hours (TWh) of electricity generation annually. This level of output is nearly double the nation's total electricity usage in 2019, and approximately 90% of projected power consumption in 2050 given a high-electrification future. Based on a National Renewable Energy Laboratory (NREL) study of OSW, the California coast has a resource potential of over 200 GW, which highlights the important role California can play in meeting the nation's 2030 goal (Musial et al., 2016a).

The California Energy Commission (CEC) recognizes 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 May 25th announcement. A recent draft report by a Joint Agency group composed of the CEC, California

Public Utilities Commission (CPUC), and California Air Resources Board (CARB) indicates 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. The report estimates that this addition of OSW would contribute toward total resource cost savings of approximately $1 billion. Another estimate places this contribution at up to $2 billion in net present value ratepayer savings between 2030 and 2040 for 7 to 9 GW of installed capacity (Energy and Environmental Economics, 2019). At the same time, the 10 GW represents only about 5% of the estimated OSW potential capacity in the state.

II. Analytical Framework

Many considerations are typically taken into account 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.

This narrow characterization of the value proposition, however, has evolved to include other considerations relating to delivery of electricity and beyond, known as co-benefits. 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. Public policy decisions, on the other hand, are based on many considerations including, of course, the value proposition. These include: direct job creation and multiplier effects on the overall economy, reducing greenhouse gases and ordinary pollutants, and improvements in equity/justice, technological innovation, and broader economic development goals.

In this report, we provide a broad analysis of the economic potential of OSW development in California in terms of the direct benefits of the value proposition and various co-benefits. We begin with an examination of the basic costs of OSW and how its advantages with regard to variability, flexibility, and reliability affect this proposition in relation to gas-fired electricity generation units and solar-battery hybrids combinations that it could displace. We also consider the social costs of carbon emissions from fossil-fuel sources in comparison to the near-zero amounts emitted by the use of this renewable resource. Additionally, we consider impacts on other societal objectives such as equity/justice. A major aspect of the study is the estimation of aggregate and sectoral economic output and employment impacts stemming from the potential development of OSW in California, which are summarized below and presented in detail in a companion report (Wei et al., 2021).

We also examine key challenges to OSW and how they might be overcome. Finally, we examine the prospects of California developing an OSW manufacturing cluster and the number of direct and indirect jobs that this might stimulate from sales within California and to the rest of the U.S.

III. Findings

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 lands 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 offshore wind 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.

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

- Resource cost savings of at least $1 billion annually 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 by 2040 estimated to be a total of 97,000 to 195,000 job-years through 2040 for the construction of the wind facilities and another 4,000 to 4,500 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 $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 offshore wind to reach its full potential in California. 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 offshore wind development.

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The California Energy Commission (CEC) recognizes 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 May 25th announcement. A recent draft report by a Joint Agency group composed of the CEC, California Public Utilities Commission (CPUC), and California Air Resources Board (CARB) indicates 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, 2021). The report estimates that this addition of OSW would contribute toward total resource cost savings of $1 billion. Another estimate places this contribution at up to $2 billion in net present value ratepayer savings between 2030 and 2040 for 7 to 9 GW of installed capacity (Energy and Environmental Economics, 2019). At the same time, the 10 GW represents only about 5% of the estimated OSW potential capacity in the state.

A large number of direct job gains have been touted as an accompanying benefit of OSW development. These construction and operation/maintenance jobs on-site have multiplier effects on the rest of the state's economy as well. Moreover, a good number of the direct job gains would likely be in areas of the state that are lagging economically, thereby promoting income equity. Reductions in ordinary air pollution and greenhouse gas emissions accomplished through the displacement of fossil-fuel installations in urban areas would also yield environmental justice co-benefits. Furthermore, 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.

Issues still need to be resolved relating to planning, including 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. However, progress is underway in these directions (Offshore Wind California, 2021).

A. Analytical Framework

Many considerations are typically taken into account 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, then 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 a reliability consideration.

Public policy decisions, on the other hand, are based on many considerations including, of course, the value proposition. 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. 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, reliability, job creation, multiplier effects on the overall economy, improvements in equity/justice, national security, technological innovation, and 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 (Burtraw et al., 1995). 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).

In this report, we provide a broad analysis of the economic potential of OSW development in California in terms of the direct benefits of the value proposition and various co-benefits. We begin with an examination of how its advantages with regard to variability and flexibility affect this proposition in relation to gas-fired electricity generation units and solar-battery hybrids that it could displace. We also consider the social costs of greenhouse gas emissions from fossil-fuel sources in comparison to the near-zero amounts emitted by the use of this renewable resource. Additionally, we consider impacts on other societal objectives such as equity/justice. We do not, however, conduct a full comparative cost analysis because that would require assessing all the costs and all the benefits of the entire mix of energy technologies. Instead, we will focus on OSW and features that make its contributions unique. The intent is to provide useful information for subsequent more complete comparisons.

A major aspect of the study is the estimation of aggregate and sectoral economic output and employment impacts stemming from the potential development of OSW in California, which are summarized below and presented in detail in a companion report (Wei et al., 2021). This is the major category of co-benefits for which we provide our own analysis, based on its successful refinement and application of methods developed in previous studies of climate action plans including specific energy technologies (Rose and Wei, 2012; Wei and Rose, 2014; Wei and Rose, 2016), and institutions (Wei et al., 2015; Wei and Rose, 2019). This is in contrast to other areas of the report that represent a synthesis and interpretation of the existing literature. We also consider dynamic features of the resource/technology evaluation, which refers to changing conditions. We also evaluate the potential to attract OSW-related industrial clusters to California, which would thereby 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 will 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.

B. Key Questions

In the course of our analysis, we address the following questions:

1. What role will OSW play in meeting the need for flexible clean resources in the California? The evaluation considers the role of OSW in terms of the potential size of the resource, future electricity demand projections, and regulatory clean energy targets.

2. What evidence is there that OSW could provide replacement power to hasten retirement of gas-fired electricity generation as well as help avoid the over-building of solar with battery storage? The evaluation identifies the relative advantages of OSW in relation to these other technologies.

3. What conclusions can be drawn about the value of offshore wind in a diverse electricity portfolio and the role of offshore wind in achieving 100% clean energy by 2045? The evaluation focuses on economic as well as various co-benefits that could be provided by OSW.

4. What is the job creation potential of producing OSW energy equipment, construction of OSW platforms and transmission lines, and operating them in terms of both the quantity and quality of jobs? Also, what is the job creation potential of further upstream supply-chain (indirect) linkages within the state. We perform our own quantitative analyses of these impacts.

5. What are the prospects for developing an OSW or general wind energy manufacturing cluster that can enhance the impacts by attracting new firms in creating synergies in terms of innovations and workforce training, as well as lower cost through economies of scale on the equipment production side? We perform our own quantitative analyses of these impacts as well.

This report is organized along the lines of answering these questions. The first three of them are evaluated in terms of literature syntheses, expert interviews, and our own informal assessment. For question 4, we perform an input-output (I-O) impact analysis that estimates the direct and indirect jobs that can be created by a range of OSW scenarios for California through 2045. Question 5 is assessed with the use of our I-O modeling but also by analyzing analog studies of the experience of other renewable electricity technologies, including more standard onshore wind energy.

II. Background

A. California Renewable Electricity Goals and Plans

California has implemented a number of policy goals intended to transition the state into a green economy, notably including SB 100, which aims at achieving a 100% clean electric grid by 2045. The target in California Senate Bill 100 is expected to be met primarily by renewable generation sources like onshore wind and solar, and geothermal along with other zero-carbon technologies like existing hydroelectric and energy storage (see SB100). Wind energy already has a strong presence in California, as it has proven to be a technologically feasible and economically viable resource. 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).

Offshore wind was made available as an optional "candidate" resource for the first time in the state's 2019-2020 Integrated Resource Planning (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 California Public Utility Commission (CPUC) has been collaborating with the Bureau of Ocean Energy Management (BOEM) and the National Renewable Energy Laboratory (NREL) to further explore offshore wind's potential in California's resource portfolio. Offshore wind has also been included in core modeling scenarios in CPUC's 2021 SB 100 joint agency report with CEC and CARB, and the modeling has determined that all offshore wind (up to 10 GW) is selected for resource planning purposes when made available. Moreover, the CPUC has also recommended for the transmission needs of offshore wind to be evaluated in the upcoming CAISO transmission planning process (California Energy Commission (CEC) et al., 2021).

California is on track to meet its goal of 60 percent 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 (California Energy Commission (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 to 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.

B. OSW Overview

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. Collier (2020) cites research that indicates OSW in five potential OSW development areas in California has the potential to generate up to 21 gigawatts (GW) of electricity in perpetuity. This could contribute up to 12% of California's anticipated renewable electricity growth by 2045. The total resource potential for the three BOEM designated call areas alone (Humboldt, Morro Bay, Diablo Canyon) is also estimated to be approximately 8.4 GW (Amul et al., 2020). OSW technical potential in California is considered to be approximately 200 GW; however, the state could possibly accommodate even larger net capacities than what these studied sites would offer (Optis et al., 2020).

Offshore Wind Benefits:

OSW offers several important benefits. We elaborate on them throughout this report and provide our own assessment of the job impacts in a companion report (Wei et al., 2021) and summarized briefly in Section VIII of this report.

- *Large Generation Potential:* It is estimated that at least 20 GW of viable offshore wind resource exist in California with capacity factors in the range of 46-55%, capable of providing around 25% of the state's *future* electricity needs (Beiter et al., 2020c; Hull et al., 2019; Collier et al., 2019).
- *Ability to Address the Grid Balancing Problem*: Pacific winds generally blow 24 hours a day and peak in the evening hours (6-9 PM), right when energy demand is highest. Also, a natural complement to solar electricity in terms of daily and seasonal peaks (Wang et al., 2019; Hull et al., 2019).
- *Ability to Help Retire Gas Plants*: OSW's reliability during peak electricity demand hours can further reduce the need for backup gas generation (BOEM, 2017).
- *High Storage Potential:* Strong capability to supply electricity storage efficiently (Union of Concerned Scientists, 2018).
- *Increasing Price Competitiveness:* By the late 2020s-early 2030s technological innovations in turbine size, as well as increased wind farm scale and industry standardization, could make offshore wind close enough in price to land-based renewables, such that it could play a significant and complementary role in the state's energy portfolio (Amul et al., 2020). Accordingly, recent research suggests that floating OSW could achieve an LCOE range of 53-$64/MWh by 2032 (Beiter et al., 2020c).
- *Ability to Reduce Need for Transmission Upgrades:* As California's major population centers are along the coasts, in some locations, such as the central coast of California, offshore wind could reduce the need for new high-voltage transmission lines for often distant land-based wind farms (BOEM, 2017).
- *Job Creation:* Our estimates below indicate that 10 GW installed OSW capacity by 2040 can stimulate a total of 97,000 to 195,000 job-years between 2020 and 2040 associated with the construction of the wind facilities and another 4,000 to 4,500 annual operation jobs by 2040.
- *Other positive economic impacts:* Offshore wind is also projected to bring new investment via the creation of industrial clusters (American Jobs Project, 2019).
- *Absence of Land/Environmental Restrictions of land-based renewables: Less intrusive on the landscape.* Environmental restrictions have also muted the potential for new development of land-based renewables (Wu et al., 2019).
- *Minimal Effects on Wildlife:* Lower negative impact on terrestrial wildlife compared with land-based renewable sources, and, depending on placement, potentially minimal negative effects on marine wildlife (H.T. Harvey & Associates, 2020).

