Northern Arizona University

2022 Collegiate Wind Competition

Project Development Team

Final Report

For the United States Department of Energy

4/24/2022

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WindJax Energy Club at NAU

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Abbreviations

BOEM	Bureau of Ocean Energy Management
GE	General Electric
GGOWF	Galveston Giants Offshore Wind Farm
GOM	Gulf of Mexico
ITC	Investment Tax Credit
JEDI	Jobs and Economic Development Impact Model (by NREL)
LCOE	Levelized Cost of Energy
NREL	National Renewable energy Laboratory
PPA	Power Purchase Agreement
SAM	System Advisory Model (by NREL)

Acknowledgements

The 2022 NAU Collegiate Wind Competition – Project Development Team would like to acknowledge our capstone advisor David Michael Willy for providing our team with the opportunity to participate in this awesome competition, and supporting us by acquiring software licenses, and providing general guidance.

2022 NAU CWC Mechanical Engineering Team

1 Introduction

Since August of 2021, the Northern Arizona University CWC Project Development Team has been hard at work, designing an offshore wind farm in the Gulf of Mexico (GOM) to satisfy the requirements of the 2022 Collegiate Wind Competition. We are proud to present the results of our efforts in this final report to the United States Department of Energy.

The WindJax began developing the Galveston Giants Offshore Wind Farm (GGOWF) by screening the provided lease blocks to evaluate their performance potential, analyze the environmental impacts, investigate the interference with human infrastructure, and determine fatal flaws. With an ideal location identified, the optimal wind farm size, turbine type, and foundation structure were then determined through research and computational experimentation. The final site layout was designed, optimized, and financially evaluated using industry approved software, and a highly iterative process which converged to the final results communicated in this report.

This report is organized into chapters which communicate the results from the:

2. Siting and environmental impacts analysis
3. Site design optimization procedure
4. Project planning
5. Financial analysis

2 Site Description

2.1 Site Selection

The first step in developing a wind farm is to analyze the potential for energy production and features of the area. The main characteristics of the site include bathymetry, wind resource, cultural and social environments, and lease boundaries. To analyze the area, ArcGIS was used in the exclusion stage to generate thematic maps using layers found at the following websites: Bureau of Ocean Energy Management (BOEM) and ArcGIS online content [1, 2]

2.1.1 Bathymetry

The water depth is a technical criterion that affects the cost of the turbine installations. Figure 1 shows that the water is shallow in the lease area, between 10 and 25 meters. In terms of the economic viability of offshore wind farm, the recommended sea depth is 50 meters [3]. Hence, any of those blocks satisfy this constraint. The lower water depths primarily influence the selection of appropriate foundation structures for the turbines and offshore substation.

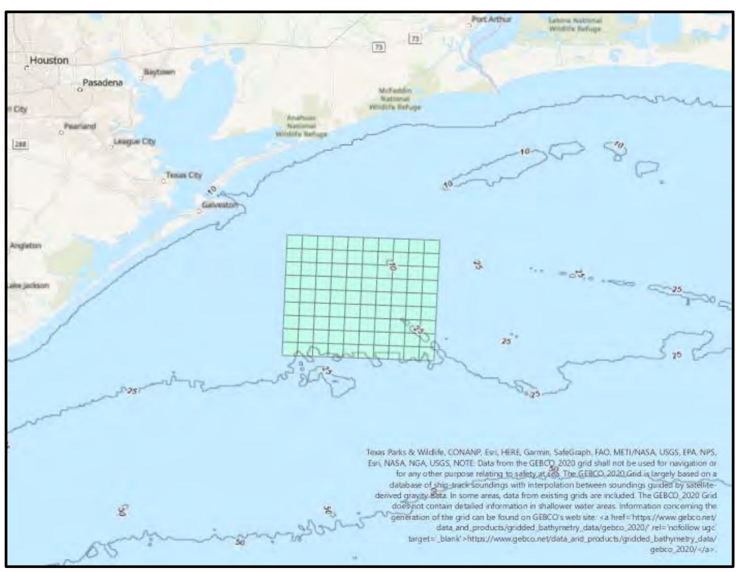

Figure 1: Bathymetric Map

2.1.2 *Shipping Routes*

The selected sites must not interfere with maritime transport. Therefore, to ensure the efficiency and safety of shipping routes, the Marine Planning Guidelines specify a two nautical mile buffer zone from the traffic lanes [4]. Figure 2 shows the shipping routes on the lease blocks, represented in yellow.

2.1.3 *Pipelines and Cables*

There are several oil and gas platforms in the sea; hence we must not anchor or dredge near the pipelines to prevent any damages. In addition, the North American Submarine Cable Association states it is prohibited "to anchor within 500 meters to gas pipelines and submarine cables" [5]. Figure 2 shows the pipelines and cables in the Galveston area.

