Title
Southern California Offshore Wind: A model-based viabiliy study

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Southern California Offshore Wind –
A model-based viability study

Capstone project report

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Abstract

To mitigate carbon emissions, energy systems around the world are electrified using renewable energy. In California, the leading renewable source is photovoltaic, which is intermittent and requires storage technology not yet deployed on a broad scale to sufficiently meet demand. To utilize its great offshore wind resource potential that can counterbalance solar and thus contribute to a stable and green energy mix in the future, floating turbines deployable in deep waters are needed as the Californian steep shelf falls off quickly. The sector, currently emerging globally, represents a high-risk investment market where costs exceed benefits. The paper finds that direct subsidies as provided through strike prices agreed upon in auction systems between governments of Europe's leading offshore wind countries and developers over the last ten years ensuring fixed rates for future electricity production can support the economic viability of projects offshore the densely populated south.

Evaluating three potential sites, the Southern California Offshore Wind model accounts for location-specific data input as well as findings from analyses conducted by the National Renewable Energy Laboratory. Based on the model, scenario analyses are conducted to consider the impact of technical progress and learning as well as carbon mitigation policies (carbon price and direct subsidy) on costs and benefits calculating the net value for deployment dates in 2022, 2027, and 2032.The results show that all three sites are unprofitable considering direct costs and benefits only although net values develop positively with the advancement of the industry. Supported by the highest carbon price as of April 2020 – Swedish carbon tax: $119/tCO2e – one site becomes profitable from 2027 onward. In contrast, taking adjusted EU strike prices for fixed-bottom systems into account, enables two sites to become economically viable in 2022 and 2027 but not in 2032. As floating systems are more expensive, it can be assumed that prices for this technology would be higher.

The paper concludes that, considering direct government support through an auction system can incentivize investments in a high-risk floating offshore wind sector, helping it to emerge in Southern California over the next ten years. With it, a stable and renewable energy supply for a growing demand can be ensured as offshore wind counterbalances solar as a complementary energy source peaking during different times of the day and providing power more constantly overall.

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This project would not have been possible without the patient support of my project committee. First, I would like to thank Corey Gabriel for hours of discussions, his motivating involvement, and caring mentorship during this insightful and outstanding year. Second, I am grateful for the great support from Mark Merrifield especially on the data processing as the fundament of this project.

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List of abbreviations

AEP – Annual energy production

BOEM – Bureau of Ocean Energy Management

CAISO – California Independent System Operator

CapEx – Capital expenditure

CCA – California Coastal Act

CfD – Contract for difference

COD – Commercial operation date

FCR – Fixed charge rate

HVAC – High Voltage alternating current

HVDC – High Voltage direct current

ITC – Investment tax credits

LACE – Levelized Avoided Cost of Energy

LCOE – Levelized Cost of Energy

MACRS – Modified accelerated cost recovery system

MPA – Marine protected area

NGCC – Natural gas combined cycle

NREL – National Renewable Energy Laboratory

PTC – Production tax credits

SOCAL – Southern California

SOCAOW – Southern California Offshore wind model

OpEx – Operational expenditure

O&M – Operation and maintenance

TOU – Time Of Use

1. Introduction

Electrifying energy systems using renewable sources is in combination with efficiency increases of today's energy production, the main driver to mitigate CO_2 emissions and minimize global warming. Compared to markets in the EU and China, the development of offshore wind to counter CO_2 emissions in the U.S. energy sector is lagging[1] even though the resource potential on the East and West coasts is remarkable. Factors contributing to this gap include political barriers[2], and the missing commitment of U.S. based companies in the oil and gas industry[3].

With the strong commitment of this year's newly elected administration to jumpstart the offshore wind industry in the U.S.[4], all entities involved need to focus on a fast development strategy for stakeholders and aspects along the value chain to build a mature industry that can meet the administration's near-term goals[5].

As the potential for offshore wind deployment is greatly dependent on well-characterized site conditions, location specific evaluations are an important lever to contribute to the successful jumpstart of the sector[6]. The following analysis conceptualizes and uses a model-based approach to evaluate the potential for offshore wind energy in Southern California (SOCAL).

The remainder of chapter 1 discusses SOCAL's energy demand and supply considering current and future developments. Subsequently, an overview concerning offshore wind, and floating offshore wind platforms in particular, is given.

In Chapter 2 the model built to conduct a site-specific value analysis for Southern California Offshore Wind (SOCAOW) is described. First, targets and the implied use of the model are defined. Second, the model set-up is developed using the concepts Levelized Cost Of Energy (LCOE) and Levelized Avoided Costs of Energy (LACE). The model is structured in 8 modules containing parameters that influence the calculations of costs and benefits. Subsequently, the processing of spatial data to set the basis for further analysis is described. Finally, a site-specific analysis is conducted beginning with the selection of three reference sites along the SOCAL coast followed by the description of assumed general wind farm characteristics as well as site-specific values. The chapter closes with two scenario analyses considering technical progress and learning as well as carbon mitigation policies.

In Chapter 3 results are summarized and implications for developing a floating offshore wind sector in SOCAL are considered

1.1. Energy market in Southern California

A growing population, especially in coastal regions, increases demand for electricity in California. The overall trend toward electrification (electrical vehicles[7]), and the occurrence

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[1] Of all 29.1 gigawatts offshore wind energy installed, the U.K. holds 33%, Germany 26% and China 24% (Global Wind Energy Council, 2020, p. 12).

[2] (*Biden's New Moonshot*, 2021)

[3] Shell, Equinor and BP, all European based companies, committed to zero emission targets and substantial CapEx redistribution towards the buildup of renewables.

[4] (*FACT SHEET*, 2021)

[5] (*Biden's New Moonshot*, 2021)

[6] (International Renewable Energy Agency, 2016, p. 6)

[7] , California policy to require all new cars sold to be zero emission by 2035 (Newsom, 2020)

of more intense heat waves (air conditioning[8]), are putting additional pressure on the energy system. During peak hours, the current energy mix is not sufficient to serve the demand, leading to rolling power outages. As the reliance on electricity grows, maintaining a reliably functioning system is an ongoing challenge in the state.

In addition to federal announcements, state policies target the expansion of renewable sources, aiming at 100% renewable energy by 2045 via Bill 100[9]. To reach these goals in the most cost-efficient way, assembly bill No. 525 states that integrating 10 Gigawatts of offshore wind will be needed by 2040[10].

As demand requires clean and reliable electricity, pressure to mitigate emissions and supply constant energy are put on producers. To satisfy demand in California, the current strategy is the use of solar energy coupled with battery storage. As battery technology is not yet developed to smoothen the intermittent character of solar, the California duck curve of net energy supply[11] results in the need for expensive electricity provided by natural gas powered peaker plants. A Time Of Use (TOU) analysis conducted by the California Independent System Operator (CAISO) from 2015 showed that for both weekday and weekend average energy demand peaks between 4 pm and 9 pm throughout the year and on average reaches its low between 10 am and 2 pm[12]. In contrast, the energy supply of renewables (mainly solar photovoltaic) currently peaks between 10 am and 3 pm[13]. Even if more advanced storage technologies were widespread, the total system demand during renewable peak time significantly exceeds the renewable energy supply[14]. To meet demand during peak hours, reliable energy sources like nuclear power plants and gas turbines are needed. Thus, when the San Onofre nuclear plant was shut down, the reliability of the energy system – especially in SOCAL – was reduced significantly. To counterbalance the gap, the use of natural gas power plants was intensified[15].

All things considered, the supply of renewable energy and the total demand in California are not in an equilibrium state. This imbalance is likely to increase if renewable energy sources are not expanded drastically.

1.2. Offshore wind

To both reach zero emission in electricity production and provide a reliable source of energy, offshore wind is a valuable contribution to the future California energy mix. Currently, lease areas for offshore wind in the U.S. are mainly located on the East coast[16]. Nevertheless, the Bureau of Ocean Energy Management (BOEM) is also establishing lease areas in California. With currently available technologies, around 17-31%[17] of California's electricity demand

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[8] (Barreca et al., 2016, p. 156)

[9] (W. Musial et al., 2019, p. xii)

[10] (Talamantes Eggman, 2021)

[11] Total supply minus supply delivered by renewable sources.

[12] (California Independent System Operator, 2015, p. 12)

[13] (California Independent System Operator, 2020, p. 1)

[14] On November 29, 2020 the gap between renewable energy supply (9500 MN) and total demand (19000 MW) at 12:30 pm was about 9500 MN which represented a 100% higher demand than supply.

[15] (California Energy Commission, 2020, p. 173)

[16] (W. Musial et al., 2019, p. x)

[17] (Dvorak et al., 2010, p. 1253)

could be met. Future use of floating offshore technologies would increase this to 174-224%[18].

Unlike solar photovoltaics which produce electricity only during sunlight, offshore wind in California blows consistently throughout the day during all seasons[19]. This makes it a reliable source for energy with the potential to counterbalance the intermittent character of solar power. Auction prices for lease areas have tripled between 2016 and 2018 auctions. Reasons for this increase include the higher certainty in market growth due to policy decisions and actions, the confidence of investors to give capital, as well as cost reduction in production.[20]

In terms of access to windy areas, a major difference between the East and West coasts is the extent of the shelf. Whereas the East coast shelf extends far offshore with depths not exceeding 60 meters, the steep West coast shelf falls off quickly. In depth up to 60 meters, fixed-bottom turbine structures can be used and have been deployed in high quantities in the EU and China[21]. Fixed-bottom structures are less complex to design and to install compared to floating structures needed in depth beyond 60 meters. The availability of suitably shallow shelf area contributes to the offshore wind industry being more developed on the East coast. In turn, the further offshore turbines are deployed the stronger and more consistent the wind tends to be, hence bigger and more-cost efficient systems can be realized with less visual impact (depending on height of viewpoint, turbines situated 25 to 30 miles offshore are not visible from shore) [22].

Due to increasing demand for stable sources of renewable energy during peak times, the potential capacity of the resource, and rapidly advancing floating technology, the development opportunities of floating offshore wind energy in the future can be compared to today's development of fixed bottom structures[23]. Currently, the industry is in a very early stage, especially in the design of suitable substructures. With less than 66MW of nameplate capacity installed[24], the precommercial phase is used to test out and improve designs. For floating structures, four designs are currently available – spar, tension leg, semisubmersible, and multifloat-spar. The maximum deployment depth is 200 meters. Semisubmersible structures are likely to be deployable in depth up to 1000 meters in the future, making them the broadest usable design. Moreover, they have less draft than spar structures and are easier to deploy since they can be installed completely in port and then towed out and connected to the offshore mooring system installed independently. Tension leg platforms are unstable if the mooring system and platform are not connected. [25] With half of the total system components common between floating and fixed-bottom systems, the adaption of knowledge from the more advanced fixed-bottom sector is a strong lever for a steep learning curve for floating systems. On the other hand, the other half of system components is specific to floating structures (see Table 1).

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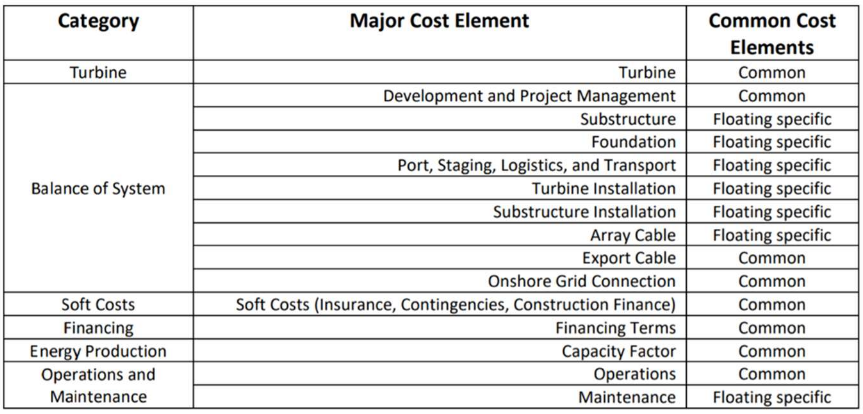
[18] (Dvorak et al., 2010, p. 1253)
[19] (Dvorak et al., 2010, p. 1253)
[20] (W. Musial et al., 2019, p. x)
[21] (Global Wind Energy Council, 2020, p. 12)
[22] (Schweber, 2021)
[23] (W. Musial et al., 2019, p. 47)
[24] (Global Wind Energy Council, 2020, p. 12)
[25] (Pacheco et al., 2017, pp. 240–241)

Table 1: Common and specific costs of floating offshore wind structures[26]



Category	Major Cost Element	Common Cost Elements
Turbine	Turbine	Common
Balance of System	Development and Project Management	Common
	Substructure	Floating specific
	Foundation	Floating specific
	Port, Staging, Logistics, and Transport	Floating specific
	Turbine Installation	Floating specific
	Substructure Installation	Floating specific
	Array Cable	Floating specific
	Export Cable	Common
	Onshore Grid Connection	Common
Soft Costs	Soft Costs (Insurance, Contingencies, Construction Finance)	Common
Financing	Financing Terms	Common
Energy Production	Capacity Factor	Common
Operations and Maintenance	Operations	Common
	Maintenance	Floating specific

Other advantages of offshore wind energy for SOCAL include the relatively short distance between energy generation sites and consumers, as a great majority of the population lives near the coast, the reduction in wildfire risk as the electricity transportation infrastructure on land is reduced, and companies that have the knowledge to build and operate large structures in the ocean (offshore oil and gas industry) are based in the state.

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[26] Table taken from (W. D. Musial et al., 2020, p. 11)

2. Southern California Offshore Wind (SOCAOW) model

2.1. Targets of SOCAOW

The goals of the SOCAOW model are to consider interdisciplinary contributing factors to evaluate potential offshore wind sites in Southern California, to use area specific characteristics to refine past analyses, and to provide a transparent approach for future research and evaluation of potential offshore wind sites in SOCAL[27]. We conduct scenario analyses using the model, resulting in site-specific data that are used for an outlook on the development of the offshore wind industry on the West coast, and to consider paths forward on how to implement the resource in SOCAL.

2.2. Model set-up

The SOCAOW is set up using a commonly used cost and benefit model to evaluate energy sources. Site-specific input is obtained using spatial data processed in ArcGIS and transferred to Excel for further calculations. Cost and benefit assumptions used in Excel are mainly based on analyses conducted by the National Renewable Energy Laboratory (NREL)[28].

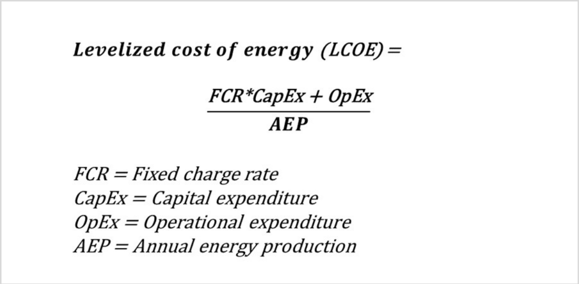
In the following the principles of LCOE and LACE are explained using the first-order equations for calculation. Subsequently, the modules and respective parameters of the SOCAOW are described which factor into the calculation of LCOE and LACE. Finally, the processing of general GIS data layer to obtain site-specific information considering locally influencing parameters is explained.

2.2.1. Costs and benefits of energy sources

To evaluate the economic potential of an energy source, the NREL uses the metrics of LCOE and LACE resulting in a net value of a specific source. To enable a comparison with a sector-wide known standard and established values, the SOCAOW uses the same approach to estimate the potential of offshore wind farms in SOCAL.

Levelized Cost Of Energy (LCOE)

LCOE represent the amount of total lifecycle costs spent per unit of generated electricity and can be calculated as described by Beiter et al.[29]:



$$\textbf{Levelized cost of energy (LCOE)} = \frac{FCR*CapEx + OpEx}{AEP}$$

FCR = Fixed charge rate
$CapEx$ = Capital expenditure
$OpEx$ = Operational expenditure
AEP = Annual energy production

Figure 1: Levelized Cost of Energy[30]

LCOE is based on three main modules: operational expenditure (OpEx), capital expenditure (CapEx) and annual energy production (AEP). To refer CapEx to an annual payment, a Fixed Charge Rate (FCR) is calculated based on the economic lifetime, debt fraction, return on invest rate, interest, and tax rate. Based on this calculation, LCOE is dependent on the spatial

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[27] Lack of site-specific detailed analysis - (Pacheco et al., 2017, p. 240)
[28] (Beiter et al., 2016), (W. D. Musial et al., 2020)
[29] (Beiter et al., 2017)
[30] Simplified figure taken from (Beiter et al., 2017, p. 6)

characteristics of a potential wind site. For example, a site closer to the coast is likely to have lower construction, operation, and maintenance costs, whereas a site located further offshore is likely to produce more energy due to higher wind speeds. In both cases costs are lowered. Parameters that influence LCOE are water depth, average wind speed, sea state severity, seabed conditions, location and characteristics of staging ports, location and characteristics of on-land assembly sites, existing grid features and proximity to potential connection points, environmentally sensitive areas, competitive-use areas[31]. Technological innovations are expected to lower the LCOE in different ways. One of the main levers is the increasing size of turbines driving up the capacity per unit 5-fold to 15 MW by the end of the next decade[32]. Among others, an improved electricity transportation and distribution infrastructure[33] as well as innovation in design and construction[34] will reduce costs.