OSW Limitations:

- *High Current Costs*: A California offshore wind industry would necessitate the use of floating turbines due to the state's deep waters, and, because of the nascent nature of this technology, the latest reports estimate that offshore wind farm levelized cost of energy (LCOE) of $92/MWh in 2022, with a decline to an LCOE of about $75/MWh by 2027 (Beiter et al., 2020c). For comparison, solar-PV and onshore wind currently have an LCOE of around $29-42/MWh and $26-54/MWh, respectively (Lazard, 2020).
- *Need for New Transmission Infrastructure:* In the case of a build-out on the California North Coast, there would be a need to invest heavily into new transmission infrastructure (Severy et al., 2020; CPUC, 2020).
- *Majority of Candidate Ports for Importation of OSW Equipment Would Require Upgrades:* In general, offshore wind components are much larger than their onshore counterparts. Hence, 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 and large areas of the ports of Los Angeles, Long Beach, and San Diego (Collier et al., 2019).
- *Concerns about Ocean Environment:* These have been expressed by the military, fishing industry, and conservationists about potential adverse effects on the ocean environment or human ocean-use conflicts. These negative effects include and are not limited to changes in water quality, increased subsea acoustic levels, potential collision with both marine and avian wildlife, and electromagnetic field transmissions from cables and substations (H.T. Harvey & Associates, 2020).

C. Operating Experiences with OSW in Other States and Countries

Floating OSW is expected to account for 6% of new installations internationally in 2030 (Lee et al., 2020). 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 (Lee et al., 2020). Due to increased scale and market competition, fixed-bottom OSW projects in the UK are now being delivered for as low as $50/MWh, making it cheaper than new gas and nuclear power (Lee et al., 2020). OSW also has a high capacity factor (yielding more energy per unit of installed capacity). For instance, the Hywind floating offshore wind farm demonstrated a capacity factor of 65 percent, 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).

As of the end of 2020, there are 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). The largest operational floating projects are currently Hywind Scotland (30 MW) in the UK and Wind Float Atlantic (25.2 MW) in Portugal. The Kincardine wind farm in the UK (48 MW) when operational will be the largest floating wind farm in the world. There are also many floating projects in pre-commercial phases, with 1,100 MW under construction and planned to be built by 2025. The largest by capacity include the Sicilian Channel TetraSpar project (250 MW), Donghae 1 in South Korea (200 MW), and Equinor Floating Canary Islands (200 MW). The scale of floating offshore farms is expected to increase significantly over the next ten years, with other projects recently announced to approach 2000 MW by around 2030 (Lee et al., 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 offshore wind projects have thus far required government financial support, as the initial high-costs would otherwise make the resource uncompetitive with other renewables. As such, government subsidies have been provided to offshore wind projects in both the United Kingdom and Netherlands. Government-supported project pipelines have also been vital in catalyzing necessary infrastructure and supply-chain investments. Offshore wind capacity targets have been implemented in the majority of nations that have developed the technology across both Europe and Asia. For example, the UK recently set a goal to build 1 GW of floating offshore wind and 40 GW of both floating and fixed-bottom offshore wind by 2030 (Reuters, 2020). In the U.S. east coast, offshore wind development has also 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 state capacity commitments in eight states at a minimum of 29 GW by 2035 (ACP, 2020). 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).

III. Role of OSW in Meeting the Need for Flexible Clean Resources

A. Extent of the Resource base

Studies to date have focused on five potential areas totaling 21 GW of viable offshore wind resource that exist in California, capable of providing around 25% of state electricity needs in perpetuity (CPUC, 2020; Beiter et al., 2020c; Collier et al., 2019). This energy output could possibly contribute up to 12% of the state's growth in renewable and storage resources by 2045.[1] The total resource potential for the three BOEM designated call areas alone (Humboldt, Morro Bay, Diablo Canyon) is estimated to be approximately 8.4 GW (Amul et al., 2020; Beiter et al., 2020c). 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 considering the injection of offshore wind energy into California's electric grid, it is vital to lay out the framework of the state's resource planning processes. California utilizes a process known as Integrated Resource Planning (IRP), whereby the CPUC models a portfolio of energy resources to meet reliability and greenhouse gas (GHG) goals for Load Serving Entities (LSEs) across the state and can direct LSEs to procure specific quantities and attributes of resources consistent with that portfolio. The IRP process evaluates various options in order to achieve cost, reliability, and environmental objectives, and is an important process for determining how LSEs can collectively meet decarbonization and reliability goals cost-effectively.

[1] 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)

Table IIIA. California Offshore Wind Reference Areas and Conditions

Item	Unit	Site 1: Morro Bay	Site 2: Diablo Canyon	Site 3: Humboldt	Site 4: Cape Mendocino	Site 5: Del Norte
BOEM designation	N/A	Call Area	Call Area	Call Area	N/A	N/A
Nameplate capacity potential	MW	2,419	4,324	1,607	6,216	6,605
Construction, operations, and maintenance port	N/A	Port Hueneme	Port Hueneme	Humboldt Bay	Humboldt Bay	Humboldt Bay

Source: Beiter et al. (2020c)

Integrated resource planning is a biennial procedure, and, in the 2019-2020 IRP process, offshore wind 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 21 GW of offshore wind energy that has been deemed technically viable 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 offshore wind 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 offshore wind in future cycles of the IRP.

B. 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. As can be seen in Figure IIIA, 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). This characteristic of OSW is important given that the rapid growth of solar penetration has created and is aggravating the "duck curve," which exhibits a pattern of hourly electricity demand minus renewable generation known as "net load." 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 gradually to its late afternoon and evening peak (Collier et al. 2017). The evening ramp—when people are returning from work and using more electricity—is typically met by natural gas plants either powering back on or ramping up generation, thereby increasing greenhouse gases and local air pollutants.

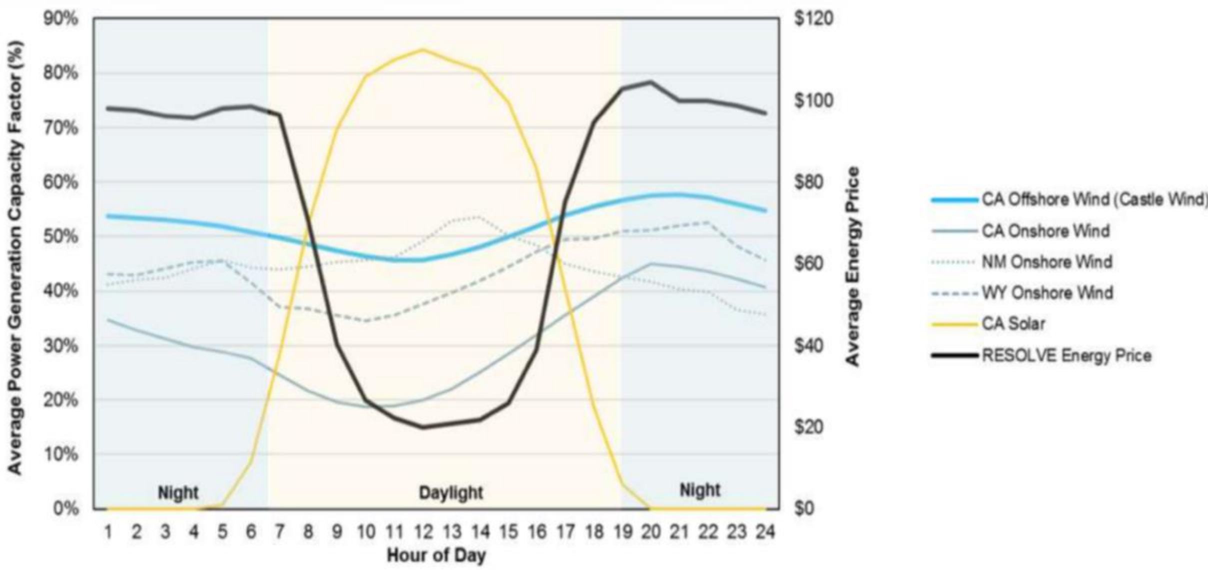


Figure IIIA: Offshore Wind Generation Profile

Source: (Hull et al., 2019).

OSW generation has the potential to eliminate this energy imbalance, as OSW has nearly opposite time-of-day generation patterns to solar generation. The ability of offshore wind turbines to deliver higher power output during peak demand periods moreover highlights its potential to offset solar curtailment (Wang et al., 2019). 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 California Independent System Operator (CAISO, 2020) has also commented that, from the 2020s onward, as power consumption grows due to vehicle and building electrification, the grid will face increasing difficulties in maintaining reliability during periods of low solar generation. The desirable generation attributes of OSW can therefore help in providing energy diversification for a high-electrification future.

As a result of OSW typically being stronger and more consistent than onshore wind, turbines can also be expected to operate at greater capacity for a larger percentage of time, 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. Specifically, modeling of avoided costs brought upon by OSW installation concludes that 8 GW of OSW deployment would provide approximately $80/MWh in lifetime average annual value to the electric grid (Collier et al., 2019). 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).

C. Potential of OSW to Replace Other Generation

Due to the fact that OSW is typically stronger and more consistent than land-based wind and can provide more constant power to the grid, OSW could further reduce the need for backup 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. This analysis is performed using the RESOLVE capacity expansion model, and also assumes that no OOS energy resources become available.

A recent NREL study has also indicated that under 2GW and 7GW hypothetical offshore wind rollout scenarios on the east coast, offshore wind provides 4% and 13.5% of total energy consumption in ISO-NE; in NYISO, OSW provides 1.4% and 5.1%, respectively. These OSW capacities primarily displace natural gas combined-cycle generation, displacing NGCC by 7% in the 2GW case and 23% in the 7GW case. However, the increased variability in the net load of OSW generation does cause NGCC plants to experience increased starts and decreased hours on-line, indicating more frequent cycling. The variability can also lead to more frequent starts, and at higher costs, for natural gas combustion-turbine plants (Beiter et al., 2020b).

Moreover, an EPA study has demonstrated that, in scenarios where offshore wind costs are low and carbon caps are persistently elevated, considerable quantities of OSW are expected to be built, mostly displacing natural gas generation. Conversely, in scenarios where offshore wind costs are higher and capacity is therefore lower, more coal-fired generation is retired, where it exists. Under the authors' modeling, natural gas generation is in fact present in all California Year 2050 power grid scenarios. However, natural gas additions are dramatically reduced as OSW cost falls (Browning and Lenox, 2020).

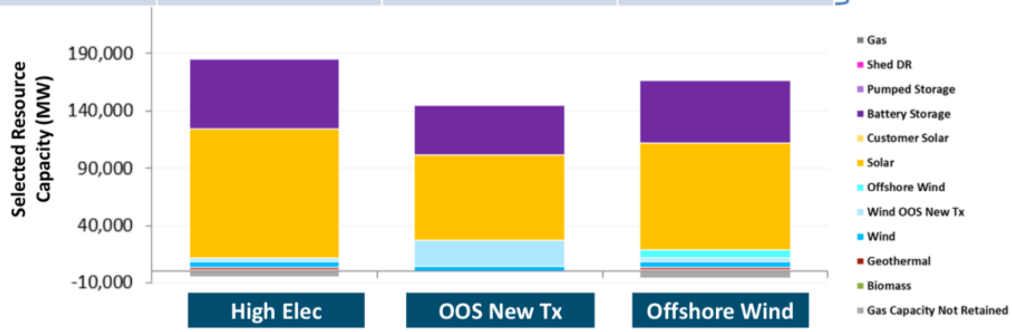
In CPUC SB100 2045 framing study scenarios, three scenarios are explored that reflect varying decarbonization strategies: high electrification, high biofuels, and high hydrogen. All scenarios assume the GHG policy constraint of 86 MMT by 2050. In considering the high electrification scenario, the sensitivity 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. Additionally, the OSW scenario results in $200,000,000 in reduced Levelized total resource cost (TRC) in comparison to the high electrification scenario without offshore wind (CPUC, 2019).