2.2 Selected Lease Blocks

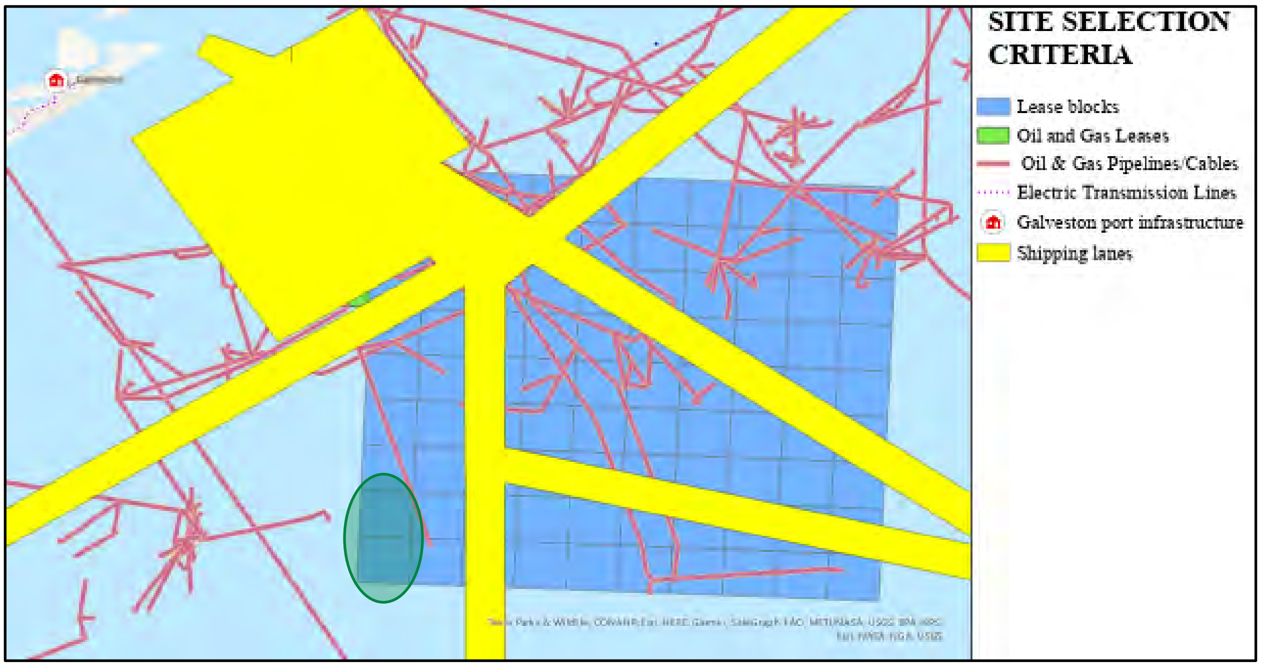

Figure 2: Selected Lease Blocks

The blocks selected for the wind farm are 292 and A63, for they do not contain any shipping lanes, pipelines, or cables. In addition, the mean wind speed is 7.4 m/s, the water depth is 17-25 m, and the area is 50 km^2. The blocks are about 54 km away from the shore, which will facilitate the transmission process to the electric transmission line by the Galveston Island and the construction process using the Port of Galveston infrastructure. Furthermore, at this distance from the shore, the visual and noise disturbance from the wind farm are eliminated. See figure above.

2.3 Wind Resource

To accurately measure the project's economic feasibility, the wind resource of the selected site must be thoroughly evaluated. The wind data used for this project are from the National Renewable Energy Laboratory (NREL) wind prospector [6]. The wind data is represented in 5 min readings, and it was recorded from January 2011 to December 2012. It includes the wind speed and direction a meteorological weather station located within a latitude of 28.669 and a longitude of -94.6447 at 100 m from the ground. The data analysis was conducted using WindPro to analyze the wind statistics and characteristics. The mean wind speed is 7.4 m/s, and corresponds to an IC wind class 3, see Weibull distribution curve below. The mean wind speed is higher during the spring and winter, with a high peak in February and April and an increase from September. The mean wind speed decreases to 5 m/s during the summer. Therefore, the turbine selected needs to have a cut in speed lower than 5 m/s. The wind in the selected site blows from the South - South East (SSE). See wind rose below.

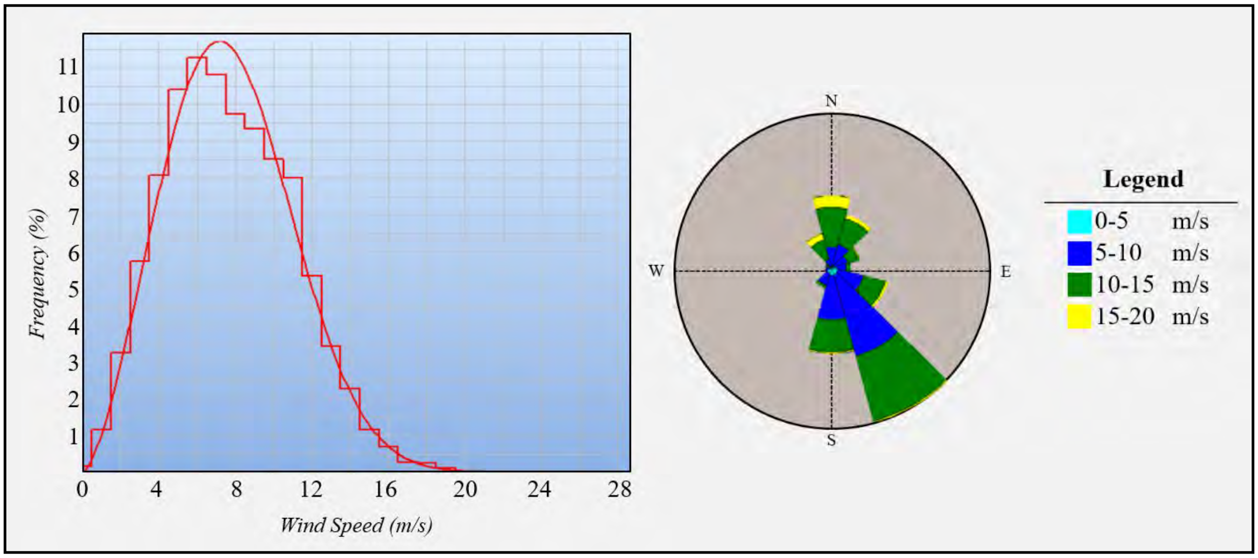

Figure 3: Wind Resource Characteristics for Selected Lease Blocks

2.4 Environmental Impact Mitigation

After analyzing the birds, marine mammals, and fish data from the National Oceanic and Atmospheric Administration and American Bird Conservancy, the lease area is within critical habitats for marine animals [7, 8]. The following subsections discuss the impacts of the offshore wind farm on marine life, birds, and humans, and some of the mitigation strategies implemented in Europe that will be applied in the Galveston Giants Offshore Wind Farm.