Levelized Avoided Costs Of Energy (LACE)

Complementary to LCOE, LACE can be used as a measure to evaluate the benefits of a source by accounting for the revenue it is assumed to earn throughout its lifetime and the value of supplied energy it contributes to the electricity system. The two terms to calculate LACE are the average marginal generation price and the capacity payment[35]:

$$\textit{Levelized avoided cost of energy (LACE)} = \frac{MP*AEP + CP*CC}{AEP}$$

$MP = \textit{Marginal price}$
$CP = \textit{Capacity payment}$
$CC = \textit{Capacity credit}$
$AEP = \textit{Annual energy production}$

Figure 2: Levelized Avoided Costs of Electricity[36]

Benefits are based on the annual revenue as a product of AEP and the achievable price per unit of energy as well as the product of capacity payment and credit[37], which expresses the value of capital within an energy market. Capacity payment is approximately comparable to the overnight capital cost of a new advanced natural-gas combustion turbine plant. The capacity credit is dependent on regional, market-specific evaluations[38].

For LCOE and especially LACE the NREL indicates the need for parameter refinements to evaluate a specific area. Moreover, supporting policies that would drive the LACE and lower LCOE are not included[39].

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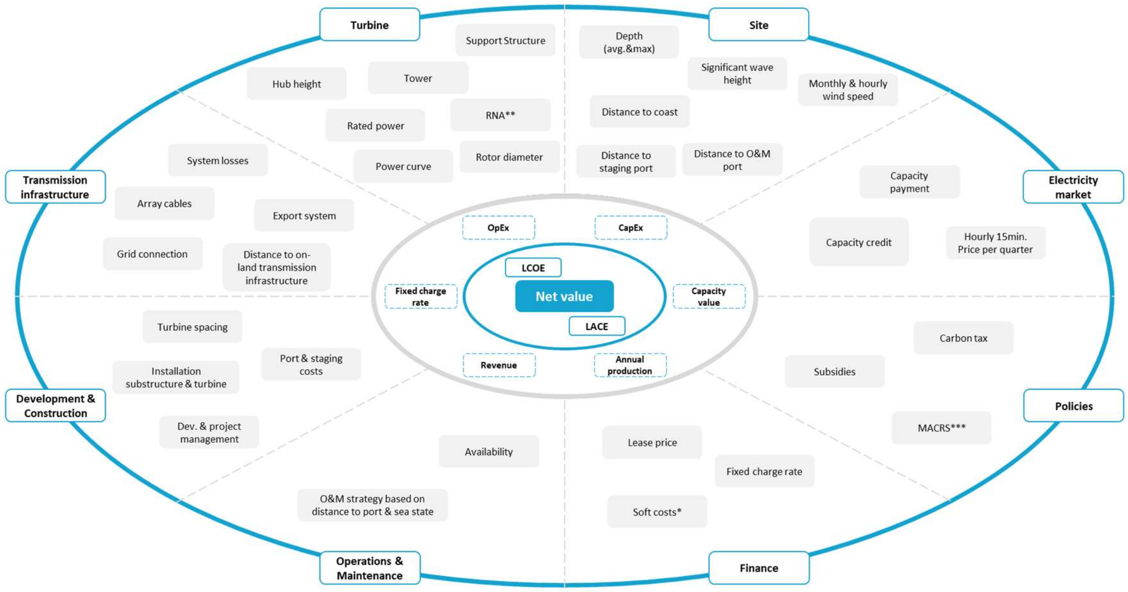
[31] (Beiter et al., 2017, pp. 6–7))
[32] (W. Musial et al., 2019, p. xii)
[33] Reduction in CapEx since less cables need to be bought and installed in total and reduction in OpEx since less equipment needs to be maintained.
[34] Reduction in CapEx due to efficiency gains and increase of AEP due to increased accessibility to sites as well as new siting opportunities.
[35] (Beiter et al., 2017, p. 8)
[36] Simplified figure taken from (Beiter et al., 2017, p. 9)
[37] Capacity payment represents the price to provide the last unit of energy to reach a regional reliability reserve requirement. Capacity credit represents the ability of an energy source to provide a unit of energy towards a reliability reserve and depends on the dispatchability of the production. (Brown et al., 2016, p. 23)
[38] (Beiter et al., 2017, p. 15)
[39] (Beiter et al., 2017, p. ix)

2.2.2. Modules – parameter (local/global) and input data

To specify the net value of potential offshore wind sites in SOCAL we use a model based on eight major modules that embody site-specific information as well as general parameters that may be constant or variable depending on site (see Figure 3). The parameters for each module are described in the following including respective data sources. Appendix A provides a detailed list of all parameters and their contributions to LCOE and LACE. Moreover, it includes future refinement and specification potential for the SOCAOW.



*Soft costs = insurance, contingencies, construction finance / **RNA = Rotor nacelle assembly / ***MACRS = Modified accelerated cost recovery system

Figure 3: Southern California Offshore Wind (SOCAOW) model

Site

The Site module includes all physical parameters related to meteorologic and oceanographic data, as well as distance measurements between the offshore site and several points of interest on land. To evaluate wind speeds at a particular site and altitude, we use a GIS wind speed data layer[40] consisting of modeled monthly and hourly speeds 100 meter above sea level[41] provided by the NREL[42]. Average and maximum water depth at each site is provided in a bathymetry GIS data layer from the California Department of Fish and Game[43]. For an approximation of the sea state, a significant wave height GIS data layer from NREL is used[44].
To evaluate distances to possible staging and O&M ports, a GIS data layer from the California state geoportal is used[45]. All distances were measured using the built-in ArcGIS inquiry tool "measure".

Turbine

Technical parameters for the turbine[46] are included in the Turbine module. As interdependent parameters, data for the rated power, rotor diameter and hub height are

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[40] (Draxl et al., 2017)
[41] (Draxl et al., 2015, p. 365)
[42] To adjust these values to the hub height of the turbine a vertical wind shear coefficient of 0.115 was utilized. (W. D. Musial et al., 2020, p. 20)
[43] (California Department of Fish and Game, 2011)
[44] (National Renewable Energy Laboratory, 2011)
[45] (California State Geoportal, 2020)

based on NREL assumptions which consider producer's information, market developments and minimum clearance considerations[47]. Tower, Rotor Nacelle Assembly (RNA) and substructure[48] cost values are based on NREL assumptions as well[49]. To refer wind speed to electricity production, power curve assumptions from NREL and the Danish Technical[50] were approximated, as described in Appendix B – Approximation of turbine power curves.

Transmission infrastructure

This module considers the array cabling to connect the turbines with each other and to a substation offshore, and the export system including substations on- and offshore as well as the export cable and the grid connection on land. The array cable length needed between two turbines is estimated as two times the depth plus the distance between two turbines[51]. The costs of array cabling are estimated as $1,500/m[52]. The approximation of export system costs depending on the distance to the coast is based on the NREL's parameter study for floating technology[53]. Any possible site for floating wind in Southern California will be more than 9 km offshore. Thus, only 220-kV High Voltage alternating current (HVAC), and 320-kV High Voltage direct current (HVDC) are considered. Depending on the distance to landfall, the model chooses a HVAC export system up to 109 km and a HVDC system beyond that as the most cost-efficient alternative. The cost functions include revenue losses of $150 / MWh[54][55]. Total costs are divided by the nameplate capacity[56] of the modeled windfarm used in the data source (600 MW[57]) resulting in a $/kW value as a scalable parameter. Land based transmission costs of $3992/MW-mile[58] are used. To estimate distance from export cable landfall to closest transmission infrastructure, an on-land transmission infrastructure GIS data layer provided by Homeland Infrastructure Foundation-Level Data is included[59].

Development and construction

The cost parameter for the development and project management is based on costs of $196/kW[60]. Construction costs are variable depending on the maximum water depth and the distance from a suitable staging port. Turbines are assumed to be spaced 8-times the rotor diameter apart[61]. The model separately estimates the construction costs for the substructures and turbines as well as port and staging costs specified for a semisubmersible

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[46] Including rotor nacelle assembly, tower, and substructure

[47] (W. Musial et al., 2020, pp. 15–16)

[48] As research and development for semisubmersible substructures goes on, no commercially available type can be referenced for cost assumptions. One of the prototypes is developed by the University of Maine – Aqua Ventus – and referenced in a study by the NREL which is used in this project for parameter assumptions as well.

[49] (W. Musial et al., 2020, p. 31)

[50] (W. Musial et al., 2020, p. 17)

[51] This assumption is a conservative estimation based on information from the NREL (Beiter et al., 2016, p. 145). Depending on water depth array cables may not lie on the ocean floor.

[52] (Beiter et al., 2016, p. 144)

[53] (Beiter et al., 2016, p. 56)

[54] (Beiter et al., 2016, p. 55)

[55] Costs and revenue losses for HVAC [million$]: 200+4.55*(distance to coast)
Costs and revenue losses for HVDC [million$]: 450+2.33 *(distance to coast)

[56] Maximum power output of a turbine.

[57] (Beiter et al., 2016, p. 61)

[58] (Beiter et al., 2016, p. 124)

[59] (Homeland infrastructure foundation-level data, 2020)

[60] (Beiter et al., 2016, p. 42), (W. Musial et al., 2020, p. 31)

[61] Assumption by author considering common practice in EU (Beiter et al., 2016, p. 144)

system with a nameplate capacity of 600MW[62] and rated turbine power of 10MW[63]. To scale costs to turbines with higher rated power, the total costs are broken down to a $/kW price.

Operation and maintenance

This module is based on the operation and maintenance (O&M) framework of the NREL[64]. The model differentiates O&M costs for semisubmersible systems depending on the meteorological (windspeed at 10m above surface) and oceanographic conditions (significant wave height) as well as the distance to the responsible O&M port[65]. Potential sites can be classified as mild, moderate, or severe depending on wind and waves[66]. Considering this classification, generally three O&M strategies – close-to-shore, medium distance, far-shore – are applicable. SOCAOW chooses the most cost-efficient alternative varying with distance to the closest O&M port and depends on the sea state. Costs include revenue losses due to decreased availability of turbines during maintenance[67]. To scale costs to turbines with higher rated power, the total costs are broken down to a $/kW price.

Electricity market

To account for monthly and hourly energy production data, the 15-minute energy price based on quarterly reports from CAISO in 2020 are used in the model[68,69]. To account for a local capacity value, the capacity payment was specified to $822/kW for an industrial framed natural gas combustion turbine in the SOCAL region[70]. The capacity credit is assumed to be 24% following estimations specific for California[71].

Finance

The model accounts for three overarching financial parameters. Presuming a delayed but comparable development of the floating wind market compared to the fixed-bottom wind market, and thus lower risk profiles for investments in the future, the FCR is set to 7%[72][73]. Cost factors such as insurance during construction, commissioning, decommissioning, procurement contingency, install contingency, and project financing are summarized in an assumed 14.8% share of capital expenditure for soft costs[74]. Additionally, this module includes a lease price for a potential site based on a winning bid by Equinor for an area offshore of New York[75].

Policies

The model incorporates the modified accelerated cost recovery system (MACRS) enabling wind projects to depreciate capital over a shortened period of 5 years defined by the Energy

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[62] (Beiter et al., 2016, p. 61)

[63] (Beiter et al., 2016, p. 163)

[64] (Beiter et al., 2016, pp. 166–185)

[65] In the SOCAOW the staging port was assumed to also serve as the O&M port.

[66] (Beiter et al., 2016, p. 174)

[67] For a detailed overview of approximated total costs and revenue loss functions for semisubmersible systems depending on the sea state see Appendix C – Approximation of O&M cost functions

[68] (CAISO, 2020)

[69] For a detailed list for each quarter and hour see Appendix D – Quarterly 15-minute energy prices

[70] (Energy Information Administration, 2021a, p. 7)

[71] (Stoutenburg et al., 2010, p. 2790)

[72] (W. Musial et al., 2020, p. 20)

[73] Assumed project lifetime 30 years (W. Musial et al., 2020, p. 16)

[74] (Stehly et al., 2020, p. 23)

[75] (W. Musial et al., 2020, p. 19)

Information Agency[76]. Considering a heat rate of 6700 Btu/kWh[77] and a fuel carbon intensity of 0.053 t/MMBtu[78] of a natural gas combined cycle power plant (NGCC), the avoided CO_2 emissions and subsequently carbon tax needed for a break-even – net value = 0 – are calculated[79]. For global comparison, different carbon taxes are taken from The World Bank carbon pricing dashboard[80]. To evaluate direct subsidies needed to level LCOE and LACE, the Contract for Difference (CfD) system used in the U.K. and across Europe in modified forms is used[81].

2.2.3. GIS data input and processing

To account for the deployment depth range of 60 to 1000 meter, the basic GIS data layer is the bathymetry raster data set for the West Coast, which was filtered for this depth range and saved as a new data layer[82]. This data layer was further filtered for Southern California waters between San Luis Obispo Bay to the Mexican border. To consider Marine Protected Areas (MPA), a shapefile was added representing California's MPAs[83] and used to delete all intersecting raster data from the bathymetry layer. Moreover, vessel traffic was considered by adding the 2011 Pacific vessel traffic shapefile provided by BOEM[84,85]. To specifically account for fishing vessel traffic and related established fishing grounds, the bathymetry data set was further intersected with all fishing vessel track data, adjusted accordingly, and saved as the final baseline data layer for deployment possibility[86,87,88]. After choosing possible sites, the monthly windspeed data layers, bathymetry layer, and significant wave height layer were intersected with each site to obtain site-specific input for the SOCAOW. Moreover, port and transmission infrastructure on land data layers were included and enabled the definition of all relevant distances needed as input for the modules.

2.3. Analysis

In the following the analysis of potential sites for offshore wind in SOCAL using the SOCAOW model is described in three parts. Based on the processed GIS data layers, the selection of possible sites is explained, and site characteristics are defined. Subsequently, the scenario analyses are described and conducted for all sites.

2.3.1. Site selection

An annual windspeed dataset[89] was intersected with the possible deployment described in chapter 2.2.3[90]. The resulting file was used to conduct an optimized hotspot analysis which considered the attribute "annual average windspeed" to evaluate areas with a high

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[76] (Internal Revenue Service, 2020)
[77] (U.S. Energy Information Administration (EIA), 2021b)
[78] (U.S. Energy Information Administration (EIA), 2021a)
[79] Carbon emission avoided: production*carbon intensity*heat rate
[80] (The World Bank, 2021)
[81] (Welisch & Poudineh, 2019, p. 4), (Jansen et al., 2020)
[82] "Bathymetry_CA_60-1000"
[83] (California Department of Fish and Wildlife, 2016)
[84] (Bureau of Ocean Energy Management, 2011)
[85] For a visualization of this dataset see Appendix E – GIS data layers visualized
[86] "Bathymetry_CA_60-1000 SOCAL_excl. MPA&Fishing"
[87] For a visualization of this dataset see Appendix E – GIS data layers visualized
[88] Array cabling is presumed to not intersect with conventional vessel traffic as cables are situated deeper than drafts of ships (National Renewable Energy Laboratory, 2020, p. 5).
[89] (Draxl et al., 2017)
[90] "Bathymetry_CA_60-1000 SOCAL_excl. MPA&Fishing"

production potential[91]. Generally, three sites representing the northern, middle, and southern part of Southern California waters aligning with the highly populated coastal stretches of Santa Barbara-Oxnard, Los Angeles, and San Diego were chosen (see Figure 4). Based on the optimized hotspot analysis and vessel traffic, three locations were set as displayed in Figure 4. Area 1 is situated offshore of Point Conception in an annual windspeed hotspot area. Area 2, also situated within a windspeed hotspot, is located about 24 km offshore of San Nicolas Island. To stay within a reasonable range to the coast, Area 3 is located about 70 km south of San Nicolas Island in a neutral spot in terms of the hotspot analysis.