Table IIIB. CPUC 2019-2020 IRP, High Electrification Scenario: OSW and OOS Transmission Sensitivities

Metric	High Electrification (Base)	OOS New Transmission (mostly wind)	Offshore Wind available
CAISO load in 2045 (TWh)	425 TWh	425	425
CAISO GHG Target in 2045	10.3 $MMTCO_2$/yr	10.3 $MMTCO_2$/yr	10.3 $MMTCO_2$/yr
Marginal GHG Abatement Cost	\$587/tCO_2	\$408/tCO_2	\$539/tCO_2
Effective SB100 % Note: 100% CES target enforced	109%	107%	108%
Gas capacity not retained (GW) Note: Does not include OTC retirements.	4.5 GW	1 GW	5.2 GW
Reserve Margin Requirement	71 GW	71 GW	71 GW
Curtailment + storage losses (%)	24%	15%	21%
Levelized Total Resource Cost (TRC)	\$55.5 bn/yr	\$54.8 bn/yr	\$55.3 bn/yr
Incremental TRC *(relative to High Electrification)*	-	*(\$0.7 bn/yr)*	*(\$0.2 bn/yr)*

Gas capacity necessary to maintain reliability, even with significant buildout of OOS or offshore resources

Availability of additional wind resources reduces curtailment and costs



Source: CPUC (2019).

IV. Basic Cost Considerations

A. Electricity Generation

Before the positive benefits offered by OSW can be realized, policy makers must assess the relevant costs and analyze the implications of OSW integration on California ratepayers. 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 2020s. The LCOE is projected to decrease to \$53-\$64/MWh in 2032 (Beiter et al., 2020c). For comparison (see Figure IVA), 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).

Table IVA indicates a steadily increasing projected trend of floating offshore wind turbine generation capacity in the most recent NREL studies on the OSW development in both the east coast and California. With larger turbines, the same amount of power can be generated by using fewer turbines, which is a key factor contributing to the continued decline in offshore wind costs.

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 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).

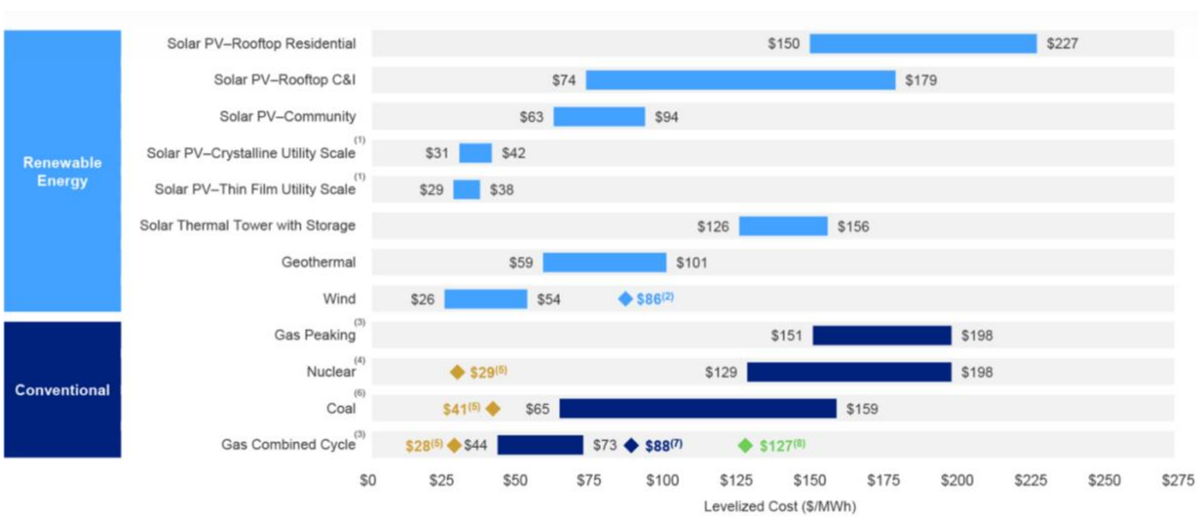


Figure IVA. Levelized Cost of Energy Comparison.

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-$3,675/kW.

Source: Lazard (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 Figure IVB).

In Figure IVC, 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 \$4,900/KW in Musial et al. (2016a) to about \$3,050/KW in Beiter et al. (2020c).

Table IVA. Technology Assumptions for California Offshore Wind Adopted

	Unit	COD Year			
		2019	2022	2027	2032
Turbine Rated Power	MW	8	10	12	15
Turbine Rotor Diameter	m	175	196	215	240
Turbine Hub Height	m	118	128	138	150
Turbine Specific Power	W/m^2	332	332	332	332
Waterline Clearance	m	30	30	30	30
Substructure Type	Name	Semisubmersible			
Minimum Water Depth	m	40			
Maximum Water Depth	m	1,300			
Wind Plant Rating	MW	1,000			
Turbine Spacing	D	7D by 7D			

Source: Beiter et al. (2020c).

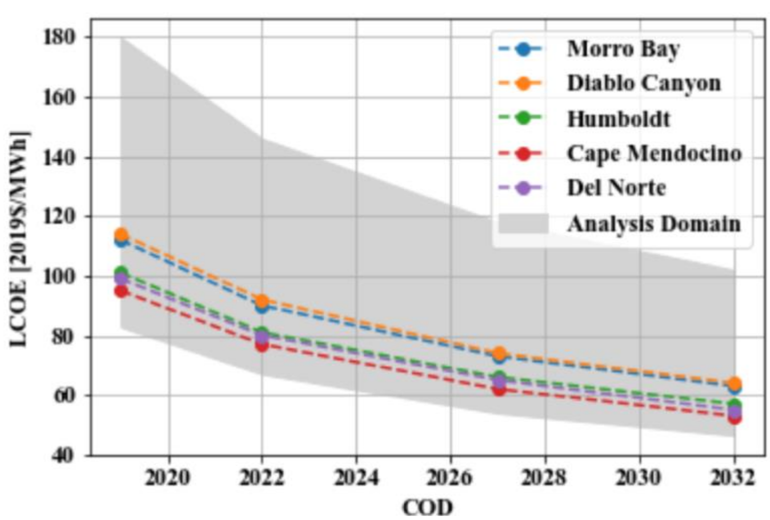


Figure IVB: Global LCOE Estimates for Floating Wind Farms

Source: Beiter et al. (2020c).

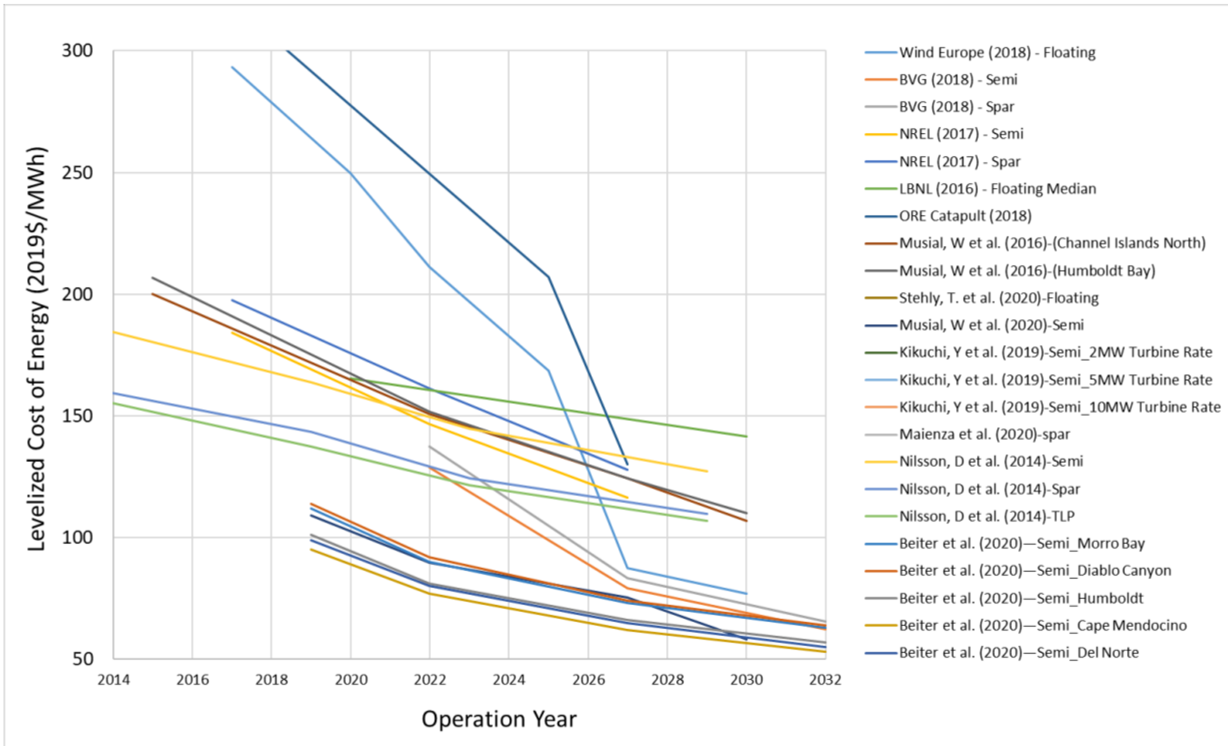


Figure IVC. Comparison of Floating OSW Cost Trends Estimated in Various Studies

Source: Developed by the authors based on LCOE data collected from the literature.

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 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 et al., 2020).

Electric generation and distribution are the largest components of electric rates (see Figure IVD). 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 et al. (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 (1,836 MW). As shown in Figure IVE, 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 et al., 2020).

Transmission cost estimates for the three study scenarios in Severy et al. (2020) are displayed in Figure IVF. The black lines within the ranges are cost estimates adjusted for terrain, land acquisition, and excavation. Hence, the adjusted 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 $1,090/kW for the on-land transmission option and $1,313/kW to $1,630/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.

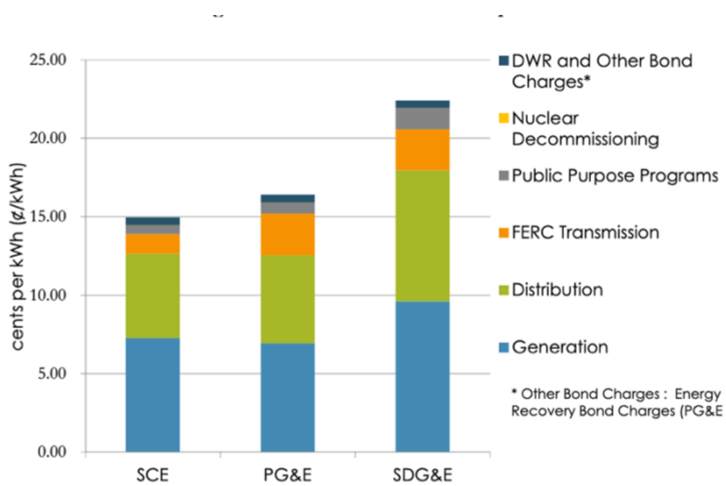


Figure IVD. California IOUs 2018 Electric Rate Components

Source: Hurd et al. (2019).