2.4.1 Marine mammals/ Sea turtles/fish

There are 28 different species of marine mammals in the GOM, protected under the Marine Mammals Protected Act. Six of those species are endangered under the Endangered Species Act [9]. There are no threatened or endangered species of whales existing in the nearshore water and the chosen offshore wind farm site. However, two protected species of dolphins typically occur in the nearshore water in GOM, the bottlenose and Risso's dolphins. In addition, there is a presence of the threatened sea turtles, loggerheads, and the smalltooth sawfish [9].

Marine mammals and fish lose their habitats and experience hearing and physical damage during the construction process, due to the piling method and the collision with vessels. In addition, the electromagnetic field emitted by the transmission cables affects the movement of fish [10]. To reduce those impacts, an air bubble curtain surrounding the foundation will be implemented during the construction process to reduce the noise and vibration from the pile driver, which was found to be effective up to 95% [11]. Additionally, the cables are buried to reduce the intensity of electromagnetic fields.

2.4.2 Birds

There is one endangered bird species in the GOM, the piping plovers [12]. Birds collide with the rotating blades and may change their migratory path because of the wind farm. Displacement is the biggest negative impact of offshore wind on birds, which is why the turbines will be placed further apart. The piping plover and most seabirds fly at a lower altitude, so having turbines with hub height over 150 m reduces the collisions. In addition, as greater collision risks occur at night, sensors systems that detect the birds' movements and adjust the turbines motions accordingly will be implemented in the project.

2.4.3 Human Environment

The offshore wind farm will impact commercial fishing through the loss of fishing grounds and the displacement of fisheries, likely resulting in a decrease in income [13]. To minimize intrusion on the local fishing industry, the WindJax will consult and collaborate with local fisheries. Also, there is no marine archeology or cultural heritage on the lease area.

2.5 Risks and Fatal Flaws

For the success of the offshore wind farm, the risks of hurricanes should be assessed, and a mitigation plan needs to be implemented. Figure 4 shows the path of hurricane from the past 20 years within 500 km of the site (represented by the red icon) generated using the software Furow [14]. As can be seen, the offshore wind turbines are at risk from hurricanes. The mitigation strategies are further explained in the turbine and foundation sections.

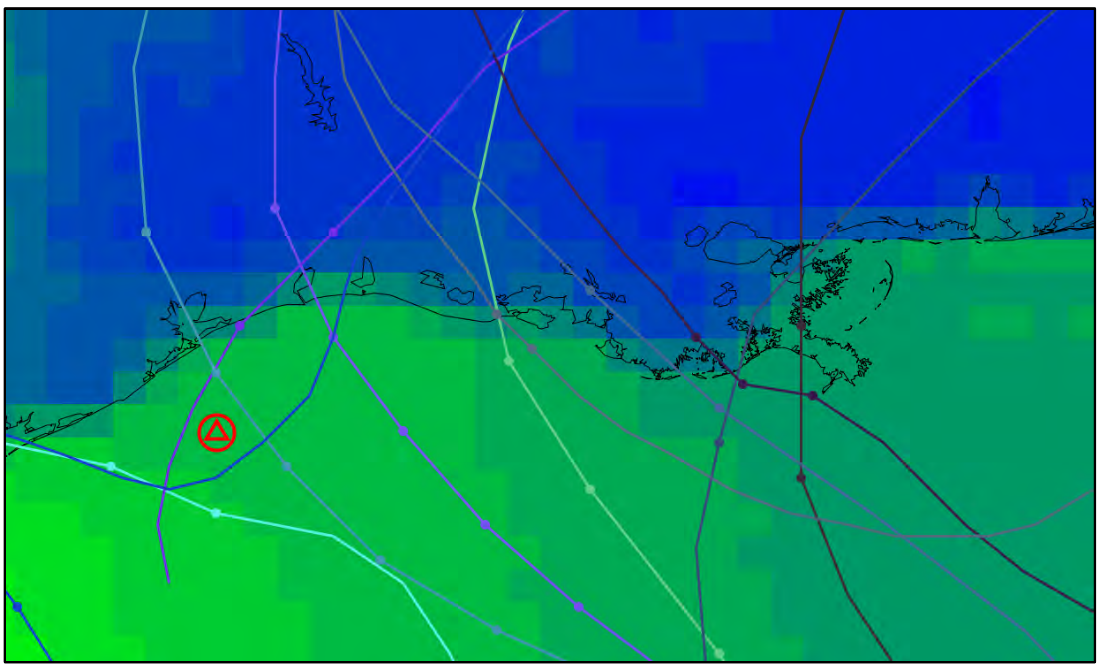

Figure 4: Historic Hurricane Paths at the Site

3 Site Layout

3.1 Design and Optimization Procedure

With a location for the project determined, the WindJax began the iterative optimization process which resulted in the final site layout. This process began with a preliminary analysis to determine an optimal wind farm size. With a rated capacity in mind, dozens of site layouts were created and evaluated, using wide varieties of turbine types and layouts. Openwind [15] and NREL's System Advisory Model (SAM) [16] were used in harmony to design an optimized turbine layout and analyze its financial performance. A visual representation of the strategy utilized by the WindJax is demonstrated in Figure 5 below.