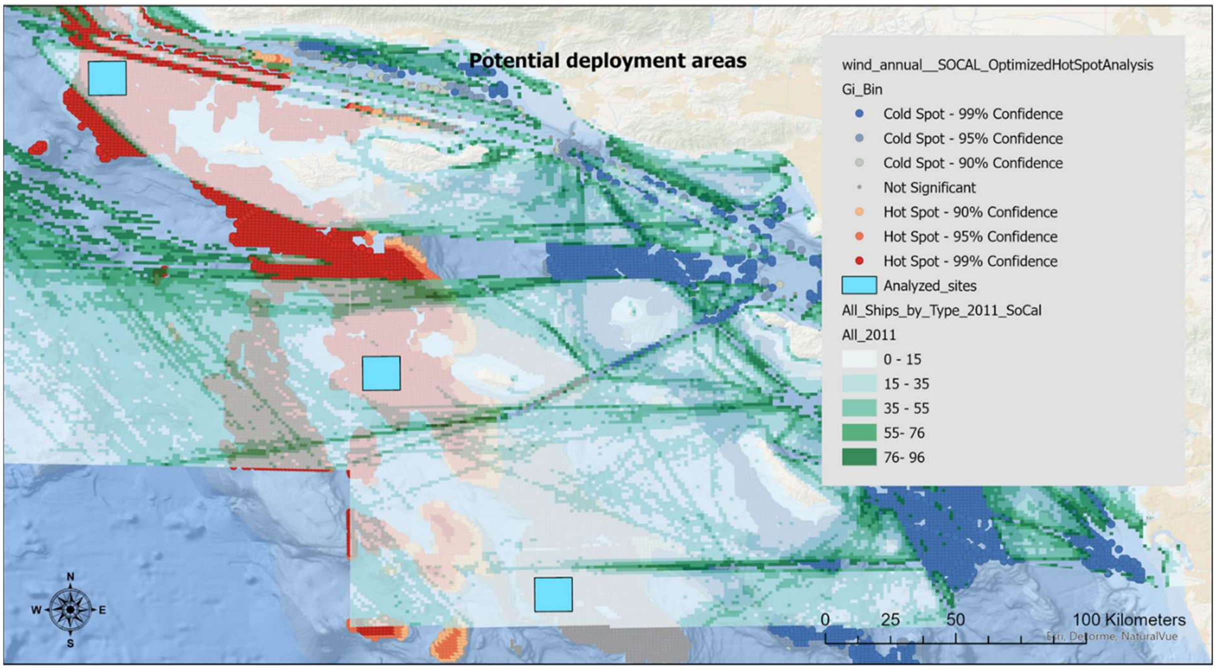

Figure 4: Sites for model-based viability study

2.3.2. Offshore wind farm characteristics

General

Following the NREL's analysis framework, the nameplate capacity of windfarms at all three sites is defined to be 600MW[92]. As described in chapter 1.2, semisubmersible substructures are currently the only technology that are assumed to allow for deployment depth exceeding 200 meters. Structures like the Aqua Ventus system developed at the University of Maine using concrete elements are less complex concerning the logistics on land and may require less maintenance due to less corrosion in seawater compared to steel structures[93]. Accounting for these characteristics, it is assumed that comparable systems will become leading technologies in the market. Being a U.S. based technology – although knowledge transfer from other, more advanced markets is certainly possible – the Aqua Ventus system functions as the reference for the SOCAOW.

Site specific

For each site selected, the GIS data is evaluated to obtain an overview concerning monthly, hourly wind speed, the depth profile and annual average significant wave height. Including

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[91] For a visualization of this dataset see Appendix E – GIS data layers visualized

[92] (Beiter et al., 2016, p. 61), (W. Musial et al., 2020, p. 16)

[93] (W. Musial et al., 2020, p. 19)

distance measurements to the coast, staging and O&M port as well as transmission infrastructure on land, an overview of site-specific parameters is provided in Table 2. Detailed plots of monthly/hourly and annual average windspeed data [m/s] at 100 meter above sea level, the depth profiles, and significant wave height profiles for each site are presented in Appendix F – Site-specific GIS data layers visualized.

Table 2: Overview site-specific parameters

Sites	**Site 1**	**Site 2**	**Site 3**
Average annual windspeed at 100m [m/s]	8.7	7.7	6.5
Depth [m]	840	408	465
Max. depth [m]	932	921	979
Distance from land [km]	30	108	153
Distance from staging port [km]	145	108	162
Significant wave height:	2.5	2.3	2.3
Distance from O&M port [km]	145	108	162
Distance on land [km]	25	1	1

The hourly, yearly average of the three sites is displayed in Figure 5. All three sites show peaking windspeeds in the evening hours and lowest values around noon. In contrast, the production of electricity using solar power peaks between 10 am and 3 pm[94] making solar and offshore wind complementary renewable energy sources. Site 1 has the highest annual hourly average windspeeds ranging between 7.84 m/s and 9.34 m/s. Site 3 has the overall lowest ranging between 5.89 m/s and 7.18 m/s. Probability ranges are expressed in the appendix using Weibull distributions based on monthly average scale and shape parameters included in the monthly, hourly windspeed dataset used[95].

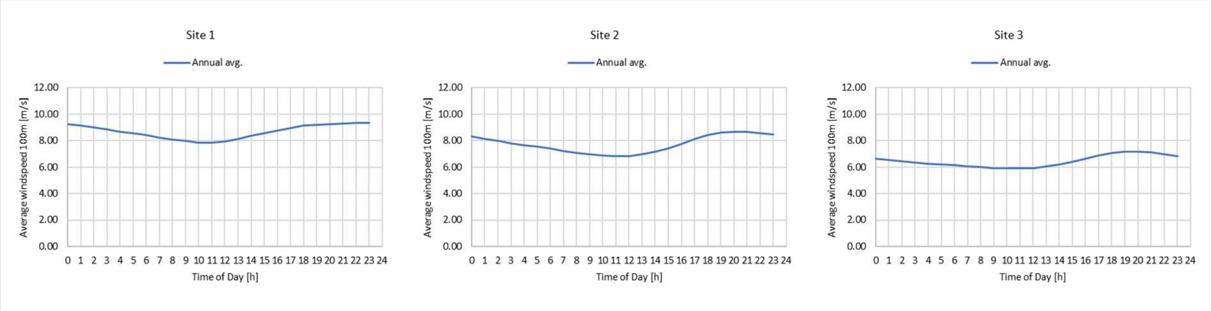

Figure 5: Annual hourly average windspeed

2.3.3. Scenario analyses

The potential sites are analyzed along two scenarios. Considering technical progress and learning over time, the net value is evaluated for 2022, 2027, 2032 as commercial operation dates (COD). Based on this, carbon mitigation policies are considered and compared.

Technical progress and learning

With technological innovations, a growing industry based on the development of supply chains and markets, as well as knowledge transfer from fixed-bottom offshore wind and the offshore oil and gas industry, the NREL predicts LCOE to decrease over time through the reduction of CapEx and OpEx as well as the increase in AEP. In this analysis the reduction of CapEx and OpEx are based on the assumed cost reductions from the NREL's Offshore

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[94] See chapter 1.1

[95] See Appendix F – Site-specific GIS data layers visualized

Regional Cost Analyzer. Using 2022 as the base case COD, the scenario accounts for CapEx reductions of 9.41% in 2027 and 25.91% in 2032. OpEx is assumed to decrease 5.74% in 2027 and 18.74% in 2032.[96]

The assumed increase of AEP is based on increasing rated turbine power which is interconnected with growing rotor diameters and hub heights. With an increase from 10MW in 2022 to 15 MW in 2032, Table 3 lists all related module parameters that change with the increase of rated power[97]. As the nameplate capacity is assumed to be constant at 600MW, less turbines will be needed to produce the same amount of electricity. Subsequently, CapEx as well as OpEx will decrease since less turbines need to be manufactured and maintained.

Table 3: Scenario assumptions

COD	**2022**	**2027**	**2032**
Total capacity [MW]	600	600	600
Turbine rated power [MW]	10	12	15
# turbines	60	50	40
Rotor diameter [m]	178	222	248
Hub height [m]	114	136	149
CapEx decrease [%]	0	9.41	25.91
OpEx decrease [%]	0	5.74	18.74

Using the site-specific input from chapter 2.3.2 as well as cost and production predictions based on technological progress and learning, LOCE, LACE and the net value of all three sites are evaluated (Figure 8).

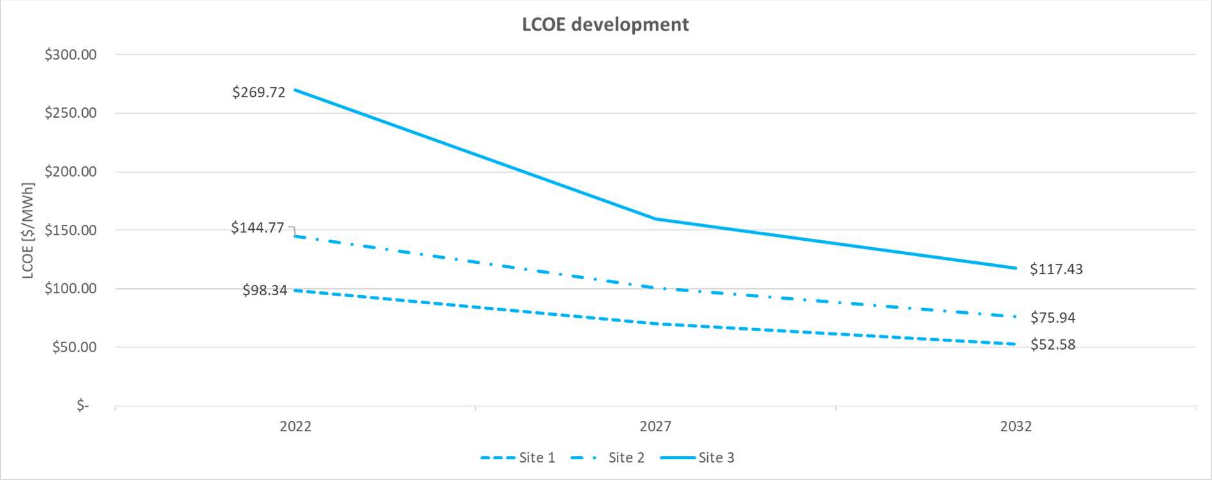

Figure 6: LCOE development in scenario 1

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[96] (W. Musial et al., 2020, pp. 13–14)

[97] Assumptions are based on (W. Musial et al., 2020, p. 16)

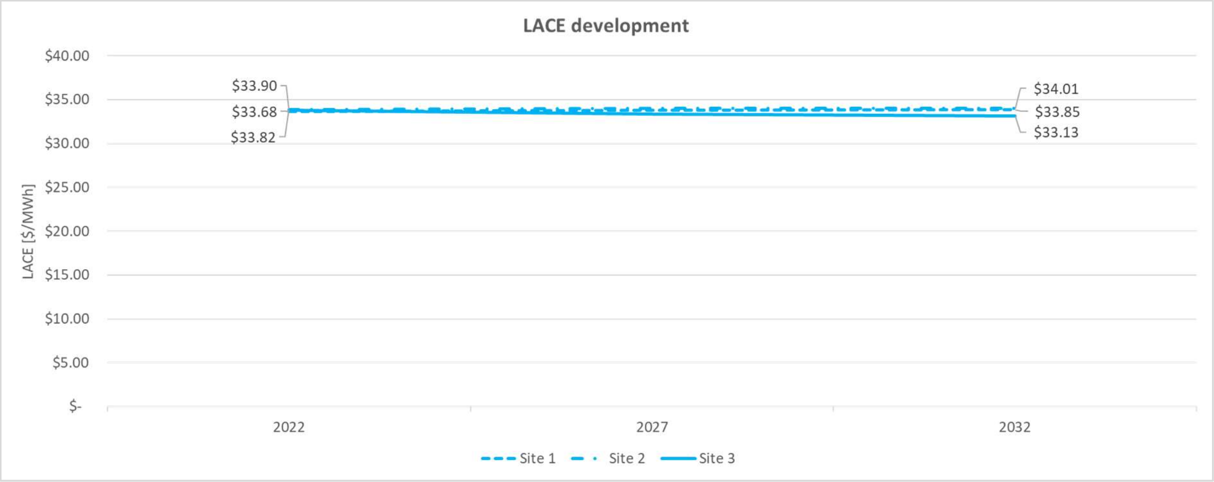

Figure 7: LACE development in scenario 1

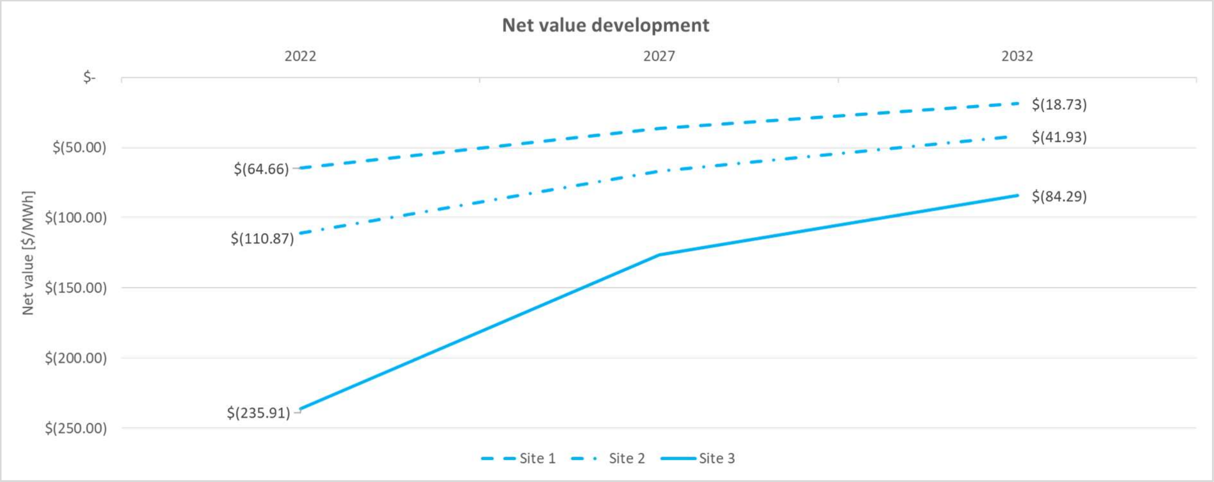

Figure 8: Net value development in scenario 1

LCOE are lowest for site 1 starting at $98.34/MWh in 2022 and decreasing to $52.58/MWh in 2032. In turn, highest LCOE are estimated for site 3 starting at $269.72/MWh in 2022 and decreasing to $117.43/MWh in 2032. Although site 1 has the greatest average depth, the site is only 30 km offshore and about 25 km away from on-land transmission infrastructure, resulting in low LCOE compared to the other sites. In contrast, site 3 is the furthest offshore but has the lowest windspeeds which drives the LCOE. LCOE of site 2 are between the other two sites starting at $144.77/MWh in 2022 and decreasing to $75.94/MWh in 2032. Comparing with calculations by the NREL that estimate LCOE up to 2027, values of the SOCAOW approximately match NREL's values[98].

As the same 15-minute prices are used to calculate the expected revenues for all three CODs and the capacity value stays constant, the LACE across all three sites only changes minimally due to the exponential form of the power curves of turbines which impacts revenue slightly. LACE ranges between $33.13/MWh and $34.01/MWh which is within the range of average offshore wind LACE estimated by the Energy Information Agency of $33/MWh[99].

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[98] Approximation of NREL visualization (Beiter et al., 2016, p. 89)

[99] (Energy Information Administration, 2021b, p. 10)

Following the temporal development of LCOE and LACE, site 1 has the highest net values ranging from -\$64.66/MWh in 2022 to -\$18.73/MWh in 2032. Net values of site 2 increase from -\$110.87/MWh in 2022 to -\$41.93/MWh in 2032. Site 3 has the lowest net values increase from -\$235.91/MWh in 2022 to -\$84.29/MWh in 2032. Compared to NREL estimated net values for 2027, SOCAOW values are slightly higher, although the visual approximation is more complex due to the color code used[100].

Carbon mitigation policies

Based on the temporal development of LCOE and LACE, and considering technical progress and learning, the second scenario focuses on carbon mitigation policy options. To incentivize the orientation towards an energy mix of mainly renewable sources, two major mechanisms can be differentiated. On the one hand, market-based policies are focusing on pricing carbon using cap-and-trade or carbon tax systems. Subsequently the production of electricity with low-emission alternatives becomes more attractive economically since less/no additional fee on production is required. On the other hand, direct subsidies are aimed exclusively at renewable sources. Amongst others, grants or tax credits are used to incentivize investors and producers to build renewable power plants by decreasing the investment risk and providing a stable outlook concerning invested capital or expected revenue.

To evaluate these two carbon mitigation policy approaches, carbon taxes and direct subsidies are compared for each timestep and site by calculating the values of the respective policy needed to reach a net value of zero. To calculate the carbon tax, the avoided emission per MWh is added to the LACE[101]. The direct subsidy needed to break even is the same as the difference between LCOE and LACE.

