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Life Cycle Assessment of Greenhouse Gas Emissions for Floating Offshore Wind Energy in California

A Group Project submitted in partial satisfaction of the requirements for the degree of
Master of Environmental Science and Management
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Bren School of Environmental Science & Management

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The Group Project is required of all students in the Master of Environmental Science and Management (MESM) Program. The project is a year-long activity in which small groups of students conduct focused, interdisciplinary research on the scientific, management, and policy dimensions of a specific environmental issue. This Group Project Final Report is authored by MESM students and has been reviewed and approved by:

Sangwon Suh

Date

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Table of Contents

Abbreviations

AHTS - Anchor Handling Tug Supplies
BOEM - Bureau of Ocean Energy Management
CO_2-eq/MWh - Carbon Dioxide Equivalent per Megawatt Hour
CPUC - California Public Utilities Commission
EOL - End of Life
FU - Functional unit
GHG - Greenhouse gas
GW - Gigawatts
GWP - Global Warming Potential
kg/MWh - Kilograms per megawatt hour
LCA - Life cycle assessment
LCI - Life Cycle Inventory LCI
LCIA - Life Cycle Inventory Analysis
LCOE - Levelized cost of energy
MWh - Megawatt-hour
NREL - The National Renewable Energy Laboratory (NREL)
PPM - Parts per million
PSV - Power Supply Vessel
ROV - Remotely Operated Vehicle
RPS - Renewables Portfolio Standards
SB100 - Senate Bill 100
WEAs - Wind energy areas

List of Figures

List of Tables

Abstract

Senate Bill 100 of California passed in 2018 establishes the requirement that 100% of the state's retail electricity be generated from eligible carbon-free resources by 2045. Given the high land prices and limited onshore wind resources in California, floating offshore wind represents a new carbon-free energy resource that can help California meet the Senate Bill 100 target. In order to facilitate the development of floating offshore wind projects in federal waters off the coast of California, the Bureau of Ocean Energy Management (BOEM) Pacific Region has tasked the Bren School with characterizing and assessing the greenhouse gas (GHG) emissions associated with the integration of offshore wind energy into California electricity markets. By performing a life cycle assessment (LCA) for a representative floating offshore wind project, this report presents the first analysis of the life cycle GHG emissions of any offshore wind project in California. Our results show that supplying 1 MWh of electricity through floating offshore wind power generates ~15kg CO_2-equivalent GHG emissions over its life cycle, which is comparable with the literature for conceptual floating offshore wind turbine models. Monte Carlo simulation establishes a 90% confidence interval range of emissions from 11.60 to 25.04kg CO2-equivalent. Our results are within the combined range of both onshore and offshore wind projects at a utility scale. Compared with other energy sources, life cycle GHG emissions from floating offshore wind in California are similar to those from hydro and nuclear. These results indicate that floating offshore wind in California produces at least 92% less GHG emissions per MWh supplied to the grid compared to natural gas. In-depth analysis of our results indicates that the turbine manufacturing stage is responsible for the majority of the life cycle GHG emissions, that recycling rates for materials have strong implications for reducing life cycle GHG emissions, and that the life cycle GHG emissions are most heavily influenced by capacity factor of the turbines and the operational lifetime of the windfarm. These results imply that, first, offshore wind has the potential to provide low-carbon electricity in California, and, second, mitigation efforts should prioritize the manufacturing and recycling phases, and the factors influencing capacity factor (i.e. site selection and generation capacity) and operational lifetime of the windfarm (i.e., maintenance schedule and mechanical durability). Our study demonstrates the potential for floating offshore wind projects to curb GHG emissions and to meet the Senate Bill 100 target.

Executive Summary

Introduction

In the United States, California has instituted one of the most aggressive Renewables Portfolio Standards (RPS). State policy, per Senate Bill 100 (SB100), requires 100% of its retail energy to be generated from eligible renewable energy resources and zero-carbon resources by December 31, 2045. This RPS is driven by the State's mandate to reduce greenhouse gas (GHG) emissions to 40% below 1990 levels by 2030 per Senate Bill 32 (SB32).

Given the large-scale renewable energy targets in California, it is important to recognize that the growth capacity of land-based wind power has slowed over the last several years. As such, offshore wind represents a renewable energy resource that can help California meet its RPS targets in addition to hydro and solar power production. Floating offshore wind is uniquely positioned to address energy challenges in California due to its ability to help alleviate land-use issues and supply the energy needs of high-density coastal populations.

Recently, the Bureau of Ocean Energy Management (BOEM) has commissioned efforts to evaluate the benefits of floating offshore wind energy projects. Although floating offshore wind energy has land-use benefits and can take advantage of the more consistent offshore wind resources, the additional underwater infrastructure and operational requirements raise concerns about the extent of their life cycle GHG benefits. Therefore, there is a need to evaluate the life cycle impacts of offshore wind projects on GHG emissions and their significance for California emissions targets.

Objectives

In order to facilitate the development of floating offshore wind projects in federal waters off the coast of CA, BOEM Pacific Region has tasked the Bren School with characterizing and assessing the GHG emissions associated with the integration of floating offshore wind energy into California electricity markets. The objectives of this project include:

1. Conducting a life cycle assessment (LCA) of the GHG emissions of a representative floating offshore wind project in California.

2. Interpretation of results in the context of California GHG emission reduction targets and air quality standards.

3. Developing policy recommendations that would facilitate offshore wind development in California.

Methods

To fulfill the first objective of the project, an LCA was conducted to quantify the GHG emissions of floating offshore wind to deliver 1 MWh of electricity to the grid of California. The type of LCA used in this project is attributional. An attributional LCA is used to determine or 'attribute' the environmental burdens associated with the production and use of a product at a given point in time. In this project, a product is a floating offshore wind farm. Life cycle stages include manufacturing, transportation, installation, operation, decommissioning, and end-of-life treatment. Materials and energy used in each life cycle stage were quantified with data collected from developer surveys, industry reports, academic literature, and other public resources. The GHG emissions were calculated with those material & energy uses and corresponding emission factors from the Ecoinvent database. All LCA calculations were performed in Microsoft Excel.

To fulfill the second objective, data for life cycle GHG emissions of other electricity generation sources were collected from industry reports, academic literature, and publicly available resources. Importantly, this project assumes that natural gas-powered electricity generation is likely to be replaced or avoided by floating offshore wind. As such, the potential reduction or avoidance of the GHG emission was measured as well as the potential cost of carbon credit purchase to meet targets of SB100.

Overall Findings

The model predicted GHG emissions of ~15.35 kg CO_2-eq/MWh with an uncertainty range of 8.58 - 30.17 kg CO_2-eq/MWh. This result is within the range of previous wind energy LCA studies (3.0 to 45 CO_2-eq/MWh for utility scale wind farms). Among life cycle stages, Manufacturing stage has the largest contribution (18.3 kg CO_2-eq/MWh) while End-of-life stage has the significant reduction credit (-9.2 CO_2-eq/MWh). In the manufacturing stage, the turbine and substructure were the major contributors, constituting 77% of manufacturing stage emissions. Among materials and energy, steel was the major contributor (49%) followed by diesel and hard coal (27%).

Compared to GHG emissions from other energy sources even conservative estimates have implications for reduction. For example, the maximum estimate of the GHG emissions for floating offshore wind was still less than 1/10th the minimum estimated value of natural gas and 1/20th the minimum estimated value of coal. These results indicate that there is a significant opportunity for California to reduce its GHG emissions and simultaneously meet its emission reduction targets and energy production goals.

The resulting emissions varied depending on a range of input parameters. This project tested nine major parameters with regards to the sensitivities in the life cycle GHG emissions results. Among these parameters, the capacity factor was found to be the most sensitive parameter; higher capacity factor significantly reduced life cycle GHG emissions per generated electricity. Longer operational life also increased the electricity generation and reduced GHG emissions per generated electricity.

Policy Recommendations

First, this project recommends floating offshore wind as a potential solution to help achieve the emission targets mandated by SB100. Given the low carbon footprint of offshore wind we analyzed, replacing fossil fuel electricity or inhibiting the growth of non-renewables by floating offshore wind, has a significant potential to reduce or prevent the production of GHG emissions from electricity in California.

Second, this project recommends policymakers evaluate capacity factor critically when it assesses potential project sites. Characterized by wind-resource availability at each specific offshore site, capacity factor is a major contributor to variance of the GHG emissions. Therefore, extensive research should be dedicated to site selection in order to maximize the windfarm's capacity factor.

Lastly, this project recommends that policymakers critically consider the operational lifetime of floating offshore wind and the recycling rate of major materials during the evaluation of potential developers for the site lease. In addition to capacity factor, these two factors have significant impact on the GHG emissions per generated electricity. While capacity factor is affected by uncontrollable factors like wind speed and amount or manufacturer's technology advancement, operational lifetime and recycling rates can potentially be improved directly by developers.

Future Research Needs

Future studies should expand the scope of this LCA and examine other environmental impacts of floating offshore wind projects. Besides GHG emissions, floating offshore wind projects would have many other environmental impacts including acidification and eco-toxicity through its life cycle.

While this study focuses on evaluating life cycle emissions based on total electricity generation, an understanding of the precise impacts of floating offshore wind on California's electricity gridmix should follow this report to understand life cycle emissions based on total consumed electricity generation.

Background

In the United States, California has instituted one of the most aggressive Renewables Portfolio Standards (RPS). State policy, per Senate Bill 100 (Passed 9.10.18), requires 100% of its retail energy to be generated from eligible renewable energy resources and zero-carbon resources by December 31, 2045.[1] This RPS is driven by the State's mandate to reduce greenhouse gas (GHG) emissions to 40% below 1990 levels by 2030 per Senate Bill 32, the most ambitious carbon goal in North America.[2] To meet its GHG emissions reduction target and RPS as well as continue its role as a pioneer in renewable energy, California seeks to evaluate floating offshore wind power as a low-carbon, renewable energy source for its energy portfolio.

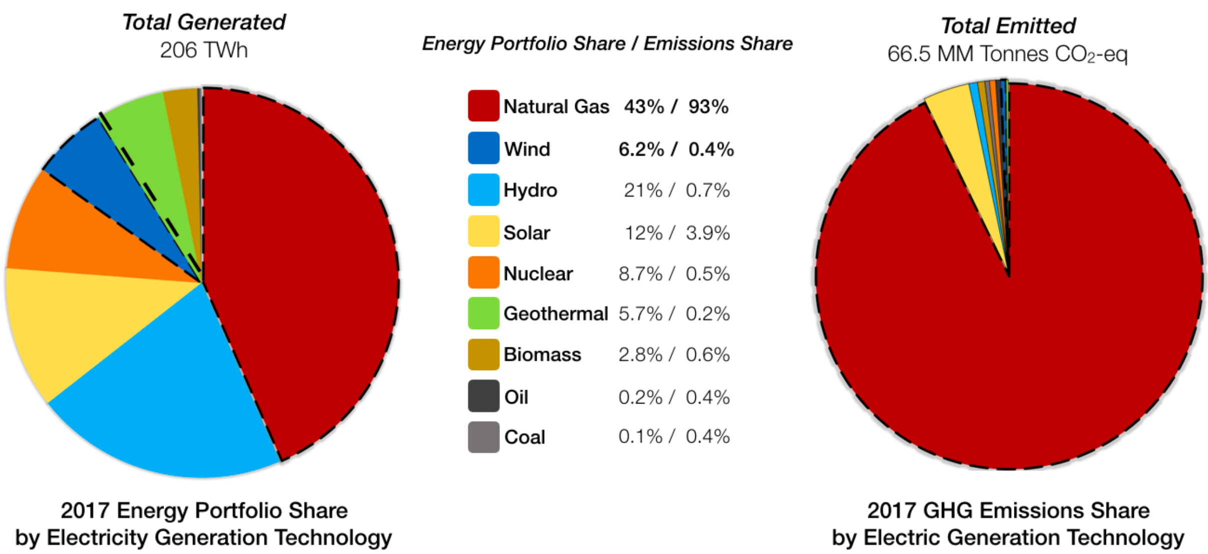

Figure 1. Portfolio share of 2017 electricity generation in California (left) and GHG emissions share of 2017 electricity generation in California (right).[3,4]

The California Public Utilities Commission (CPUC) is moving ahead with renewable development. As of 2016, 15 gigawatts (GW) of RPS cumulative capacity had been approved by the CPUC and to meet California's RPS, more than 3 GW of renewable energy must be approved and implemented by 2030. Most of these new energy sources are

[1] SB-100 California Renewables Portfolio Standard Program: emissions of greenhouse gases. (2017-2018). Senate Bill No. 100. CHAPTER 312. Accessed February 27, 2019. https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201720180SB100.
[2] California Air Resources Board. "Climate pollutants fall below 1990 levels for first time." Accessed February 27, 2019. https://ww2.arb.ca.gov/news/climate-pollutants-fall-below-1990-levels-first-time.
[3] California Energy Commission. "Total System Electric Generation." Accessed February 27, 2019. https://www.energy.ca.gov/almanac/electricity_data/total_system_power.html.
[4] Turconi, Roberto, Alessio Boldrin, and Thomas Astrup. "Life cycle assessment (LCA) of electricity generation technologies: Overview, comparability and limitations." *Renewable and sustainable energy reviews* 28 (2013): 555-565. http://orbit.dtu.dk/files/118476742/2012_RSER_Turconi_Life_cycle_assessment_LCA_of_electricity_generation_technologies_overview_comparability_and_limitations_self_archive.pdf.

expected to be filled by solar and wind power. Given that solar power can only be generated during the day, wind power will be used to fill high demand for electricity in the morning and at night.

Given the large-scale renewable energy targets in California, it is important to recognize that the growth capacity of land-based wind power has slowed over the last several years. Although cumulative wind power capacity more than doubled from 2,376 megawatts (MW) to 5,542 MW between 2006 and 2012 (15.2% annual growth), there was only a 2.1% growth rate from 5,542 megawatts to 5,656 megawatts (0.5% annual growth) between 2012 and 2016. As such, floating offshore wind represents a renewable energy resource that can help California meet its RPS target, complements solar power production, and avoids the land-use restrictions and environmental issues that challenge future land-based wind power development. Floating offshore wind is uniquely positioned to address energy use in California due to its ability to help alleviate land-use issues and serve the high coastal population.

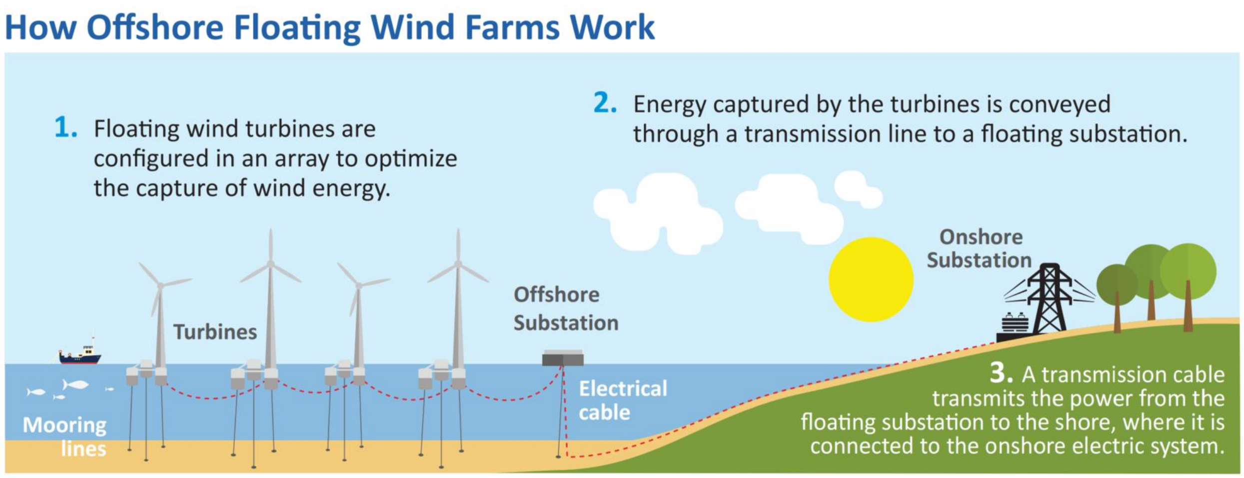

Figure 2. A general overview of a floating offshore wind farm. The wind turbines are connected to the ocean floor with mooring lines and an anchoring system. Then electric array cables connect the turbines to an offshore substation which then transmits the energy to the onshore grid.[5]

Previously, high costs were seen as a major barrier to offshore development. Although floating offshore wind power is currently more expensive than land-based renewable energy resources, offshore wind technology efficiency and cost-effectiveness continues to improve.[6] The National Renewable Energy Laboratory (NREL) estimated that the levelized cost of energy (LCOE) of floating offshore wind power has the potential to decrease from approximately $185/megawatt-hour (MWh) in 2015 to approximately $100/MWh by 2030.

[5] California Energy Commission. "California Offshore Renewable Energy Fact Sheet", March 1, 2017. Accessed February 27, 2019. https://efiling.energy.ca.gov/GetDocument.aspx?tn=216308.
[6] Beiter, Philipp, Walter Musial, Levi Kilcher, Michael Maness, and Aaron Smith. *An Assessment of the Economic Potential of Offshore Wind in the United States from 2015 to 2030*. No. NREL/TP-6A20-67675. National Renewable Energy Lab.(NREL), Golden, CO (United States), 2017. https://www.nrel.gov/docs/fy17osti/67675.pdf

Additional reductions took place in the European market which were not included in the figures above.[7]

Floating offshore wind development offers benefits to gross domestic product as well. NREL estimated that developing 10 GW of floating offshore wind in California would create a cumulative gross domestic product benefit of $19.7 billion during construction and operations.[8] The decreasing costs of offshore production combined with the economic benefits enhance the viability of floating offshore wind power development.

These financial benefits are important, but the advantages floating offshore wind has over other energy sources in terms of GHG emissions could be highly influential due to California's ambitious reduction goals. Recently, the BOEM has commissioned efforts to evaluate the benefits of floating offshore wind energy projects.[9] Although floating offshore wind energy has financial and land-use benefits and can take advantage of the more consistent floating offshore wind resources, the additional underwater infrastructure and operational requirements raise concerns about their life cycle GHG benefits. This project helps evaluate these benefits and addresses the need for more research on the life cycle impacts of floating offshore wind projects on GHG emissions and their significance for California emissions targets.[10]

Floating offshore wind technologies are still in their nascent stage, there is only one commercial-scale floating offshore wind farm operating at the time of writing (Hywind Scotland Pilot Park Project), and discussions of floating offshore wind development in California are fairly new. However, a thorough literature review of onshore, fixed offshore, and floating offshore LCAs as well as a review of manufacturing specifications provided a basis for the assumptions required for a representative California floating offshore wind project. This project leveraged the Bren School's significant expertise and resources for LCAs, including prior research on LCAs for renewable energy generation, transmission, and distribution to complete the LCA. Based on these resources and the model results, this project provides decision makers with scenarios and policy recommendations that inform the viability of floating offshore wind power projects in California.