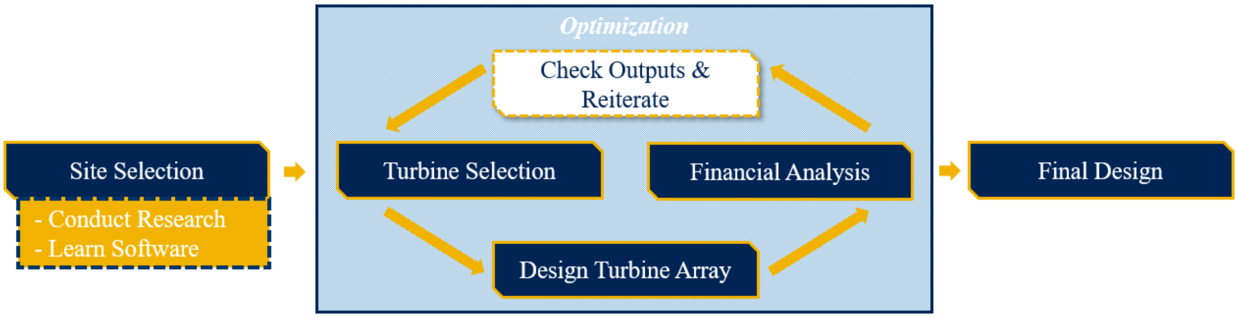

Figure 5: Design Procedure

3.1.1 Determining Optimal Wind Farm Size

With financial feasibility at the core of this project, it was important to model the relationship between the size of the offshore wind farm, and levelized cost of energy (LCOE). To determine this relationship, a computational experiment was performed within Openwind, in which the levelized cost of energy for 16 different sites was plotted against the rated power of the wind farm. The experiment was set up in a way such that the rated power of the wind farm was the only variable that changed in each trial. Each site used generic 5 MW turbines, was located in the same four lease blocks at the bottom left corner of those provided, and was constricted to a gridded layout with minimum separation of 8 rotor diameters. Openwind's "optimize for cost of energy" tool was used to simultaneously minimize wake losses and cable lengths. Each site went through about 100 iterations, and the number of turbines increased by 5 each trial. The results from this experiment are shown below in Figure 6.

**Openwind was not used for the financial analysis, so the LCOE values that it reported were only of relative importance. For this reason, they were normalized based on the maximum value gathered through experimentation.*

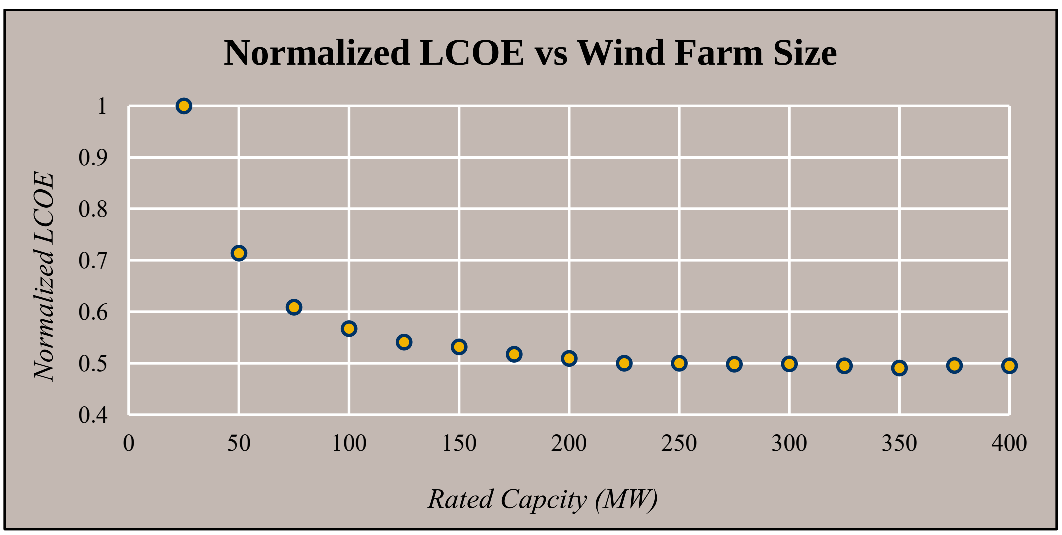

Figure 6: Normalized LCOE vs Wind Farm Size

The results from this figure indicate that the marginal decrease in LCOE stagnates beyond 200 MW. For this reason, our final site layout was designed around this maximum capacity. Using appropriately sized turbines and adequate spacing, a wind farm of this size could be achieved in just two lease blocks. Additionally, since this project would pioneer offshore wind development in the GOM which is prone to hurricanes, it makes sense to stick to a smaller size so that the financial losses would be less severe in the case of an extreme weather event.