Figure 9 and Figure 10 show the temporal development of a carbon price and a subsidy needed per site. Overall direct subsidies needed to break even are always lower than the carbon price required. With the lowest LCOE throughout all COD and LACE being constant over time and across sites, site 1 requires the lowest carbon price (\$182.10/MWh in 2022 to \$52.73/MWh in 2032) and subsidy (\$64.66/MWh in 2022 to \$18.73/MWh in 2032) to reach a net value of zero. In contrast, site 3 requires the highest carbon price and subsidy of \$664.34/MWh / \$235.91/MWh in 2022 and \$237.38/MWh / \$84.29/MWh in 2032.

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[100] Approximation of NREL visualization (Beiter et al., 2016, p. 97)

[101] Based on the emissions that a modern natural gas turbine would produce for the same amount of energy (see chapter 2.2.2). The emissions are approximated at 0.34t/MWh. For site 1, the break even in year 2022 would imply an increase of LACE of \$64.66/MWh. Dividing this gap by the emission, results in a carbon price of \$182.10/t needed to reach a net value of zero.

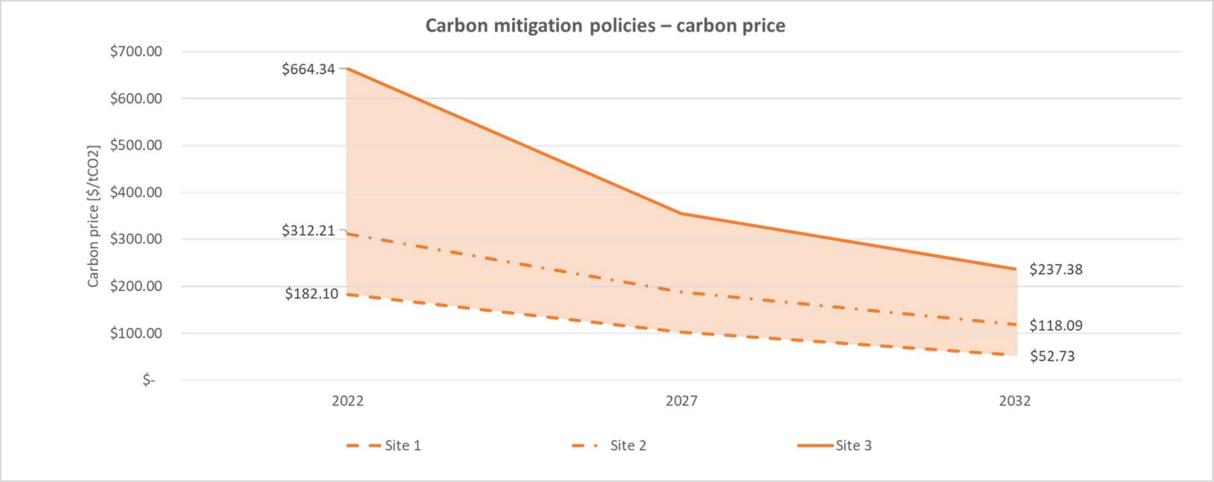

Figure 9: Carbon price development in scenario 2

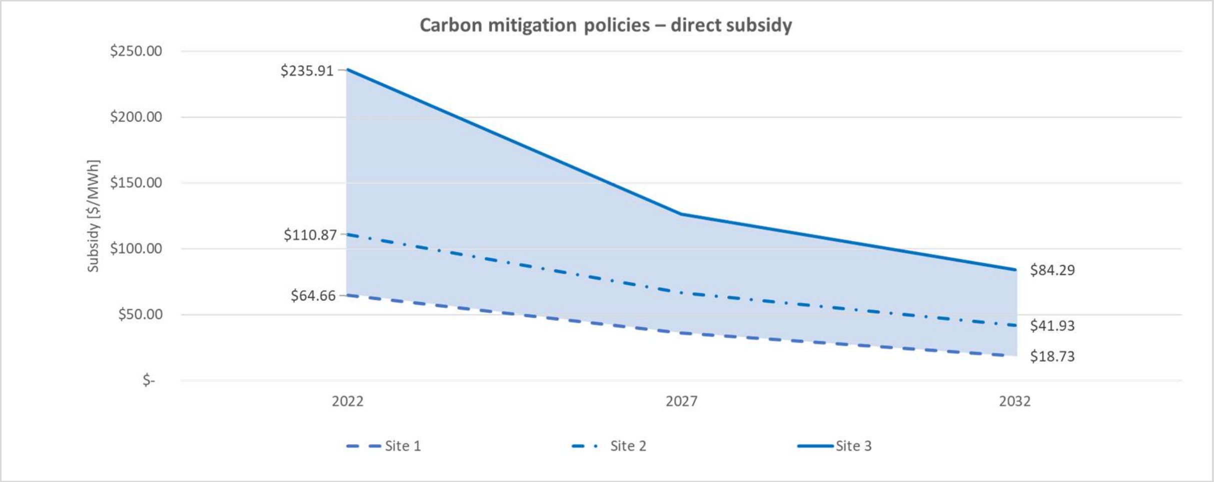

Figure 10: Direct subsidy development in scenario 2

To put these results into perspective, current carbon pricing systems and direct subsidies defined by administrations globally are analyzed. The World Bank's report on carbon pricing (emission trading systems or carbon taxes) includes 61 countries or states within countries that implemented a price on carbon (whole economy or sector-specific) up to April 2020. As of this date, the carbon tax of $119/tCO_2e$ implemented in Sweden is the highest price for carbon globally. 7 other countries or states within countries have prices above $30/tCO_2e$. The 53 remaining administrations implemented lower carbon prices with many below $10/tCO_2e$. California's carbon tax is at $15/ tCO_2e$.[102] Figure 11 shows the Swedish and Californian carbon prices in comparison to prices needed to break even.

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[102] (World Bank Group, 2020, p. 12)

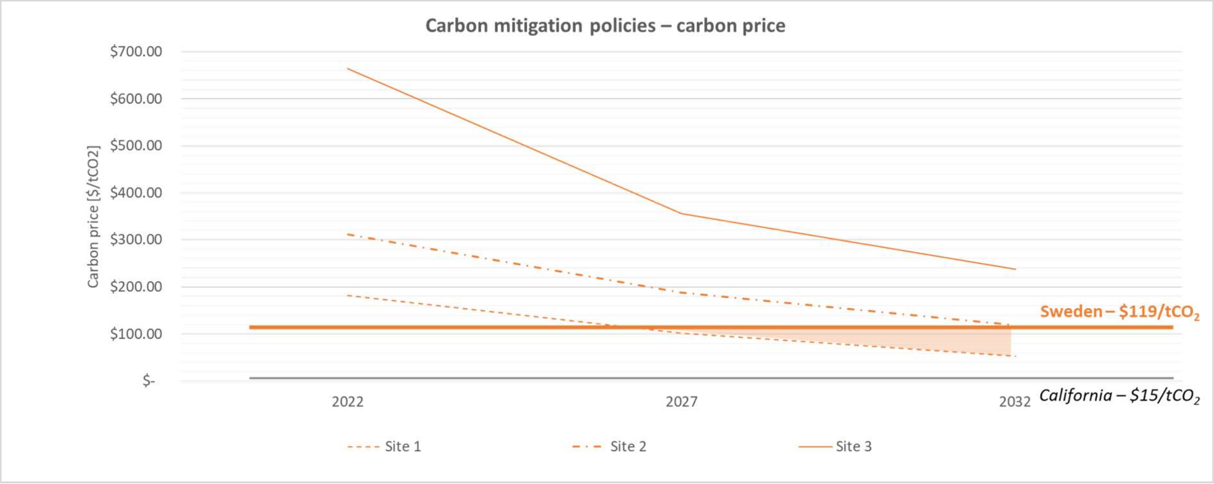

Figure 11: Scenario 2 comparison with implemented carbon prices

To specifically support a developing offshore wind industry, the five leading offshore wind nations in the EU (74% of global offshore wind capacity[103]) – U.K. (33%), Germany (26%), Denmark (6%), Belgium (5%), Netherlands (4%) – use an auction system that defines a constant price for produced energy over a fixed period of years ensured by the government. Subsequently producers can plan with more secure revenue forecasts and investment risks are lowered[104]. Using a regression analysis, Jansen et al. approximate trends of bids between 2010 and 2025 based on strike prices in all five countries. Harmonized strike prices range from €150/MWh (~$170/MWh) to €50/MWh (~$51/MWh) overall decreasing with time between 2010 and 2020. As these prices include the wholesale electricity price of the respective market, Table 4 expresses comparable strike prices needed for the three potential sites in SOCAL using an average electricity price of $34.28/MWh[105] for California.

Table 4: Strike prices needed for break-even

Sites	**Site 1**			**Site 2**			**Site 3**		
COD [yr]	**2022**	**2027**	**2032**	**2022**	**2027**	**2032**	**2022**	**2027**	**2032**
Subsidy [$/MWh]	$ 64.66	$ 36.25	$ 18.73	$ 110.87	$ 66.86	$ 41.93	$ 235.91	$ 126.24	$ 84.29
Strike price [$/MWh]	**$ 98.94**	**$ 70.53**	**$ 53.01**	**$ 145.15**	**$ 101.14**	**$ 76.21**	**$ 270.19**	**$ 160.52**	**$ 118.57**

A direct subsidy implemented in the U.S. today are production tax credits (PTC) and investment tax credits (ITC). As an investment heavy sector, floating offshore wind is profiting more from ITC than using PTC[106]. Previous analyses estimate the ITC to increase LACE by about $17/MWh[107]. Thus, ITC cannot support any site at any COD to break even and is not sufficient for offshore wind projects in SOCAL.

Figure 12 shows the average EU strike prices between 2010 and 2020 adjusted for the average Californian electricity price and projected onto the next ten years ($136/MWh in 2022 to $16/MWh in 2032) as well as the increased LACE if ITC was applied. Whereas the ITC is not able to support any site in any given point in time, the strike prices would cover site 1 and site 2 in 2022 and 2027.

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[103] (Global Wind Energy Council, 2020, p. 12)

[104] (Jansen et al., 2020, p. 615)

[105] Average of quarterly and hourly price used for revenue calculations in the SOCAOW.

[106] (Energy Information Administration, 2021b, p. 2)

[107] (Beiter et al., 2016, p. xvii)

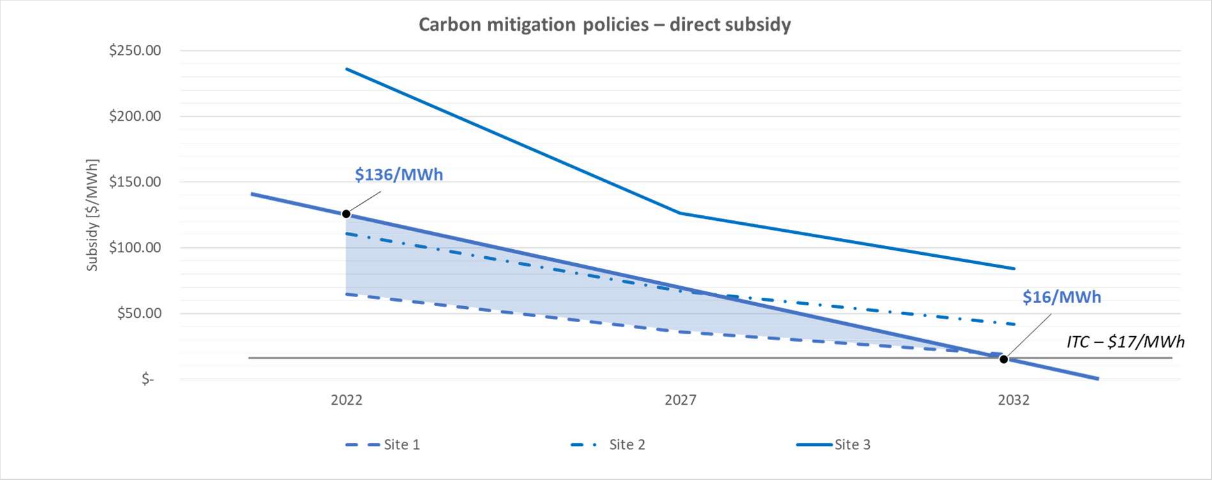

Figure 12: Scenario 2 comparison with implemented auction systems in the EU and ITC

3. Conclusion and outlook

Using the SOCAOW, possible deployment areas in Southern California could be evaluated considering site-specific data input. Nonetheless, the model does not represent a comprehensive evaluation. A floating offshore wind farm requires close cooperation of a broad variety of disciplines. The consideration of all interdisciplinary aspects is beyond the scope of this project. Based on the NRELs work on the potential of offshore wind in the U.S., the SOCAOW can function as a first step towards a transparent base for further, truly interdisciplinary research and development.

Considering monthly, hourly wind data shows that offshore wind in SOCAL is peaking during the evening hours throughout the year at all three sites[108]. With a renewable energy market focused on solar power in California, the production characteristics of offshore wind perfectly counterbalance the already established source providing energy during daylight hours. Considering this match, offshore wind can contribute to a reliable energy mix in SOCAL in general and close the supply gap originating from the shutdown of the San Onofre nuclear power plant. Doing so it can help to mitigate emissions by replacing natural gas plants currently used to secure supply.

Taking today's assumptions on technical progress and learning into account, the SOCAOW evaluates sites in SOCAL comparable to analyses conducted by the NREL. The results show that none of the three sites along the SOCAL coast is economically viable in the next ten years. With a negative net value of -$64.66/MWh in 2022 and -$18.73/MWh in 2032, site 1 of Point Conception has the most potential. As windspeeds decrease for both sites further south, the net values of the respective sites decrease simultaneously. Based on the result of scenario 1, the traditional approach of comparing LCOE and LACE was extended by evaluating carbon mitigation policies to support the economic viability of floating offshore wind in SOCAL. First, carbon prices needed to break even at each site and COD were calculated. Comparing with implemented market-based systems around the world shows that especially in initial phases when support is needed most, a carbon price will not be sufficient. To provide reliable financial support in high-risk technology sectors like floating offshore wind, direct government support is needed[109]. Second, direct subsidies needed to break even at the three analyzed sites were calculated. Comparing with strike prices of auction systems implemented in the five leading offshore wind countries in the EU, suggests that sites 1 and 2 would be economically viable in 2022 and 2027 using EU strike prices between 2010 and 2020. As all auctions were considering fixed bottom offshore wind turbines that are less costly, strike prices for floating offshore wind farms are likely to cover a higher range which could extend the support for site 1 and 2 up to 2032.

Considering the scenario analyses using the SOCAOW, a floating offshore wind industry can emerge in California when an approach comparable to the EU auction systems is established. A reliable forecast for future revenue expressed through a strike price secured by a government through a bidding system, would attract investors. With the state's progressive mindset, a long coastline, deep waters, large ports, offshore industry knowhow and inventory, California can be successful in matching the federal Administration's call for jumpstarting the offshore wind industry with developing markets and supply chains ready to

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[108] Chapter 2.3.2

[109] (Cullenward & Victor, 2020, pp. 1–30)

answer future demand. Amplifying rapid technical progress in the floating industry[110] can increase learning, lower costs, and increase production. Additionally, emphasizing interdisciplinary R&D can support a just transition from the traditional oil and gas industry. With most demand for electricity focused in densely populated coastal areas, offshore wind can mitigate fire hazards by avoiding extended transmission infrastructure on land. Jumpstarting the floating offshore wind industry can make California a role model and pioneer in the federal administration's climate change plans. As a driver for offshore technology, the state can lead the globally emerging floating offshore industry.