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).

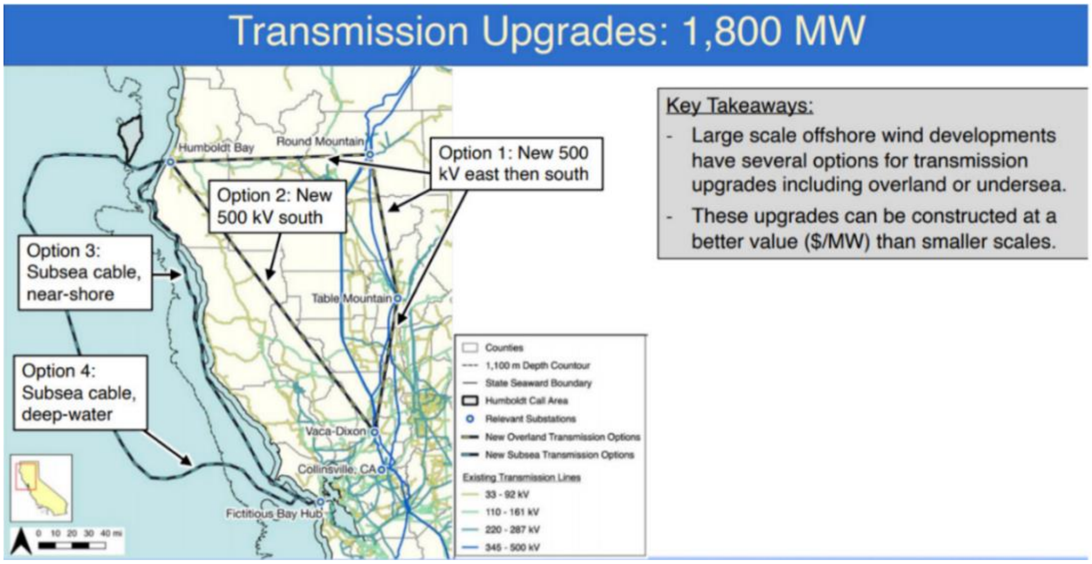


Figure IVE: Transmission Options for Large-Scale Offshore Wind Farm on North Coast (1836 MW)
Source: Offshore Wind California (2021).

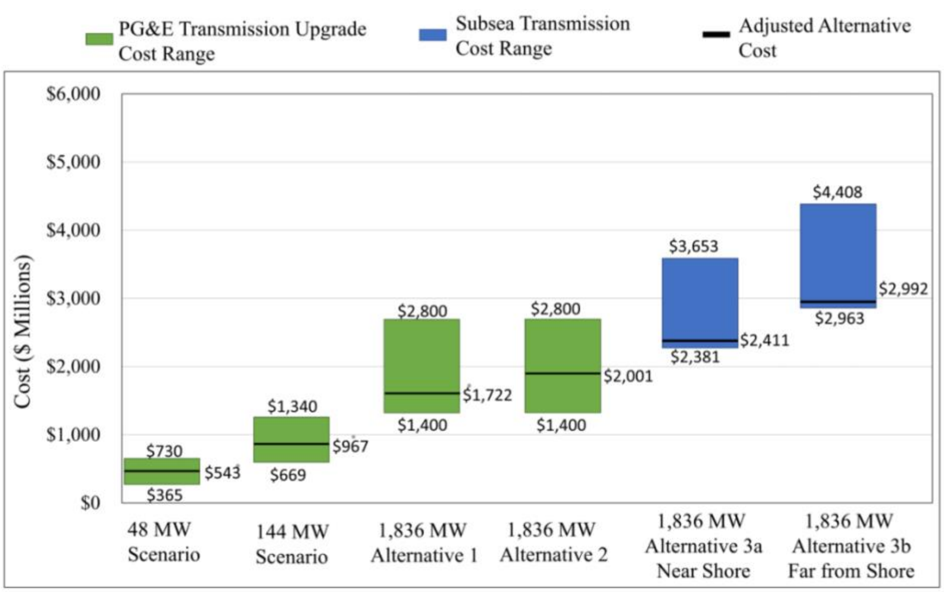


Figure IVF: Transmission Upgrade Costs for Various OSW Installment Scenarios

Source: Severy et al. (2020).

Regarding current transmission availability, it should be noted that the first California offshore wind farm is likely to 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 et al. 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).

V. Value of offshore wind in a diverse electricity portfolio to achieve 100% clean energy by 2045

In this section, we first evaluate the major benefits of OSW from within the broad framework introduced in Section I. This begins with the evaluation of its 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. We then proceed to discuss various co-benefits of OSW, including reliability, job creation, equity and environmental justice.

A. The Basic Value Proposition – Direct Benefits

While California's state utility and energy agencies have not until very recently begun to model offshore wind in integrated resource planning portfolios (IRPs) (CPUC, 2020), empirical studies of the technology in the wake of the erection of offshore wind farms around the globe have provided evidence of this technology's potential for transforming California's power grid. The rapid development and deployment of offshore wind has come at a crucial time, as California has implemented a number of policy goals intended to transition the state into a green economy, notably including SB 100, which aims at achieving a 100% clean electric grid by 2045. Ultimately, California's decisions on how to achieve this target will also be dependent on the economic and grid-system viability of existing and future technologies, and, in this context, it is vital to examine the specific value that offshore wind can provide to a diverse electricity portfolio and what part it can play in advancing the carbon-free power sector.

One key component of OSW's value proposition involves the more traditional cost-related benefit of integrating the technology into the state power grid. A recent estimate by the CEC (2021) in a joint agency report estimates that the inclusion of OSW into the state's portfolio of clean electricity generation could contribute significantly to the $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 to 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.

B. Reliability Co-Benefits

The first area of analysis in determining the efficacy of offshore wind 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).[2] As was shown in an earlier section by the “duck curve,” solar generation typically peaks around noon and land-based wind peaks around midnight; these peak times are incompatible with the time of peak energy demand, which occurs in the evening (CAISO, 2016). 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., 2020). The hourly generation profile of offshore wind 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, offshore wind 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, offshore wind 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 offshore wind 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).[3]

C. Job Creation

The suitability of offshore wind 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 offshore wind 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). Offshore wind is also projected to bring new investment via the creation of industrial clusters; a study focusing on the East Coast offshore wind 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 estimated the job and GDP impacts for the OSW development scenarios of 10 GW and 16 GW in California by 2050.

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[2] “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).

[3] Compared with the onshore wind turbine, there is a lot of space for the floating offshore wind turbine on the risk-bearing capability to handle severe circumstances, such as unknown and complex environment effects (Leimeister et al 2018). For example, the wind turbine that has the highest failure rate contains blades and electrical systems. These two components have a low resistance to the salt and humidity environment, in which the floating offshore wind turbine will operate. The average time between failure is 595.06 hours without optimizing the design of the floating offshore wind turbine (Zhang et al. 2016).

The cumulative GDP impacts during construction phases alone are estimated to be $16.2 billion to $39.7 billion in California, and the job impacts are 135,000 to 327,000 job-years between 2020 and 2050 for the two development scenarios, respectively (Speer et al., 2016). Hackett and Anderson (2020) estimated that nearly 13,000 jobs will be stimulated during the construction period of a large scale (1,836MW) offshore wind farm. Our estimates, to be presented in more detail in Section VI below, indicate that a 10 GW installed OSW capacity in California by 2040 can stimulate a total of 65,000 to 130,000 job-years between 2030 and 2040 for the construction of the wind facilities and another 4,000 to 4,500 annual operation jobs starting in the Year 2040. The job impacts are very comparable when we adjust for the differences in capacity between the two 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., 2020).

D. Environmental Benefits

Environmental benefits relate to the role OSW could play in preserving California's natural resources and achieving greenhouse-gas (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). Offshore wind 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 threaten California's ability to achieve 100% clean energy without offshore wind. For example, there has been recent controversy over the expansion of renewable energy into lands indigenous to the state's famed Joshua Trees since the Western Joshua Tree is a candidate for listing under the California Endangered Species Act because of climate change, and thus its protection under CESA could impede renewable energy and any other types of development in the area (Sahagún, 2020). California has also suffered from drought for several years, and the offshore wind 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).[4] 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

[4] This displacement effect precipitated by offshore wind is quite significant, especially given that the Western Interstate Energy Board projects that, utilizing current renewables technologies, California will need to dispatch more than 18 GW of flexible energy per-hour to meet net load ramps by 2035, which would otherwise primarily be met with natural gas and battery storage (Brownlee et al., 2019).

reduction of 4.73 million metric tons of carbon dioxide equivalents in the year 2040.[5] 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. Investment in research and technology innovations are required to reduce the risk of failure of turbines operating in the hurricane- and earthquake-prone regions of the U.S. (NYSERDA 2019). The well-designed offshore wind 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.

E. 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.[6] 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, such as in the City of Los Angeles. Given California's coastal resource base, it is reasonable to consider that there is the potential to develop 10 GW of OSW by 2040, which would go a long way in achieving environmental justice goals.

VI. Job Creation Potential of Producing OSW

We summarize our analysis of the impacts of offshore wind development in California on the state's economy (see more details in the companion report—Wei et al., 2021). The impacts are evaluated in terms of major macroeconomic indicators of employment, gross domestic product (GDP), gross output, and personal income. We quantify not only the direct impacts of construction and operation of the offshore wind 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

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[5] Year 2018 statistics (including capacity factor and heat rate) of peaking natural gas-fired power plants in California are used in the calculation (CEC, 2020b)

[6] Seventy percent of current gas-fired peaker plants are in communities with environmental justice concerns (Brightline Defense, 2020). Although there is mention in the literature that OSW can utilize current transmission lines from these facilities, this likely to be limited, because so many of the peaker plants are in urban areas, where OSW is likely to run into relatively stronger opposition than elsewhere. At the same time, there is pressure to close these plants, since they typically operate on days when air quality is the worst.

input-output 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).

A. Study Areas and Development Scenarios

The major source of data on the projected capital expenditures and O&M costs of commercial-scale offshore wind projects in California used in Wei et al. (2021) 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, with an average wind speed of over 7 meters per second. The water depth of the analysis domain ranges from 40 meters to 1,300 meters. Floating offshore wind technology is well-suited to this water depth.[7]

We analyze the economic impacts of a hypothetical deployment scenario of a cumulative 10 GW of offshore wind capacity by 2040 in California. Since we use the latest NREL study (Beiter et al., 2020c) as the primary data source for the estimates of capital expenditures and O&M costs associated with the construction and operations of the wind plants, we choose to focus on the same five study areas as in the NREL study. Table VIA presents the hypothetical offshore wind deployment scenario we adopt. We assume that a total of 10 GW offshore wind capacity will be installed by 2040 across the five selected study sites. One should note that the deployment scenario we adopt in this study is for illustrative purposes for the economic impact analysis. It is not intended as a forecast of the potential actual deployment schedule amongst call areas in California.