3.2 Turbine Selection

Figure 7: General Electric Haliade-X [17]

Throughout multiple iterations of turbine selection and site layouts, the **General Electric (GE) Haliade-X Turbines** was chosen for use in the project boundary. This turbine, as seen in Figure 7, was selected primarily for its size, with a rotor diameter of **220 m** which outputs a maximum power of **14 MW**. With a **IC wind class** rating, the mean wind speeds of the gulf are too low for operating this turbine at full output [17]. However, through dozens of experimental micrositing iterations, it was found to produce more efficient power for the average wind speeds of the gulf compared to smaller turbines of different classes. Further, using turbines with a greater rated power achieves a desirable total power output despite the installation of fewer turbines. Ultimately, this reduces the number of foundations to be installed, the number of turbines to maintain, and reduces their associated costs while generating a greater amount of electricity for the people of Texas.

Concerning the worry of hurricanes and weather extremes in the gulf, the Haliade-X is the largest turbine to ever become Typhoon-Certified through Det Norske Veritas. This milestone indicates that the turbine "is able to reliably withstand the [hurricanes] that are likely to affect it within [its] lifetime" [18]. This certification is paramount to the safe operation of the project for its entire lifespan. Although this certification has only been obtained for the 12 and 13 MW versions of the Haliade-X, it can be assumed that GE is in the works of obtaining the same for the 14 MW version.

Beyond maximizing power output, minimizing project cost, and improving operational safety, utilization of GE turbines directly supports the growth and development of the American renewable energy industry. Through our financial stimulation of this American company, the WindJax hope to broaden domestic manufacturing jobs associated with the creation of the turbines [19]. Implementation of the domestically made turbines also lessens the complexity of their transportation, and the costs associated with doing so, compared to foreign ones. All in all, the use of the GE Haliade-X is optimal from an economic, financial, and operational standpoint.

3.3 Foundation Selection

The foundation type that has been selected for the GGOWF is a steel truss jacket foundation. This is due to the soft soil conditions of the ocean floor in the GOM. According to the BOEM, jackets are possible in softer clay and silt. The maximum water depth for jacket structures is 60 m [20]. Because the water depth in the selected lease area does not exceed this, it is suitable. A monopile structure is not a suitable option as the soft soil is not sufficient to support the turbine. Oil and natural gas companies have been utilizing jacket structures in the GOM for years with great success. The jacket structures used by the oil and natural gas companies have held up well against the weak soil conditions and the loads from breaking waves. Jacket structures are still not perfect under these conditions, so additional steel is used in construction to mitigate additional risks caused by the soft soil [21].

Figure 8: Jacket Foundations, Twisted Jacket on Right [20]

Out of the two jacket foundations depicted in Figure 8, the manufacturer of the one on the right has boasted surviving Hurricane Katrina when utilized in a GOM oil rig. Not only that, but this foundation costs less to manufacture and is easier to install [22]. For these reasons, the “Twisted Jacket” foundation, by Keystone Engineering, will be used for the applications of this project off the coast of Galveston, Texas.

3.4 Turbine Positions

The Galveston Giants Offshore Wind Farm was designed and optimized in Openwind using the eddy viscosity, deep-array wake model. This model accounts for two-way interactions between the turbines and atmosphere, and was specifically recommended for offshore wind farm design, due to its close agreement with experimental data [23]. The final site consists of 12 Haliade-X turbines, spaced 10.7 rotor diameters apart, in a gridded layout with rows orthogonal to the primary wind direction. The top right corner of the project boundary is trimmed to show that construction will not occur within 500 m of the nearest pipeline.

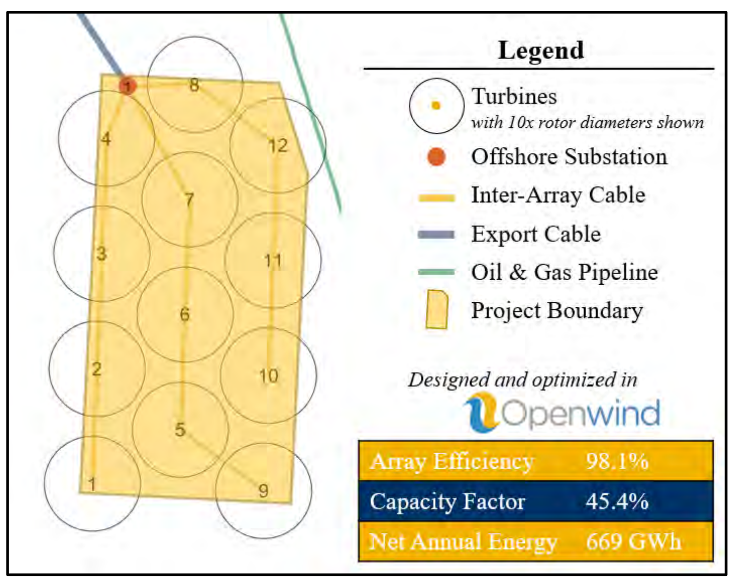

Figure 9: Detailed Layout View

The decision to use a gridded layout was heavily inspired by offshore wind farms that have been successfully implemented in Europe, which overwhelmingly feature gridded layouts [24]. The primary reasons for this are, improved constructability, shorter cable lengths, expandability, and preference from the US Coast Guard for surveillance and navigation [25].