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[110] Shared mooring systems, light wind downwind turbines, streamlining the development process

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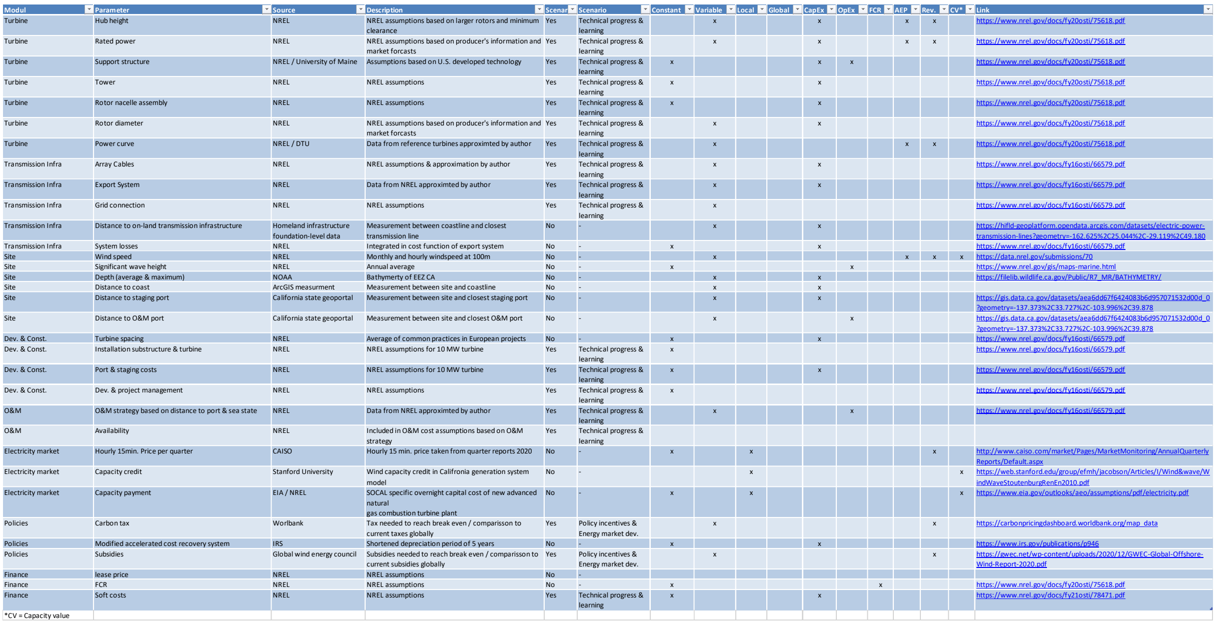
Appendix A – SOCAOW parameter overview & refinement potential

Parameter overview:

Table 5: Parameters SOCAOW



Modul	Parameter	Source	Description	Scenar	Scenario	Constant	Variable	Local	Global	CapEx	OpEx	FCR	AEP	Rev.	CV*	Link
Turbine	Hub height	NREL	NREL assumptions based on larger rotors and minimum clearance	Yes	Technical progress & learning		x			x			x	x		https://www.nrel.gov/docs/fy20osti/75618.pdf
Turbine	Rated power	NREL	NREL assumptions based on producer's information and market forcasts	Yes	Technical progress & learning		x			x			x	x		https://www.nrel.gov/docs/fy20osti/75618.pdf
Turbine	Support structure	NREL / University of Maine	Assumptions based on U.S. developed technology	Yes	Technical progress & learning	x				x	x					https://www.nrel.gov/docs/fy20osti/75618.pdf
Turbine	Tower	NREL	NREL assumptions	Yes	Technical progress & learning	x				x						https://www.nrel.gov/docs/fy20osti/75618.pdf
Turbine	Rotor nacelle assembly	NREL	NREL assumptions	Yes	Technical progress & learning	x				x						https://www.nrel.gov/docs/fy20osti/75618.pdf
Turbine	Rotor diameter	NREL	NREL assumptions based on producer's information and market forcasts	Yes	Technical progress & learning		x			x						https://www.nrel.gov/docs/fy20osti/75618.pdf
Turbine	Power curve	NREL / DTU	Data from reference turbines approximted by author	Yes	Technical progress & learning		x						x	x		https://www.nrel.gov/docs/fy20osti/75618.pdf
Transmission Infra	Array Cables	NREL	NREL assumptions & approximation by author	Yes	Technical progress & learning		x			x						https://www.nrel.gov/docs/fy16osti/66579.pdf
Transmission Infra	Export System	NREL	Data from NREL approximted by author	Yes	Technical progress & learning		x			x						https://www.nrel.gov/docs/fy16osti/66579.pdf
Transmission Infra	Grid connection	NREL	NREL assumptions	Yes	Technical progress & learning		x									https://www.nrel.gov/docs/fy16osti/66579.pdf
Transmission Infra	Distance to on-land transmission infrastructure	Homeland infrastructure foundation-level data	Measurement between coastline and closest transmission line	No	-		x			x						https://hifld-geoplatform.opendata.arcgis.com/datasets/electric-power-transmission-lines?geometry=-162.625%2C25.044%2C-29.119%2C49.180
Transmission Infra	System losses	NREL	Integrated in cost function of export system	No	-	x				x						https://www.nrel.gov/docs/fy16osti/66579.pdf
Site	Wind speed	NREL	Monthly and hourly windspeed at 100m	No	-		x						x	x	x	https://data.nrel.gov/submissions/70
Site	Significant wave height	NREL	Annual average	No	-	x					x					https://www.nrel.gov/gis/maps-marine.html
Site	Depth (average & maximum)	NOAA	Bathymerty of EEZ CA	No	-		x			x						https://filelib.wildlife.ca.gov/Public/R7_MR/BATHYMETRY/
Site	Distance to coast	ArcGIS measurment	Measurement between site and coastline	No	-		x			x						
Site	Distance to staging port	California state geoportal	Measurement between site and closest staging port	No	-		x			x						https://gis.data.ca.gov/datasets/aea6dd67f6424083b6d957071532d00d_0?geometry=-137.373%2C33.727%2C-103.996%2C39.878
Site	Distance to O&M port	California state geoportal	Measurement between site and closest O&M port	No	-		x				x					https://gis.data.ca.gov/datasets/aea6dd67f6424083b6d957071532d00d_0?geometry=-137.373%2C33.727%2C-103.996%2C39.878
Dev. & Const.	Turbine spacing	NREL	Average of common practices in European projects	No	-	x				x						https://www.nrel.gov/docs/fy16osti/66579.pdf
Dev. & Const.	Installation substructure & turbine	NREL	NREL assumptions for 10 MW turbine	Yes	Technical progress & learning	x										https://www.nrel.gov/docs/fy16osti/66579.pdf
Dev. & Const.	Port & staging costs	NREL	NREL assumptions for 10 MW turbine	Yes	Technical progress & learning	x				x						https://www.nrel.gov/docs/fy16osti/66579.pdf
Dev. & Const.	Dev. & project management	NREL	NREL assumptions	Yes	Technical progress & learning	x										https://www.nrel.gov/docs/fy16osti/66579.pdf
O&M	O&M strategy based on distance to port & sea state	NREL	Data from NREL approximted by author	Yes	Technical progress & learning		x				x					https://www.nrel.gov/docs/fy16osti/66579.pdf
O&M	Availability	NREL	Included in O&M cost assumptions based on O&M strategy	Yes	Technical progress & learning											
Electricity market	Hourly 15min. Price per quarter	CAISO	Hourly 15 min. price taken from quarter reports 2020	No	-	x		x						x		http://www.caiso.com/market/Pages/MarketMonitoring/AnnualQuarterlyReports/Default.aspx
Electricity market	Capacity credit	Stanford University	Wind capacity credit in Califronia generation system model	No	-			x							x	https://web.stanford.edu/group/efmh/jacobson/Articles/I/Wind&wave/WindWaveStoutenburgRenEn2010.pdf
Electricity market	Capacity payment	EIA / NREL	SOCAL specific overnight capital cost of new advanced natural gas combustion turbine plant	No	-	x		x							x	https://www.eia.gov/outlooks/aeo/assumptions/pdf/electricity.pdf
Policies	Carbon tax	Worlbank	Tax needed to reach break even / comparisson to current taxes globally	Yes	Policy incentives & Energy market dev.		x							x		https://carbonpricingdashboard.worldbank.org/map_data
Policies	Modified accelerated cost recovery system	IRS	Shortened depreciation period of 5 years	No	-	x				x						https://www.irs.gov/publications/p946
Policies	Subsidies	Global wind energy council	Subsidies needed to reach break even / comparisson to current subsidies globally	Yes	Policy incentives & Energy market dev.		x							x		https://gwec.net/wp-content/uploads/2020/12/GWEC-Global-Offshore-Wind-Report-2020.pdf
Finance	lease price	NREL	NREL assumptions	No	-											
Finance	FCR	NREL	NREL assumptions	No	-	x						x				https://www.nrel.gov/docs/fy20osti/75618.pdf
Finance	Soft costs	NREL	NREL assumptions	Yes	Technical progress & learning	x				x						https://www.nrel.gov/docs/fy21osti/78471.pdf
*CV = Capacity value																

Refinement potential:

Wind speed data: Statistical distributions of monthly, hourly windspeed data was not considered when calculating annual production. For further refinement of the SOCAOW the Weibull distributions are to be used to define a more accurate capacity factor.

Seabed characteristics: Especially for mooring system design and construction, seabed characteristics need to be considered in a more detailed model.

Operation and Maintenance: Approximation of O&M costs based on NREL's assumptions can be refined concerning digitalization of wind farm operation, weather conditions and air pollution (faster blade erosion due to particles in air). Additionally, O&M facilities on islands and / or out-of-service offshore rigs have the potential to lower costs.

Electricity market: The SOCAOW does not consider future market developments and how it might affect capacity value and electricity prices.

Financial vs. economic costs / benefits: LCOE and LACE are mainly representing financial evaluations and do not account for social impacts that need to be considered to evaluate offshore wind in a broader sense. On the cost side, these impacts are the interferences of offshore wind farms with preexisting ocean uses such as fishing, environment, navigation, and the military[111]. To address possible negative impacts on fisheries, developers need to partner with fishermen and federal agencies to discuss solutions and set up trust funds for possible impacts. The main negative environmental impacts of offshore wind farms are collisions of birds with rotors and underwater noise pollution and subsequent impacts on marine mammals, especially whales and seals[112]. Negative effects on birds are expected to

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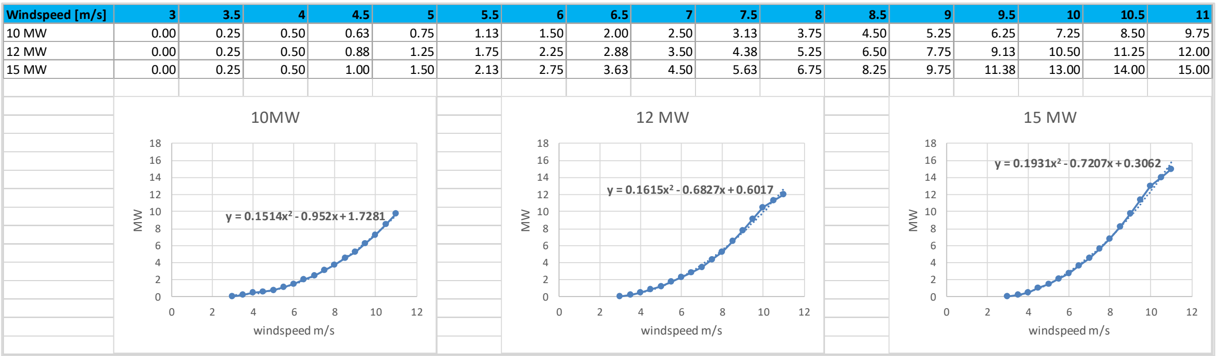
[111] (W. Musial et al., 2019, p. 16)

[112] (Snyder & Kaiser, 2009, pp. 8–9)

be dependent on the location of the site to a noteworthy extend. Noise pollution is especially high during the construction phase, specifically pile driving which is not needed to install floating offshore structures. Nonetheless, anchoring methods are going to emit noise to a certain extent as well. To ease navigation through offshore wind farms, developers set up transit corridors. To avoid interferences with military activities, BOEM, developers, and the Army Corps of Engineering are working together closely. The following aspects are to be considered when evaluating benefits in an economic sense. Although structures of offshore wind farms are not comparable with those of offshore oil rigs, studies have shown that they act as a breeding ground as well as retreat for fish[113]. Subsequently, animals feeding of these fish would benefit. Moreover, directly related jobs are expected to be created during the development and construction phase as well as the operation and maintenance phase[114]. Since the supply chain for developing, installing, and operating offshore wind farms reaches beyond directly related industries[115], also indirect benefits in terms of jobs that are induced by a growing industry need to be considered. Since the oil and gas industry has a lot of knowledge on how to build resilient structures in the ocean and machines to handle large materials, jobs could be transferred. Moreover, only looking at the coastal state would not reveal the total amount of jobs created. Although the operation of offshore wind farms is bound to coastal states, the supply chain extends to the whole country, which enables producers and service providers nationwide to make business in this new market[116]. Finally, but likely to be of highest importance, is the fact that the production of electricity through offshore wind does not emit CO_2. Thus, it does not contribute to the threat of global warming. Nonetheless, like charging an electric car with electricity from the public grid, the production of turbines and all components is using energy, that is currently, at least partly, produced using fossil fuel.

Appendix B – Approximation of turbine power curves



Windspeed [m/s]	3	3.5	4	4.5	5	5.5	6	6.5	7	7.5	8	8.5	9	9.5	10	10.5	11
10 MW	0.00	0.25	0.50	0.63	0.75	1.13	1.50	2.00	2.50	3.13	3.75	4.50	5.25	6.25	7.25	8.50	9.75
12 MW	0.00	0.25	0.50	0.88	1.25	1.75	2.25	2.88	3.50	4.38	5.25	6.50	7.75	9.13	10.50	11.25	12.00
15 MW	0.00	0.25	0.50	1.00	1.50	2.13	2.75	3.63	4.50	5.63	6.75	8.25	9.75	11.38	13.00	14.00	15.00

Figure 13: Turbine power curve approximation

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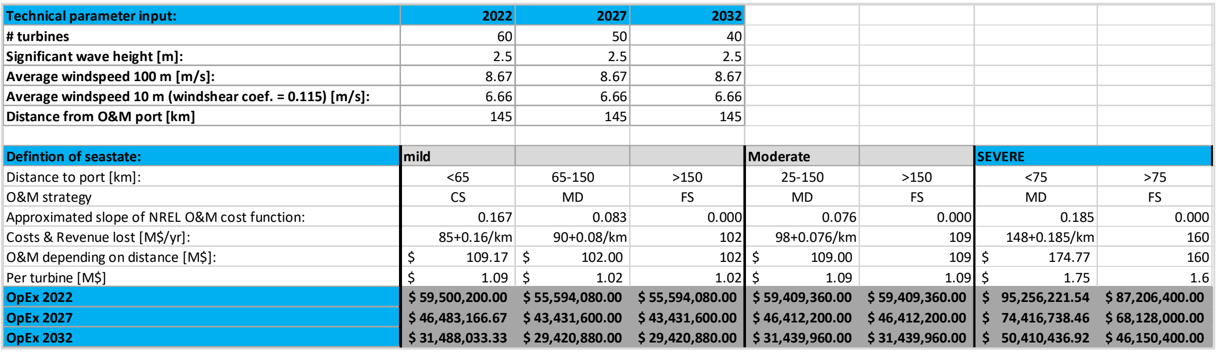
[113] (Snyder & Kaiser, 2009, p. 9)

[114] (Zhang et al., 2020, p. 17)

[115] Project development, manufacturing (Steel, foundations, towers, blades, cables, turbines), testing facilities, ports and transmission infrastructure, vessel construction, onsite maintenance (Hensley & Wanner, 2020, p. 6)

[116] (Hensley & Wanner, 2020, p. 13)

Appendix C – Approximation of O&M cost functions



Technical parameter input:	**2022**	**2027**	**2032**				
# turbines	60	50	40				
Significant wave height [m]:	2.5	2.5	2.5				
Average windspeed 100 m [m/s]:	8.67	8.67	8.67				
Average windspeed 10 m (windshear coef. = 0.115) [m/s]:	6.66	6.66	6.66				
Distance from O&M port [km]	145	145	145				
Defintion of seastate:	**mild**			**Moderate**		**SEVERE**	
Distance to port [km]:	<65	65-150	>150	25-150	>150	<75	>75
O&M strategy	CS	MD	FS	MD	FS	MD	FS
Approximated slope of NREL O&M cost function:	0.167	0.083	0.000	0.076	0.000	0.185	0.000
Costs & Revenue lost [M$/yr]:	85+0.16/km	90+0.08/km	102	98+0.076/km	109	148+0.185/km	160
O&M depending on distance [M$]:	$ 109.17	$ 102.00	102	$ 109.00	109	$ 174.77	160
Per turbine [M$]	$ 1.09	$ 1.02	1.02	$ 1.09	1.09	$ 1.75	1.6
OpEx 2022	**$ 59,500,200.00**	**$ 55,594,080.00**	**$ 55,594,080.00**	**$ 59,409,360.00**	**$ 59,409,360.00**	**$ 95,256,221.54**	**$ 87,206,400.00**
OpEx 2027	**$ 46,483,166.67**	**$ 43,431,600.00**	**$ 43,431,600.00**	**$ 46,412,200.00**	**$ 46,412,200.00**	**$ 74,416,738.46**	**$ 68,128,000.00**
OpEx 2032	**$ 31,488,033.33**	**$ 29,420,880.00**	**$ 29,420,880.00**	**$ 31,439,960.00**	**$ 31,439,960.00**	**$ 50,410,436.92**	**$ 46,150,400.00**

Figure 14: Approximation of O&M cost functions exemplary for site 1

Appendix D – Quarterly 15-minute energy prices

Figures are taken from the 2020 quarterly reports from CAISO[117]