B. Simulation Results

Table VIB and Table VIC summarize the economic impacts on the California economy stemming from the capital expenditures for the deployment of 10 GW offshore wind by 2040 in the state. Table VIB presents the results for the development of 3 GW OSW between 2020 and 2030 and Table VIC presents the results for the development of 7 GW OSW between 2030 and 2040. In both cases, lower- and upper-bound locally produced content (RPC) adapted from Speer et al. (2016) are used. The impacts are estimated for employment, gross domestic product (GDP), gross output (sale revenue), and personal income. 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,

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[7] 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 1,000-MW at each possible site in the analysis domain. Detailed cost analysis is conducted for five study areas: 1) Morro Bay; 2) Diablo Canyon; 3) Humboldt; 4) Cape Mendocino; and 5) Del Norte. The first three areas are Bureau of Ocean Energy Management (BOEM) Call Areas, and the latter two are the additional areas identified by NREL and BOEM (Musial et al., 2016a) that also have large future commercial-scale development potentials.

respectively. The estimated impacts on GDP, gross output, and personal income are $4.0 billion, $7.8 billion, and $3.7 billion for the lower RPC scenario, and $7.9 billion, $15.0 billion, and $7.4 billion in the higher RPC scenario (all nearly doubled compared to the lower RPC scenario).

Table VIA. Hypothetical Offshore Wind Deployment Scenarios in California between 2020 and 2040

	Morro Bay	Diablo Canyon	Humboldt	Cape Mendocino	Del Norte	Total
Capacity Potential (MW)	2,419	4,324	1,607	6,216	6,605	21,171
Hypothetical Deployment Scenario						
Between 2020 and 2030 (MW)	1,000	1,000	1,000			3,000
Between 2030 and 2040 (MW)	1,000	2,000		2,000	2,000	7,000
Cumulative by 2040 (MW)	2,000	3,000	1,000	2,000	2,000	10,000

Table VIB. Economic Impacts of Capital Expenditures for the Deployment of 3 GW of Offshore Wind in California between 2020 and 2030

Impact Indicator	Category	Lower RPC	Higher RPC
Employment (job-years)	**Wind farms**	22,049	42,923
	Transmission upgrades	5,247	11,210
	Total	27,296	54,133
GDP (million 2019$)	**Wind farms**	2,818	5,391
	Transmission upgrades	629	1,342
	Total	3,447	6,733
Gross Output (million 2019$)	**Wind farms**	5,987	11,160
	Transmission upgrades	996	2,113
	Total	6,983	13,272
Personal Income (million 2019$)	**Wind farms**	2,642	5,062
	Transmission upgrades	600	1,280
	Total	3,241	6,342

Table VIC. Economic Impacts of Capital Expenditures for the Deployment of 7 GW of Offshore Wind in California between 2030 and 2040

Impact Indicator	Category	Lower RPC	Higher RPC
Employment (job-years)	**Wind farms**	42,334	82,305
	Transmission upgrades	20,459	43,959
	Total	62,792	126,264
GDP (million 2019$)	**Wind farms**	5,424	10,361
	Transmission upgrades	2,448	5,254
	Total	7,871	15,615
Gross Output	**Wind farms**	11,542	21,475

(million 2019$)	**Transmission upgrades**	3,846	8,227
	Total	15,388	29,702
Personal Income (million 2019$)	**Wind farms**	5,084	9,728
	Transmission upgrades	2,335	5,013
	Total	7,418	14,741

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, gross output, and personal income are $8.2 billion, $15.9 billion, and $7.7 billion for the lower RPC scenario, and $16.2 billion, $30.7 billion, and $15.3 billion in 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.

Table VID presents the annual economic impacts associated with the operation and maintenance of the offshore wind 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 3,979 jobs and 4,513 jobs[8] in for the lower and higher RPC scenarios, respectively. The average annual GDP, gross output, and personal income impacts are estimated to be $463 million, $812 million, and $429 million, respectively, for the lower RPC scenario, and $530 million, $956 million, and $492 million respectively, for the higher RPC scenario. Appendix D presents the decomposition of the total economic impacts of capital investment and O&M expenditures into direct, indirect, and induced impacts.

Table VID. Economic Impacts of Operation and Maintenance of Offshore Wind Projects in California

Impact Indicator	2030		2040	
	Lower RPC	Higher RPC	Lower RPC	Higher RPC
Employment (jobs)	1,375	1,560	3,991	4,526
GDP (million 2019$)	160	183	465	532
Gross Output (million 2019$)	280	331	814	959
Personal Income (million 2019$)	148	170	430	493

Sectors that are directly stimulated by the capital expenditures include Construction, Ship Building and Repairing (including offshore floating platforms manufacturing), Turbine Manufacturing, and

[8] 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.

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.

C. Comparison with Other Studies

In general, the results are in line with recent estimates found in other studies. As a summary of the Wei et al. (2021) analysis results for the OSW Development scenarios, the construction of wind farms and associated transmission lines can stimulate 97,000 to 195,000 job-years of employment and about 4,000 to 4,500 annual operation and maintenance jobs in totality for all facilities built by 2040 throughout their operational life-cycles.

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).[9]

Hackett and Anderson (2020) estimated the economic impacts of offshore wind projects in Humboldt Bay and Cape Mendocino area. The estimated job impacts range from 2,000 for a 48 MW pilot project to 13,000 for a 1,836 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 5,500, 9,000, 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

[9] 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.

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 to 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 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 2,000 to 5,000 jobs per year found in the other studies reviewed above.

VII. 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 on the basis of estimates by NREL (Speer et al., 2016) of a potential increase of in-state production of OSW-related equipment. We focus on the simulation in which we assume a rapid growth of wind energy manufacturing and service industries in California in the future two decades, and thus 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 to be generated compared to 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. The results are presented in Table VIIA. The first numerical row presents the employment and GSP impact of increasing the in-state supply of wind turbine tower and rotor nacelle assembly to 50% and 25%, respectively, in the lower-bound case, and to 100% and 50%, respectively in the upper-bound case for the development of 10 GW OSW in California in the next two decades. The estimated employment impacts are between 9,000 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, 2020b). We further assume that the total domestic share of turbine components for OSW is between 40% and 60% (Zhang et al., 2020; AWEA, 2020b), and the development of wind energy manufacturing clusters in California would enable California to obtain 25% to 50% domestic market share. The estimated employment impacts are 16,000 to 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.[10]

Table VIIA. Economic Impacts of Growth of Wind Turbine Manufacturing Clusters in California, 2020 to 2040

	Employment Impact (job-years)		GSP Impact (million 2018$)	
	Lower-Bound	Upper-Bound	Lower-Bound	Upper-Bound
In-state Supply	9,074	18,148	1,497.3	2,994.5
Exports to Rest of U.S.	15,983	47,950	2,307.9	6,923.7
Total	25,057	66,098	3,805.2	9,918.2

VIII. Key Challenges

Offshore wind is a superior energy resource in many regards, and it has legitimate potential to become part of a cost-effective, reliable, and environmentally-friendly electricity generation portfolio in California. However, there are a variety of challenges concerning OSW that likely need to be addressed before policy makers and industry move forward in the near future to make Californian offshore wind energy a reality.

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 local load, and not to transmit electricity to the rest of the state. 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 et al., 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).

Seaport capacity

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

Few ports in California could serve as importation, manufacturing, or assembly hubs. In general, the size of the offshore wind turbines will be significantly larger than those that are used for onshore wind power.[11] Since OSW components are so large, 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 and large areas of the ports of Los Angeles, Long Beach, and San Diego. Wind turbines of this size also cannot be delivered using highway or railway transportation and have to be shipped over waterway from the manufacturing site to the generation site. Moreover, a few high-capacity ports in California, including the Port of Los Angeles and Port of Long Beach, would most likely be too busy to accommodate offshore wind manufacturing and assembly (Collier et al., 2019). Another consideration is that many ports in the state are already booked for the long-term, mainly for shipping activities (BOEM, 2016). 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 (such as bridges) 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 offshore wind 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. A Request for Proposals was issued by HBHD for parties to submit plans of developing a 100-acre offshore wind manufacturing facility at the port (Collier et al. 2019). The Humboldt port authority also has many ongoing plans for developing and improving port infrastructure to support the development of offshore wind farms. Many of the projects will focus on enhancing the harbor and terminal access, initiating channel maintenance, constructing new multipurpose terminals and facilities, and improving the associated roadway network (Hackett, 2020). 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 with this port is that it experiences 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.

Other reports, such as Hamilton et al. (2021), have studied the potential for a specialized offshore wind port along California's Central Coast. The authors discuss how 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. The manufacturing of some OSW components, such as the floating foundations, will likely occur abroad in East Asia due to a current lack of assembly capacity on the West Coast, and therefore specialized ports represent the greatest opportunity for enhancing employment impacts and regional economic stimulus overall. Ports serve as the central hub in the OSW supply-chain, as they act as coordination points for assembly,

[11] The size of the rotor depends on the turbine capacity, and the current largest offshore wind turbine with an installed capacity of 10 GW is nearly 750 feet tall. The rotor diameter is projected to exceed 800 feet as the capacity increases to the range of 12 to 15 GW (Musial et al., 2018).

manufacturing, installation, and maintenance over the lifetime of the wind farm.[12] Economic co-benefits of offshore wind generation ultimately rely heavily on the existence of specialized port infrastructure.

Environmental and Wildlife concerns

The North Coast Offshore Wind Feasibility Project has assessed two potential offshore wind scenarios along California's northern coast with multiple build-out scenarios. As detailed in the report, 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 offshore wind 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, the improvements to overland transmission infrastructure which would be required to sustain a utility-scale build-out along the North Coast 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.

Thus far, environmental impact assessments for floating offshore wind have been limited because no project larger than 30 MW has been built yet anywhere in the world. Moreover, the smaller projects that have been built are primarily close to shore and in relatively shallow waters. This differs with the plans for the California wind farms, which will be situated far from the coastline and in deep waters. The contrast in marine ecosystems warrants further environmental evaluation (Collier, 2020).

Important Bird Areas (IBAs) are also located eastward of all three call areas. As the call areas are situated near areas of high ecological importance to sea birds, it is very possible that these populations could be at increased risk from offshore wind development. These risk-related events may include collision and habitat displacement (NRDC et al., 2019).

The California Current Ecosystem furthermore includes a number of large marine species from whales to sea turtles which could be adversely impacted by offshore wind operations. Many of these species are protected under the Endangered Species Act (ESA) and Marine Mammal Protections Act. Many NOAA designated Biologically Important Areas (BIAs) also exist along the California coasts. The bounty of marine mammals and conservation areas in California waters warrants a type of caution in offshore wind development which does not exist in the European waters, where the only operational floating farms are currently located (Natural Resources Defense Council (NRDC et al., 2019).

Floating offshore wind will avoid some of the primary impacts of fixed-bottom offshore wind, however, which come from disturbance of benthic habitat and acoustic impacts from installation of a platform into the sea-floor.

Military Concerns

[12] During the approximately 25-year operating period of the OSW farm, ports provide facilities for the repair of turbine components, galvanizing the local supply-chain and providing steady work for O&M staff (Hamilton et al., 2021).

The Navy initially expressed significant concerns with offshore wind 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 representative Salud Carbajal has also led a team in 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 offshore wind leasing for 399 square miles in Morro Bay and the original Humboldt Call Area. In total, this space could allow for 4.6 GW of initial offshore wind development. While there will likely be on-going discussions between DOI, DOD and California on mitigations to protect DOD's long-term interests in the Central Coast, as well as to determine the space and timing for additional phases of offshore wind leasing in California, this announcement represents a major step forward in the establishment of an offshore wind industry in the state (DOI, 2021).

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. It should be noted that while the Humboldt call area does in fact overlap with Essential Fish Habitat (EFH) designations, it does not overlap with EFH conservation areas. Offshore wind development near these coastal regions proposes potential challenges for commercial fisheries, through both active fishing 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).