[7] Musial, Walt, Donna Heimiller, Philipp Beiter, George Scott, and Caroline Draxl. *2016 Offshore Wind Energy Resource Assessment for the United States*. No. NREL/TP-5000-66599. National Renewable Energy Lab. (NREL), Golden, CO (United States), 2016.
[8] Speer, Bethany, David Keyser, and Suzanne Tegen. *Floating Offshore Wind in California: Gross Potential for Jobs and Economic Impacts from Two Future Scenarios*. No. NREL/TP-5000-65352. National Renewable Energy Lab. (NREL), Golden, CO (United States), 2016. https://www.nrel.gov/docs/fy16osti/65352.pdf
[9] AECOM. "Evaluating Benefits of Offshore Wind Energy Projects in NEPA - BOEM." https://www.boem.gov/Final-Version-Offshore-Benefits-White-Paper/. Accessed 6 Mar. 2019.
[10] Haapala, Karl R., and Preedanood Prempreeda. "Comparative life cycle assessment of 2.0 MW wind turbines." *International Journal of Sustainable Manufacturing* 3, no. 2 (2014): 170-185. http://www.ourenergypolicy.org/wp-content/uploads/2014/06/turbines.pdf

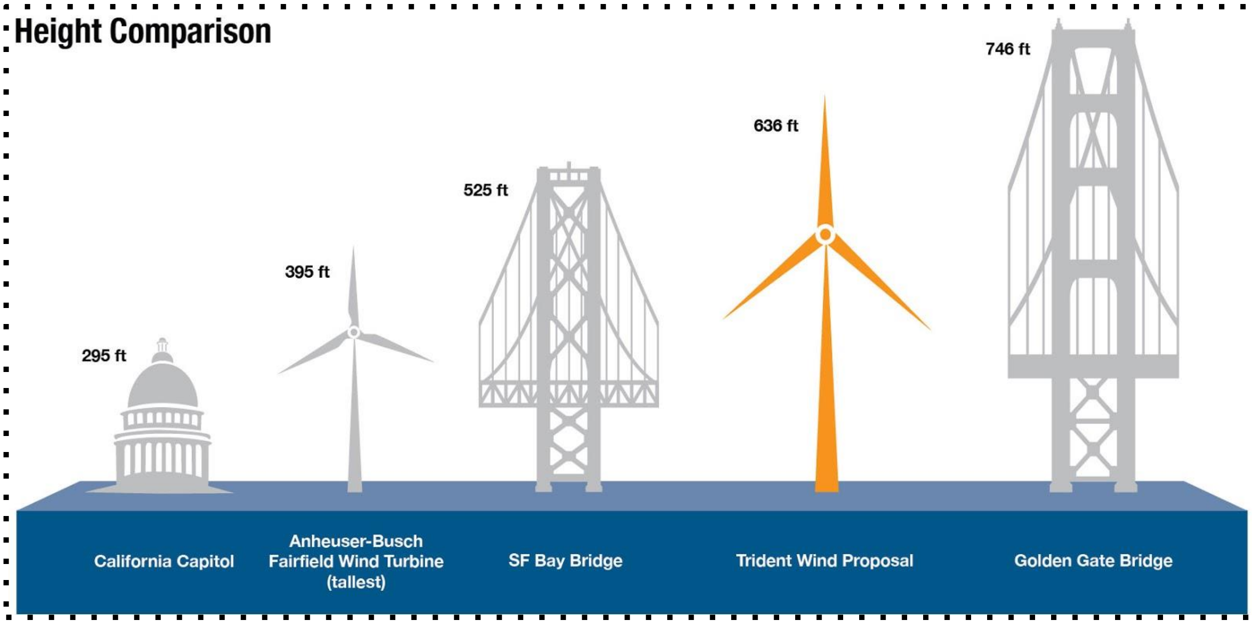

Figure 3. Height comparison of floating offshore wind turbines to other structure.[11]

Significance

Although California's population-growth has averaged 333,000 per annum since 2010,[12] the California Air Resources Board announced in 2018 that greenhouse gas pollution in California fell below 1990 levels for the first time since emissions peaked in 2004.[13] While solar and land-based wind power sources have significantly contributed to California's renewable portfolio over the last decade, further development in these renewable energy sectors has nonetheless slowed over the last several years due to the occurrence of stronger land-use restrictions, civil complaints, and environmental issues.[14] Despite California's growing solar PV deployment, solar penetration into the grid remains relatively small compared to non-renewable energy sources. This is due to two major constraints for solar electricity generation: The first constraint is that solar generation is intermittent, meaning that solar electricity production can vary by day, changes in cloud cover, and seasonal changes in solar irradiance. The second constraint on solar electricity is the potential for solar power plants to produce more electricity during the day than is needed to meet electricity demand. This type of overgeneration from excess electrical output can

[11] California Energy Commission. "California Partners with Federal Government on Offshore Wind". March 14, 2017. Accessed February 27, 2019. http://calenergycommission.blogspot.com/2017/03/california-partners-with-federal.html.

[12] Department of Finance. "New Demographic Report Shows California Population Nearing 40 Million Mark With Growth Of 309,000 In 2017." Accessed February 27, 2019. http://www.dof.ca.gov/Forecasting/Demographics/Estimates/e-1/documents/E-1_2018PressRelease.pdf.

[13] California Air Resources Board. "Climate pollutants fall below 1990 levels for first time." Accessed February 27, 2019. https://ww2.arb.ca.gov/news/climate-pollutants-fall-below-1990-levels-first-time.

[14] Nikolewski, Rob. "Why wind energy has calmed down: Land-use rules and resident's opposition limit industry's growth potential in state." *Los Angeles Times*. September 5, 2017.

cause power outages and damage to the grid.[15] Moreover, further increases in solar power present the threat of curtailment (potentially large-scale reductions in the output of solar grids to reduce periods of over-generation) and natural gas ramping (As more solar generation is added to the grid during this time, it is able to meet an increasingly large portion of the daytime load, but the grid also requires increasing amounts of other generation to ramp up to meet evening peaks as the sun goes down) (Figure *4*). Under these circumstances, floating offshore wind power represents an emerging resource that can be used as an alternative solution for sourcing renewable energy in California.

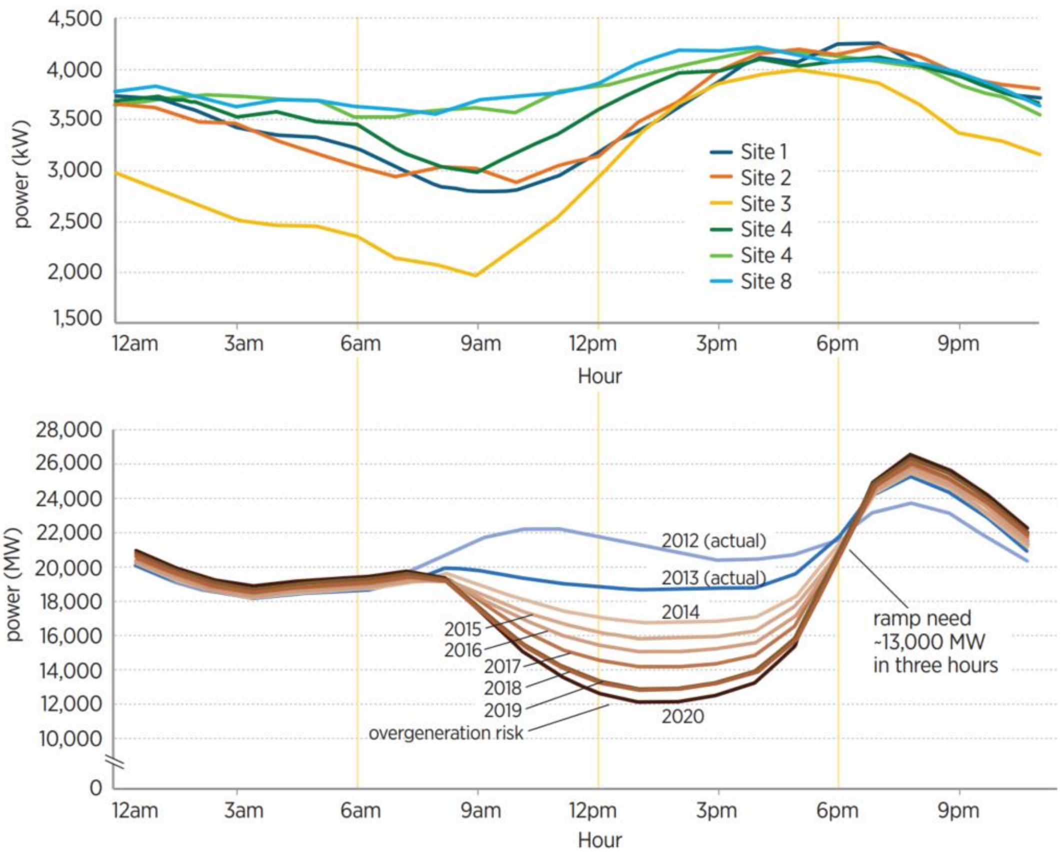

Figure 4. The “duck curve” and modeled generation profiles for 6-Mw offshore wind turbines at six California sites. Adding offshore wind into California’s electricity portfolio may help alleviate overgeneration and ramping challenges as solar and land-based wind generation continue to grow.[16]

Although BOEM has commissioned analyses on the life cycle costs and economic impacts of potential offshore wind energy in California, impacts of floating offshore wind projects on GHG emissions and their significance specifically for California’s emission targets and

[15] Denholm, Paul, Matthew O'Connell, Gregory Brinkman, and Jennie Jorgenson. Overgeneration from solar energy in California. A field guide to the duck chart. No. NREL/TP-6A20-65023. National Renewable Energy Lab.(NREL), Golden, CO (United States), 2015.
[16] U.S. Department of Energy and U.S. Department of the Interior. "National Offshore Wind Strategy: Facilitating the Development." Accessed February 27, 2019. https://www.boem.gov/National-Offshore-Wind-Strategy/.

energy portfolio have yet to be studied.[17] This group project informs policy makers by providing an assessment of the impacts of floating offshore wind power projects on GHG emissions in California in an effort to facilitate floating offshore wind development.

The information from this project will inform offshore energy planning and analysis in California and also inform energy portfolio planning by the California Public Utilities Commission (CPUC) and other state agencies.

Sourcing Wind Energy: Onshore vs Offshore

While renewable energy represents an important part of any climate-change mitigation strategy, land-based wind energy involves creating a large geographic footprint in tandem with long-distance transmission lines that require extensive permitting. With more than 52% of the U.S. population concentrated in coastal watershed counties,[18] floating offshore wind projects avoid these land-based restrictions. However, floating offshore wind production requires additional structural elements and different materials. In this report we use LCA to analyze how floating offshore wind environmental impacts compare with conventional wind impacts.

Current Developments

BOEM Pacific Region, as the statutory authority that issues leases for ocean energy development, is moving ahead in the process of leasing specific sites. BOEM Pacific Region has identified three possible sites for the first floating offshore wind farm off the coast of California.

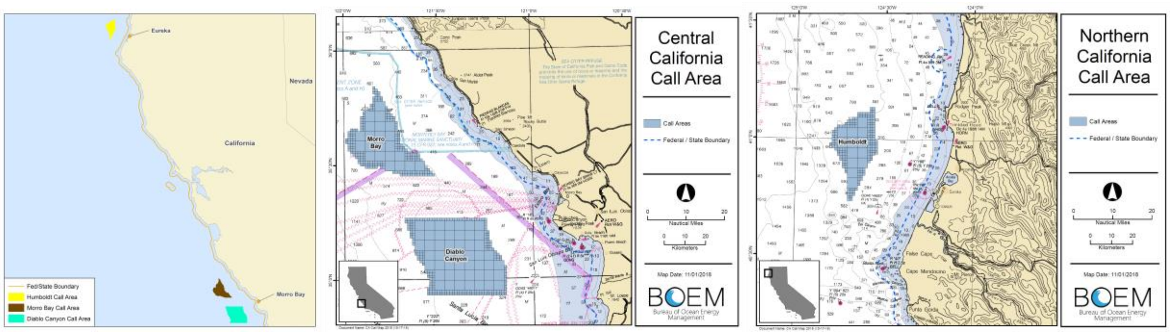

Figure 5. Possible lease sites being considered by BOEM.[19, 20, 21]

[17] Speer, Bethany, David Keyser, and Suzanne Tegen. *Floating Offshore Wind in California: Gross Potential for Jobs and Economic Impacts from Two Future Scenarios*. No. NREL/TP-5000-65352. National Renewable Energy Lab.(NREL), Golden, CO (United States), 2016. https://www.nrel.gov/docs/fy16osti/65352.pdf

[18] NOAA. "NOAA's National Coastal Population Report." Accessed February 28, 2019. https://aamboceanservice.blob.core.windows.net/oceanservice-prod/facts/coastal-population-report.pdf.

[19] BOEM. “CA Call Areas.” Accessed February 28, 2019. https://www.boem.gov/uploadedImages/BOEM/Renewable_Energy_Program/State_Activities/CA/CA_Call_Areas_10_16_2018.jpg?n=7732&sa=D&ust=1548448080346000&usg=AFQjCNHZqx9ozU9TU77KSJK5aAoKXs4PYA

[20] BOEM. “Central California, NOAA Chart.” Accessed February 28, 2019. October 19, 2018, https://www.boem.gov/Central-California-Call-Areas-Map-NOAA/

[21] BOEM. “Northern California, NOAA Chart.” Accessed February 28, 2019. October 19, 2018, https://www.boem.gov/Humboldt-Call-Area-Map-NOAA-Chart/

Currently, there is a comment period in place for public comments about these possible developments. Once this ends, wind energy areas (WEAs) will be identified, followed by self-nominations for leases, followed by a leasing auction as required by Federal requirements.

Objectives

In order to facilitate the development of floating offshore wind projects in federal waters off the coast of CA, BOEM Pacific Region has tasked the Bren School with characterizing and assessing the GHG emissions associated with the integration of floating offshore wind energy into California electricity markets. Due to the deep waters off the California coast, floating offshore wind platforms are the most practical development technology instead of fixed-bottom structures. Specifically, the project objectives include:

1. Conducting a life cycle assessment (LCA) of the overall GHG emissions of a representative floating offshore wind project in California, including manufacturing of wind farm components, installation, operation, and decommissioning.

2. Interpretation of results in the context of California GHG emission reduction targets and air quality standards.

3. Developing policy recommendations that would facilitate floating offshore wind development in California.

The bulk of this report focuses on the development of an LCA model for the overall GHG emissions of a representative floating offshore wind project in California (Objective #1).

Introduction to Life Cycle Analysis

The first objective of this report is to quantify the GHG emissions of an offshore floating wind farm by conducting a LCA. LCA is an analysis tool which quantifies environmental impacts of a project, product, or process from raw material acquisition to end-of-life management; otherwise known as “cradle to grave.” There are two main types of LCA: attributional LCA and consequential LCA. Attributional LCA is used to determine or attribute the environmental burdens associated with the production and use of a product at a given point in time. A consequential LCA is used to quantify the environmental impacts of a product as a result of a change in a system. In this report, an attributional LCA is appropriate.

LCAs have many uses, such as providing a means to systematically compare inputs and outputs of two projects, products or processes, identifying which stages of a life cycle have the greatest environmental impacts, establishing a comprehensive baseline to which future research can be compared, providing guidance in the development of new products; to verify a product's environmental claims, and to provide information to decision makers in industry, government, and non-governmental organizations.[22] LCA guidelines have been established by the International Organization for Standardization (ISO) 14040 family of standards.[23]

The entire life cycle for a man-made product goes from obtaining everything needed to make the product, through manufacturing it, using it, and then deciding what to do with it once it is no longer being used. Returning to the natural life cycles described above this means going from the birth of the product to its death. As such, this kind of view is often called a "cradle to grave" view of a product, where the cradle represents the birthplace of the product and the grave represents what happens to it when we are done with it.[24]

An LCA consists of three stages: Inventory analysis, impact assessment, and improvement analysis (interpretation). The inventory analysis consists of scoping the system under consideration, and data collection. The scoping process defines the LCA's purpose, boundary conditions, and assumptions. The impact analysis stage of an LCA takes these data and systematically quantifies the resulting environmental impacts from the material and process data inventoried throughout all life cycle stages within the system boundary. Finally, the improvement analysis stage of the LCA is using the results of the study to identify which processes, underlying materials, or products under investigation can be improved. This can be done by isolating the most harmful or detrimental stages, analyzing the material and energy inputs, outputs, and processes involved in those stages, and identifying methods of reducing related environmental impacts.[25] Evaluating whether a different energy source improves environmental quality and sustainability requires an examination of the entire life cycle of the alternatives.[26] To make informed decisions, consumers, companies, and government agencies must know the implications of their choices for environmental quality and sustainability.

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[22] Dolan, Stacey L. "Life cycle assessment and emergy synthesis of a theoretical offshore wind farm for Jacksonville, Florida." PhD diss., University of Florida, 2007. https://cep.ees.ufl.edu/emergy/documents/dissertations_theses/Dolan_2007_LCAandEmergySynthWindFarmJax_FL_Thesis-UF.pdf

[23] International Organization for Standardization. Environmental Management: Life Cycle Assessment; Principles and Framework. No. 2006. ISO, 2006. https://www.iso.org/standard/37456.html

[24] Matthews, H. Scott, Chris T. Hendrickson, and Deanna H. Matthews. "Life cycle assessment: quantitative approaches for decisions that matter." Retrieved June 1 (2015): 2016. https://www.lcatextbook.com/

[25] Dolan, Stacey L. "Life cycle assessment and emergy synthesis of a theoretical offshore wind farm for Jacksonville, Florida." PhD diss., University of Florida, 2007. https://cep.ees.ufl.edu/emergy/documents/dissertations_theses/Dolan_2007_LCAandEmergySynthWindFarmJax_FL_Thesis-UF.pdf

[26] Matthews, H. Scott, Chris T. Hendrickson, and Deanna H. Matthews. "Life cycle assessment: quantitative approaches for decisions that matter." Retrieved June 1 (2015): 2016. https://www.lcatextbook.com/

Scope

Functional Unit

In LCA, the functional unit provides the quantified description of the performance of a system. A functional unit (FU) of analysis, defined as the amount of product, material, or service to which the LCA is applied, is used to put the data on a common basis for direct comparison.

In the case of the floating offshore wind farm, this is 1 MWh electricity generated and delivered to the onshore electricity grid.[27] This unit is easily comparable to the performance of other power generation used in California, such as natural gas. This allows the impacts associated with the measured performance to be compared.

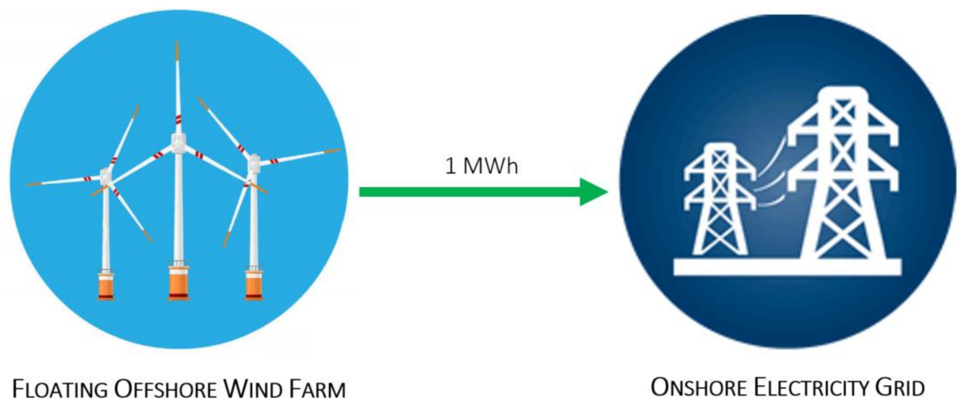

Figure 6. The functional unit allows users to compare distinct stages of environmental burden throughout the life cycle of a floating offshore wind project.