Q1 2020:

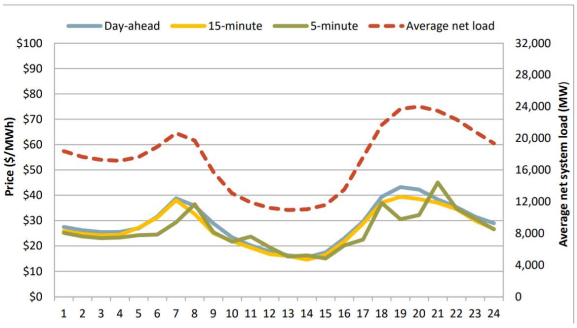


Figure 15: Electricity price first quarter 2020[118]

Q2 2020:

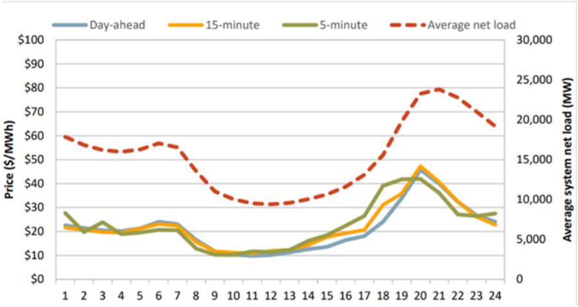


Figure 16: Electricity price second quarter 2020[119]

Q3 2020:

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[117] (CAISO, 2020)

[118] Figure taken from (California ISO, 2020a, p. 12)

[119] Figure taken from (California ISO, 2020b, p. 23)

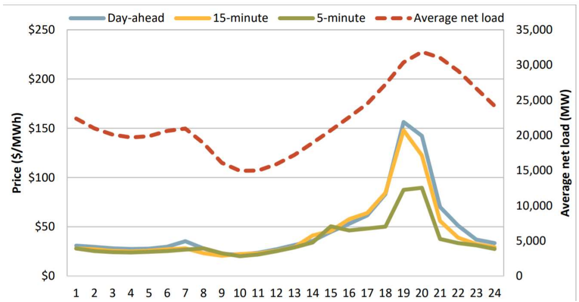

Figure 17: Electricity price third quarter 2020[120]

Q4 2020:

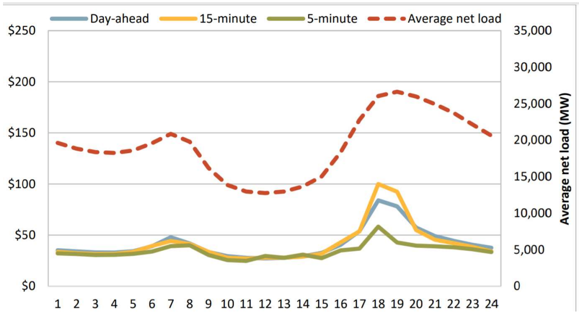

Figure 18: Electricity price fourth quarter 2020[121]

Appendix E – GIS data layers visualized

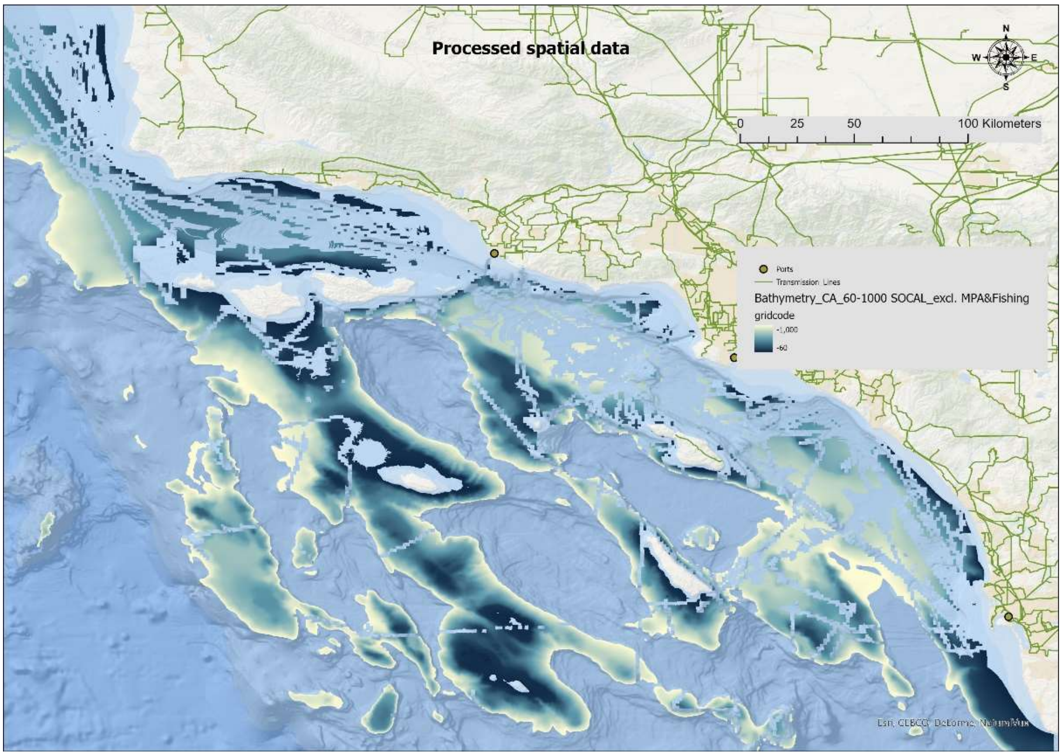

Figure 19: Bathymetry 60-1000 m excl. Marine Protected Areas & Fishing vessel tracks

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[120] Figure taken from (California ISO, 2021a, p. 25)

[121] Figure taken from (California ISO, 2021b, p. 21)

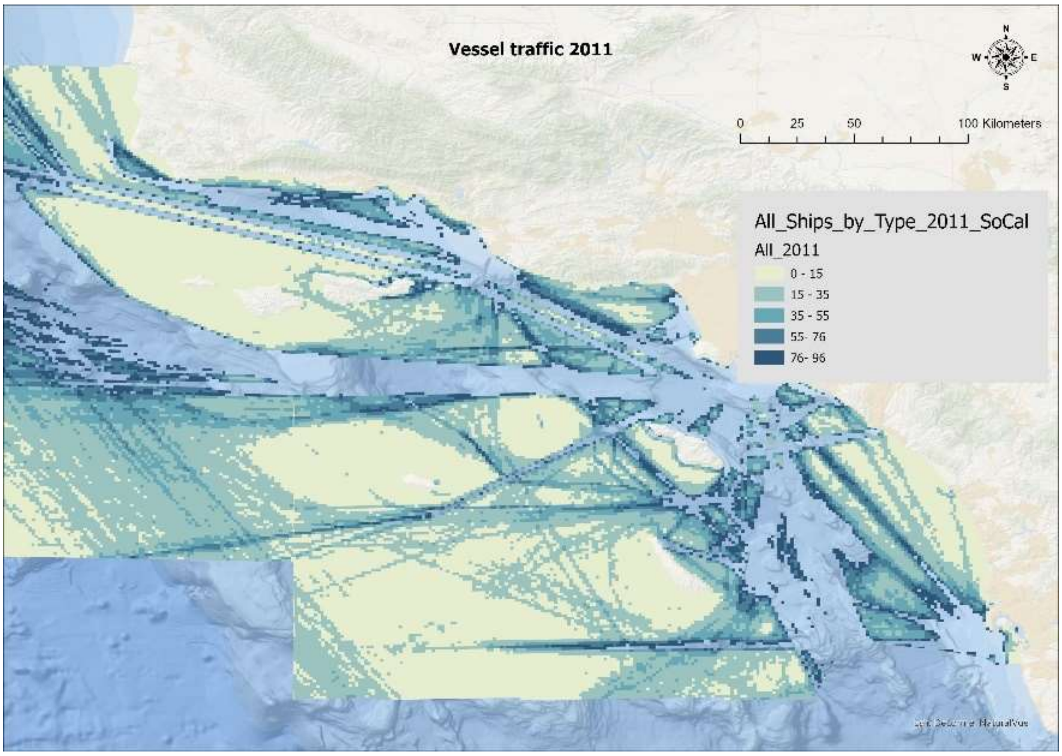

Figure 20: Vessel traffic 2011

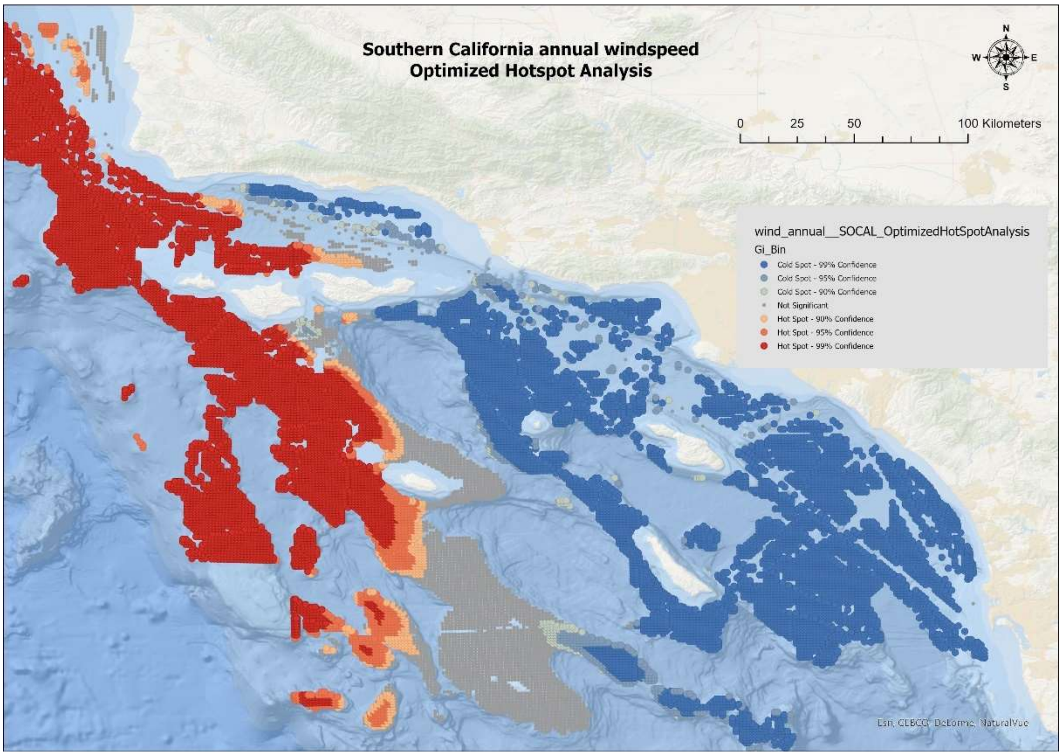

Figure 21: SOCAL annual average windspeed – Optimized hotspot analysis

Appendix F – Site-specific GIS data layers visualized

Distances from sites to land, ports, and on-land distances to transmission infrastructure

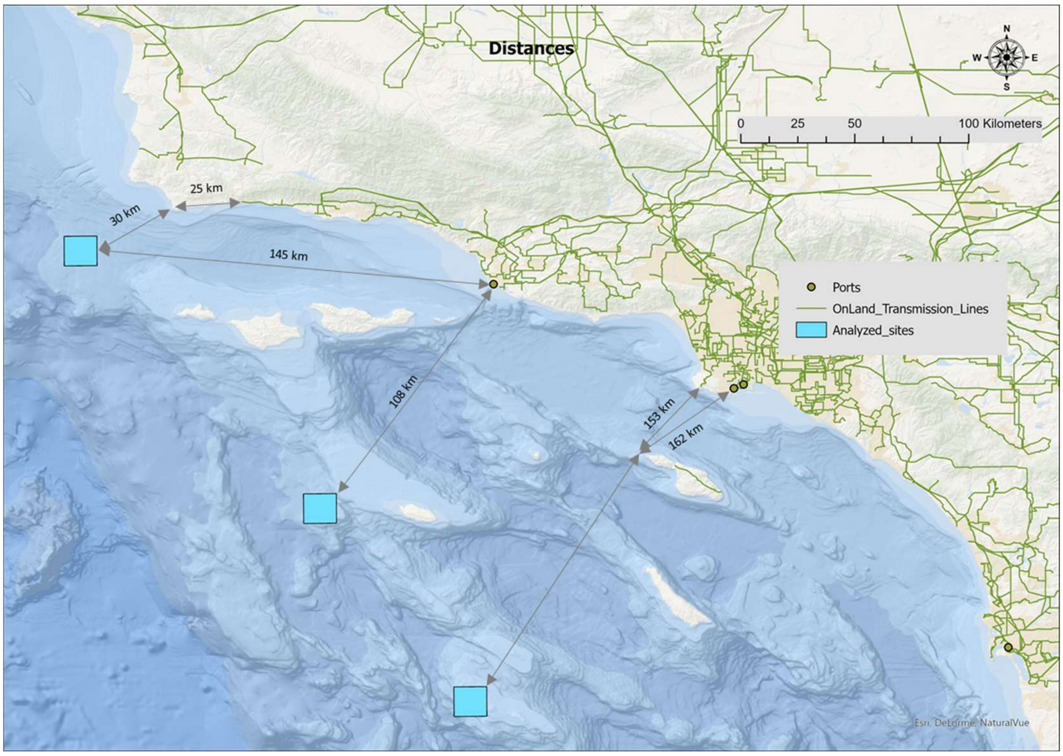

Figure 22: Distance measurements from sites

Site 1 – Point Conception:

Site parameter overview

Table 6: Site 1 - Parameter overview

COD		**2022**		**2027**		**2032**	
Total capacity [MW]		600		600		600	
Turbine nameplate capacity [MW]		10		12		15	
Rotor diameter [m]		178		222		248	
Hub height [m]		114		136		149	
Turbine spacing (D8) [m]		1424		1776		1984	
Area [km2]		99.36		113.55		98.41	
# turbines		60		50		40	
Depth [m]		840		840		840	
Max. depth [m]		932		932		932	
Distance from land [km]		30		30		30	
Distance from staging port [km]		145		145		145	
Significant wave height [m]:		2.5		2.5		2.5	
Distance from O&M port [km]		145		145		145	
Distance on land [km]		25		25		25	
CapEx decrease [%]		0		9.41		25.91	

Monthly, hourly, and annual average windspeed at 100 meter above sea level:

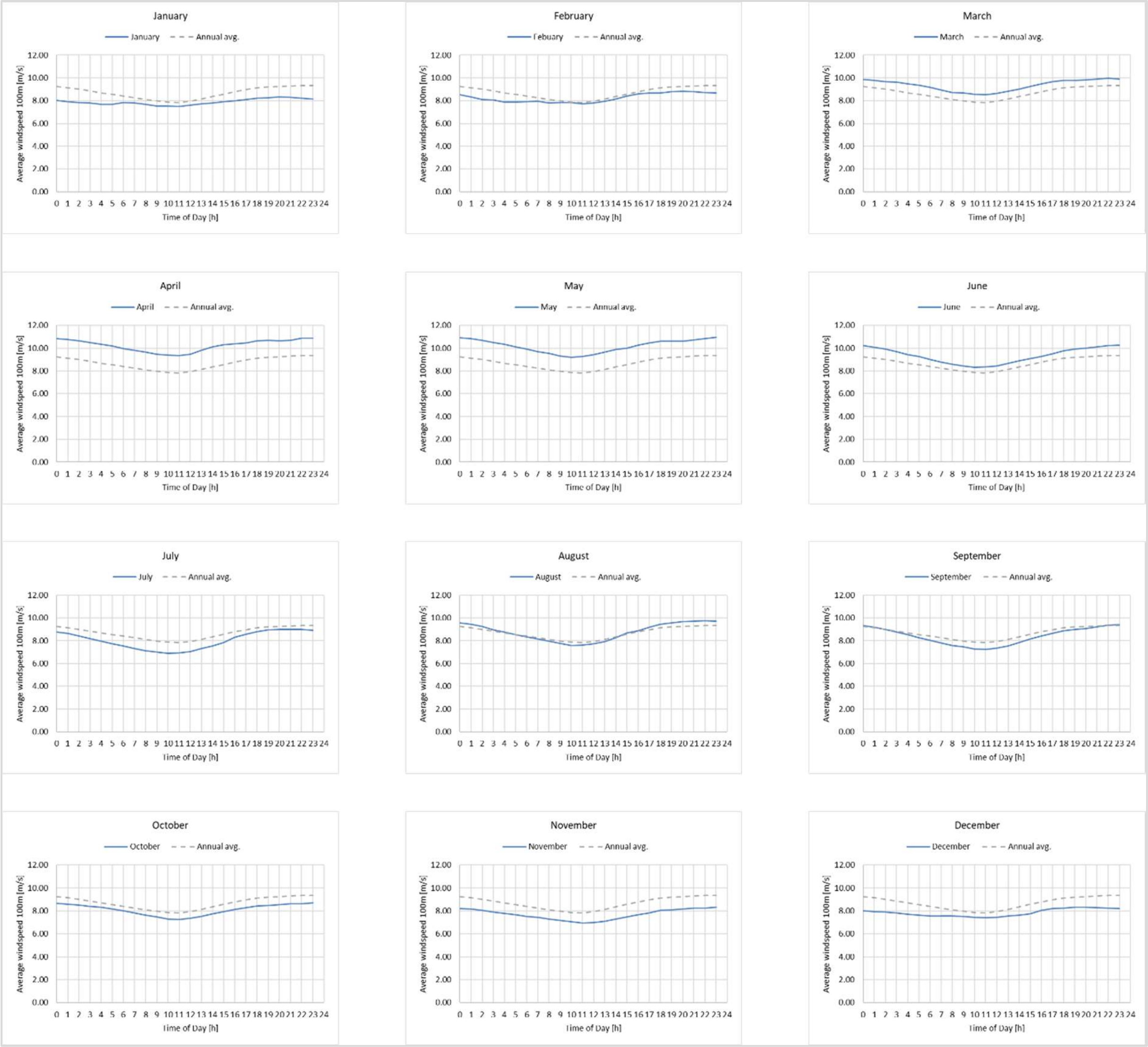

Figure 23: Site 1 - Windspeed data

Monthly average Weibull distribution of windspeed at 100 meter above sea level:

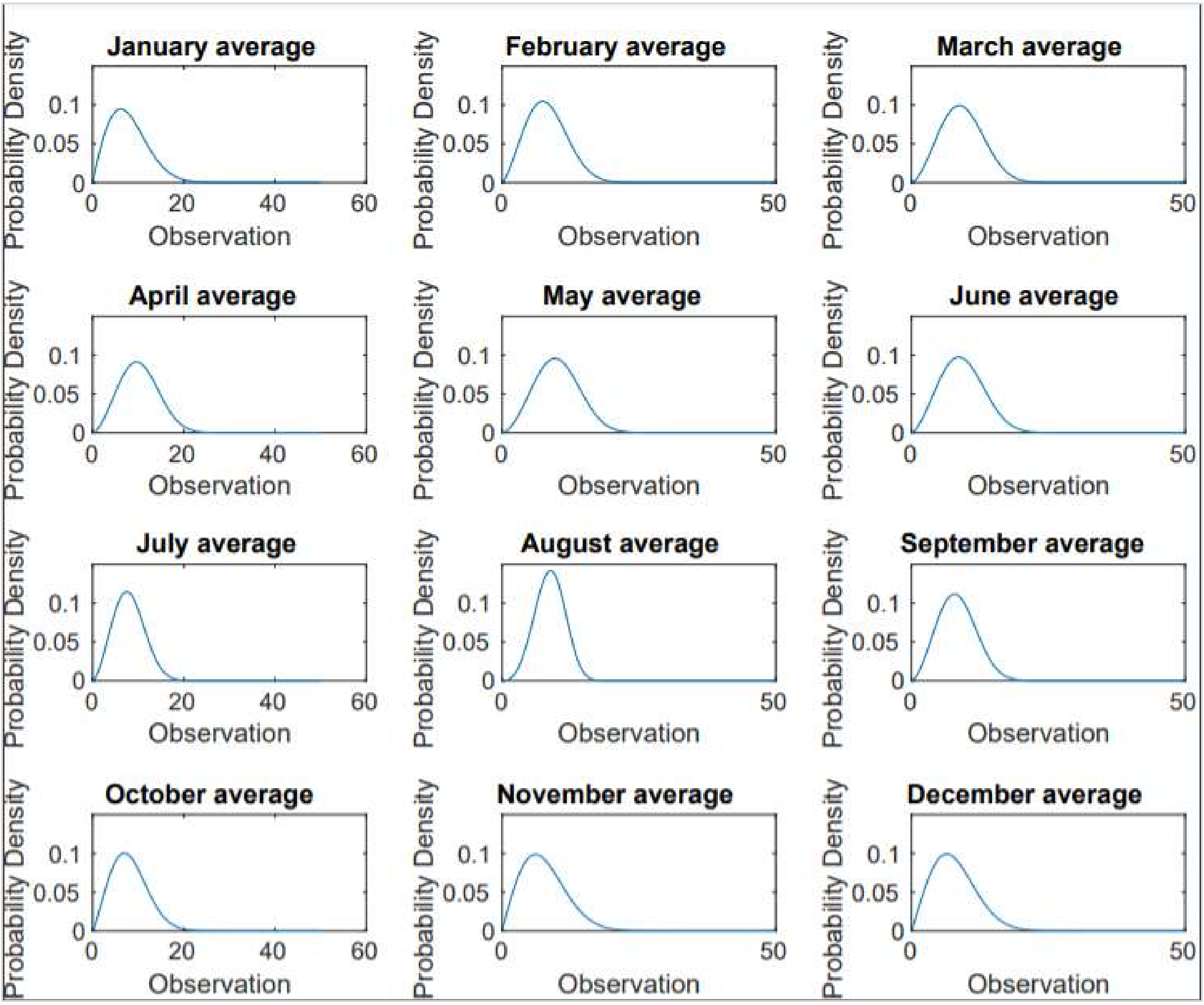

Figure 24: Site 1 - Weibull distribution

Depth profile:

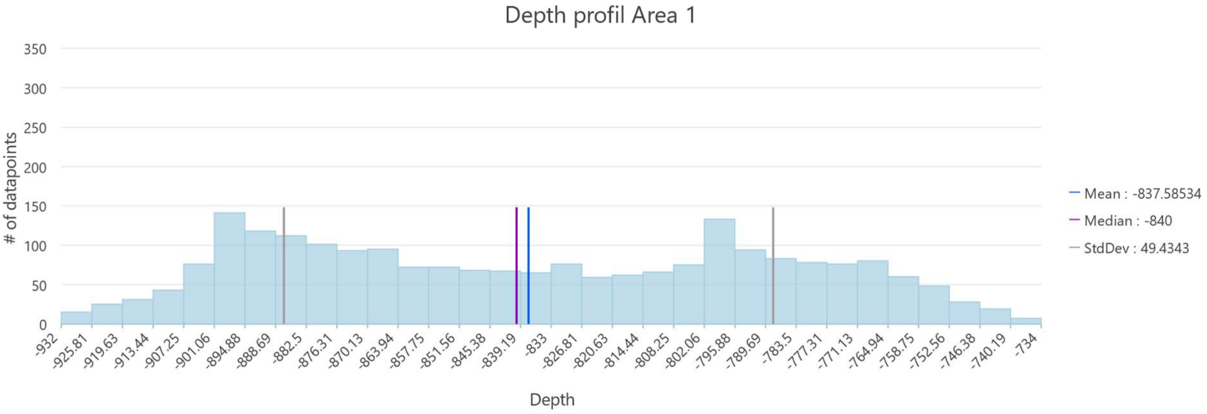

Figure 25: Site 1 - Depth profile

Significant wave height:

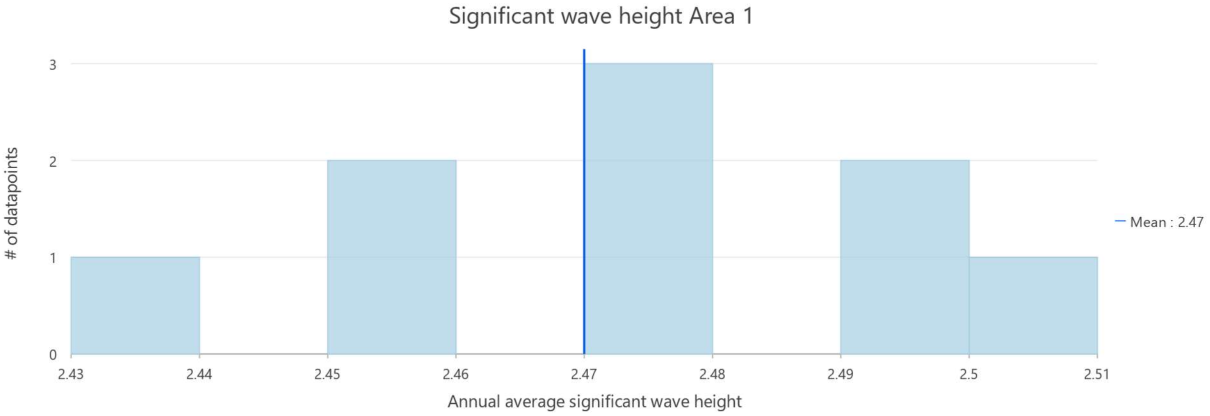

Figure 26: Site 1 - Significant wave height

Site 2 – San Nicolas Island West:

Site parameter overview:

Table 7: Site 2 - Parameter overview

COD		2022		2027		2032	
Total capacity [MW]		600		600		600	
Turbine nameplate capacity [MW]		10		12		15	
Rotor diameter [m]		178		222		248	
Hub height [m]		114		136		149	
Turbine spacing (D8) [m]		1424		1776		1984	
Area [km2]		99.36		113.55		98.41	
# turbines		60		50		40	
Depth [m]		408		408		408	
Max. depth [m]		921		921		921	
Distance from land [km]		108		108		108	
Distance from staging port [km]		108		108		108	
Significant wave height [m]:		2.3		2.3		2.3	
Distance from O&M port [km]		108		108		108	
Distance on land [km]		1		1		1	
CapEx decrease [%]		0		9.41		25.91	

Monthly, hourly, and annual average windspeed at 100 meter above sea level:

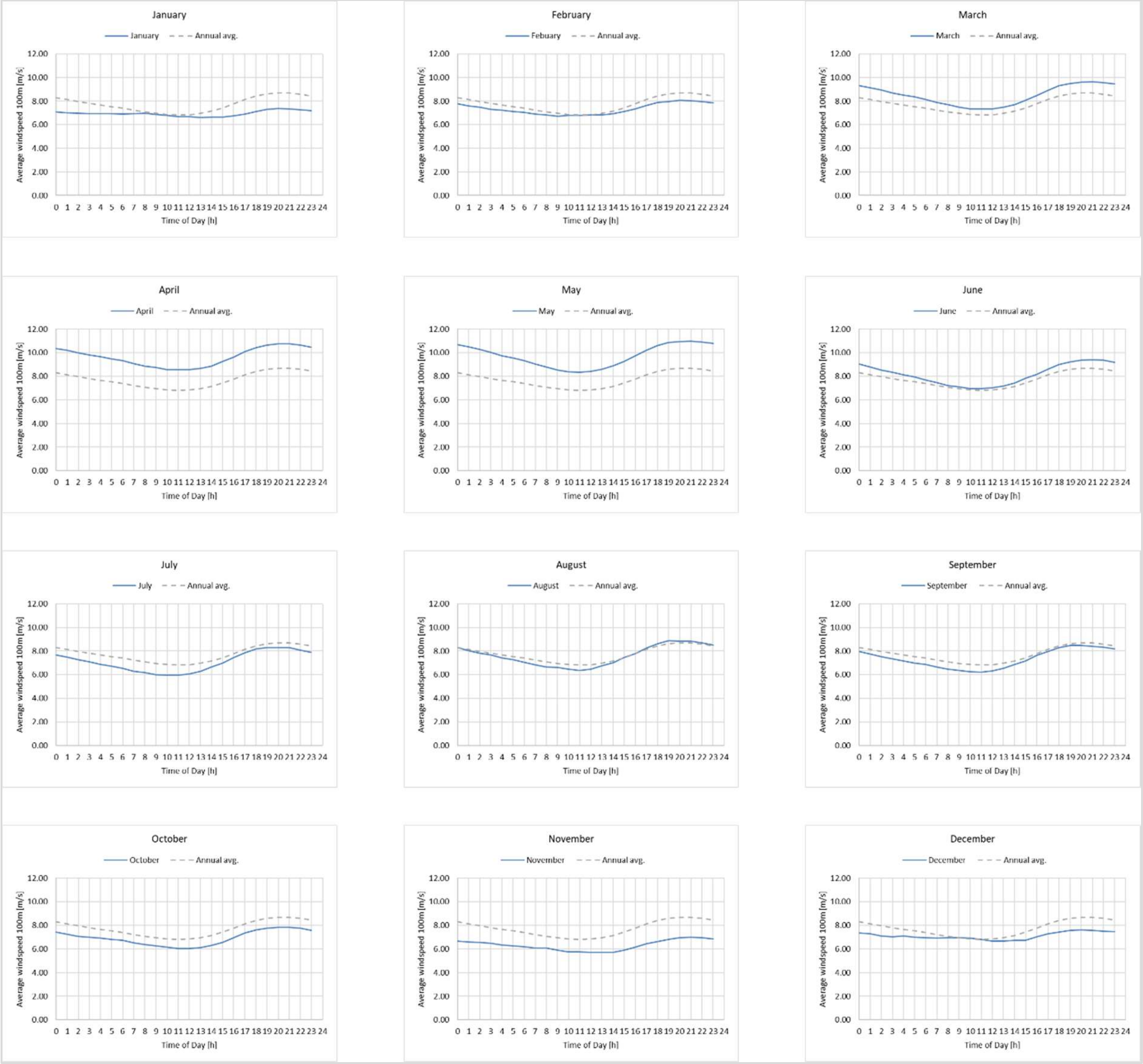

Figure 27: Site 2 - Windspeed data

Monthly average Weibull distribution of windspeed at 100 meter above sea level:

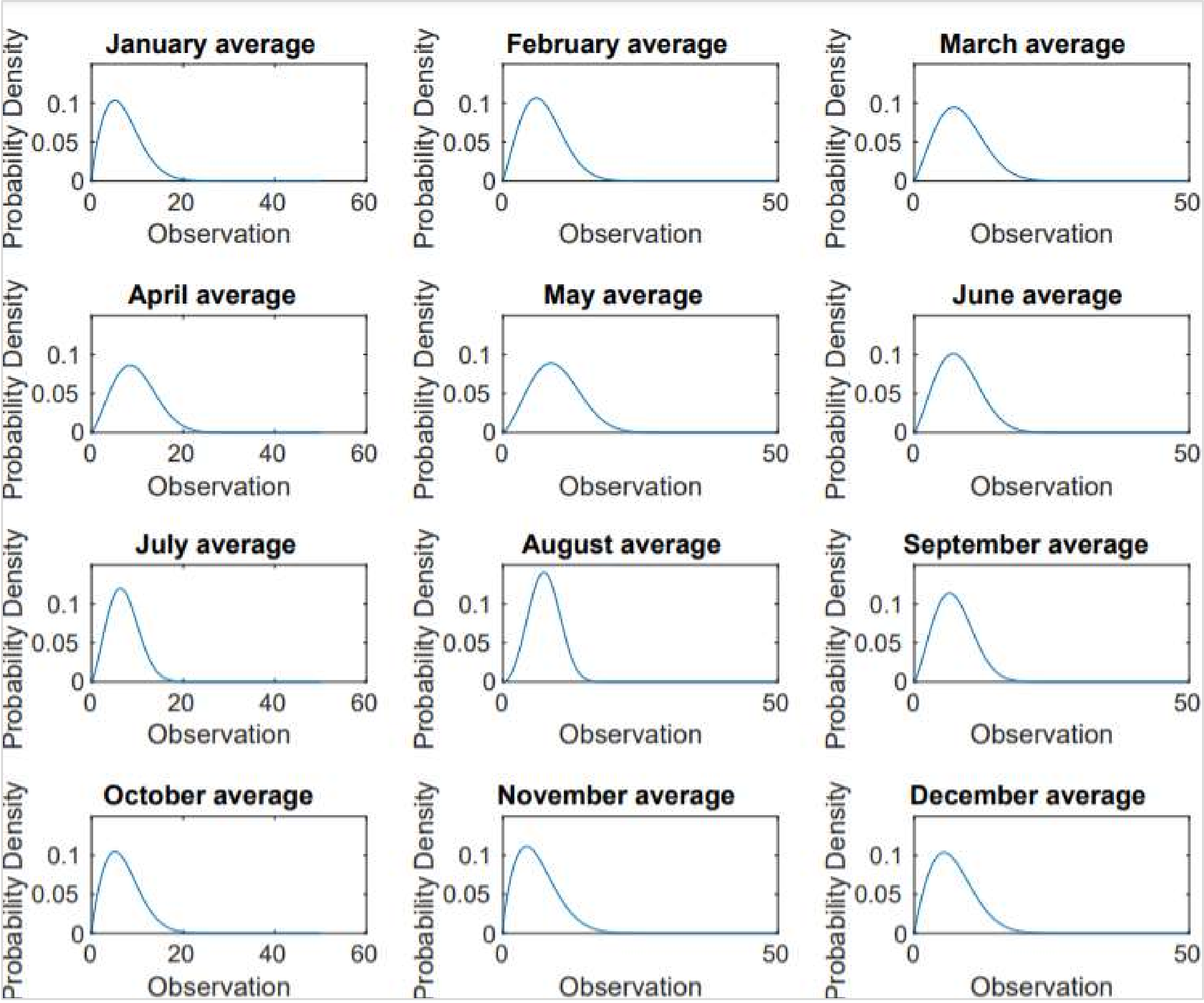

Figure 28: Site 2 - Weibull distribution

Depth profile:

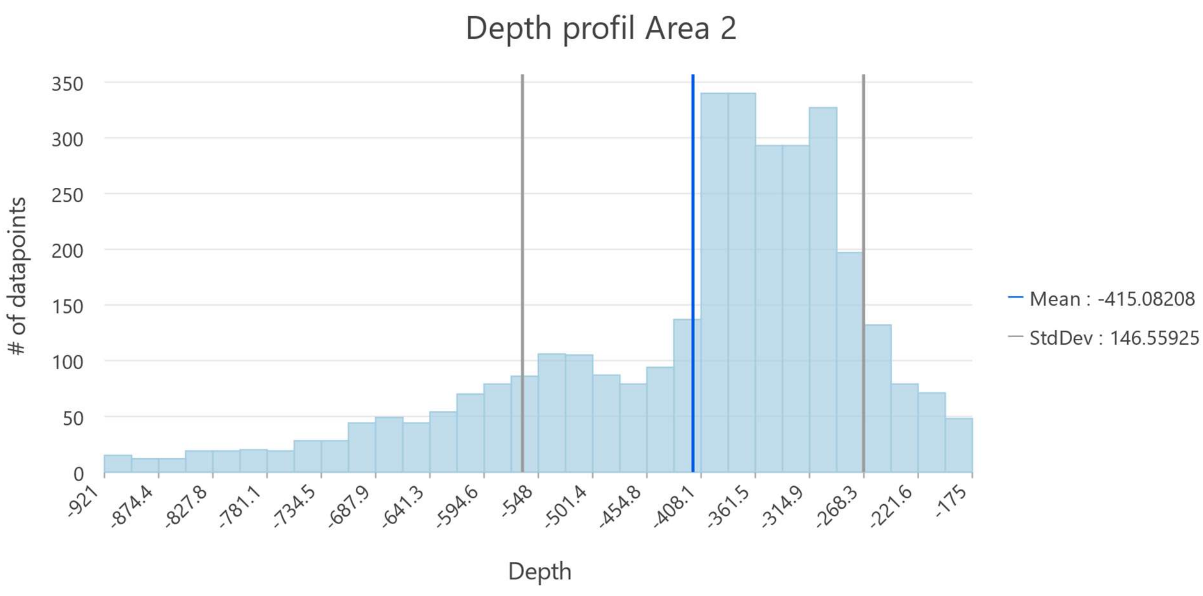

Figure 29: Site 2 - Depth profile

Significant wave height:

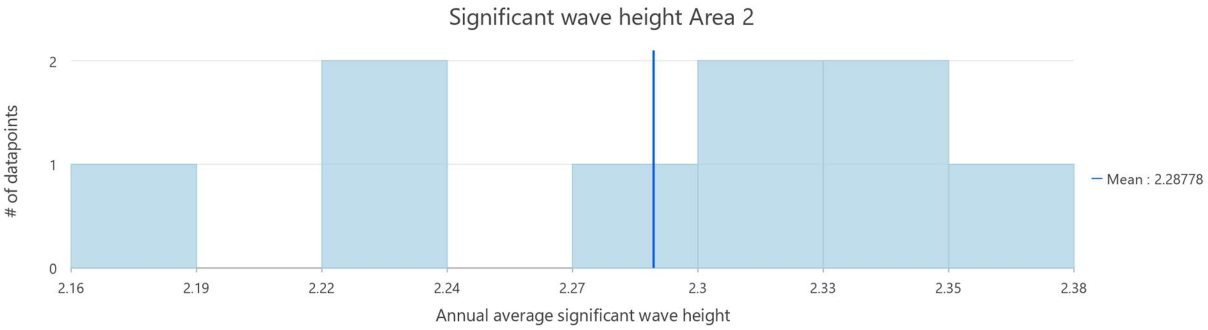

Figure 30: Site 2 - Significant wave height

Area 3 – San Nicolas Island South:

Site parameter overview:

Table 8: Site 3 - Parameter overview

COD		**2022**		**2027**		**2032**	
Total capacity [MW]		600		600		600	
Turbine nameplate capacity [MW]		10		12		15	
Rotor diameter [m]		178		222		248	
Hub height [m]		114		136		149	
Turbine spacing (D8) [m]		1424		1776		1984	
Area [km2]		99.36		113.55		98.41	
# turbines		60		50		40	
Depth [m]		465		465		465	
Max. depth [m]		979		979		979	
Distance from land [km]		153		153		153	
Distance from staging port [km]		162		162		162	
Significant wave height [m]:		2.3		2.3		2.3	
Distance from O&M port [km]		162		162		162	
Distance on land [km]		1		1		1	
CapEx decrease [%]		0		9.41		25.91	

Monthly, hourly, and annual average windspeed at 100 meter above sea level:

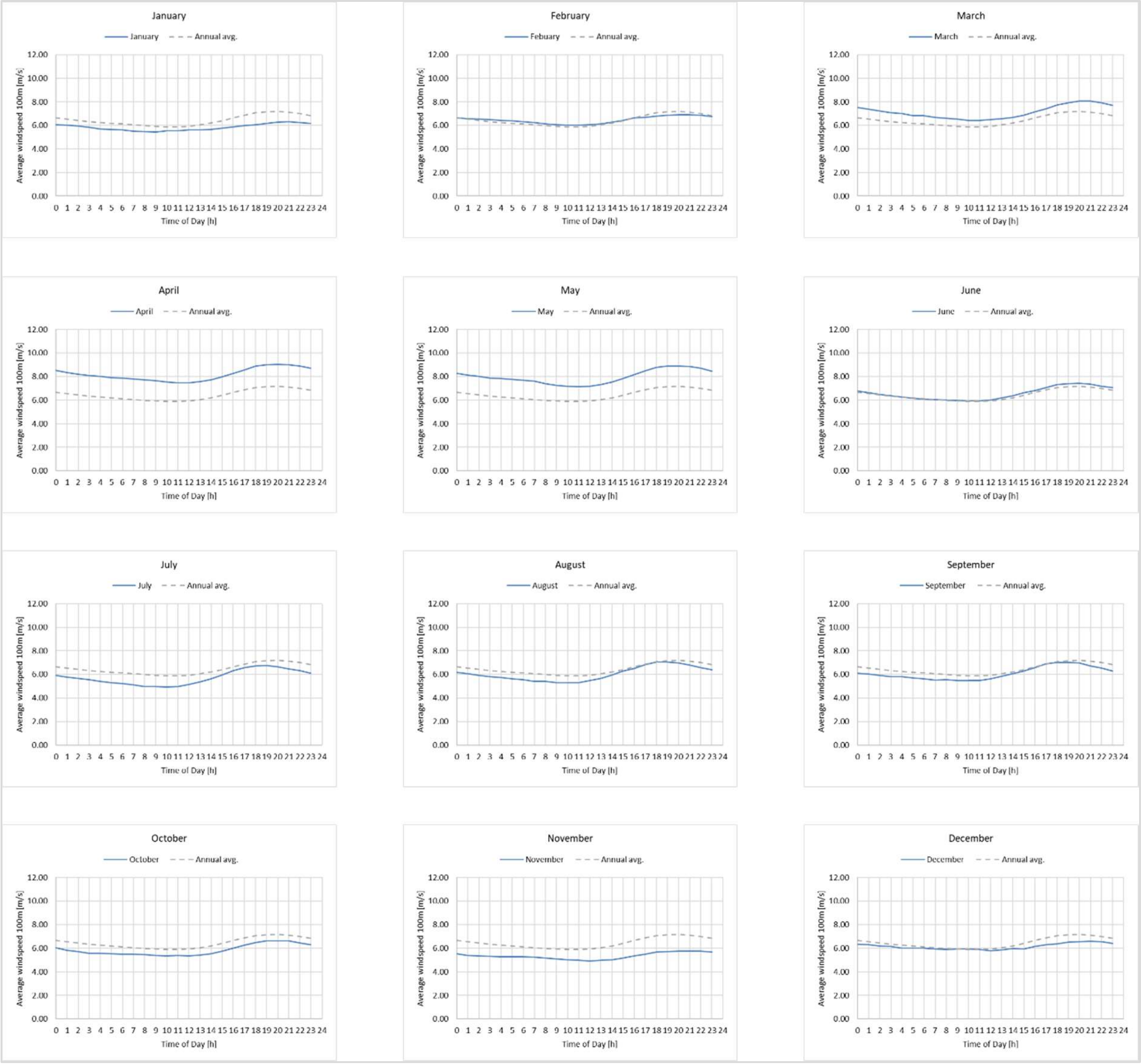

Figure 31: Site 3 - Windspeed data

Monthly average Weibull distribution of windspeed at 100 meter above sea level:

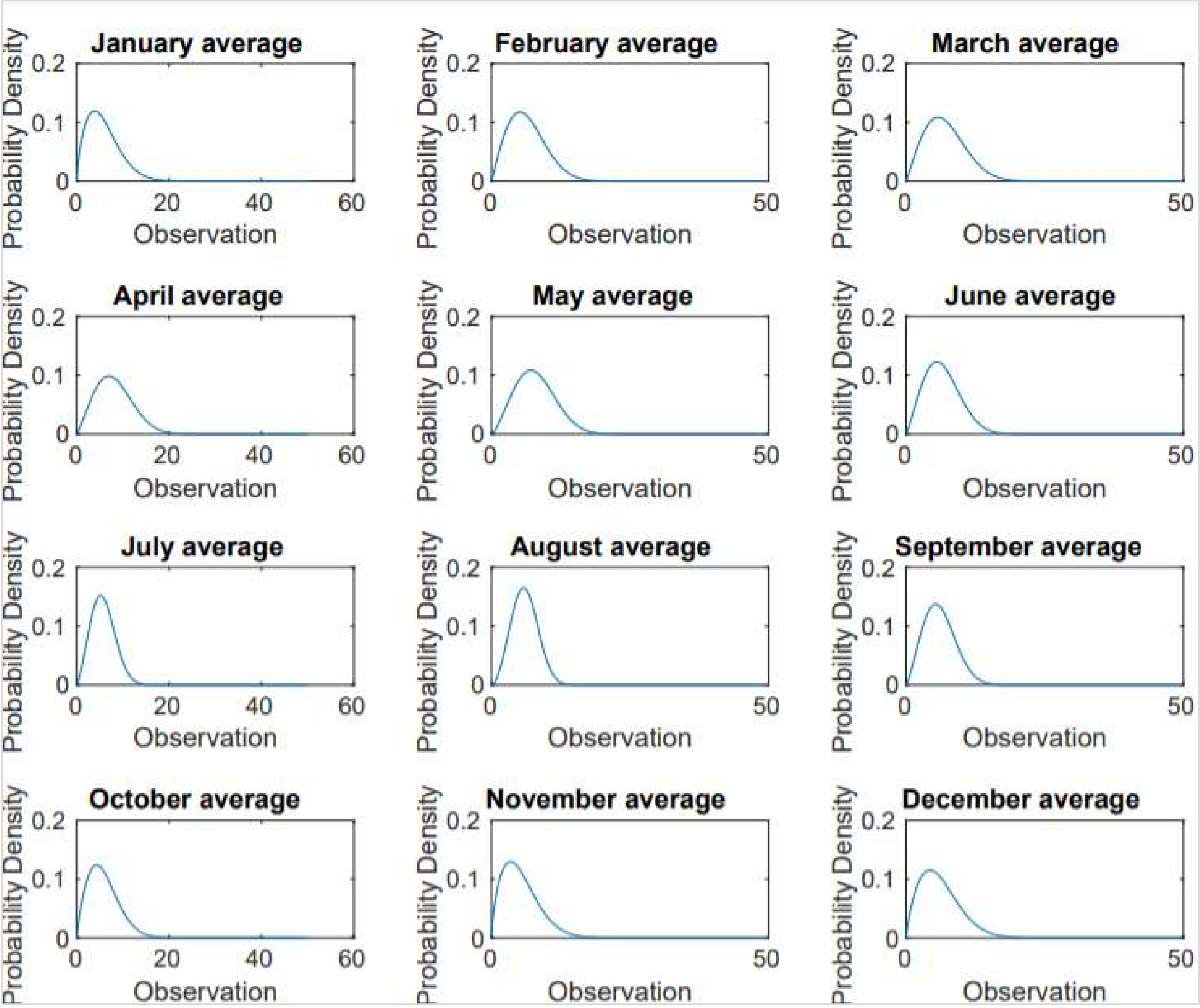

Figure 32: Site 2 - Weibull distribution

Depth profile:

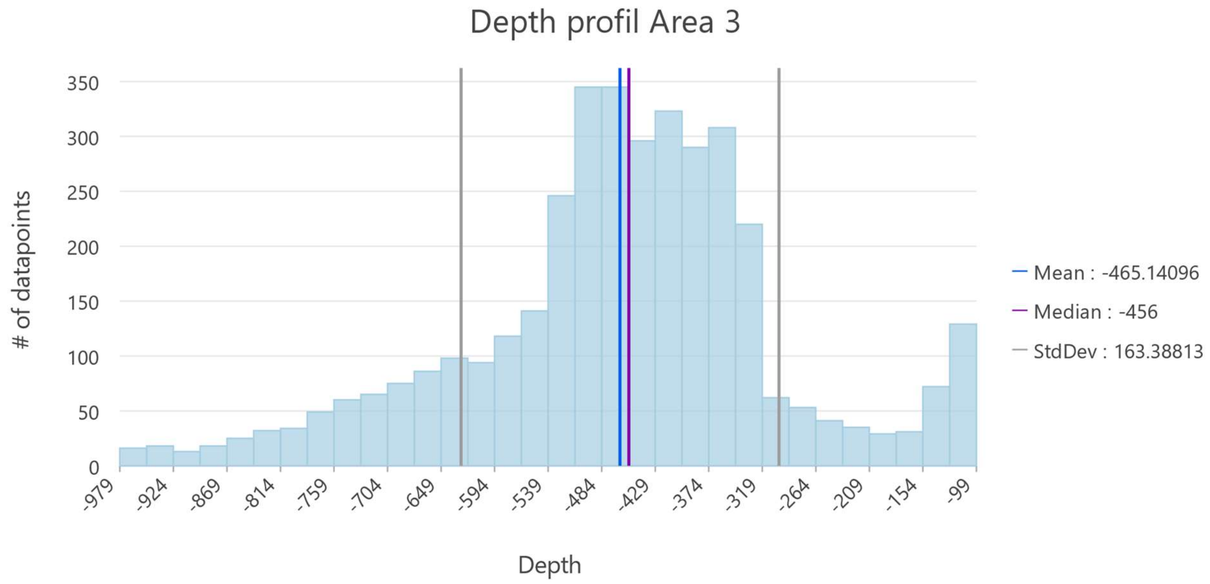

Figure 33: Site 3 - Depth profile

Significant wave height:

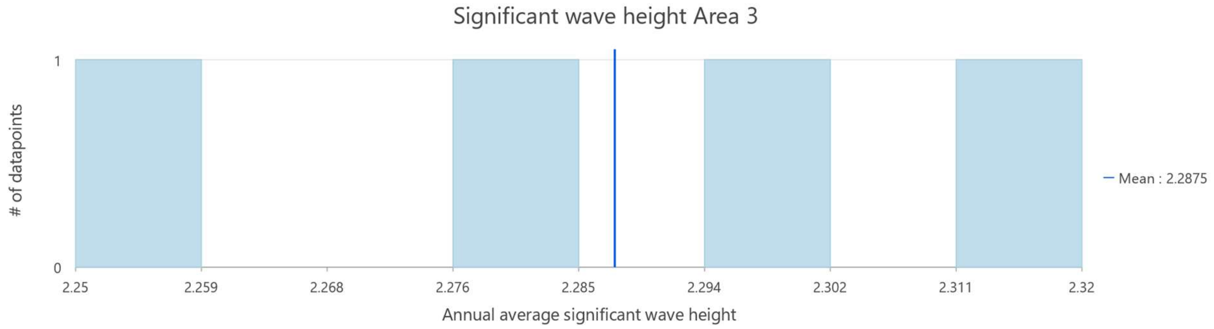

Figure 34: Site 3 - Significant wave height