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, as the vessels work in different speed even under the same condition. Meanwhile, vessel operations are impacted from high daily rates other uncertainties, such as the equipment used, the weather, and the market (Topham et al., 2019a); Topham et al. (2019b). However, it is worth noting that the vessel availability challenges and Jones Act compliance for fixed-bottom OSW are expected to be much less of an issue for floating OSW.

Lack of Wind Power Supply Chain

Despite being the state with the fourth largest wind power potential, California has very limited in-state supply-chain of the main generating components for large wind facilities. Currently, the state has minimal to no manufacturing of large-size turbine, rotor blades, nacelles, tower and other major components (Collier et al., 2019).[13] Therefore, California may need to import major components from other states or countries. Many developers actually do not view shipping cost as a main issue compared to the manufacturing cost of the various components. 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., 2020). 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 offshore wind 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 local 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. It should be noted that private investment into a local supply-chain may be contingent on state offshore wind targets or another line of sight to a market of sufficient scale (Amul et al., 2020). Therefore, clear long-term state goals of offshore wind 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 to incentivize technological innovations, building channels of knowledge exchange, attracting capital investment opportunities from both domestic and foreign sources, establishing training capacity to prepare a skilled offshore wind workforce, and encouraging the 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).

Decommissioning of offshore wind project

The final challenge of offshore wind projects is the decommission phase. While the U.S. is still in the initial stage of offshore wind development, many wind farms in Europe will be entering the lifetime extension, repowering, or decommissioning decision-making process. The decommission plans should ideally be integrated in the design phase of an OSW project. According to European experience, major challenges of OSW project decommission include: 1) limited and unclear guidelines and lack of specific regulations, 2) the 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., 2019a).

Another important consideration is the cost associated with decommission expenditure (DECEX). Maienza et al. (2020) believe DECEX of an offshore wind project includes the expenditures for decommissioning and site clearance. Contributions to DECEX are generally calculated as a percentage of installation procedures costs. After decommissioning, the site must be cleared based on approved regulations. Site clearance requires to remove all components of the offshore wind farm from the site

[13] 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).

area. However, Spyridonidou et al. (2020) think DECEX is equal to 2% of the corresponding total investment cost, without considering a significant value that could be collected from recycling the salvaged construction materials.[14]

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 for qualifying offshore energy projects. This provision extends the applicable safe harbor to ten years, meaning that any OSW project which begins construction prior to 2026 may delay operation for ten calendar years and still fall eligible for the 30% ITC (IRS, 2020).

IX. Summary and Conclusions

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 lands 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 offshore wind 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 IXA presents a summary of these findings. The first numerical column presents our own calculations, and the second column presents a range for these estimates, given the uncertainties. In

[14] Decommissioning costs are calculated as the sum of percentages of installation costs and components cost (Maienza et al. 2020). For example, the disassembly on land is calculated at 50% of the installation effort (Kausche et al. 2018). The vessels' availability related to transportation accounts for a very large part of the total decommissioning costs (Topham et al., 2019a). The return transport and the decommissioning at sea should approximate the reverse order of the transport operation and the installation in the installation phase (Maienza et al.,2020; Laura et al., 2014; Kausche et al., 2018).

places where we did not perform the calculations ourselves, we present summaries of the findings of others in the third column. This column also includes some results from three other studies on construction and operation job impacts to compare with our findings, and we note that our results pertaining to Construction are almost in the exact middle of the range of the other studies. Final column of the table provides some comments to clarify the presentation.

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 4,000 to 4,500 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 $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 offshore wind to reach its full potential in California. The first is affordability; floating offshore wind 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 et al., 2020). All candidate ports in California are also expected to require upgrades to enable offshore wind, 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 offshore wind development.

Table IXA. Summary of Benefits and Co-Benefits of Offshore Wind Energy

Benefit or Co-Benefit	Our Calculation	Our Calculation Range	Best Other Calculation	Comment
Cost Saving	n.a.	n.a.	$1 billion CEC (2021) up to $2 billion NPV (2030-40) E^3 (2019)	does not include transmission cost
Reliability	n.a	n.a.	complement to other renewables (general literature)	complementary daily timing
Jobs – Construction & Operation	146,120 job-years (Construction 2020-2040); 4,246 annual jobs in 2040 (Operation)	96,970 to 195,271 job-years (Construction 2020-2040); 3,979 to 4,513 annual jobs in 2040 (Operation)	70,806 to 211,111 job-years[a] (Construction); about 2,000 to 5,000 annual jobs (Operation) Hackett and Anderson (2020) American Jobs Project (2019) Zhang et al. (2020)	includes both direct and indirect jobs
Jobs – Industrial Cluster[b]	45,578 job-years	25,057 to 66,908 job-years	n.a.	in-state and exports to rest of U.S.
Environmental – Basic	$191.5 million[c]	$42.56 to $340.45 million[c]	n.a	societal cost of carbon impact savings only
Environmental – Other	n.a	n.a.	moderate reduction for ordinary pollutants; moderate reduction for land preservation (general literature)	does not include all environmental impacts
Environmental Justice	n.a	n.a.	improved health by race/income; economic stimulus for lagging regions (general literature)	does not include all environmental justice attributes

[a] The studies cited evaluate the job impacts for OSW projects at different capacity scales. We translated the estimates to a 10 GW OSW installation using linear extrapolations.

[b] This analysis is only conducted for potential higher in-state production capacities of wind turbine components.

[c] 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).

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Appendices

Appendix A. Global OSW Developments and Trends

Operational Projects (Demonstration and trial phase)	Projects under Construction or plan to be built by 2025 (Pre-commercial phase)	Projects announced in developing partnerships or auctions and to be operational by 2030 (Commercial phase)
Hywind Demo, Norway (2.3 MW)- 2009	EolMed project, France (24.8 MW)- 2021	JERA, ademe and Ideol project (2000 MW)- Japan
WindFloat 1 Prototype, Portugal (2 MW)- 2011	Provence Grand Large floating, France (25.2 MW)- 2021	Equinor & KNOC floating projects (800MW)-South Korea
Kabashima Floating, Japan (2 MW)- 2013	DemoSATH, Spain (2 MW)- 2021	Ulsan 1GW floating (1000 MW)- South Korea
Fukushima FORWARD, Japan (2 MW)- 2013	Hywind Tampen, Norway (88 MW)- 2022	Equinor floating project (300 MW)- Greece
Fukushima FORWARD, Japan (7 MW)- 2016	Atlantic Marine Energy Test Site, Ireland (30MW)- 2022	FLAGSHIP Iberdrola (10 MW)- Norway
Hywind Scotland, UK (30 MW)- 2017	Les Éoliennes Flottantes du Golfe du Lion, France (30 MW)- 2023	Erebus demonstration (TOTAL) project (96 MW)- UK
Floatgen, France (2 MW)- 2017	Groix Belle Ile wind farm, France (28.5 MW)- 2023	Parque Eólico Gofio (50 MW)- Spain
Fukushima FORWARD, Japan (5 MW)- 2017	CTG first floating tender, China (10 MW)- 2022	Industry proposed floating projects (1000 MW)- Norway
Kincardine, UK (2 MW testing)- 2018	Aqua Ventus, USA (12 MW)- 2023	Celtic Sea Floating (1000 MW)- The UK
Hibikinada KitaKyushu Demo, Japan (3 MW)- 2019	Goto (GCS) Floating, Japan (21MW)- 2023	French floating auctions (750MW)- France
PLOCAN's Test Site, Spain (0.2 MW)- 2019	Celtic Sea Folating, UK (32MW)- 2024	
WindFloat Atlantic, Portugal (25.2 MW)- 2020	Equinor floating Canary Islands, Spain (200 MW)- 2025	
Nezzy2 Floating, Germany (testing-1.5 MW)- 2020	Donghae 1, South Korea (200 MW)- 2024	
Kincardine, UK (48MW)- 2020	Redwood Coast offshore wind project, USA (150 MW)	
TetraSpar Demo, Norway (3.6 MW)- 2020e	Sicilian Channel TetraSpar floating project, Italy (250MW)- 2025	

Figure AI. Global Floating Offshore Wind Project Pipeline

Source: Lee et al. (2020).

Project Status	Number of Projects	Proposed Capacity
Installed	8	46 MW
Approved	14	200 MW
Permitting	2	488 MW
Proposed	14	4,162 MW
Total	**38**	**4,896 MW**

Table AI. Global Floating Offshore Wind Project Experience to Date

Source: Amul et al., 2020.

Floating Technology Trends

Wind turbine:

California expects to use larger turbines for its floating offshore wind development (Collier et al. 2017). The next-generation capacity of offshore wind turbines will be 10 MW to 12 MW technology. It appears that the industry is likely to increase turbine size beyond 12 MW, and turbines are expected to continue to grow in size over time (Musial et al., 2019a). The turbine rated power is assumed to increase to 15 MW by 2032 in the most recent NREL study of California offshore wind (Beiter et al., 2020c).

All offshore wind turbines used in floating applications have been designed for fixed-bottom applications. Thus, the market information including new technologies and cost for turbines on fixed-bottom foundations applies directly to floating systems (Musial et al., 2019a). However, floating wind turbines differ from fixed-bottom turbines since their platforms allow six degrees of substructure motion, which can influence the individual turbine's dynamic behavior, especially those subjected to downstream turbulence. Therefore, the coupled hydrodynamic-aerodynamic design, advanced control systems, and strategies will be required to optimize performance and protect the turbine from excessive loads and accelerations, especially under extreme conditions (Musial et al., 2019a); NYSERDA, 2019).

Floating structure platforms:

The floating structure platform has a lower cost than the fixed-bottom structure due to the lower cost of the support structure and other parts of the system, including enabling serial fabrication, inshore assembly and commissioning, and by minimizing expensive offshore labor, including O&M.[15] Offshore wind energy substructures have been classified into three types: semi-submersible, tension-leg platform (TLP), and spar-buoy (Spar) (Musial et al., 2016a; Porter et al., 2019).

Most floating projects in the U.S. pipeline plan use semisubmersible substructures since semisubmersible floating foundations have a shallow draft and are stable even after the turbine is installed. Also, the second-generation floating concepts of alternative hybrid substructures, TetraSpar floater, and SBM tension leg platform, representing hybrid platform technologies could have lower cost and future market share (Musial et al., 2019a).

Table AII. Floating Substructure Characteristics

Variable	**Semi-submersible**	**TLP**	**Spar**
Water Depth	66 m-1000 m	90 m- 140 m	< 60m
Distance from Port to Site	50 km-500 km		
Material	Steel	Steel	Steel
Installation Concept	Assembled in port and towed to site	Assembled in port and towed to site	Prototype assembled in protected deep water location
Primary Installation Vessels	Anchor Handling Tug, support tugs	Multiple Ocean Tugs	Anchor Handling Tug, Crane Barge
Road/Rail	Highway connection required. Rail preferred.	Highway connection required. Rail preferred.	Highway connection required. Rail preferred.

Sources: Musial et al. (2016a) and Porter et al. (2019).

[15] Moreover, one study found that the structural integrity of jacket type offshore wind turbine support structures can become unsafe after 18 years, which is earlier than most design life estimates of 20 years, based on theoretical analysis (Shittu et al. 2020).