Reference Flow

In this report, a reference flow is characterized by a single, complete wind farm inclusive of turbines, floating substructures, mooring lines, anchors, inter-array cables, export cables, and a substation. Furthermore, the reference flow includes the complete operational lifetime, decommissioning of the wind farm, and related component recycling.

System Boundary

The system boundary for a representative floating offshore wind project, inclusive of turbines, floating substructures, mooring lines, anchors, inter-array cables, export cables, and substation, is cradle to grave.

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[27] Raadal, Hanne Lerche, Bjørn Ivar Vold, Anders Myhr, and Tor Anders Nygaard. "GHG emissions and energy performance of offshore wind power." *Renewable energy* 66 (2014): 314-324. https://www.sciencedirect.com/science/article/pii/S0960148113006654?via%3Dihub

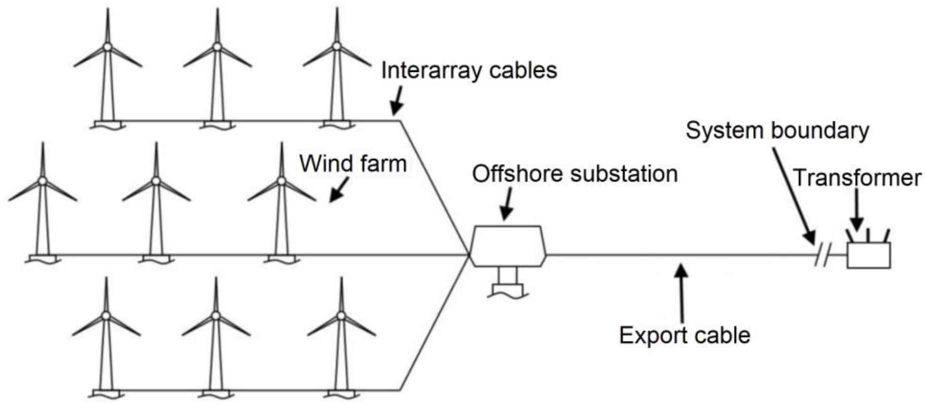

Figure 7. System boundary for a representative floating offshore wind project, adapted from Thomson and Harrison, 2015.[28]

In life cycle inventory analysis (LCIA), this encompasses raw material acquisition, manufacturing, transport, installation, operation and maintenance, decommissioning, recycling, and disposal at the end of life. Other system boundaries include the exclusion of onshore cabling and transformers, capital construction and manufacturing equipment (multi-use with other industries), and manufacturing processes.

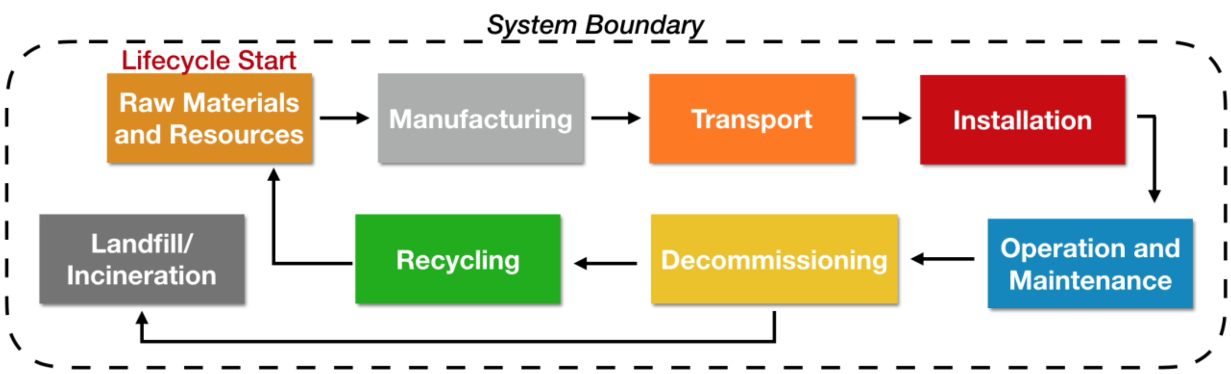

Figure 8. System boundary.

Methodology

Life Cycle Modeling

This report uses Microsoft Excel to perform inventory analysis and to classify elementary flows by GHG emissions. Within the Excel model, we use the IPCC Emissions Factor Database 3.0 (11.9.18) to complete life cycle inventory analysis (LCIA) calculations. The methodology used throughout this report is based on the methodology for life cycle inventory (LCI) as described in the ISO 14044 Standard document. LCI quantifies the

[28] Thomson, R. Camilla, and Gareth P. Harrison. "Life cycle costs and carbon emissions of offshore wind power." *ClimateXChange, Edinburgh* (2015). https://www.research.ed.ac.uk/portal/files/19730353/Executive_Summary_Life_Cycle_Costs_and_Carbon_Emissions_of_Wind_Power.pdf

energy consumption and environmental emissions for a given product based on the study scope and boundaries established. Both life cycle analysis and impact assessment were performed entirely in Microsoft Excel. This study addresses the specific concern of carbon dioxide equivalent emissions per lifetime generation in a representative floating offshore wind project located in federal waters off the state of California.

$$\frac{Life\ Cycle\ GHG\ Emissions\ (kg\ CO_2\ equivalent)}{Life\ Cycle\ Generation\ (MWh)} = kg\ CO_2\ equivalent\ per\ MWh$$

Baseline Parameters and Assumptions

Table 1. Baseline parameters used in the project's representative windfarm.

Turbine		**Remarks**
Hub height (m)	150	
Rotor diameter (m)	164	
Generation Capacity		
Generation capacity per turbine (MW)	8	
Turbines per site	75	
Total generation capacity (MW)	600	(Generation capacity per turbine x # of turbine)
Capacity factor	50%	
Effective total generation capacity (MW)	300	(Total generation capacity x Capacity factor)
Generation per turbine per year (MWh)	70,080	
Operational life – 25 years (Hours)	219,000	(Operation life (25 year) x 365 days/year x 24 hours/day)
Lifetime electricity generation (MWh)	65,700,000	(Effective total generation capacity (MW) x Operation life (hours))
Environment		
Distance from shore to project site (km)	35	
Water depth at project site (m)	450	
Average wind speed (m/s)	8	
Average wave height (m)	2.5	

Data Collection

The emissions factors per unit material and component production were derived from the Ecoinvent dataset.[29] Due to the uncertainty in the (national/international) sourcing of materials for the proposed offshore floating wind project, the Global [GLO] process was utilized as a baseline convention in this report. Rest of World [RoW] and Europe [RER] were also used where appropriate. IPCC 2013: Climate Change GWP 100a values were used for kg CO_2-Eq. TRACI values were also considered as they are based on IPCC values, but TRACI's update schedule is intermittent making IPCC values more reliable.[30] The Ecoinvent dataset pulls the IPCC values from the IPCC Emission Database.[31]

The factors were used for material requirements. Regression analysis was performed across multiple turbines to determine key material and equipment requirements for manufacturing.

Transportation emissions are calculated based on the shipping intensity or tonnes*km required for transoceanic shipping and truck transport.[32] Shipping routes and distances were calculated using a shipping map and route calculator.[33, 34] Installation emissions were calculated based on activities related to constructing a transmission network and the diesel burned from vessel transport and idling time during installation. Data regarding the fuel burned per hour for the fleet required were obtained from Raadal and Vold's report looking at six conceptual designs.[35]

Operations and maintenance data assumptions, including the frequency and time required for scheduled and major maintenance, turbine failure rates, and cable inspections, were determined through a literature review of previous LCAs and a market and technology review.[36, 37]

Decommissioning data was adapted from that collected for installation.

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[29] Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., and Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. *The International Journal of Life Cycle Assessment*, [online] 21(9), pp.1218–1230. http://link.springer.com/10.1007/s11367-016-1087-8.

[30] Discussion with Sangwon Suh 1/15.

[31] IPCC. "Emission Factor Database." Accessed February 29, 2019. https://www.ipcc-nggip.iges.or.jp/EFDB/downloads.php

[32] Yang, Juhua, Yuan Chang, Lixiao Zhang, Yan Hao, Qin Yan, and Changbo Wang. "The life-cycle energy and environmental emissions of a typical offshore wind farm in China." *Journal of Cleaner Production* 180 (2018): 316-324. https://www.sciencedirect.com/science/article/pii/S0959652618300969

[33] Dr. Jean-Paul Rodrigue."Main Maritime Shipping Routes - The Geography of Transport Systems." Accessed March 2, 2019. ept. of Global Studies & Geography, Hofstra University. https://transportgeography.org/wp-content/uploads/Map_Main-Maritime-Routes.pdf.

[34] "SEA-DISTANCES.ORG - Distances." Accessed March 2, 2019. https://sea-distances.org/.

[35] Raadal, Hanne Lerche, Bjørn Ivar Vold, Anders Myhr, and Tor Anders Nygaard. "GHG emissions and energy performance of offshore wind power." *Renewable energy* 66 (2014): 314-324. https://www.ostfoldforskning.no/media/1164/2412.pdf

[36] Raadal. "GHG emissions and energy performance of offshore wind power."

[37] James, Rhodri, and M. Costa Ros. "Floating offshore wind: market and technology review." *Carbon Trust: UK* (2015): 168. https://www.carbontrust.com/media/670664/floating-offshore-wind-market-technology-review.pdf

End-of-life cycle data from various previous LCAs reports and research papers regarding wind turbine recycling was used to determine recycling rates.

Survey

This project administered a survey to several wind turbine manufacturers and wind farm developers. The survey was developed after a literature review that included an examination of survey design techniques to extract the most information possible from professionals in the field. Results are shown in the Appendix along with the entire form of the survey. These results combined a review of currently existing technology and consultation with BOEM formed the basis of the initial parameters which established the baseline scenario.

Data Quality and Uncertainty

Cut-off Criteria

Streamlining may be used when defining the boundary conditions, identifying which stages of the process or product's life cycle will be considered and which will be assumed to be outside the scope of analysis. There are also two rules used to further streamline the scope, the five percent and one percent rules. The five percent rule allows for the elimination of a material from the analysis if it is ≤ 5% of the total product mass. The one percent rule allows for the elimination of an input if it is ≤ 1% of the total input mass. Materials or inputs with inherent toxicity are exceptions to these rules and must be included in the analysis regardless of their percent of total mass or inputs.[38]

Impact Category and Category Indicator: Global Warming Potential

Global warming is an average increase in the temperature of the atmosphere near the Earth's surface and in the troposphere. Contributing to changes in global climate patterns, global warming can occur from a variety of causes, both natural and human induced. In the context of this report, global warming refers to the warming that occurs as a result of increased emissions of GHG from human activities.

The Global Warming Potential (GWP), or, "the capacity of a greenhouse gas to influence radiative forcing, expressed in terms of a reference substance (for example, CO_2-equivalent units) and specified time horizon (e.g. GWP 20, GWP 100, GWP 500, for 20, 100, and 500 years respectively)."[39] This factor links the project's ability to influence global average surface-air temperature and other climate parameters. In our report we are analyzing the

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[38] Curran, Mary Ann. "Life cycle assessment: principles and practice National Risk Management Research Laboratory, Office of Research and Development." *US Environmental Protection Agency, Ohio* (2006).
[39] Manfredi, Simone, Karen Allacker, Kirana Chomkhamsri, Nathan Pelletier, Danielle Maia de Souza, and Action Leader. "Deliverable 2 and 4A of the Administrative Arrangement between DG Environment and the Joint Research Centre No N 070307/2009/552517, including Amendment No 1 from December 2010." (2012). http://ec.europa.eu/environment/eussd/pdf/footprint/PEF%20methodology%20final%20draft.pdf

environmental impacts based on Global Warming Potential on a 100-years time horizon (GWP 100).

To conduct a life cycle assessment (LCA) of the overall GHG emissions of a floating offshore wind project in California, our report measures the contribution to climate change in kilograms of carbon-dioxide-equivalent (kg CO_2-eq), which is the impact category used for our analysis. Our report is quantifying all environmental impacts of every life cycle stage of our theoretical floating offshore wind project in terms of kg CO_2-eq calculated using GWP-100 emission factors. This factor links the project's ability to influence global average surface-air temperature and other climate parameters on a 100-years time horizon.

The characterization factor used in this report is the IPCC-value for GWP-100 (IPCC 2013, Climate Change GWP-100a). This metric is the European Commission's standard Environmental Footprint unit for the Impact Category of Climate Change and is also used in The Bern model over a 100 year time horizon.

Life Cycle Inventory Analysis

Methodology for Baseline Wind Plant Assessed

The representative wind plant is based on the most advanced and commonly used technology as of 2018. Due to the emerging nature of floating wind technology, no single existing project specification could be adopted in California. Therefore, a combination of technologies were selected as a best fit for a current wind development in California's deep outer-continental shelf. Material weights, energy inputs, and other specifications were sourced primarily from publicly available manufacturer data.

Component and Process Descriptions

Using the Hywind Scotland project as a model, the figure below shows the individual components of a single representative turbine, substructure, and cabling. A detailed discussion of these components as well as other processes involved in the life cycle of the representative wind farm follows.

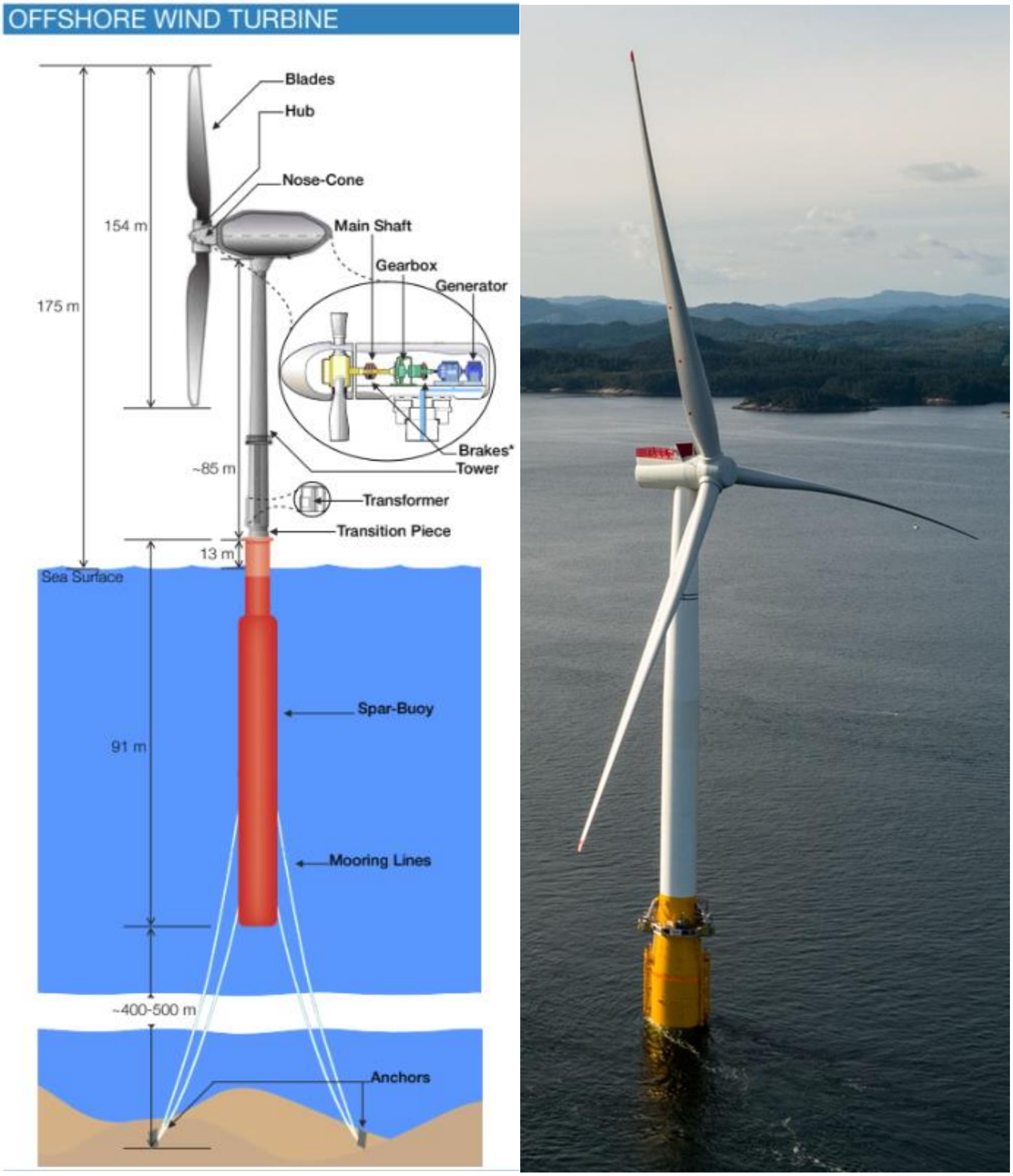

Figure 9. Original design of representative wind turbine, substructure, and mooring/anchoring system adapted from the Hywind Scotland commercial pilot park to deployment in federal waters off CA.[40]

[40] Helen Campbell. "Offshore Wind Moves Soar With Potential - Breakbulk Events & Media." Accessed March 2, 2019. http://www.breakbulk.com/mag518-offshore-wind-moves-soar-with-potential/.

Floating Substructure Manufacturing

The spar design floating substructure consists of a single steel column with a low center of gravity that increases stability, while maintaining buoyancy.[41] The design is typically smaller than the semi-submersible and hybrid substructures, which generally reduces manufacturing costs. Since a large portion of the column is underwater, installation and maintenance is generally more complicated near shallow waters, and turbine installation must take place away from the local staging port. With a diameter of up to 15 meters and plate thickness of up to 130 millimeters, a single substructure contains a total of 1,700 to 2,500 tonnes.[42] The high end of 2,500 tonnes was used in LCA calculations. A single ballast tank is included in the submerged end of each substructure, to provide stability. The ballast is a combination of sea water and solid weight, which is typically made of concrete or iron ore. Although ballast specifications vary by the unique installation site characteristics, the Hywind Scotland project utilized a range of 5,000 to 7,000 tons of solid mass per substructure, which was used as a benchmark for LCA calculations.[43] The high end of 7,000 tons concrete was assumed in calculations for conservatism, as concrete generally has a larger CO_2-equivalent life cycle emission impact.