SAM predicted a net annual energy of **510 GWh for the same layout. Since this value was far more conservative and produced in the same program which conducted the financial analysis, it was used in the financial calculations to avoid overstating the economic feasibility. However, greater confidence is placed in the net annual energy predicted by Openwind, due to its emphasis on wake modeling and energy capture.*

3.5 Transmission System Design

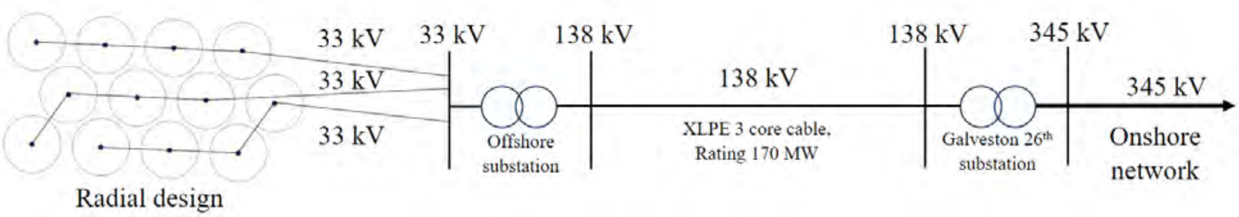

Figure 10: Design of Electrical Transmission System

Figure 10 presents the diagram of the electrical transmission system to transport the energy to the people of Texas. 3 inter array cables of 33 kV are used, with 4 turbines connected to each cable. An offshore substation is installed at the wind farm to step up the voltage to 138 kV. Then, a 3-core cable high voltage alternative current (HVAC), rating power 170 MW, with cross-linked polyethylene (XLPE) insulation system, is used to transport the power from the offshore substation to the 138 kV Galveston 26th substation 34 mi away. The voltage is then stepped up to 345 kV to connect the power to the higher transmission line in Galveston city, in order to minimize electrical losses. The cables are provided from the Nexans company, and the offshore substation is installed by the Ørsted and Eversource companies [26, 27].

4 Project Logistics

4.1 Overview

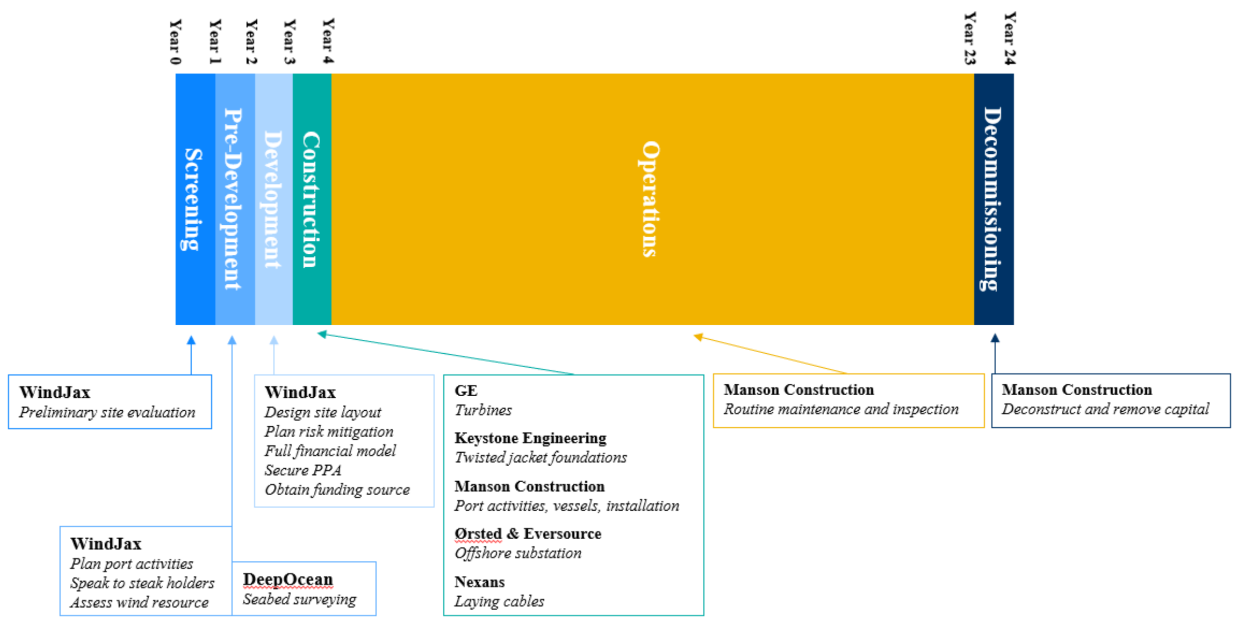

Figure 11: Project Timeline – Galveston Giants Offshore Wind Farm

4.2 Screening

During the screening phase, overall feasibility of the project is assessed. The site's resources are evaluated, and fatal flaws are investigated. This phase of the project is considered complete by the WindJax since the Fall of 2021.

4.3 Pre-development

During this stage, high quality and more thorough wind resource data is collected through newly placed meteorological masts on site. Access to the offshore site will be evaluated during this stage as well. Ensuring it is reasonable to travel from the Galveston port to the site 54 km offshore is crucial for project success. At this stage in the project, the WindJax will conduct conversations with the project stakeholders. Discussions with local government and community leaders will show the desire, feasibility, and need for an offshore wind power plant providing power to the Galveston community. More detailed scans of the ocean floor will also be conducted during this phase to determine the exact location of each tower and ensure the path for transmission cables is free of obstruction. This service will be provided through the survey company "DeepOcean" and should take roughly four months [28].

4.4 Development

In this phase, the WindJax will finalize the wind power plant design and begin coordinating with local electric companies for pursuit of a Power Purchase Agreement (PPA). A PPA with primary energy providers in the areas such as, Express Energy, 4Change Energy, and Constellation [29] will also be pursued during this phase of the project.