Electrical and Power System Technology:

As floating offshore wind platforms moving with the winds and waves, the attachment point for the electric cable is in motion. The dynamic behavior will require developers and cable manufacturers to develop dynamic cable designs to ensure that cyclic loads and bends on the cable will not compromise the system (Musial et al., 2019a). Prysmian stated that it had developed a submarine cable system designed for floating offshore wind applications (T&D World, 2019).

The array cables are designed to satisfy the requirements on physical strength, flexibility, and temperature characteristics of the offshore site. Array cables also incorporate fiber-optic cables, plant control, and communications (Musial et al. 2019a). HVDC transmission is considered in the offshore wind project for long transmission distances due to the lack of active power transfer capacity limitations, lower cable cost, and lower active losses (Musial et al., 2016a).

Deepwater mooring systems:

Assessments and innovative technology of mooring and anchoring system designs should include the following features. They should have the potential to exceed assumed practical limits (e.g., 1000 m maximum depth) for the Pacific coast and mooring line and electric array cable configuration to minimize the impact on fishing activities and other existing use activities. The new mooring designs should minimize cost and maximize performance for various platform types, include methods to automate anchor and mooring line installation (NYSERDA. 2019).

Table AIII. BOEM Individual Lease Sales, Renewable Energy Program

Lease Area	State	Lessee	Date	Acreage	Cost
OCS-A 0522	MA	Vineyard Wind LLC	February 2019	132,370	$135,100,000
OCS-A 0521	MA	Mayflower Wind Energy LLC	February 2019	127,388	$135,000,000
OCS-A 0520	MA	Equinor Wind US LLC	February 2019	128,811	$135,000,000
OCS-A 0508	NC	Avangrid Renewables, LLC	March 2017	122,405	$9,066,650
OCS-A 0512	NY	Statoil Wind US LLC	December 2016	79,350	$42,469,725
OCS-A 0498	NJ	RES America Developments Inc.	February 2016	160,480	$880,715
OCS-A 0501	MA	Offshore MW LLC	March 2015	166,886	$150,197
OCS-A 0500	MA	RES America Developments Inc.	March 2015	187,523	$281,285
OCS-A 0483	VI	Virginia Electric and Power Company	September 2013	112,799	$1,600,000
OCS-A 0487	RI/MA	Deepwater Wind New England, LLC	July 2013	67,252	$3,089,461
OCS-A 0486	RI/MA	Deepwater Wind New England, LLC	July 2013	97,498	$3,089,461

Source: Developed by authors using Bureau of Ocean Energy Management Documents.

Appendix B. Offshore Wind Generation Costs

Table BI. Floating offshore wind capacity factor estimation

Source	Region	2015	2018	2019	2022	2027	2030	2032
Musial et al. (2020)-Semi	U.S. (Maine)			46%	47%	49%		51%
Kikuchi et al. (2020)-Semi	Japan			40%				
Stehly et al. (2020)-Floating	U.S. (Pacific Coast)		37.9%					
Musial et al. (2016a)-Semi	U.S. (California, Channel Island North)	47%			51%	58%	60%	
	U.S. (California, Humboldt Bay Area)	49%			53%	59%	60%	
Beiter et al. (2020c)	U.S. (California, Morro Bay)			46.5%	47.2%	48.7%		49.4%
	U.S. (California, Diablo Canyon)			45.3%	46.1%	47.7%		48.4%
	U.S. (California, Humboldt)			49.9%	50.8%	52.6%		53.5%
	U.S. (California, Cape Mendocino)			52.6%	53.4%	55.0%		55.8%
	U.S. (California, Del Norte)			51.7%	52.6%	54.3%		55.2%

Sources: Musial et al. (2020); Kikuchi et al. (2020); Stehly et al. (2020); Musial et al. (2016a); Beiter et al. (2020c).

The capacity factor of the floating offshore wind projects increases because of the growth of their annual electricity production. The growth of annual electricity production of floating offshore wind results from technology advance and innovation, such as greater turbine size, less maintenance, and stable electrical transmission.

Table BII summarizes floating offshore wind parameters and cost percentages gathered from the literature. Roughly speaking, capital expenditures account for about two-thirds of the total LCOE, while the operation costs account for the other one-third.

Table BII. Analyzed Floating Offshore Wind Parameters and Cost Percentage

	Region	Assumed Operation Year	Floating structure type	Installed Capacity (MW)	Turbine Rate (MW)	Lifetime	CapEx %	OpEx %
Castro-Santos et al. (2016)	Spain	2015	Floating	105	5		69.0%	31.0%
		2015	Semisubmersible	6	6	30	60.2%	39.8%

Musial et al. (2016a)	U.S. (California, Channel Island North)	2022	Semisubmersible	8	8	30	62.5%	37.5%
		2027	Semisubmersible	10	10	30	66.0%	34.0%
		2030	Semisubmersible	10	10	30	65.8%	34.2%
Musial et al. (2016a)	U.S. (California, Humboldt Bay Area)	2015	Semisubmersible	6	6	30	61.4%	38.6%
		2022	Semisubmersible	8	8	30	63.9%	36.1%
		2027	Semisubmersible	10	10	30	67.7%	32.3%
		2030	Semisubmersible	10	10	30	68.3%	31.7%
Kikuchi et al. (2019)	Japan	2018	Semisubmersible	100	2	20	80.8%	19.2%
		2018	Semisubmersible	100	5	20	71.0%	29.0%
		2018	Semisubmersible	100	10	20	65.5%	34.5%
Kikuchi et al. (2020),	Japan	2019	Spar	5	5	20	68.4%	31.6%
		2019	Semisubmersible	5	5	20	71.6%	28.4%
		2019	Barge	5	5	20	69.9%	30.1%
Musial et al. (2020)	U.S. (Maine)	2019	Semisubmersible	600	6	30	65.5%	34.5%
		2022	Semisubmersible	600	10	30	68.9%	31.1%
		2027	Semisubmersible	600	12	30	69.9%	30.1%
		2032	Semisubmersible	600	15	30	72.5%	27.5%
Stehly et al. (2020)	U.S. (Pacific Coast)	2018	Floating	600	5.5	25	61.0%	39.0%
Maienza et al. (2020)	Italy	2019	Spar	125	5	25-30	76.3%	19.6%
Beiter et al. (2020c)	U.S. (California, Morro Bay)	2030	Semisubmersible	1000	12-15	30	62.0%	38.0%
	U.S. (California, Diablo Canyon)	2030	Semisubmersible	1000	12-15	30	62.3%	37.7%
	U.S. (California, Humboldt)	2030	Semisubmersible	1000	12-15	30	62.2%	37.8%
	U.S. (California, Cape Mendocino)	2030	Semisubmersible	1000	12-15	30	60.8%	39.2%
	U.S. (California, Del Norte)	2030	Semisubmersible	1000	12-15	30	61.6%	38.4%
CPUC (2019)	U.S. (California, Morro Bay)	2030	Semisubmersible	1000	12-15	30	62.6%	37.4%
	U.S. (California, Diablo Canyon)	2030	Semisubmersible	1000	12-15	30	62.6%	37.4%
	U.S. (California, Humboldt)	2030	Semisubmersible	1000	12-15	30	64.0%	36.0%
	U.S. (California, Cape Mendocino)	2030	Semisubmersible	1000	12-15	30	62.6%	37.4%
	U.S. (California, Del Norte)	2030	Semisubmersible	1000	12-15	30	62.6%	37.4%

Sources: Calculated by authors based on Castro-Santos et al. (2016), Musial et al. (2016a), Kikuchi et al. (2019), CPUC (2019), Kikuchi et al. (2020), Musial et al. (2020), Maienza et al. (2020), Stehly et al. (2020), and Beiter et al. (2020c)

Large scale capacity of floating offshore wind project:

With high capacity of turbine and high total installed capacity of floating offshore wind farm, both CAPEX and OPEX are projected to decrease.

Table BIII. Large scale total capacity floating offshore wind project

Commercial Operation Year	Project	Floating type	Installed Capacity (MW)	Turbine Rate (MW)	CapEx (2020$/kW)	OpEx (2020$/kW/yr)
2018	Kikuchi et al. (2019)	Semi-submersible	100	2	10,308	123
				5	6,013	123
				10	4,663	123
2015	Castro-Santos, L. (2016)	Floating	105	5	2,802	50
2020	Maienza et al. (2020)	Spar	125	5	3,456	36
2018	Stehly et al. (2020)	Floating	600	5.5	5,569	142
2019	Musial et al. (2020)	Semi-submersible	600	6	4,885	86
2022				10	4,212	63
2027				12	3,760	54
2030				15	3,058	39
2019	Beiter et al. (2020c)_Morro Bay	Semi-submersible	1000	8	4,637	123
	Beiter et al. (2020c)_Diablo Canyon				4,529	121
	Beiter et al. (2020c)_Humboldt				4,502	118
	Beiter et al. (2020c)_Cape Mendocino				4,392	122
	Beiter et al. (2020c)_Del Norte				4,524	123
2030	Beiter et al. (2020c)_Morro Bay	Semisubmersible	1000	15	3,139	64
	Beiter et al. (2020c)_Diablo Canyon				3,128	63
	Beiter et al. (2020c)_Humboldt				3,064	62
	Beiter et al. (2020c)_Cape Mendocino				2,976	64
	Beiter et al. (2020c)_Del Norte				3,076	64

Sources: Castro-Santos et al. (2016), Kikuchi et al. (2019), Musial et al. (2020), Maienza et al. (2020), Stehly et al. (2020), and Beiter et al. (2020c).

Table BIV. Decomposition of the CAPEX

Year	Source	Region	Type	Total capacity (MW)	Turbine rate (MW)	Turbine	Platform	Electrical infra-structure	Installation cost	Other costs
2017	Stehly et al. (2018)	U.S. (North Atlantic)	Semi-submersible	600	5.64	27.14%	29.49%	20.96%	2.44%	20.0%
2018	Stehly et al. (2020)	U.S. (Pacific Coast)	Semi-submersible		5.5	24.30%	26.95%	18.66%	8.22%	21.9%
2022	Musial et al.(2020)	U.S. (Maine)	Semi-submersible	600	10	31.13%	20.41%	18.72%	7.49%	22.2%
2027	Musial et al.(2020)	U.S. (Maine)	Semi-submersible	600	12	32.21%	20.87%	17.87%	6.78%	22.3%
2032	Musial et al.(2020)	U.S. (Maine)	Semi-submersible	600	15	33.85%	22.90%	15.47%	5.44%	22.3%
2019	Kikuchi et al. (2020)	Japan	Spar	5	5	27.78%	15.05%	13.89%	25.46%	17.8%
2019	Kikuchi et al. (2020)	Japan	Semi-submersible	5	5	23.86%	25.25%	11.93%	21.87%	17.1%
2019	Kikuchi et al. (2020)	Japan	Barge	5	5	25.86%	18.75%	12.93%	23.71%	18.8%
2018	Kikuchi et al. (2019)	Japan	Semi-submersible	100	2	11.90%	27.38%	7.14%	33.33%	20.2%
2018	Kikuchi et al. (2019)	Japan	Semi-submersible	100	5	24.49%	26.53%	12.24%	22.45%	14.3%
2018	Kikuchi et al. (2019)	Japan	Semi-submersible	100	10	31.58%	26.32%	15.79%	13.16%	13.2%
2019	Maienza et al. (2020)	Southern Italy	Spar	125	5	38.95%	35.27%	8.62%	13.63%	3.5%
2019	Harrison (2020)		floating	25	8.4	41%	22%	13%	13%	11.0%
2019	Beiter et al. (2020c)	U.S. California	Semi-submersible	1000	8	29%	27%	18%	6%	20.0%

Sources: Stehly et al. (2020); Musial et al. (2020); Kikuchi et al. (2019); Kikuchi et al. (2020); Maienza et al.(2020); Harrison (2020); Beiter et al. (2020c).