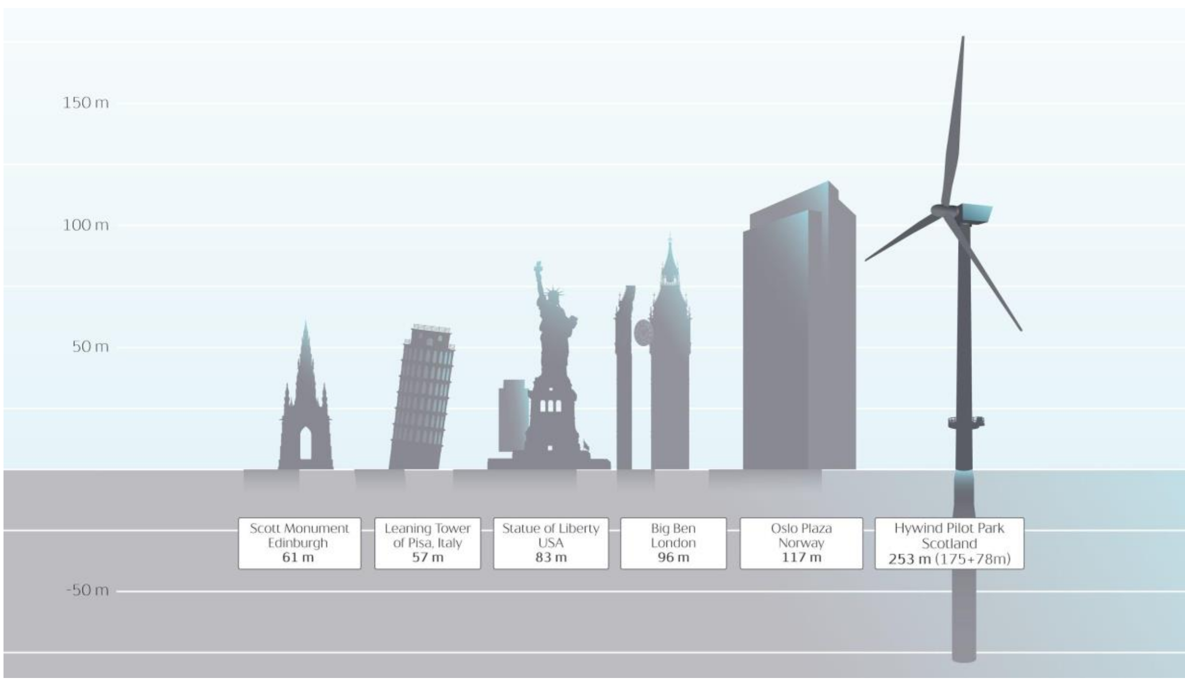

Figure 10. Size comparison of Hywind Scotland floating offshore wind turbine and substructure with world landmarks.[44]

[41] James, Rhodri, and M. Costa Ros. "Floating offshore wind: market and technology review." *Carbon Trust: UK* (2015): 168. https://www.carbontrust.com/media/670664/floating-offshore-wind-market-technology-review.pdf

[42] "Statoil-Environmental Statement April 2015 - Equinor." Accessed March 2, 2019. https://www.equinor.com/content/dam/statoil/documents/impact-assessment/Hywind/Statoil-Environmental%20Statement%20April%202015.pdf.

[43] Statoil-Environmental Statement April 2015 - Equinor

[44] Energy Voice. "Statoil-hywind-comparison." Accessed March 2, 2019. https://www.energyvoice.com/wp-content/uploads/sites/4/2017/10/Statoil-hywind-comparison.jpg.

Mooring Lines

Catenary style mooring lines are the most common system for offshore floating wind developments. Combined with a spar substructure, mooring consists of three lines curving from the foundation structure to the sea floor.[45] The spread results in a larger total footprint of the structure, as well as segments that lie on the seafloor. As a commonly used convention, the ocean depth to catenary line length represents a 1:6 ratio. Based on product specifications, industry prominence, and expected capacity to supply a California project of unprecedented size, the GAMA 98 polyester rope from Lankhorst was selected. The specific product model is utilized for a high minimum breaking force. At the highest end for strength and size, the rope weighs 56.9 to 59.2 kilograms per meter, out of the water.[46,47] The high end of 59.2 kilograms per meter was used in LCA calculations. Although steel chains are utilized in most current floating offshore wind developments, the significantly deeper application depth at a California site would require synthetic mooring for economic feasibility and practicality for installation and decommissioning.

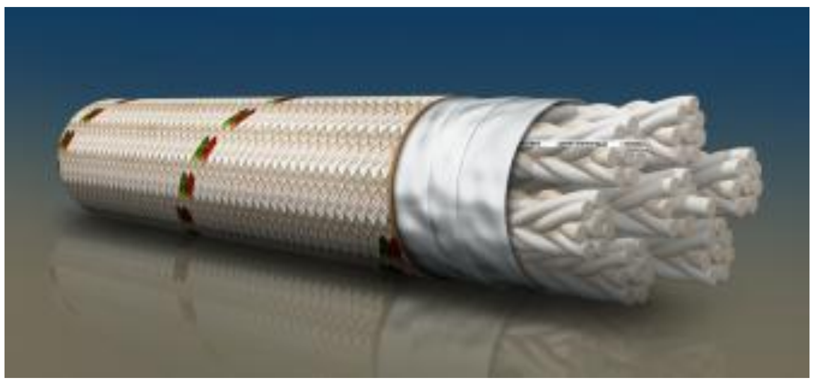

Figure 11. Manufactured by Lankhorst Offshore, GAMA 98 polyester ropes are made from high efficiency subrope cores laid parallel within an outer braided jacket. Each rope typically include 7 to 18 sub-ropes that result in a torque-free mooring line.[48]

Anchors

Anchor specifications depend highly on the ocean floor substrate at the installation site. As drag-embedded anchors generally have the widest applicability, they were determined reasonable for LCA calculations. Vryhof Anchors are currently the most deployed in global floating offshore developments, so the manufacturer could reasonably be expected to supply a California project.[49] Furthermore, the company supplied anchors for Hywind Scotland, the commercial pilot park on which material requirements are based. Due to existing application and highest end size, the Vryhof Stevpris Mk6 anchor was modelled,

[45] "Statoil-Environmental Statement April 2015 - Equinor."
[46] "GAMA 98 - Lankhorst Ropes." Accessed March 2, 2019. http://www.lankhorstoffshore.com/Offshore/deepwatermooring/products_deepwatermooringropes/GAMA98.
[47] Lankhorst Ropes. Lankhorst Brazil Factory Begins Production. Accessed February 28, 2019. http://www.lankhorstoffshore.com/Offshore/news_media/news_offshore/page_9/Lankhorst-Brazil-Factory-Begins-Production
[48] "GAMA 98 - Lankhorst Ropes." Accessed March 2, 2019.
[49] Quest floating wind energy. "Q FWE Current Project Sheets", Version August 2018.

with a weight per anchor of 30 tons.[50] Based on the Hywind Scotland specifications, a single anchor per mooring line was used, for a total of three anchors per substructure.

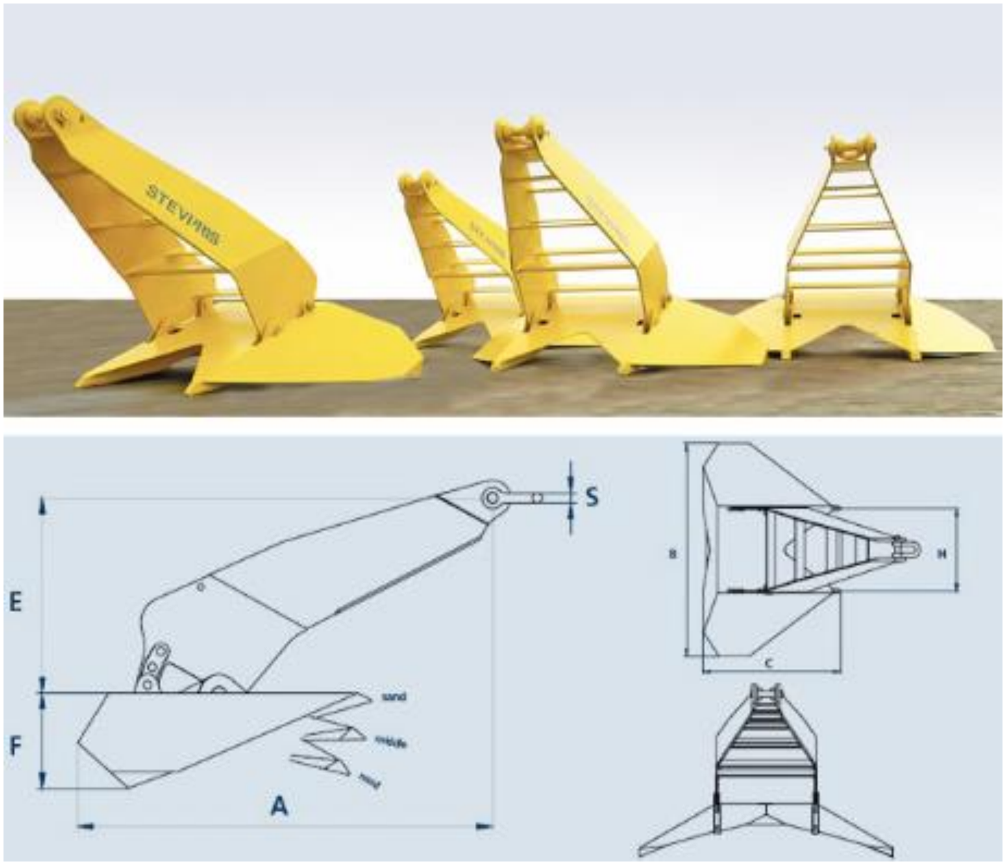

Figure 12. Anchor geometry provides an extremely high weight/strength ratio. The fluke shape minimizes soil disturbance during penetration and its enlarged surface provides holding power. The fluke width provides stability both on the seabed and during penetration.[51]

Turbine Manufacturing

A wind turbine consists of several major parts including the tower, nacelle, hub and blades. Nacelle is the most complicated part of a wind turbine, housing many electrical and mechanical components such as the gear box, main shaft, generator, and control systems as in the figure below.[52]

[50] "Vryhof Anchors - Products - Anchors: Stevpris Mk6." Accessed March 2, 2019. http://www.vryhof.com/products/anchors/stevpris_mk6.html.

[51] "Vryhof Anchors - Products - Anchors: Stevpris Mk6." Accessed March 2, 2019. http://www.vryhof.com/products/anchors/stevpris_mk6.html

[52] Vestas, (2017). "Life Cycle Assessment of Electricity Production from an onshore V136-3.45 MW Wind Plant." Vestas Wind Systems (2017). https://www.vestas.com/~/media/vestas/about/sustainability/pdfs/v1363%2045mw_mk3a_iso_lca_final_31072017.pdf.

Figure 13. Nacelle and interior components (gear box, main shaft, generator, and control systems).

There is not significant difference in design between onshore wind turbines and offshore wind turbines except foundation types. Offshore wind turbines are usually designed with scaling up onshore wind turbines to achieve greater generation capacity.

CO_2-equivalent emissions from turbine manufacturing are calculated based on the mass of materials and the ecoinvent process database. To determine the mass of materials of turbine in this study, the upscaling of the mass of materials of turbine models previously studied is applied based on the rotor diameter. A previous study shows that there are strong proportional relationship in terms of size between the rotor diameter and other turbine components including blades, tower, and nacelle.[53] Data of the mass of materials was collected from 8 turbine models including 6 onshore wind turbine models of Vestas and 2 offshore wind turbine models of Yang et al. (2018).[54, 55]

Table 2. Manufacturing materials of wind turbines previously studied.

Manufacturer	**Vestas**						**Sinovel**	
Turbine model	V90-3MW	V105-3.45MW	V112-3.45MW	V117-3.45MW	V126-3.45MW	V136-3.45MW	SL3000 3.6MW	SL3000 5MW
Generation Capacity(MW)	3	3.6	5	3.45	3.45	3.45	3.45	3.45
Rotor diameter (m)	88	105	112	117	126	136	116	126

[53] de Lara Garcıa, J. S. "Wind turbine database: Modelling and analysis with focus on upscaling." PhD diss., Master's thesis, Department of Applied Mechanics, Chalmers University of Technology, 2013. http://publications.lib.chalmers.se/records/fulltext/179591/179591.pdf
[54] "Vestas |Sustainability." Accessed March 2, 2019. https://www.vestas.com/en/about/sustainability#!available-reports.
[55] Yang, Juhua, Yuan Chang, Lixiao Zhang, Yan Hao, Qin Yan, and Changbo Wang. "The life-cycle energy and environmental emissions of a typical offshore wind farm in China." *Journal of Cleaner Production* 180 (2018): 316-324. https://www.sciencedirect.com/science/article/pii/S0959652618300969.

Mass of materials (Tonnes)								
Steel	192.4	231.3	311.7	304.8	398.1	465.3	407.9	495.3
Iron	32.6	70.1	70.1	70.1	72.1	71.9	78.3	118.8
Aluminum	1.7	4.5	4.5	5.5	7.0	7.6	0.0	0.0
Nonferrous heavy metal (Copper)	2.7	3.2	3.2	3.1	3.2	3.3	5.2	9.6
Polymer materials	8.7	16.0	16.7	17.3	18.3	21.3	0.0	0.0
Process polymers	1.2	0.7	0.7	0.7	0.5	0.9	0.0	0.0
Other materials and material compounds	12.6	25.9	26.2	28.8	25.8	24.8	216.0	242.0
Electronics / electrics	1.7	3.1	3.3	3.3	3.4	3.7	0.0	0.0
Lubricants and liquids	1.2	1.9	1.9	1.9	1.9	1.9	0.0	0.0
Not specified	1.6	0.2	0.2	0.1	0.1	0.1	0.0	0.0
Total	256.4	356.9	438.5	435.6	530.4	600.8	707.4	865.7

Simple linear regression analysis is conducted for the mass of each material of those 8 turbine models and the size of the rotor diameter with the following model.

Mass of material (tonnes) = α (The size of rotor diameter) + β

Table 3. Linear regression model and Chi-test results for manufacturing materials of wind turbine.

Material	α	β	p-value	Projected mass for this study
Steel	6.6173	-415.1066	**0.000**	**643.7**
Iron	1.0504	-48.5750	**0.000**	**119.5**
Lights alloys, cast and wrought alloys	0.0785	-5.2417	0.096	7.3
Nonferrous heavy metals, cast and wrought alloys	0.0540	-2.0400	0.441	6.6
Polymer materials	0.1088	-0.3020	**0.000**	**17.1**
Process polymers	-0.0132	2.1253	0.946	0.0
Other materials and material compounds	1.7153	-123.2976	**0.000**	**151.2**
Electronics / electrics	0.0138	0.7050	0.441	2.9
Lubricants and liquids	-0.0008	1.4035	0.804	1.3
Not specified	-0.0280	3.5265	Not available	-1.0

Though simple linear modeling would not fit every material, the model works well for major materials. Chi-test shows less than 0.0001 of p-value for steel, iron, polymer materials, and other materials and material compounds.

Substation Manufacturing

In this study, one floating offshore substation is assumed to support up-to 1000 MVA. A substation is assumed to consist of two ABB's transformers whose model name is Trafostar 500MVA. To determine the mass of materials and the energy use of transformer manufacturing in this study, the upscaling of the mass of materials and the energy use of one transformer previously studied is applied based on the number of transformers installed. Data of the mass of materials was collected from ABB's report of Environmental Product Declaration as below.[56]

Table 4. Manufacturing materials and energy for ABB's transformer (TrafoStar 500MVA).

ABB TrafoStar 500 MVA - Manufacturing materials and energy		Per Transformer
	Transformer oil (ton)	63
	Copper (ton)	39.96
	Insulation materials (ton)	6.5
	Wood (ton)	15
	Porcelain (ton)	2.65
	Electrical steel (ton)	99.64
	Construction steel (ton)	53.62
	Paint (ton)	22
Materials	Other (ton)	83
	Electrical energy (MWh)	750
Energy	Heat energy (MWh)	300

Inter-Array and Export Cable Manufacturing

CO_2-equivalent emissions from turbine manufacturing are calculated based on the mass of materials and the ecoinvent process database. To determine the mass of materials of turbine in this study, the following layout are assumed for 75 wind turbines. Spacing

[56] Transmission, ABB Power. *Environmental Product Declaration: Power transformer TrafoStar 500 MVA*. Technical Report]. Ludvika, Sweeden, 2003. http://search.abb.com/Library/Download.aspx?DocumentID=SEEPD_TPT_TrafoStar0001_1&LanguageCode=en&DocumentPartId=&Action=Launch

between turbines and rows are assumed based on the previous research conducted by the National Renewable Energy Laboratory (NREL).[57] The previous research indicated that spacing between turbines in a column would be 5 to 10 times of rotor diameters and spacing between columns would be 7 to 12 times of rotor diameters. In this study, 10 columns of turbines are assumed, 8 times of rotor diameter is assumed for spacing between turbines in a column, and 10 times of rotor diameter is assumed for spacing between columns. Spacing between wind farm and substation is assumed twice as much as spacing between columns. Based on the assumed layout, the length of inter-array cables is calculated. To be conservative, two times of water depth is added to the distance between every two turbines to calculate the length of required cable connecting turbines. The same calculation method is applied between turbines and substation, and between a substation and the shore. Based on these assumptions, the required cable length is calculated as 189 km for inter-array and 35.9 km for export to the shore.

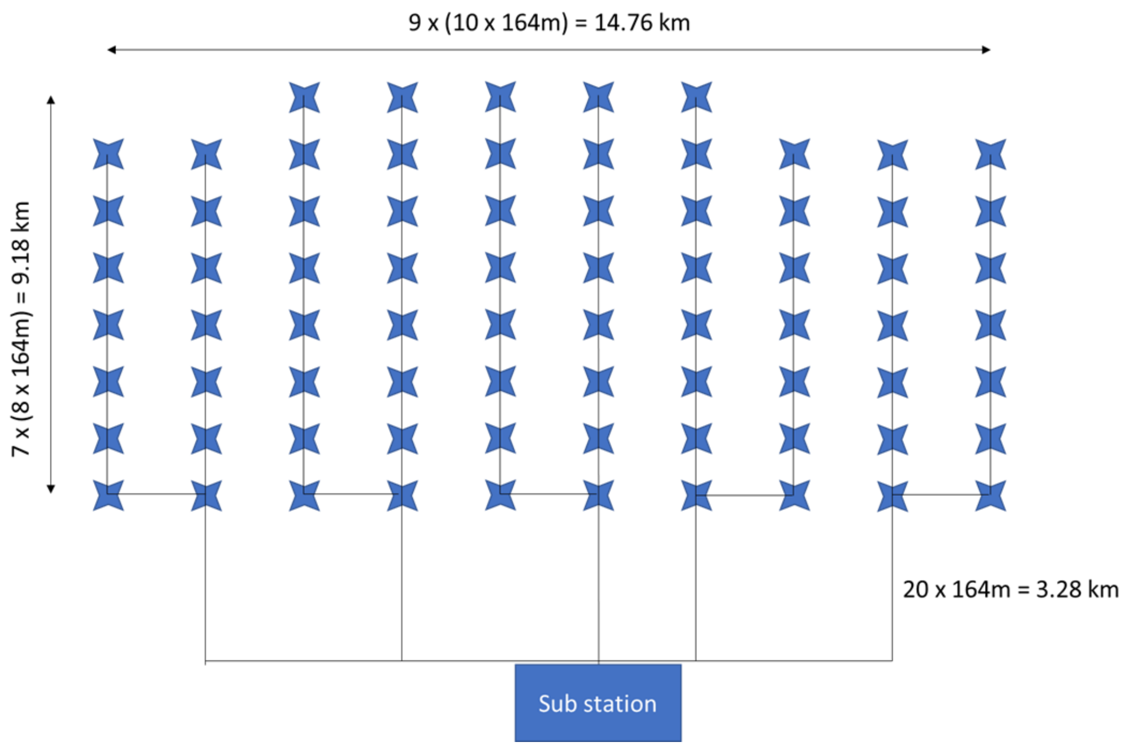

Figure 14. Example cable array.