In the final stages of development, plans for the windfarm will be finalized and submitted for permitting from the governing bodies, both local and federal. A financing plan will be formalized and executed. The development stage will be considered complete once the project is funded, plans are approved, and construction is ready to commence.

4.5 Construction

Once a Notice to Proceed has been received, the project will break ground. The WindJax plan to contract Manson construction to complete the transport, assembly, and installation of the wind turbines [30]. Manson will also act as the general contractor and subcontract the electrical work. They can be available for material transport. They have the port infrastructure along with the ship fleet capable of completing a project of this magnitude. The construction period is estimated to take one year to complete.

4.6 Operation

Once the project has been completed, tested, and verified to be safe, it will begin to produce electricity. At this point, it is considered to be in the operational phase. The WindJax will contract a plant operator to operate, manage, and maintain the wind power plant. Manson will remain the primary contract holder for necessary repairs. Their capable ship fleet will see continued use for maintenance.

4.7 Decommissioning

When decommissioning a wind farm, the raw materials are worth more in salvage than the components they made up. The WindJax will follow guidelines and regulations established by the BOEM, for the decommissioning of offshore wind farms [31]. The decommissioning process is expected to take no longer than a year, and Manson is anticipated to be the primary party involved in the decommissioning process.

5 Financial Analysis

5.1 Introduction

For the financial analysis, the primary tools used were the Jobs and Economic Development Impact (JEDI) model and SAM. Both programs were created by NREL for the evaluation of potential wind power plants. As new sites were designed within Openwind, a financial analysis was done on them to see financial feasibility as well as give a comparison between sites and the advantages and disadvantages of different parameters. For example, the team found that using a larger capacity wind turbine, even if not in the ideal IEC wind class, was better financially because of the high cost associated with installing turbines offshore. JEDI was utilized for the capital and operational expenditures as it provided more accurate and thorough results than SAM. Instead of using the internal CapEx and OpEx functions in SAM, results from JEDI were input directly into SAM. SAM was then utilized to run a full financial analysis complete with a cash flow analysis. SAM accounts for inflation, depreciation, and other critical market factors.

5.2 Overall Market Conditions

The overall market for renewable energy in the United States is very promising. With an average of $13.6 billion invested annually since 2006 [32], the wind energy sector in the United States is now a favorable investment opportunity. With many tax credits and policies set up to encourage and stimulate growth in the wind energy sector, now is the optimal time for WindJax to develop this power plant.

5.3 Key Assumptions

There were critical assumptions made during the financial analysis of the GGOWF. It is assumed that the current market towards renewable energy remains strong and the federal government continues to promote it through policy and tax incentives. It was assumed that the hypothetical developer WindJax is large enough with enough experience in the industry to secure investment and loans for this project. Inflation was assumed to be 2.3% and the nominal discount rate was assumed to be 1.41% [33]. Federal and Texas income tax were assumed to be 21% and 0% respectively [34]. Property tax was assumed to be 0% [35]. It was assumed the project would have a salvage value of 0%. It is assumed that the tax and inflation rates will not vary significantly beyond the historical trends. The debt was assumed to be financed with $450,000 in closing costs and an upfront fee of 2.75%. It was also assumed that wind resources in the GOM will not change dramatically over the 20-year life of the farm.

5.4 Incentives

Because this is a renewable energy project, WindJax is eligible for tax incentives from the Federal Government. The tax credit utilized for this project will be the 30% Investment Tax Credit (ITC). This tax credit was chosen because of its availability to offshore wind projects that begin construction before December 31, 2025 [36]. An ITC is also the more favorable tax credit for offshore wind and the accompanying capital costs because it benefits the project up front [36].

5.5 Capital Cost

The capital costs for the GGOWF were found utilizing the JEDI model. Parameters were taken directly from the site and transmission system design. 12 Haliade X 14 MW turbines in a grid layout were input into JEDI. The water depth on the site is 17 – 24 m but a conservative number of 25 m water input into JEDI. The site is 54 km from shore. A twisted jacket foundation was utilized. 138 kW and 33 kV cables were input for the export and array cables, respectively. The results from the JEDI model resulted in **$680 million**, or **$4,051/kW** in total capital expenditures. Turbine components accounted for **$219 million**, or **$1,301/kW** while balance of system costs totaled **$268 million** or **$1,598/kW**. Soft costs, including construction finance and contingency costs, totaled **$194 million** or **$1,152/kW**. Table 1 shows a complete breakdown of the capital expenditures as calculated with the JEDI model. All the costs shown include labor, vessels, and materials and account for all expenses that can be foreseen within an offshore wind power plant.

Table 1: Capital Expenditures Breakdown

Category	Cost	Cost/kW	% of Total Cost
Turbine Components	$218,658,000	$1,301	32.12%
Substructure and Foundation	$66,285,736	$395	9.74%
Electrical Infrastructure Components	$65,377,175	$389	9.61%
Assembly and Installation	$22,015,393	$131	3.24%
Ports and Staging	$7,150,698	$43	1.05%
Development and Other Project Costs	$95,867,615	$571	14.09%
Engineering and Management	$11,760,000	$70	1.73%
Soft Costs	$19,971,177	$1,152	28.44%
TOTAL	**$680,524,618**	**$4,051**	**100%**

5.6 Annual Operational Cost

Utilizing the Offshore Wind cost modeling tool in JEDI, the annual operating expenses for the wind power plant are **$119/kW/year**, or **$19,971,177**. This annual cost includes all the expenses broken up into maintenance and operational costs. The maintenance costs include the labor, vessels, and materials for upkeep for both the onshore and offshore infrastructure. The total cost for maintenance annually is **$13,769,708** or **$82kW/year**. The cost of operations will be **$6,201,469** or **$37 per kW**. Operations includes the costs incurred from administration, insurance, and overall monitoring and management of the wind power plant.