Table BV. LCOE Projections Across Various Studies and Capacity Factors

Report/Article	LCOE ($/MWh)	Commercial Operation Date	Capacity Factor
The California Offshore Wind Project: A Vision for Industry Growth (American Jobs Project, 2019)	1) $89 (LBNL) 2) $46-69 (Equinor) 3) $79 (LBNL)	1) 2030 2) 2030 3) 2050	Not specified
The Economic Value of Offshore Wind Power in California (Hull et al., 2019)	1) $45-68 (Wind Europe) 2) $50	1) 2030 2) 2040	52%
California Offshore Wind: Workforce Impacts and Grid Integration (Collier et al., 2019)	1) $100 2) $62-88 (NREL ATB)	1) Mid-late 2020s 2) 2025-2030	46-55%
Potential Offshore Wind Areas in California: An Assessment of Locations, Technology, and Costs (Musial et al., 2016)	1) $138 2) $113 3) $100	1) 2022 2) 2027 3) 2030	62-75%
Cost of Floating Offshore Wind Energy Using New England Aqua Ventus Concrete Semisubmersible Technology (Musial et al., 2020)	1) $88 2) $74 3) $57 *(2018 $/MWh)*	2027	1) 47% 2) 49% 3) 51%
Oregon Offshore Wind Site Feasibility and Cost Study (Musial et al., 2019)	1) $95-138 2) $74-102 3) $53-74 *(2018 $/MWh)*	1) 2022 2) 2027 3) 2032	1) 36-52% 2) 38-53% 3) 40-55%

Source: Developed by the authors based on LCOE data collected from literature.

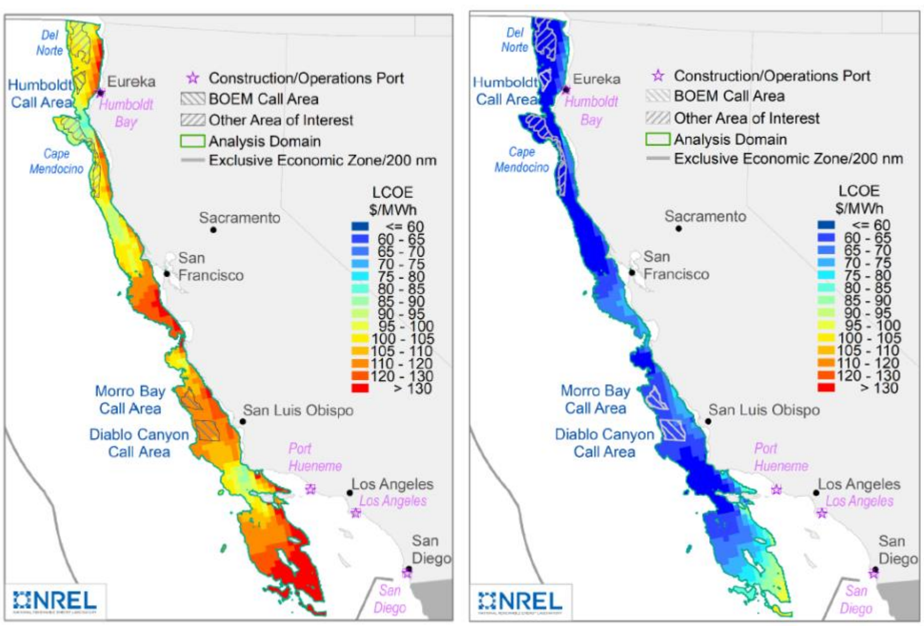

Figure BI. LCOE Estimates, COD 2019-2032 (Mid-CAPEX Scenario)
Source: Beiter et al. (2020c).

Appendix C. Reference Study Modeling Assumptions

The locational data for the five offshore wind study areas in California are presented in Appendix Table C1. Distance from site to cable landfall for the offshore wind study areas in California ranges from 29.5-48.7 km. Mean water depth for these sites ranges from 640-1013 m (Beiter et al., 2020c). These distances are considerably longer than those of established offshore wind farms in the UK and US East Coast. For example, the Hywind Scotland wind farm is about 15 mi (24 km) from shore and is located in water depths of up to 129 m (British Broadcasting Corporation, 2017). The Wind Float Atlantic farm is located approximately 20 km from shore and is in water depths of 100 m (Principle Power). However, the longer distance is estimated to have very minimal effects on the cost of OSW in California (NREL, 2020).

Appendix Table C1. Locational Data for California Offshore Wind Study Areas

Item	Unit	Site 1: Morro Bay	Site 2: Diablo Canyon	Site 3: Humboldt	Site 4: Cape Mendocino	Site 5: Del Norte
BOEM designation	N/A	Call Area	Call Area	Call Area	N/A	N/A
Distance from site to cable landfall (export cable)	km	43.5	48.7	42.0	29.5	43.7
Construction, operations, and maintenance port	N/A	Port Hueneme	Port Hueneme	Humboldt Bay	Humboldt Bay	Humboldt Bay
Distance from site to port	km	317.7	247.5	55.5	122.4	122.2
Mean water depth	m	1,013	640	832	835	807

Source: Beiter et al. (2020c).

Payroll parameters are based on Bureau of Labor Statistics (BLS) data for workers in the construction and O&M labor categories (Table 13).

Table 13. Payroll Parameters for JEDI Model Associated with Offshore Wind Development (2017)

	Wage per hour ($2015)	Employer Payroll Overhead (%)
Construction Labor		
Foundation	49.00	37.6
Erection	49.00	37.6
Electrical	51.00	37.6
Management/ Supervision	46.59	37.6
O&M Labor		
Technician Salaries	43.00	37.6
Monitoring & Daily Operations Staff and Craft Labor	34.00	37.6
Administrative	24.00	37.6
Management/Supervision	58.00	37.6

Figure CI. Payroll Parameters, JEDI Model

Source: Musial et al. (2020a).

Parameter	Baseline Value (COD 2019)	Variation Relative to Baseline (Low, High)	Resulting LCOE Values (Low, High) [2019$/MWh]
WACC [%]	5.4	90%, 110%	107; 117
CapEx [2019$/kW]	4,637	90%, 110%	104; 120
OpEx [2019$/kW-yr]	122	90%, 110%	109; 115
NCF [%]	46.5	99%, 101%	111; 113
Export Cable Distance [km]	43.5	90%; 110%	111; 112
Construction Port Distance [km]	317.7	90%; 110%	111; 112

Figure CII. LCOE Sensitivity Analysis

Source: Beiter et al. (2020c).

	This Study	Prior California Floating Cost Assessment (Musial et al. 2016a)	2018 Annual Technology Baseline (NREL 2019a)
Turbine size, 2019/2032 (MW)	8–15	6–10	3.4–10
Plant size (MW)	1,000	600	600
Fixed charge rate (%)	7.2%	10.5%	9.5%
Wind speed data	CA20 resource data set	17-yr AWS Truepower/ MERRA[32] data set	Wind Toolkit data[33]
Aggregation	Site-specific	Site-specific	Average (techno-resource group)

Figure CIII. Modeling Assumptions Comparison to Earlier Studies

Source: Beiter et al. (2020c).

Appendix D. Decomposition of Economic Impacts of 10 GW OSW Development in California

In Appendix Tables D1 and D2, we present the decomposition of the total impacts of capital investment (including transmission upgrades) and impacts associated with the operation of the offshore wind facilities into the direct, indirect, and induced impacts.

Appendix Table D1. Decomposition of Economic Impacts of Capital Expenditures for the Development of 10 GW of Offshore Wind by 2040 in California

Impact Indicator		2020 to 2030 Total		2030-2040 Total	
		Lower RPC	Higher RPC	Lower RPC	Higher RPC
Employment (job-years)	Direct	13,590	27,871	28,398	58,446
	Indirect	6,802	13,226	13,707	26,727
	Induced	11,299	22,559	23,174	46,442
	Total	31,691	63,656	65,279	131,615
GDP (million 2019$)	Direct	1,754	3,535	3,653	7,393
	Indirect	966	1,836	1,947	3,714
	Induced	1,251	2,497	2,565	5,141
	Total	3,971	7,869	8,166	16,248
Gross Output (million 2019$)	Direct	4,044	7,719	8,228	15,779
	Indirect	1,745	3,307	3,515	6,685
	Induced	2,009	4,010	4,120	8,256
	Total	7,797	15,036	15,862	30,720
Personal Income (million 2019$)	Direct	1,721	3,475	3,586	7,271
	Indirect	874	1,662	1,761	3,360
	Induced	1,147	2,289	2,352	4,713
	Total	3,742	7,426	7,699	15,344

Appendix Table D2. Decomposition of Economic Impacts of Operation and Maintenance of Offshore Wind Projects in California

Impact Indicator		2020 to 2030 Total		2030-2040 Total	
		Lower RPC	Higher RPC	Lower RPC	Higher RPC
Employment (job-years)	Direct	598	629	1,730	1,820
	Indirect	352	442	1,019	1,280
	Induced	425	488	1,230	1,413
	Total	1,375	1,560	3,979	4,513
GDP (million 2019$)	Direct	71	78	207	226
	Indirect	42	51	121	148
	Induced	47	54	136	156
	Total	160	183	463	530

Impact Indicator		2020 to 2030 Total		2030-2040 Total	
		Lower RPC	Higher RPC	Lower RPC	Higher RPC
Gross Output (million 2019$)	Direct	133	155	385	447
	Indirect	72	89	208	258
	Induced	76	87	219	251
	Total	280	331	812	956
Personal Income (million 2019$)	Direct	66	72	190	208
	Indirect	39	48	114	140
	Induced	43	50	125	143
	Total	148	170	429	492

Appendix E. Offshore Wind Potential Concerns

Stressor	Small Build-Out Scenario -50 MW	Medium Build-Out Scenario -150 MW	Commercial Build-Out Scenario -1800 MW
Marine Environment			
Rotating Blades (seabird and bat collision)	Low	Medium	High
Mooring and Interarray Cables (cetacean collision or entanglement)	Low	Low	High
Acoustic (marine mammal behavior)	Low	Low	High
Habitat Change (benthic and pelagic invertebrates, fish)	Low	Medium	High
EMF (fish and invertebrate behavior)	Low	Low	Medium
Water Quality (contaminants, increased turbidity from sediments)	Low	Low	Medium
Humboldt Bay			
Dock Improvements (eelgrass, fish, marine mammals)	Low	Low	Medium
Dredging (habitat, acoustic, water quality)	Low	Low	Medium
Vessels (acoustic, collision, nonnative aquatic species, bird disturbance and displacement)	Low	Low	Medium
Terrestrial Environment			
Acoustic (behavior)	Low	Low	Medium
Ground Disturbance (sensitive habitats, listed plant and wildlife species, wildlife habitat)	Low	Low	Medium
Vegetation Clearing (sensitive habitats, wildlife habitat)	Low	Low	Medium
Hydrology and Water Quality (wetlands, riverine, and lacustrine water bodies)	Low	Low	Medium
Transmission Lines and Towers (bird collision, electrocution)	Low	Low	Medium
Invasive Plants	Low	Low	Medium

Notes: Relative Risk: Low Medium High

Figure EI. OSW Build-Out Scenarios and Potential Environmental Risks

Source: H.T. Harvey & Associates (2020).