[57] "Offshore Wind Plant Electrical Systems - BOEM." Accessed March 2, 2019. https://www.boem.gov/NREL-Offshore-Wind-Plant-Electrical-Systems/.

In this study, the following submarine cable data is used to calculate the mass of cable.

Table 5. Material breakdown of submarine cable.[58]

Material	Mass (Tonne per km)
Copper	8.12
PE (Polyethylene)	2.29
PP (Polypropene)	1.54
Lead	9.65
Steel	14.41

Transportation

Transportation emissions are calculated using two Ecoinvent processes (transport freight sea transoceanic ship and transport freight lorry >32 metric ton EURO3). Emissions from these processes are based on the mass of components and the distance travelled from manufacturing origin to the installation port (i.e., tonnes*km). As characteristic ships and shipping conditions are used in these processes, speed is not a required input although it can impact fuel consumption rate.[59]

Assumptions about components sourcing are based on current literature review and data collection as well as research into the organizations assisting in the Hywind project.[60, 61] Components are assumed to be shipped either via transoceanic ship or commercial trucking. Distances were calculated with a shipping route calculator.[62]

CO_2-emissions from transportation of materials to recycling facilities are assumed to be negligible so End-of-Life transportation was not included in this analysis. In addition, assumptions about specific manufacturing facilities and transport to respective ports is not included. Generally, components shipped from Europe are assumed to be shipped from Rotterdam, NL.

Table *6* below shows the assumptions for each transported item, including transport method and distance. Given these assumptions, the resulting Tonnes*Km can be multiplied by the respective Ecoinvent process to determine each component's respective contribution to transportation CO_2 emissions.

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[58] Yang, Juhua, Yuan Chang, Lixiao Zhang, Yan Hao, Qin Yan, and Changbo Wang. "The life-cycle energy and environmental emissions of a typical offshore wind farm in China." *Journal of Cleaner Production* 180 (2018): 316-324. https://www.sciencedirect.com/science/article/pii/S0959652618300969

[59] Spielmann, M., C. Bauer, R. Dones, and M. Tuchschmid. "Transport services: Ecoinvent report no. 14." Swiss Centre for Life Cycle Inventories, Dübendorf (2007). https://db.ecoinvent.org/reports/14_transport.pdf

[60] Hamilton, Bruce Duncan. US Offshore Wind Manufacturing and Supply Chain Development. No. DE-EE0005364. Navigant Consulting, Inc., 2013. https://www1.eere.energy.gov/wind/pdfs/us_offshore_wind_supply_chain_and_manufacturing_development.pdf

[61] 4C Offshore. "Organisations working on Hywind Scotland Pilot Park." Accessed February 28, 2019. https://www.4coffshore.com/windfarms/contracts-on-hywind-scotland-pilot-park-uk76.html

[62] Sea-Distances.org. "Distances." Accessed February 28, 2019. https://sea-distances.org/

Table 6. Component, transportation assumptions, resulting Tonnes * Km, and % contribution of each component to transportation emissions.

Component	Method	KM	Tonnes * KM	Contribution	Transport Notes
Turbine	Ship	15,336	1,151,918,185	21%	Rotterdam to Humboldt through Panama Canal
Transition Piece	Ship	15,336	170,234,173	3%	Rotterdam to Humboldt through Panama Canal
Substructure (Steel)	Ship	15,336	2,952,259,310	55%	Rotterdam to Humboldt through Panama Canal
Anchors	Ship	15,336	104,901,058	2%	Rotterdam to Humboldt through Panama Canal
Mooring Line	Ship	14,308	557,431,382	10%	Rio de Janeiro to Humboldt through Panama Canal
Substation	Ship	15,336	11,820,386	0%	Rotterdam to Humboldt through Panama Canal
Cable Array	Ship	15,336	104,538,096	2%	Rotterdam to Humboldt through Panama Canal
Cable Export	Ship	15,336	19,827,333	0%	Rotterdam to Humboldt through Panama Canal
Substructure (Concrete)	Truck	556	299,468,400	6%	Sacramento to Humboldt

Installation

Installation activities consist of laying the cabling, towing the foundations and turbines out to the site, and assembling the final units. Emissions are based on fuel consumption during this process which was calculated based on the assumed fleet required, time-based fleet fuel consumption parameters, and time requirements based on the assumed installation process.

The installation process occurs as follows:

- Cables are laid with trenching ships.
- Foundations are towed to site, installed, and stabilized with Anchor Handling Tug Supplies (AHTS).
- One Power Supply Vessel (PSV) transports the turbines offshore.
- One offshore crane (the Saipem 7000) installs the turbines with support of an AHTS.

Emissions from cable laying are calculated by multiplying the required length of cabling (in kilometers) by the ecoinvent process for transmission network construction for high voltage electricity. In addition, emissions from the fuel consumption of a trenching ship are included.

Emissions from towing the foundations and turbines as well as assembling the final units were calculated based on the fuel consumption related to these activities. Assumptions include:

- 3 Anchor Handling Tug Supplies (AHTS) transport the foundations/platforms to site.
  - ~4 hours for towing the foundation, 1.3 hours for return, and 2 hours for preparations and loading.
  - Two foundations are towed at a time.
- One AHTS is used to supporting the PSV towing process and the crane vessel.
  - ~3 hours of transport and 60 hours for unloading
  - 12 hours on for each turbine to support the S7000.
- One Power Supply Vessel (PSV) transports the turbines to site.
  - ~3 hours of transport, 12 hours for loading, and 60 hours for unloading.
  - Three turbines are transported at a time.
- One offshore crane vessel (S7000) installs the turbines while being supported by one AHTS.
  - Each turbine takes 10 hours and it takes another 4 hours transition between turbines.
  - 2 turbines can be installed each day.

Operations and Maintenance

Operations and maintenance activities consist of scheduled maintenance, major maintenance, cable servicing, and replacement parts.

Similar to the installation emissions, fuel consumption was calculated based on the assumed fleet required, time-based fleet fuel consumption parameters, and time requirements. Emissions from scheduled maintenance, major maintenance, and cable servicing are based on fuel consumption.

Emissions of replacement parts are calculated based on failure rates from the literature review.[63] These rates determine the percent of turbines and substructures that fail over the life of the project. This percent failure rate is multiplied by the emissions generated from each component part to determine emissions from replacement parts.

In addition to replacement part emissions, fuel consumption emissions from operations and maintenance were calculated based on the following assumptions:

- Scheduled Maintenance: 2 visits a year with 3 turbines serviced a day.
  - Fuel consumption for each trip consists of trip out as well as 3 hours of idling time for both a small boat and helicopter.
- Major Maintenance: 5% of turbines require major maintenance each year with 1 turbine being serviced each day.

[63] Lysne Sanden, Inghild, and Bjørn Ivar Vold. "Life cycle analysis of floating wind turbines with regard to internal and external factors compared with bottom-fixed wind turbines." Master's thesis, 2010. https://brage.bibsys.no/xmlui/handle/11250/188652

    - Fuel consumption for each trip consists of trip out as well as 3 hours of idling time for a specialized vessel and a crane vessel.
- Cable Servicing: It is assumed 1 kilometer of cable can be inspected each hour and cables must be inspected every 2 years.
    - Fuel consumption for each trip consists of fuel burned by a specialized vessel as well as a Remotely Operated Vehicle (ROV) which is estimated by the machine operation diesel >= 74.57 kW underground mining Ecoinvent process.

Decommissioning

Decommissioning is assumed to be a reflection of installation. However, in decommissioning the fuel requirement for the trenching ship is omitted.

End of Life (EOL) Treatment

An LCA of any class of energy supply needs to take into account the entire life cycle and linked environmental impacts to be equally comparable. If floating offshore wind is set to remain as a sustainable alternative, it is essential that the materials and components involved be optimally managed from the extraction of natural resources, manufacturing, and installation, through operation and maintenance, until decommissioning and end of life treatment, which would be considered as either recycling, landfill, or incineration.

Wind power is one of the fastest growing energy sources in the world.[64] The total world's energy wind generation in 2014 was 296 GW, and in 2018 wind generation jumped to 539 GW, meaning it almost doubled in a matter of four years.[65] According to research papers, the mean recyclability of a modern wind turbine's mass, not taking into account the substructure, is estimated to be 80%.[66, 67] As floating offshore wind energy is a relatively new technology, research and analyses on the recyclability of these projects are scarce. Previous LCAs on offshore wind suggest that the recyclability in these type of wind energy is even higher, because of the retrievability of the substructure of offshore wind turbines. Some offshore wind projects use floating substructures, which is even easier to retrieve, decommission and recycle. The quantity of material that is being put out there to increase the global wind energy capacity, and the high recyclability nature of these projects, make it indispensable to include the end of life treatment on an LCA of a floating offshore wind energy project.

Based on the review of previous LCAs on onshore and offshore wind projects, our proposed end of life process is described in the following diagram:

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[64] Global Energy Council. “Global Wind Statistics.” Accessed February 28, 2019. https://gwec.net/global-figures/graphs/

[65] World Wind Energy Association. “Total Installed Capacity 2012-2018.” Accessed February 28, 2019. http://wwindea.org/information-2/information/

[66] Andersen, Niklas, Ola Eriksson, Karl Hillman, and Marita Wallhagen. *Wind Turbines’ End-of-Life: Quantification and Characterisation of Future Waste Materials on a National Level,* (*Energies* 9, 12, 2016). http://mdpi.com/journal/energies

[67] Ortegon, Katherine, Loring F. Nies, John W. Sutherland. “Preparing for end of service life of wind turbines*”.* J*ournal of Cleaner Production*, 39 (2013): 191-199.

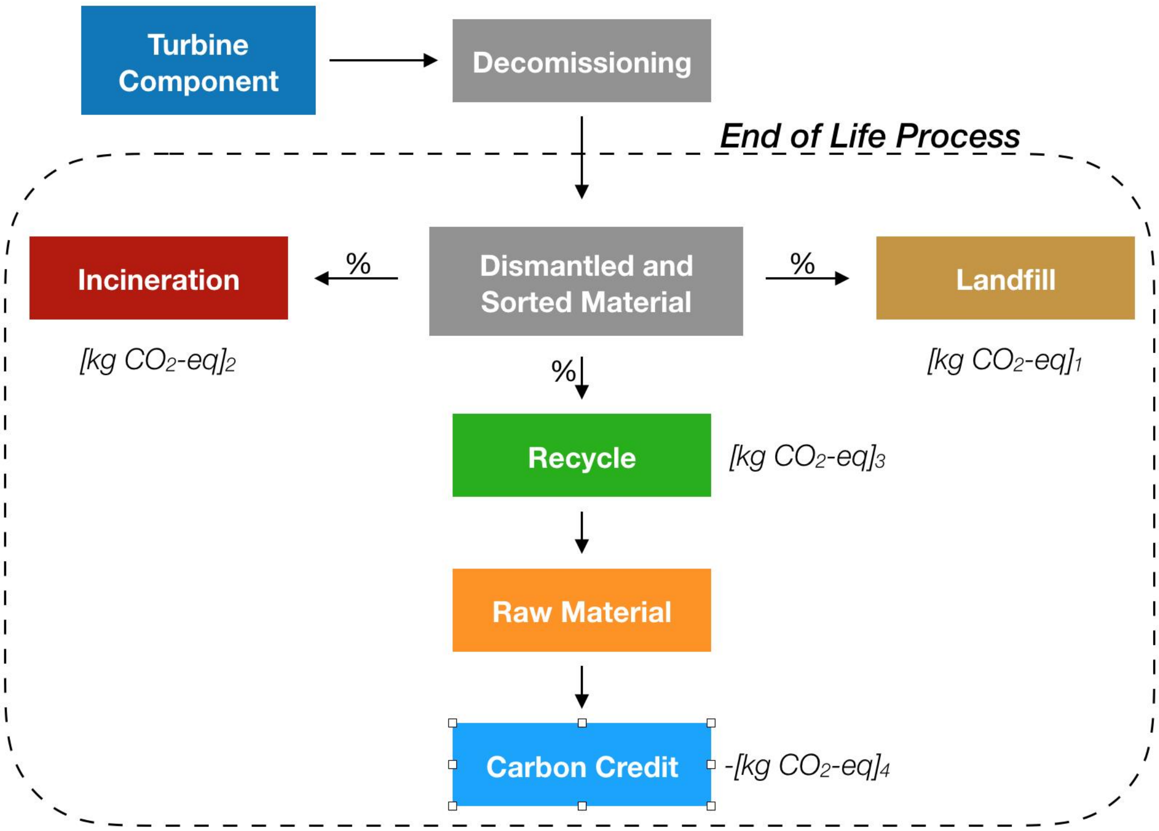

Figure 15. End of Life Process Diagram.

The process depicted in Figure 15 consists basically on the landfilling, incineration, and recycling of the material obtained after the dismantling and sorting of the decommissioned specific turbine component. After each turbine component is dismantled, a certain percentage of the material is going to be directed to either of the three processes mentioned before. The percentages are determined by the nature of the material, and the recyclability of the components. In our LCA analysis, we account for the carbon intensive process of incinerating, landfilling, and recycling, at the same time that we account for the carbon credit that would be obtained after putting back into the market the raw material obtained after recycling. On the next section, our analysis is going to define the most likely scenario for each material found in the decommissioning of our proposed floating offshore wind project, and explain the LCA process behind the end of life treatment of the project.

Recycling, Incineration, and Landfilling Ratios

At the end of life of its useful life, the wind plants components are transported back to shore and dismantled. The waste management options analyzed include: recycling, deposition to landfill, and incineration with energy recovery in some cases. The LCA model for disposal of the project accounts for the specific recycling rates of different components depending of the major material they are built from, material purity, eased on disassembly, based on previous research and LCA literature.[68,69,70,71,72,73]

The end of life treatment of the turbine is extensive and detailed. It is assumed that the entire turbine and floating substructure is transported back to shore and dismantled. The transport and dismantling process is assumed to be the same as the portion of transportation from shore to project plus installation. The entire turbine is not treated homogeneously; as further detailed in the table below:

Table 7. Recycling, Incineration, and Landfilling Ratios.

Recycling, Incineration, and Landfilling Ratios					
Material	**Recycled**	**Landfilled**	**Incinerated**	**Energy Recover**	**Credited As**
Steel	90%	10%	0%	No	Scrap Steel
Iron	90%	10%	0%	No	Scrap Iron
Aluminum	90%	10%	0%	No	Aluminium Ingot Mix
Copper	90%	10%	0%	No	Copper Mix
Lead	90%	10%	0%	No	Scrap Lead
Zinc	90%	10%	0%	No	Scrap Zinc
Polymers	0%	10%	90%	No	Waste to Energy
Other Plastics	0%	0%	100%	Yes	Waste to Energy
Glass Fiber	0%	0%	100%	Yes	Waste to Energy
Lubricants	0%	0%	100%	Yes	Waste to Energy
Cables	66%	0%	34%	Yes	Waste to Energy
Mooring Cable	0%	0%	100%	Yes	Waste to Energy

[68] Cherrington, R., V. Goodship, J. Meredith, et al. “Producer responsibility: Defining the incentive for recycling composite wind turbine blades in Europe”. *Energy Policy* 47 (2012): 13-31.
[69] Vestas. “Life cycle assessment of offshore and onshore sited wind power plants based on Vestas V90-3.0MW turbines”. Vestas Wind Systems A/S (2006).
[70] Raadal, Hanne Lerche, Bjørn Ivar Vold, Anders Myhr, and Tor Anders Nygaard. "GHG emissions and energy performance of offshore wind power." *Renewable energy* 66 (2014): 314-324. https://www.ostfoldforskning.no/media/1164/2412.pdf
[71]Bonou, Alexandra, Alexis Laurent, and Stig I. Olsen. "Life cycle assessment of onshore and offshore wind energy-from theory to application." Applied energy 180 (2016): 327-337. https://www.sciencedirect.com/science/article/pii/S0306261916309990?via%3Dihub
[72] Weinzettel, Jan, Marte Reenaas, Christian Solli, and Edgar G. Hertwich. "Life cycle assessment of a floating offshore wind turbine." *Renewable Energy* 34, no. 3 (2009): 742-747. https://www.sciencedirect.com/science/article/pii/S0960148108001754
[73] Elsam. “Life Cycle Assessment of offshore and onshore sited wind farms”. Vestas Wind Systems A/S, (2004).

Concrete	70%	30%	0%	No	Concrete Aggregate
All Other Materials	0%	100%	0%	No	None

The materials mentioned in the table accounts for the major materials used on the entirety of the project. Any other materials obtained from the dismantling process of the wind turbine array, is assumed to be totally landfilled.

LCA Process Behind End of Life (EOL) Treatment

Using Table 7 described in the previous section, it can be calculated the amount of material that would be destined to landfill, recycling, and incineration at the end of the life cycle of the offshore wind project. Once obtained the total weight destined to each of the three processes, the following LCA process diagram is used to obtain the kg CO_2-eq that would be generated by each process:

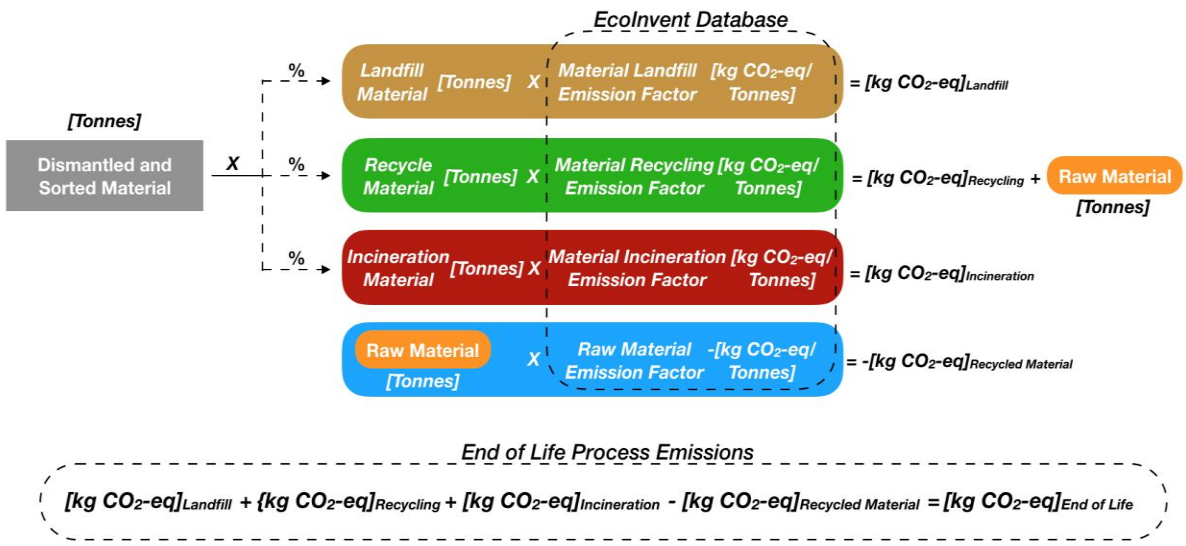

Figure 16. LCA Process Flow of End of Life (EOL) Treatment.