5.7 Net Annual Energy Production and Levelized Cost of Energy

The net annual energy production was found utilizing SAM. The wind resource used for the analysis was "Southeastern TX – offshore (NREL AWS Truepower representative file)". With the input of the characteristics of the GE Haliade X 14MW turbine, the GGOWF produced **510 GWh** energy annually. With this net annual energy production, the LCOE of the GGOWF is **$.0995/kWh (real)** and **$.1240/kWh (nominal)**.

5.8 Power Purchase Agreement

WindJax will seek to enter a Power Purchase Agreement (PPA) with a utility in the Galveston. WindJax will offer power from the GGOWF at a price of **$.12/kWh** the first year with a 3% escalation each year. This yields a real and nominal PPA of $.1249/kWh and $.1555/kWh respectively.

5.9 Local Market Conditions

The price of electricity in the area the Galveston area will directly impact the GGOWF as it will determine if WindJax PPA price agrees with the market it is being sold to. Energy in the Greater Houston area was sold to residential consumers at a rate between $.1213 and $.1892 in the fourth quarter of 2021 [37]. The utility company must apply their markup prior to selling to the consumer, but WindJax believes with this being the first offshore wind energy project in Texas, there will be a competitive market for the electricity.

5.10 Financing Plan

The Galveston Giants Offshore Wind Farm will be operated under a single owner. The WindJax will be this single owner and will fund the project through sponsor equity, tax equity, and debt capital. The sponsor equity will be funded internally through investors in the GGOWF. The tax equity will come from the 30% ITC being utilized. These first two sources will account for 30% of the total capital costs, while the remaining 70% will be funded through initial construction debt that will be refinanced into term debt following the completion of construction. This lending structure recognizes the high risk of a project this size while providing some protections to the lender. [32] The lender will allow access to the funding as needed, rather than as a lump sum up front [32]. Following standards in the industry a construction debt rate of 5% and a term debt rate of 4% will be used [38]. The loan will be for a term of 18 years. WindJax will maintain a reserve fund that can cover up to six months of operating costs. This is to add security to the project in the event of a shutdown. This could be due to hurricanes or other natural or manmade hazards to the project. All profits from the power plant will directly benefit WindJax and their subsequent investors.

5.11 Cash Flow Analysis

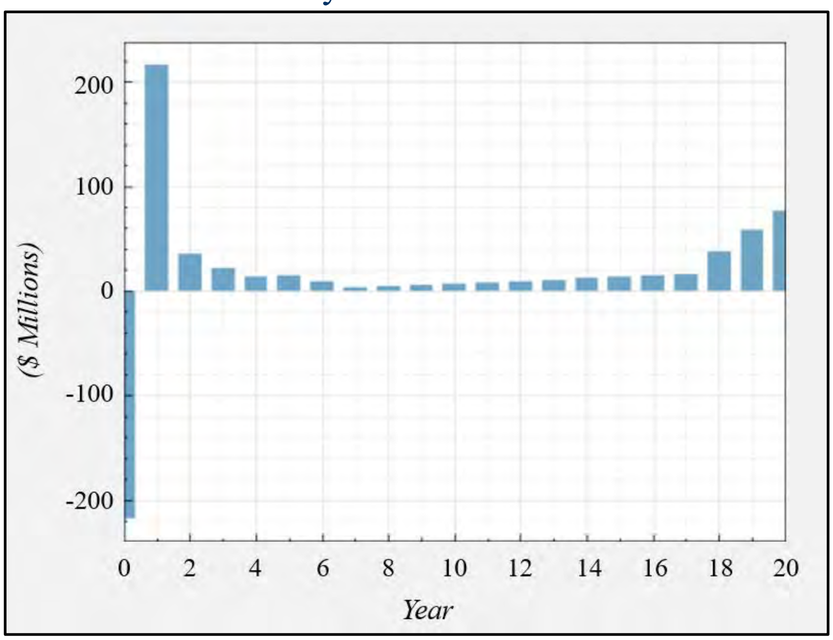

Figure 12: 20 Year Cash Flow Analysis

The negative cash flow in the first year shows the massive initial capital expense of the project. The rise in positive cash flow in year 18 shows the ending of the term debt after 18 years, providing strong positive cash flow in the final few years of the project.

6 Conclusion

In less than a year, the WindJax developed a comprehensive plan, and proved the economic viability of the Galveston Giants Offshore Windfarm. Given the global pressure to transition to fossil-free energy, and the Biden Administration's goal to install 30 GW of offshore wind energy by 2030 [39], projects including this one, are overdue when it comes to meeting our national sustainability goals. Development in the GOM presents a unique challenge, with its predisposition to hurricanes. By incorporating foundations which have successfully withstood hurricanes in the past and turbines which are certified to withstand the most severe weather conditions, the WindJax have taken the necessary precautions to ensure the GGOWF is best equipped for this challenge. Producing 510 GWh of available energy each year, will allow the WindJax to sell the GGOWF's energy at a price of $.12/kWh. Within these margins, the WindJax will offer a final bid price of **$15 million** for lease blocks 292 and A63 to the BOEM for the development of the first offshore wind farm in the Gulf of Mexico.

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