In Figure *16*, the diagram describes the process flow once obtained the total weight after dismantling every turbine component. It has to be noted that landfill, recycling, and incineration are carbon-intensive processes, which emission factors are retrieved from the EcoInvent Database. The material obtained after going through the recycling process is assumed that would be placed back into the market. The quality of the recycled material is expected to be lower quality than the material put into recycling. Table *7* specifies how the recycled product should be credited. As a result, the emission factors retrieved to calculate the avoided emissions by putting back recycling material into the market will always be lower than the emission factor used to calculate the emissions of the materials at the beginning of the life cycle.

The total end of life (EOL) treatment emissions would be the sum of each of the EOL processes' emissions, and the subtraction of the "avoided" emissions of putting back into the market the recycled product material. Such equation is clearly described in Figure *16*.

Results

General Results

The model predicts GHG emissions of ~15.35 kg CO_2-eq/MWh with an uncertainty range of 8.58 - 30.17 kg CO_2-eq/MWh. This result is in the range of previous LCA studies of wind energy (uncertainty and comparison to previous LCA studies discussed in more detail below).

The figure below shows the contribution to GWP by life cycle stage: manufacturing (18.3 kg CO_2-eq/MWh), transportation (1.3), installation (1.1), operation and maintenance (2.7), decommissioning (1.1), end of life (-9.2), and the Total contribution (15.35).

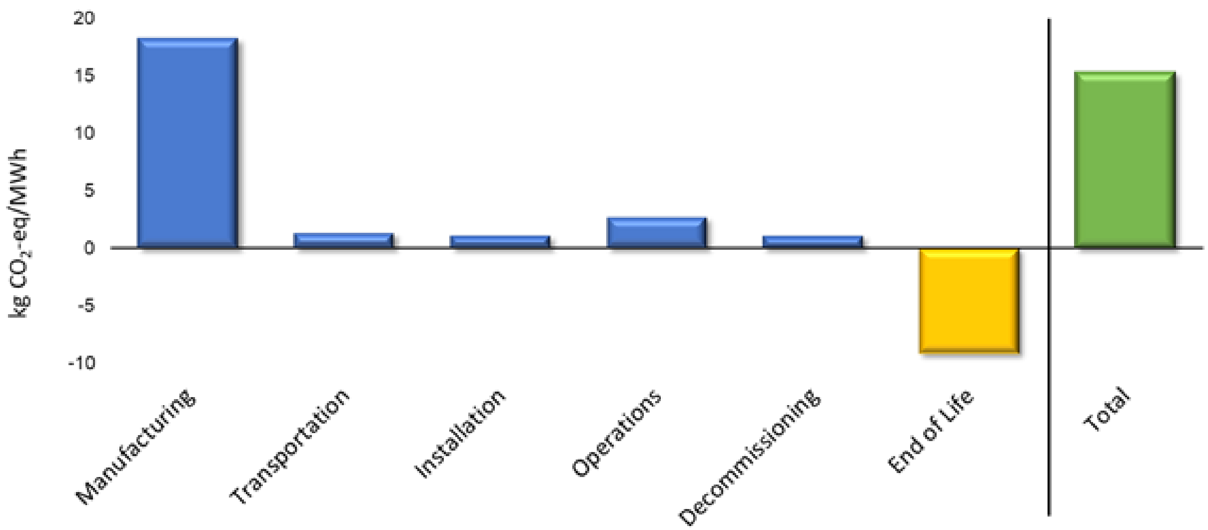

Figure 17. Contribution to GWP by Life Cycle Stage.

Impacts by Component and Material

Figure 18 shows the potential impacts of global warming per MWh of electricity produced by the wind farm by manufacturing component which dominates the life cycle. The production of the substructure (41%), turbine (36%), and mooring and anchoring (19%) are the primary components contributing to this impact category.

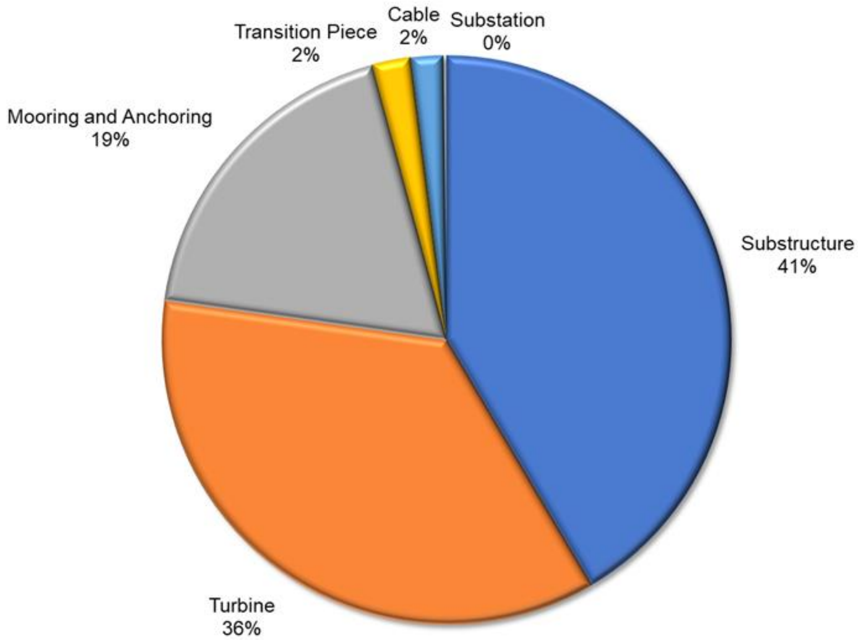

Figure 18. Contribution to GWP by manufacturing component. The sum of the Turbine, Transition Piece, Substructure, Mooring and Anchoring, Substation, and Cable constitute Manufacturing.

The figure below shows the contribution of the materials of the representative wind farm. Steel is the main contributor (49% of material emissions). This is followed by fossil fuels which is mostly diesel and hard coal (27%), Polymer Materials which is mostly composed of synthetic mooring rope (15%), and then other metals (4%), concrete (3%), and electronics (2%).

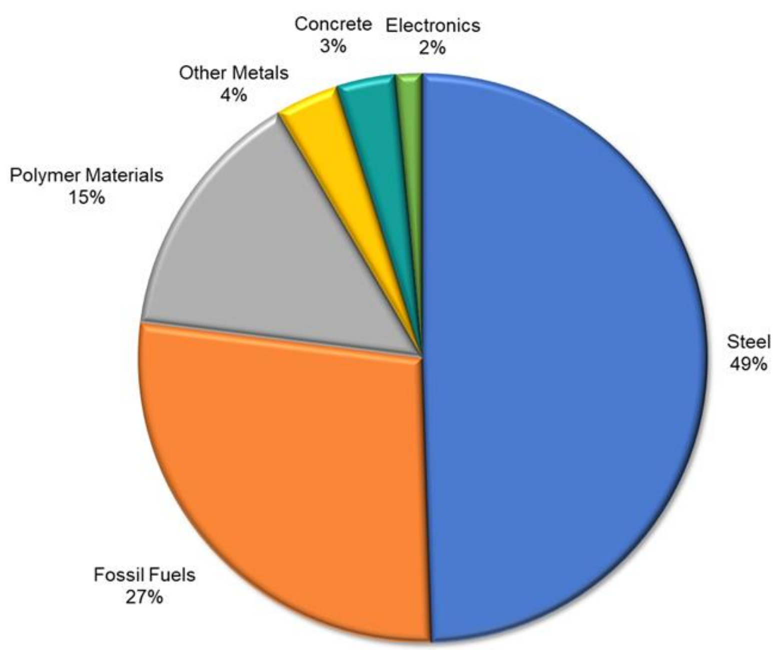

Figure 19. Contribution to GWP by Material.

Uncertainty

There is inherent uncertainty in some of the parameters of importance above which could influence the actual GWP. For example, the actual capacity factor is not known and will fluctuate by year and the actual failure rate of turbines over the life of the project is not known. These factors can greatly influence GHG emissions.

To quantify how this uncertainty impacts our GHG emissions result, a Monte Carlo simulation was performed using the software program @Risk. Input parameter ranges were chosen to be conservative, but are still within realistic ranges for each parameter. The simulation ran 1000 iterations. Ranges for input parameters include:

- Capacity Factor: uniform distribution from 35-65%
- Distance From Shore: uniform distribution from 30-100 kilometers.
- Operational Life: uniform distribution 20-35 years.
- Water Depth: triangular distribution 300-500-1000 meters.
- Transportation of Major Components: uniform distribution 5000-20000 km.
- Installation Operational Factor: uniform distribution 40-80%.
- Scheduled Maintenance Visits a Year: discrete distribution 1-3 visits per year.
- Major Maintenance Requirement: uniform distribution 2-15% of turbines per year.
- Turbine Failure and Replacement Requirement: uniform distribution 2-10% a year.

Results of the simulation are presented in Figure 20 below. The simulation results had a right skew with possible emissions reaching a maximum of 30.2 kg CO_2/MWh.

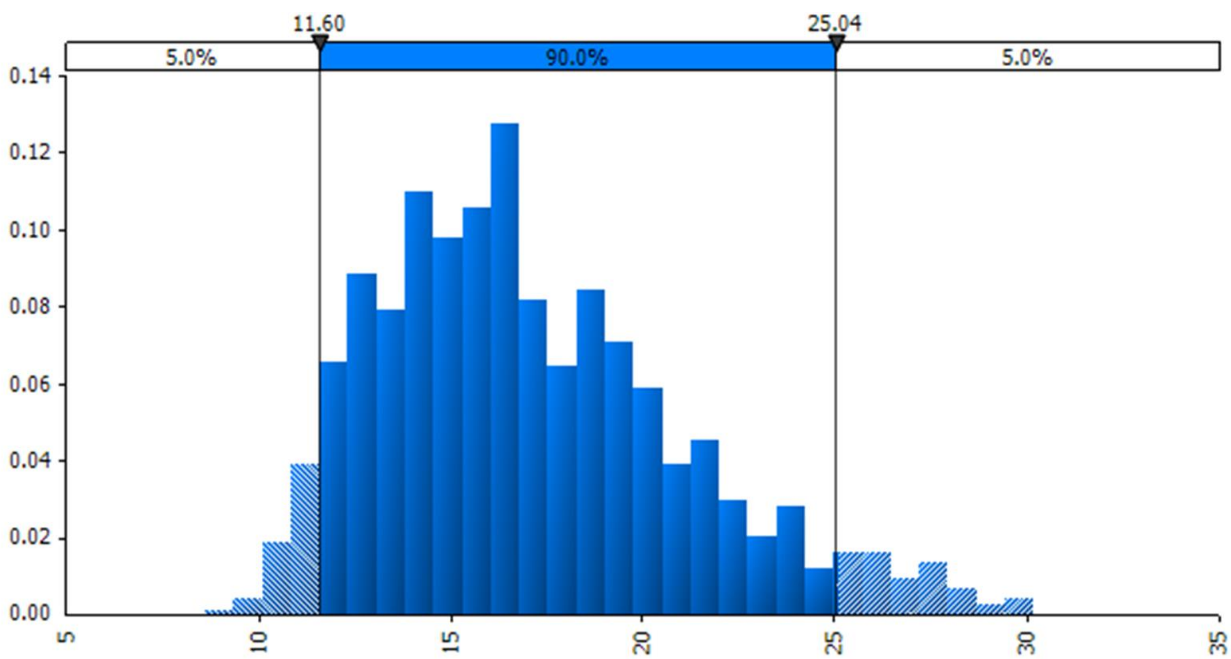

Figure 20. Total GWP (kg CO2/MWh) probability distribution based on uncertainty parameters above. The 90% confidence interval is also shown.

Based on the same simulation, the tornado diagram below shows the parameters that contribute the most to the variability of the GWP. This identifies the Capacity Factor and Operational Life as the two leading contributors to variation in the result. Ranges are assumed to be realistic as they are based on technology reviews, LCAs of floating and stationary offshore wind, and direct input from developers and BOEM. Therefore, the figure below is expected to be a fair representation of the parameters that contribute the most to the variability in the result.

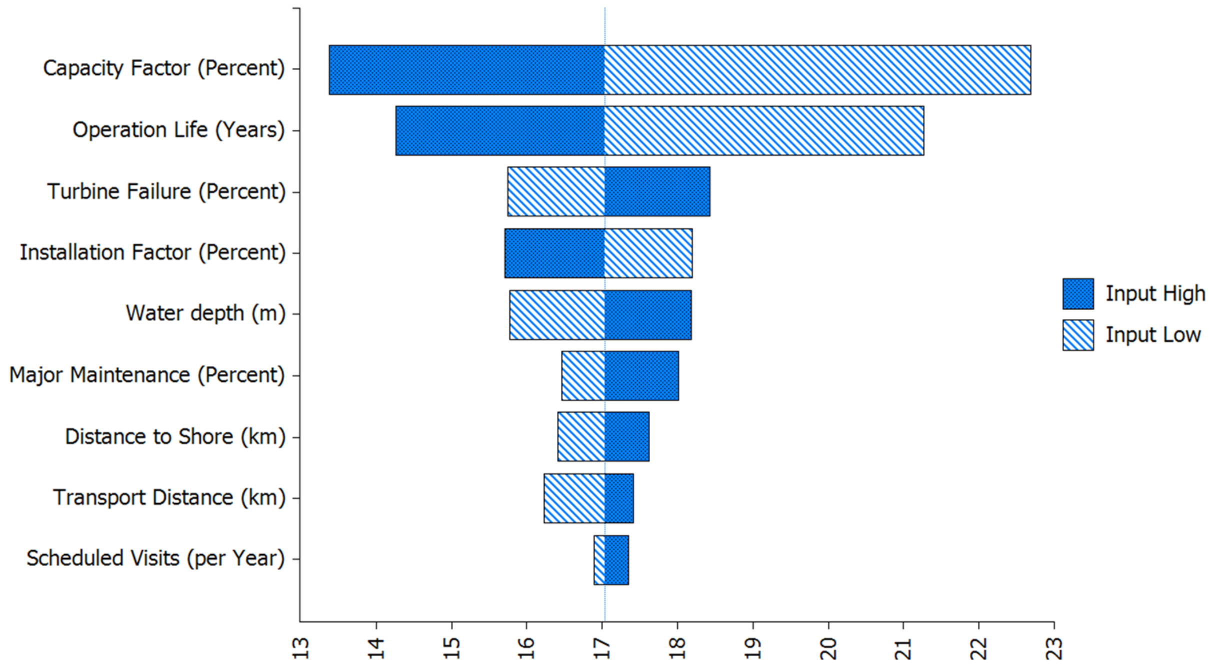

Figure 21. Total GWP (kg CO2/MWh) tornado diagram showing the largest contributors to the variability in GWP results. The dark shading shows what happens at the high end of each parameter. For example, the higher the Capacity Factor, the less emissions per MWh, but the higher the transport distance the more emissions per MWh.

Comparison to Literature Values

Although few LCA studies exist on floating offshore wind energy, our results are in the same range as previous emissions estimates for floating offshore wind energy.

In 2012 Raadal and Vold reviewed six conceptual offshore wind concepts assuming a NREL 5 MW turbine, a rotor diameter of 126 m, water depth of 200 m, and 200 km off the British Coast. GHG emissions were between 18.0 and 31.4 kg CO_2-eq/MWh with foundation and platform materials contributing the most overall emissions.[74] A 2008 LCA of a conceptual

[74] Raadal, Hanne Lerche, Bjørn Ivar Vold, Anders Myhr, and Tor Anders Nygaard. "GHG emissions and energy performance of offshore wind power." *Renewable energy* 66 (2014): 314-324. https://www.sciencedirect.com/science/article/pii/S0960148113006654?via%3Dihub

design by the Norwegian Sway Company assuming 5 MW turbines, a depth of 100-300 meters, and 50 km from shore found emissions of ~11.52 kg CO_2-eq/MWh.[75]

More LCAs exist on fixed offshore and onshore wind energy. There are even studies on particular wind farms. For example, a study reviewing Alpha Ventus, the first German offshore wind farm, found emissions of 32 kg CO_2-eq/MWh. 5 MW turbines were utilized in a water depth of 30 meters.[76] A similar study modeled on China's first offshore wind energy project found emissions of 25.5 kg CO_2-eq/MWh. This study assumed 3.6 MW wind turbines 9.2 km away from shore in 10 meters of water.[77]

General studies and literature reviews have been conducted on emissions of fixed offshore and onshore wind energy. A 2017 characterization of the life cycle GHG emissions from wind energy systems determined a range of 3.2 to 24 kg CO_2-eq/MWh based on 8 previous studies.[78] A 2012 systematic review of utility-scale wind power that performed a harmonization of LCA literature found an emissions range of 3.0 to 45 kg CO_2-eq/MWh and a median of 11 kg CO_2-eq/MWh. This review looked at ~240 LCAs of onshore and offshore wind farms and used 126 estimates of life cycle GHG emissions.[79] Furthermore, a general 2016 study looking at fixed offshore wind energy and assuming 4.0 and 6.0 MW Siemens turbines found emissions of 11 kg CO_2-eq/MWh.[80]

Studies of onshore wind energy generally have lower estimates of GHG emissions due to lower material, installation, and maintenance requirements. In the same Raadal and Vold study above, they reviewed two existing onshore Norwegian wind farms and found emissions of 11.0 and 15.1 kg CO_2-eq/MWh.[81] A LCA conducted by Vestas, the manufacturer of one of the turbines our conceptual turbines were based on, found GHG emissions were 7.6 kg CO_2-eq/MWh for an onshore wind farm composed of 3.45 MW turbines.[82]

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[75] Weinzettel, Jan, Marte Reenaas, Christian Solli, and Edgar G. Hertwich. "Life cycle assessment of a floating offshore wind turbine." *Renewable Energy* 34, no. 3 (2009): 742-747. https://www.sciencedirect.com/science/article/pii/S0960148108001754
[76] Wagner, Hermann-Josef, Christoph Baack, Timo Eickelkamp, Alexa Epe, Jessica Lohmann, and Stefanie Troy. "Life cycle assessment of the offshore wind farm alpha ventus." *Energy* 36, no. 5 (2011): 2459-2464. https://www.sciencedirect.com/science/article/abs/pii/S0360544211000594
[77] Yang, Juhua, Yuan Chang, Lixiao Zhang, Yan Hao, Qin Yan, and Changbo Wang. "The life-cycle energy and environmental emissions of a typical offshore wind farm in China." *Journal of Cleaner Production* 180 (2018): 316-324. https://www.sciencedirect.com/science/article/pii/S0959652618300969
[78] Kadiyala, Akhil, Raghava Kommalapati, and Ziaul Huque. "Characterization of the life cycle greenhouse gas emissions from wind electricity generation systems." *International Journal of Energy and Environmental Engineering* 8, no. 1 (2017): 55-64. https://link.springer.com/article/10.1007/s40095-016-0221-5
[79] Dolan, Stacey L., and Garvin A. Heath. "Life cycle greenhouse gas emissions of utility-scale wind power." *Journal of Industrial Ecology* 16 (2012): S136-S154. https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1530-9290.2012.00464.x
[80] Bonou, Alexandra, Alexis Laurent, and Stig I. Olsen. "Life cycle assessment of onshore and offshore wind energy-from theory to application." *Applied energy* 180 (2016): 327-337. https://www.sciencedirect.com/science/article/pii/S0306261916309990?via%3Dihub
[81] Raadal, Hanne Lerche, Bjørn Ivar Vold, Anders Myhr, and Tor Anders Nygaard. "GHG emissions and energy performance of offshore wind power." *Renewable energy* 66 (2014): 314-324. https://www.sciencedirect.com/science/article/pii/S0960148113006654?via%3Dihub
[82] Vestas. "Life Cycle Assessment of electricity production from an Onshore V136-3.45 MW Wind Plant" Accessed February 28, 2019.

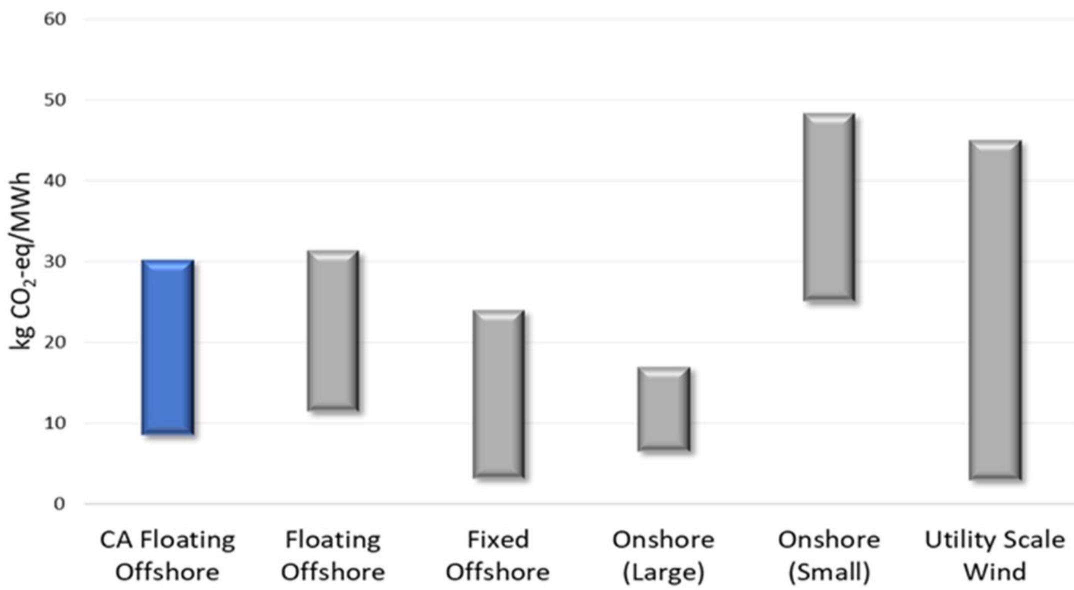

Figure 22. Comparison with previous wind energy LCA results.

Comparison with Other Energy Sectors

The figure below shows the GHG emissions of this project's representative wind farm in comparison to other energy sources. The GWP of floating offshore wind is similar to the range of nuclear and hydroelectric energy generation and towards the low end of estimates for solar.

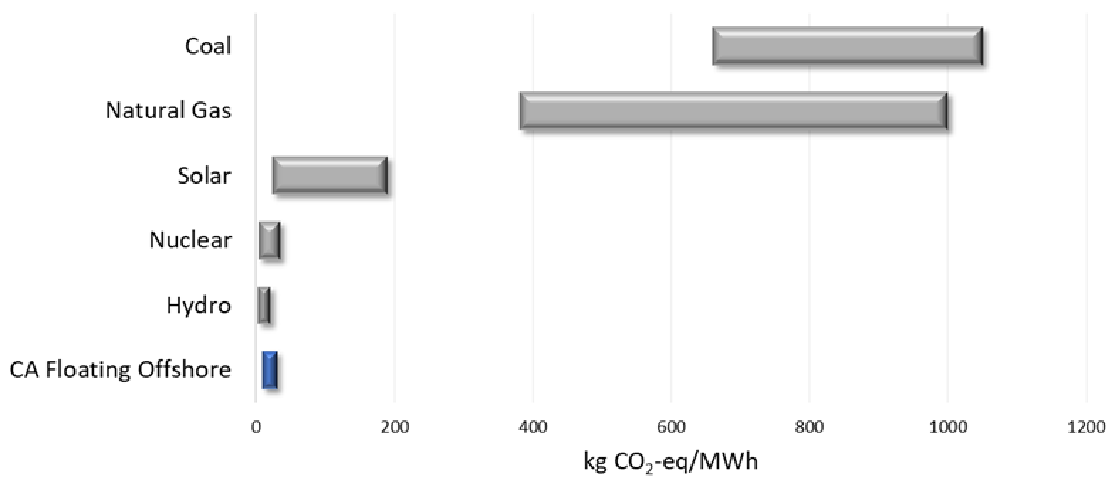

Figure 23. Comparison of GHG emissions from floating offshore wind and other energy sources.[83]

https://www.vestas.com/~/media/vestas/about/sustainability/pdfs/v1363%2045mw_mk3a_iso_lca_final_31072017.pdf

[83] Turconi, Roberto, Alessio Boldrin, and Thomas Astrup. "Life cycle assessment (LCA) of electricity generation technologies: Overview, comparability and limitations." *Renewable and sustainable energy reviews* 28 (2013): 555-565.

Furthermore, the maximum estimate for GWP for floating offshore wind (30.2 kg CO_2-eq/MWh) is less than 1/10th the value of the minimum estimate for Natural Gas and 1/20th the value of the minimum estimate for Coal. These values demonstrate a significant opportunity for California to reduce its GHG emissions and help to satisfy their emission reduction and energy production goals.

Interpretation

Sensitivity Analysis

The following sensitivity analysis provides additional insights into the interpretation of results and further quantifies the impact of uncertainty of possible GWP. This allows for the development of specific policy recommendations and highlights possible limitations of the project as well as areas for future research. Sensitivity analysis is a tool for studying the robustness of results and their sensitivity to uncertainty factors in LCA. It highlights the most important set of model parameters to determine whether data quality needs to be improved, and to enhance interpretation of results.[84] Sensitivity is the influence that one parameter (the independent variable) has on the value of another (the dependent variable - i.e. kg CO_2-eq/MWh).[85]

As a tool for sensitivity, scenario analysis involves analyzing different scenarios combining different parameter values, to analyze the influence of discrete input parameters on either output parameter values or priority values.[86]

While data values for the turbine, substructure, operation, maintenance, and end-of-life were assigned in consultation with industry experts combined with a thorough review of existing literature, a number of assumptions had to be made in order to perform this LCA. This analysis explores different scenarios to assess the extent to which the validity of these assumptions may impact results.

The results by life cycle stage, by material, and the uncertainty analysis helped to establish several parameters of importance. These parameters contribute the most to GHG emissions and/or have inherent uncertainty which contributes to significant variation in the result. Establishing these parameters provides a way to prioritize as it identifies the factors

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http://orbit.dtu.dk/files/118476742/2012_RSER_Turconi_Life_cycle_assessment_LCA_of_electricity_generation_technologies_overview_comparability_and_limitations_self_archive.pdf

[84] Wei, Wei, Pyrene Larrey-Lassalle, Thierry Faure, Nicolas Dumoulin, Philippe Roux, and Jean-Denis Mathias. "How to conduct a proper sensitivity analysis in life cycle assessment: taking into account correlations within LCI data and interactions within the LCA calculation model." *Environmental science & technology* 49, no. 1 (2014): 377-385. https://www.ncbi.nlm.nih.gov/pubmed/25436503

[85] Zoltan Budavari et al. “Methods and guidelines for sensitivity analysis, including results for analysis on case studies.” LoRe-LCA. https://www.sintef.no/globalassets/project/lore-lca/deliverables/lore-lca-wp5-d5.2-emi_final.pdf

[86] Zoltan Budavari et al. “Methods and guidelines for sensitivity analysis, including results for analysis on case studies.” LoRe-LCA. https://www.sintef.no/globalassets/project/lore-lca/deliverables/lore-lca-wp5-d5.2-emi_final.pdf

that contribute the most to total emissions.[87] Prioritization should focus on the components or stages of floating offshore wind has the highest carbon footprint, and thus contributes the most to climate change.[88] Several parameters that influence the magnitude of results are explored in more detail below.[89]

Electricity Generation

As the environmental impact of wind power generation is measured by dividing total emissions by total electricity generation in lifetime, maximizing total electricity generation over the lifetime of the windfarm is critical to limiting emissions. The major parameters driving electricity generation in lifetime of wind farm are capacity factor, operational life, and possible curtailment of electricity.

Capacity factor

In this study, a capacity factor of 50% is assumed for baseline scenario. However, the capacity factor will vary depending on location and throughout the windfarm's life cycle. In the United States, the average capacity factor of both onshore and offshore wind power was 34.6% in 2017.[90] Internationally, the 12 month average from Mar 2017 to Feb 2018 was 45.8% in Denmark[91], 44.3% in the UK[92], and 40.2% in Germany.[93] Recently, Hywind Scotland, the world's first floating offshore wind farm, has reported that it achieved 65% of capacity factor. Multiple studies show that offshore wind conditions are better than those on land.[94] In California, the capacity factor would likely be close to that of Hywind Scotland because of the larger distance from shore where wind is more consistent. Furthermore, BOEM Pacific Region estimates capacity factor will continue to increase due to technological developments.

Average wind conditions are a major factor in determining the GHG emissions per MWh of electricity produced and highly influence the capacity factor. A decrease in average wind

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[87] H. Scott Matthews, Chris T. Hendrickson, and Deanna Matthews "Life Cycle Assessment: Quantitative Approaches for Decisions that Matter, 2014." Open access textbook, retrieved from https://www.lcatextbook.com/

[88] H. Scott Matthews, Chris T. Hendrickson, and Deanna Matthews "Life Cycle Assessment: Quantitative Approaches for Decisions that Matter, 2014." Open access textbook, retrieved from https://www.lcatextbook.com/

[89] Raadal, Hanne Lerche, Bjørn Ivar Vold, Anders Myhr, and Tor Anders Nygaard. "GHG emissions and energy performance of offshore wind power." *Renewable energy* 66 (2014): 314-324. https://www.sciencedirect.com/science/article/pii/S0960148113006654?via%3Dihub

[90] U.S. Energy Information Administration. " Table 6.7.B. Capacity Factors for Utility Scale Generators Not Primarily Using Fossil Fuels, January 2013-December 2018." Accessed February 28, 2019. https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_6_07_b

[91] Energy Numbers. "Capacity factors at Danish offshore wind farms." Accessed February 28, 2019. http://energynumbers.info/capacity-factors-at-danish-offshore-wind-farms

[92] Energy Numbers. "UK offshore wind capacity factors." Accessed February 28, 2019. http://energynumbers.info/uk-offshore-wind-capacity-factors

[93] Energy Numbers. "Germany's offshore wind capacity factors." Accessed February 28, 2019. http://energynumbers.info/germanys-offshore-wind-capacity-factors

[94] Wagner, Hermann-Josef, Christoph Baack, Timo Eickelkamp, Alexa Epe, Jessica Lohmann, and Stefanie Troy. "Life cycle assessment of the offshore wind farm alpha ventus." *Energy* 36, no. 5 (2011): 2459-2464. https://www.sciencedirect.com/science/article/abs/pii/S0360544211000594

speed would increase relative GHG emissions; however, an increase in average wind speed would decrease relative GHG emissions.

This sensitivity analysis presents the results for a variance of 35% to 65% of capacity factors for the assumed wind farm site. No other factors are assumed as variables in this analysis.

For our baseline scenario, a reduction of capacity factor from 50% to 35% results in a greenhouse gas emissions increase of 6.58 kg CO_2-eq/MWh or 43%, an increase in capacity factor to 65% results in a decrease of 3.54 kg CO_2-eq/MWh or 23%. As the results indicate, the impacts per MWh directly and significantly correspond to the capacity factor of the wind farm site.

Operational Life

In this study, 25 years of the operational life is assumed for baseline scenario. However, operational life may vary depending on conditions such as the harshness of weather conditions, improved durability of materials, and the level of maintenance.

This sensitivity analysis presents the results for a variance of ±10 years in operational life of wind farm. No other factors are assumed as variables in this analysis.

For our baseline scenario, a decrease in operation life from 25 to 20 years results in a greenhouse gas emissions increase of 3.43 kg CO_2-eq/MWh or 42%. A further reduction to 15 years results in an increase of 60%. An increase in operational life to 30 years results in a decrease of 2.29 kg CO_2-eq/MWh or 15% and an increase to 35 years a decrease of 26%.

The required amount of replacement parts may vary depending on the conditions of wind farm site and the level of maintenance. Based on collected data from literature review, a typical rate for the replacement of parts is included in baseline scenario (2.5% failure per year).

This sensitivity analysis presents the results for the estimated range included in the uncertainty analysis above (2%-10%). No other factors are assumed as variables in this analysis. GHG emissions would increase by 2.70 kg CO_2-eq/MWh or 18% for a failure rate of 10%, or decrease by 1% for a failure rate of 2%.

Curtailment

Due to intermittency issues as well as grid integration and management issues, curtailment of wind energy resources could become an issue, especially as wind energy expands. A full examination of grid impacts and projections of the growth of floating offshore wind is not within the scope of this report, but our model allows for an analysis of possible curtailment. For example:

$$\frac{Life\ Cycle\ GHG\ Emissions\ (kg\ CO_2\ equivalent)}{Life\ Cycle\ Generation\ (MWh) * (1 - \%\ Curtailment)} = kg\ CO_2\ equivalent\ per\ MWh$$

This sensitivity analysis presents the results of a % curtailment of 25%. No other factors are assumed as variables in this analysis. GHG emissions would increase by 5.12 kg CO_2-eq/MWh or 33%.

Technological Advancement

In this study, the baseline rotor diameter is assumed to be 164 meters for an 8 MW wind turbine. However, due to technology advancement, it is likely that turbines with larger generation capacity may be developed without significantly increasing material use. For instance, MHI-Vestas, one of leading offshore turbine manufacturers, is currently developing 10 MW turbines with the same rotor diameter as the 8 MW turbines which they developed.[95] The new turbines are projected to be ready for installation by 2021. Larger generation capacity per turbine will reduce the number of turbines to be installed to meet the total generation requirements. For a 600 MW wind farm, only 60 10 MW turbines are needed while 75 8 MW turbines are needed. If material use does not increase much between 8 MW and 10 MW turbines, the total material use for the wind farm will reduce significantly.

A reduction in the number of turbines will lead to reduced number of moorings, anchors, cables, ancillary and replacement parts, as well as maintenance requirements. Therefore, technology advancement in generation capacity per turbine without increasing material uses would have larger impacts over the entire project.

This sensitivity analysis presents the results for different generation capacities per turbine, 6MW, 8MW and 10MW for the same rotor size of 164 meters. Material and energy uses for turbine manufacturing are assumed as constant for all three cases. No other factors are assumed as variables in this analysis. GHG emissions would increase by 5.01 kg CO2-eq/MWh or 33% for a 6 MW turbine, or decrease by 3.00 kg CO2-eq/MWh or 20% for a 10 MW turbine. As the results indicate, the impacts per MWh directly correspond to the reduced material use due to the possibility of technology advancement in generation capacity per turbine.

End-of-Life

The End-of-Life baseline scenario described above constitutes percentages of the materials being landfilled, incinerated, and recycled. After dismantling, a certain percentage of the material is going to be directed to either of the three processes. The baseline scenario accounts for the carbon intensive process of incinerating, landfilling, and recycling, and the carbon credit that would be obtained after putting back into the market the raw material

[95] MHI Vestas Offshore Wind. "Turbines & Innovations." Accessed February 28, 2019. http://www.mhivestasoffshore.com/innovations/

obtained after recycling. A sensitivity analysis the End-of-Life includes modifying the proportions of different materials being directed to either process.

This sensitivity analysis presents the results for two scenarios with a lower recycling rate. No other factors are assumed as variables in this analysis. GHG emissions would increase by 3.41 kg CO2-eq/MWh or 22% for scenario of 50% recycling and 50% landfill of steel. In the worst case of 0% recycling and 100% landfill of steel, GHG emissions would increase by 7.41 kg CO2-eq/MWh or 48%.

California GHG Emission Reduction Targets and Air Quality

California faces issues with solar and land-based wind inputs (i.e. curtailment and land-use restrictions) and must still implement its RPS standards (Senate Bill-350 Clean Energy and Pollution Reduction Act of 2015). As a result, without floating offshore wind energy, it is assumed that natural gas consumption would increase to meet increasing energy demand.

While the results of this LCA covers cradle to grave emissions, wind energy is classified as both carbon-free and renewable in terms of RPS standards. Therefore, although the LCA results do not directly address RPS targets, they underscore the underlying goal of the state's GHG emission reduction targets. As a validation of RPS methodology, the LCA indicates that wind can reduce GHG emissions by replacing non-renewable energy sources. To directly relate these results to GHG emission reduction, a reasonable range can be defined by comparing life cycle emissions of floating offshore wind and natural gas. Natural gas is used as a comparison due to its dominance over the California grid mix. As of 2017, natural gas accounted for approximately 43% of state electricity generation, and 93% of GHG emissions. By comparison, wind was responsible for approximately 6.2% of electricity generation, and 0.4% of GHG emissions.[96, 97] Therefore, a primary objective for the state is to reduce the proportion of non-renewables like natural gas, and replace that generation with low-carbon alternatives such as floating offshore wind. If this substitution of wind is assumed, a single 600 megawatt floating wind farm has the potential to reduce emissions by 934 to 2,598 million kilograms of CO_2 equivalent. This calculation assumes a simple 1:1 ratio of wind energy generated to natural gas production avoided. Additionally, the calculation uses a natural gas range of 380 to 1,000 kg CO_2-eq/MWh.

Development of floating offshore wind will improve air quality. Although these impacts will be unevenly distributed throughout California, these impacts will include measurable impacts. Numerous studies, including an analysis of the benefits of switching to renewables conducted by the National Renewable Energy Laboratory, show causal links between the

[96] California Energy Commission. "Total System Electric Generation." Data as of June 21, 2018. Accessed February 28, 2019. https://www.energy.ca.gov/almanac/electricity_data/total_system_power.html
[97] Turconi, Roberto, Alessio Boldrin, and Thomas Astrup. "Life cycle assessment (LCA) of electricity generation technologies: Overview, comparability and limitations." *Renewable and sustainable energy reviews 28* (2013): 555-565.
http://orbit.dtu.dk/files/118476742/2012_RSER_Turconi_Life_cycle_assessment_LCA_of_electricity_generation_technologies_overview_comparability_and_limitations_self_archive.pdf

method of energy production and the impacts on air quality including the associated health impacts and resulting costs avoided.[98]

In addition to greenhouse gases, extraction and burning of fossil fuels, including natural gas, emits other pollutants that are regulated by the EPA's Clean Air Act. These gases include carbon monoxide, nitrogen oxides, sulfur oxides, and other volatile organic compounds. The EPA and California have ambient air quality standards that regulate the amount of pollutants in the air based on the parts per million (PPM). However, it is difficult to quantify how floating offshore wind power would impact this measurement. Other measurements exist in life cycle analysis that utilizes the same approach to quantifying GHG emissions. This includes quantifying the kilograms per megawatt hour (kg/MWh) emitted from natural gas power plants.[99]

Multiple life cycle analyses exist that describe in detail the kilograms per megawatt hour (kg/MWh) emitting from natural gas power plants.[100, 101] It is assumed that floating offshore wind power will be used instead of natural gas. Therefore, the kg/MWh produced from each pollutant could be multiplied by the total amount of MWh that wind power is estimated to produce. Then the same calculation could be used to determine the total emissions from the life cycle of the wind power plant. The difference in these calculations quantifies the total weight of pollutants avoided. Although multiple life cycle analysis of this type exists for natural gas, there are few studies that quantify the amount produced from floating offshore wind. However, a future analysis could either extrapolate from exiting life cycle analysis of land-based wind power and stationary offshore wind. Once available, the results of the life cycle analysis currently underway can be used to perform the same calculations.

Conclusions

Growing awareness of the link between GHG emissions and global climate change has prompted interest in evaluating methods for carbon emissions reductions. In California, floating offshore wind projects are being evaluated as a means of reaching the state's RPS and emission reduction targets. This report represents the first analysis of the impacts of

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[98] Wiser, Ryan, Galen Barbose, Jenny Heeter, Trieu Mai, Lori Bird, Mark Bolinger, Alberta Carpenter et al. *A retrospective analysis of the benefits and impacts of US renewable portfolio standards*. No. TP-6A20-65005. Lawrence Berkeley National Lab.(LBNL), Berkeley, CA (United States), 2016. https://www.nrel.gov/docs/fy16osti/65005.pdf

[99] Spath, Pamela L., and Margaret K. Mann. *Life cycle assessment of a natural gas combined cycle power generation system*. No. NREL/TP-570-27715. National Renewable Energy Lab., Golden, CO (US), 2000. https://www.nrel.gov/docs/fy00osti/27715.pdf

[100] Spath, Pamela L., and Margaret K. Mann. *Life cycle assessment of a natural gas combined cycle power generation system*. No. NREL/TP-570-27715. National Renewable Energy Lab., Golden, CO (US), 2000. https://www.nrel.gov/docs/fy00osti/27715.pdf

[101] Jaramillo, Paulina, W. Michael Griffin, and H. Scott Matthews. "Comparative life-cycle air emissions of coal, domestic natural gas, LNG, and SNG for electricity generation." *Environmental science & technology* 41, no. 17 (2007): 6290-6296. https://pubs.acs.org/doi/abs/10.1021/es063031o

floating offshore wind projects on GHG emissions in offshore waters along the California coast.

In terms of model fidelity, our results are comparable with literature results for conceptual floating offshore wind turbine models and are within the combined range of both onshore and offshore wind projects at a utility scale. In relation to other energy sectors, floating offshore wind life cycle emissions are similar to hydro and nuclear. Floating offshore wind has the potential to significantly decrease GHG emissions when compared to fossil fuels including natural gas.

Analysis of our results indicates that the manufacturing life cycle stage is responsible for the majority of emissions, that recycling rates for materials have strong implications specifically for reducing GHG emissions, and that the variability in emissions are most widely influenced by capacity factor of the turbines and the operational lifetime of the windfarm.

Policy Recommendations

Consideration of Environmental Benefits of Floating Offshore Wind

This project's results demonstrate that floating offshore wind has the potential to decrease GHG emissions when compared to fossil fuels including natural gas. Previous research shows that wind energy also improves air quality when compared to the use of fossil fuels. These benefits should be considered when assessing energy development in California.

Consideration of Life Cycle Emissions in State RPS

To inform sustainable development measures and help California reach its Renewables Portfolio Standard, policymakers should consider emissions across whole life cycles as well as modify the use of the number zero when referring to renewable energy sources. It is critically important to understand that GHG emissions occur throughout the life cycle of a floating offshore wind project rather than just the operational stage alone. Although state energy policies use the generation stage of power production systems in isolation to assess their contribution to GHG emissions, policymakers must also consider the sum of life cycle emissions and evaluate the problem of reducing material and energy-related emissions related to manufacturing, transportation, maintenance, and decommissioning.

Most Influential Floating Offshore Wind Life Cycle Stages

The manufacturing stage is responsible for generating the greatest share of emissions. This life cycle stage encompasses all emissions from cradle-to-gate production of windfarm components. In terms of end-of-life processes, recycling rates also strongly influence the overall life cycle emissions by providing a credit for reuse of materials in lieu of landfilling. Compared to other life cycle stages, manufacturing and recycling are represent the strongest areas to invoke regulatory requirements, conditions, or stipulations to significantly reduce emissions.

Most Influential Floating Offshore Wind Project Parameters

Sensitivity analysis highlights the most important set of model parameters to determine where improvements can be most effective. Through this analysis, the most influential floating offshore wind project parameters is the capacity factor of the turbines and the operational lifetime of the windfarm.

For capacity factor, site selection and generation capacity of turbine models should be critically evaluated for any future projects. Given the strong influence of capacity factor on emissions, the wind quality (intensity and consistency) of offshore locations should be considered essential criteria for floating offshore wind projects; potentially at the expense of project parameters that create efficiencies elsewhere (ex. shorter distances from shore). It may also be worth investigating whether or not to sacrifice wind intensity for greater wind consistency. In terms of generation capacity, increasing efficiency through technological improvement can also increase capacity factor (i.e. installing 12MW instead of 8MW turbines). Policymakers should give greater consideration to developers who have the ability to use turbines with greater generation capacity.

For the operational lifetime of a floating offshore wind project, this parameter specifically enhances electricity generation rather than material improvement, reduction, or replacement. By extending the operational lifetime of a floating offshore windfarm, emissions are reduced by using the same amount of raw materials to create more electricity over a longer period of time. Given its strong influence on emissions, policymakers should consider options to maximize this factor.

Constraints on Policy Recommendations

Importantly, this LCA represents an exploratory study. Although uncertainty analysis has been performed, the underlying data-inputs are projections for which a future project may ultimately contradict. The proposals suggested above represent our key policy recommendations based on the best information available to us at the time of writing. Our policy recommendation is for floating offshore wind life cycle emission improvements only (no involvement with the costs of implementation or integration into CA electricity grid). The credibility and reliability of our results are limited by the circumstances surrounding this report (See the *Limitations and Future Research* section below for assumptions).

Limitations

LCA Scope

This report is modeled after the reporting requirements established by ISO-14044. Our scope only includes a Life Cycle Assessment of GHG Emissions which its impact category is Global Warming Potential (GWP), other environmental impacts were not examined, and the financial limitations costs were not considered. The end-of-life (EOL) scenarios were deemed uncertain.

High Data Complexity

The development of an LCA model requires not only a high quantity of data but a significant understanding of the manufacturing and construction process. The study's LCA model accounts for hundreds of different materials, manufacturing processes, components, and many more items that were analyzed. Each of those items brought a different level of complexity depending on its nature. Due to time constraints, the model analyzes the items that would represent the majority of the environmental impacts. Even though the study has included as much life cycle information as possible, the level of detail among the field of material and energy requirements are not equally detailed across components. Going forward, further research could expand and incorporate the analysis of more variables.

Emission Factors

This study relied on the Emission Factors provided by the Intergovernmental Panel on Climate Change (IPCC) compiled on the EcoInvent Database. The EcoInvent Database compiles hundreds of thousands of different emission factors from diverse sources, therefore locating the specific emission factors for all the processes required to set an offshore wind farm project is an arduous task. Again, the time constraint affected the ability to locate the precise emission factor for each LCI item analyzed. However, the comparison analysis established that the results are within the ranges for previous estimates of a floating offshore wind project. However, the precision of the model could be improved by further refinement of the emission factors.

Proprietary Nature of Data

Floating offshore wind development is a relatively new technology. It was first introduced in the 90s, but it has just begun to be used on an industrial scale over the last decade. There is a limited number of manufacturers and data is scarce and proprietary. The lack of industry data has represented a significant impediment for this study; therefore a high number of onshore and offshore academic and manufacturers LCAs, studies, and technical reports were reviewed. It is expected that over time further information would become available.

Theoretical Nature of Project

The theoretical nature of the floating offshore wind farm project presents a high level of uncertainty and requires a large number of assumptions. The parameters were developed from a broad literature review, direct contact and survey responses from developers, and studies made on offshore wind projects in different parts of the world with similar characteristics to the coastal waters of California, but inherent uncertainty still exists. The characteristics and assumptions made for the LCA model can be redefined with further research and data acquisition.

Future Research

Environmental Impact Categories

This study only takes into account Global Warming Potential (GWP), but there are many different categories of environmental impacts, the six impact categories that are considered as the most important today are; Acidification Potential (AP), Eutrophication Potential (EP), Global Warming Potential (GWP), Ozone Depletion Potential (ODP), Photochemical Ozone Creation Potential (POCP), and Primary Energy Use. In order to obtain LCA results on GWP, the quantity of materials, energy, and processes required to build and maintain the offshore wind project throughout its life cycle has to be analyzed and calculated. Such information would serve as a basis to perform the analysis to obtain any of the before-mentioned impact categories; therefore going further it would be recommended to analyze other environmental impacts.

End of Life Scenario

In this study, one of the most significant assumptions is the end of life (EOL) scenario. Through literature review, recycling rates are determined for each component and material. It is assumed that the market would reuse the entirety of the recycled product. So far, no floating offshore wind project has reached the end of its life cycle; the technology is relatively novel. Therefore, not enough data and studies on the recycling market of the components has been performed.

Advancement of Floating Offshore Wind Technology

The technology on fixed offshore wind is relatively novel, and floating offshore is even newer. The oldest commercial-scale floating offshore wind project in the world was deployed in 2009, while the prototype of a fixed offshore wind turbine was first tested in 1991. Floating offshore has just recently become commercially viable, while developers and manufacturers are trying to cope with the enormous material (generally steel and concrete) requirements of these massive structures. As technology evolves, updates on the LCA model assumptions can be updated as academic and manufacturer information becomes more available.

Project and Site Characteristics Optimization Model

Capacity factor and operation period are the two major contributors to the results, while turbine failure, installation factors, and water depth have similar contributions. This analysis assumed that each factor was a standalone variable, but some factors interact with others. For example, as the distance from shore increases, it would raise water depth and affect wind intensity, while at the same time, water depth would affect material usage in mooring lines and cabling. Further analysis could include the development of an optimization set-up where such interactions would be represented in a numerical model. Such a tool would help the study to determine an optimal curve or path so that the different project and site characteristics could be determined to achieve an efficient mix of variables.

Impact on California's Electricity Grid

An important second step of this study, is to evaluate the impact of the electricity generation of the proposed offshore wind project on the CA electricity grid. This analysis has produced the results of the total electricity generation (MWh) of the project by year and over its lifetime, but the impact of curtailment on adding more wind energy to the system that already has overgeneration has yet to be studied. In the face of curtailment, the more renewable energy feeds the grid, the less efficient it becomes. The analysis of potential curtailment in the face of high adoption levels of offshore wind energy has yet to be studied.

The effectiveness of floating offshore wind energy in assisting CA reach its emission reduction targets are ultimately linked to how offshore wind energy is integrated into the electrical grid. While we have demonstrated that the life-cycle emissions from a floating offshore wind project are similar to solar and nuclear, intermittency and the threat of curtailment remain as barriers to implementation in response to SB100.

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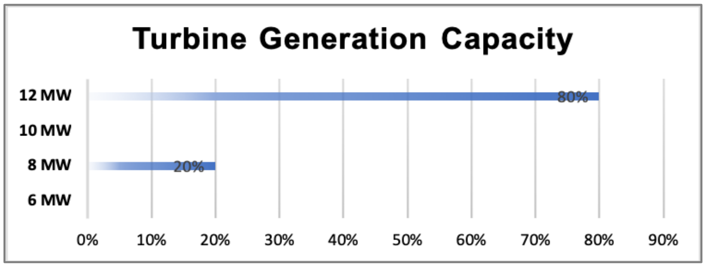
Appendix (Developer survey)

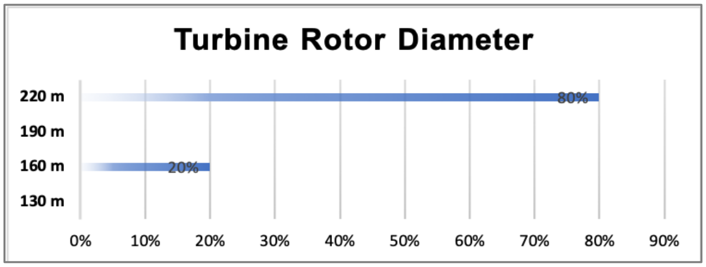
Turbine/Project Specifications
The responses you provide should consider the deployment of a floating offshore wind-farm specifically in California using currently available technology. The offshore wind-farm would have the following environmental characteristics:

— Average distance from shore: 35km
— Average installation depth: 450m
— Average wind speed at 100m hub height: 8m/s
— Average wave height: 2.5 m

Feel free to choose the 'other' option to write a more appropriate value according to your expertise.



Total Respondents: 5



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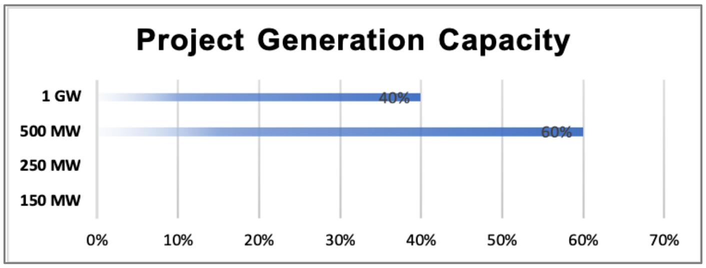

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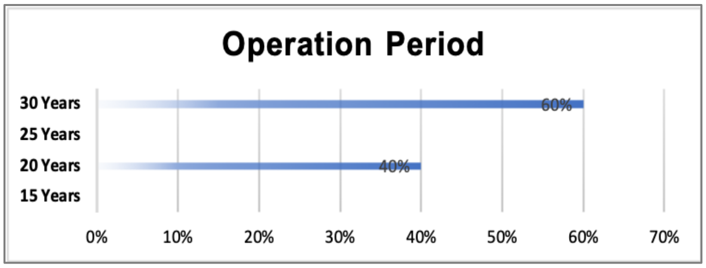

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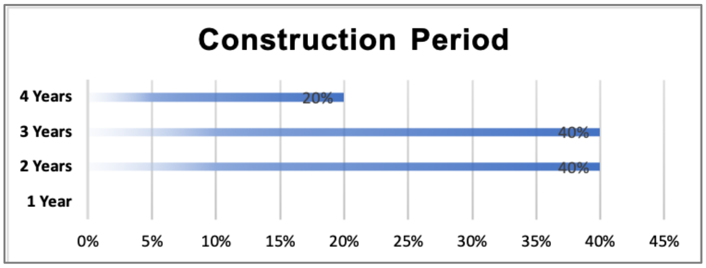

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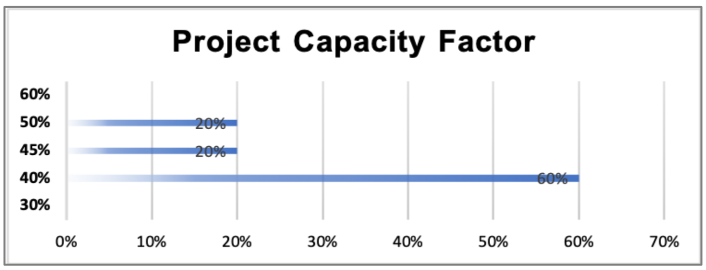

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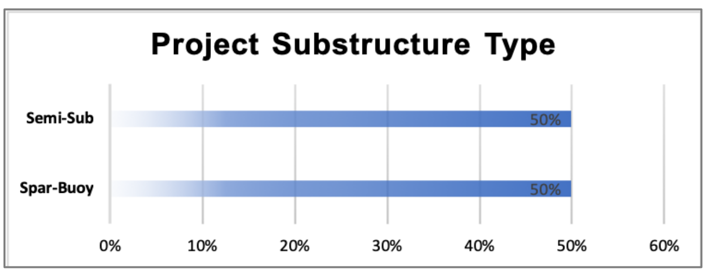

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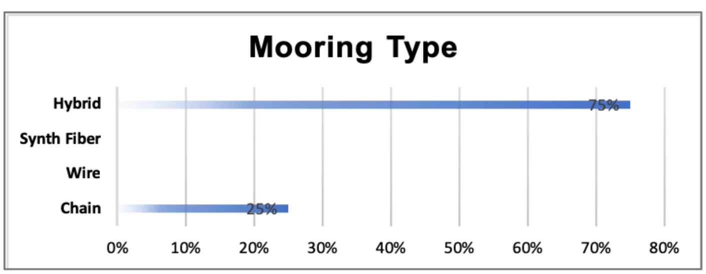

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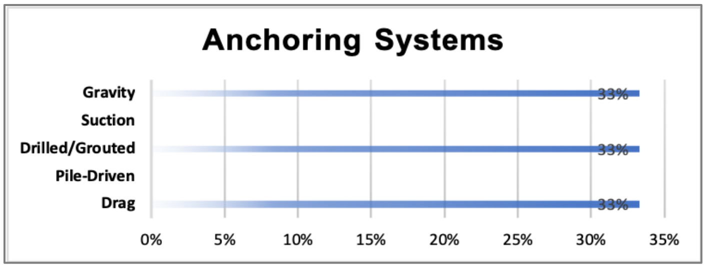

Total Respondents: 4

What distance from shore would necessitate a floating substation?

1. “Depending on seabed conditions and environmental constraints.”
2. “10 meters.”
3. “Any distance.”
4. “Over 100 meters deep.”
5. “It depends on the wind farm capacity itself. For 500MW probably 20miles+ but to be checked based on project specifics.”

What number of turbines or size of a project would necessitate a floating substation?

1. “300 MW connected for each substation.”
2. “100MW.”
3. “200 MW+.”
4. “Probably beyond 100MW at 20 miles + offshore.”

The open-space below is for any additional comments from survey participants. If there is anything you would like us to know regarding the floating offshore wind industry and its potential development in CA, please comment below. This question is not required, but we would be thankful if answered.

1. “It will be a lot cheaper for the consumer if T-lines are built to carry wind energy from the midwest of the US to California, than any offshore wind farm can ever deliver power to California. Offshore wind in California is therefore not the lowest cost solution.”
2. “Please consider feasibility to add WTGs to exiting oil platforms off Coast.”