Engineering Design for an Offshore Wind Turbine Farm

Overview

The transition toward new, clean energy systems and solutions is a critical challenge of our time. To that end, a university-based energy research institute (the client), in collaboration with a student wind energy group, is considering the feasibility and impacts of construction of a 180 megawatt (MW) offshore wind turbine farm in a south-central region of the USA. The purpose of the project is to provide low-cost, renewable energy to help local utilities and their customers reach their carbon emission goals and diversify their generation portfolio.

A multidisciplinary team of five senior engineering design students accepted the challenge of developing an engineering analysis and design for the construction of the wind farm, transmission line, and operations facility. Each member of the student team brought a specific area of expertise to the project spanning construction management, structural engineering, geotechnical engineering, and environmental engineering. The student team provided a formal presentation of their preliminary and final designs to a panel of judges consisting of licensed engineers, research scientists, and members of the public.

Project Description

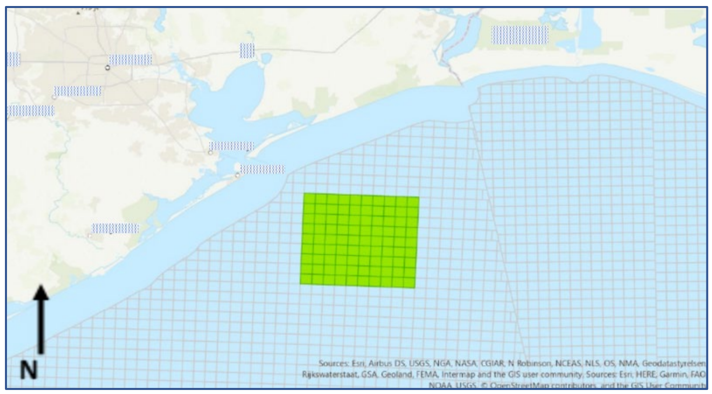
A formal Request for Proposals (RFP) was provided by the client to the student team. The offshore wind farm envisioned in the RFP included the following components:

- Approximately 12 wind turbines (enough to reach 180 MW).
- A collector system, transmission substation, and transmission line to connect and convert the electrical output of the wind turbines to the high-voltage transmission grid.
- A local wind farm power monitoring and teaching facility to include a power monitoring room, a classroom suitable for 40 students, a mechanical room, a computer room for wind farm monitoring, control and data logging and sanitary facilities. This building will be designed to blend into its surroundings and shall be at least LEED Gold Certified.
- Site improvements for the new facility including walkways, driveways, parking, underground power and data lines, and other site amenities.

Two offshore lease blocks, the wind turbine type, and the location of the onshore substation were previously selected by the client based on prior studies. Each turbine operates at a hub height of 150 meters with a rotor diameter of 240 meters. The turbines are based on the IEA Wind TCP Task Force's definition of the 15-MW reference turbines. The two lease blocks are located 24.85 miles offshore. Additional analysis was still required to optimize the location of the wind turbines to minimize wake loss and cable length.

The client communicated to the student team that an important overall goal of the project is to minimize the Levelized Cost of Energy (LCOE), meaning the design must be as cost efficient as possible without compromising the structural integrity and efficiency of the system. The total budget for all activities associated with this project is $700,000,000.

Location of the Existing Substation and Potential Monitoring/Teaching Facility.



Lease Blocks Selected for the Offshore Wind Farm.

Design Alternatives

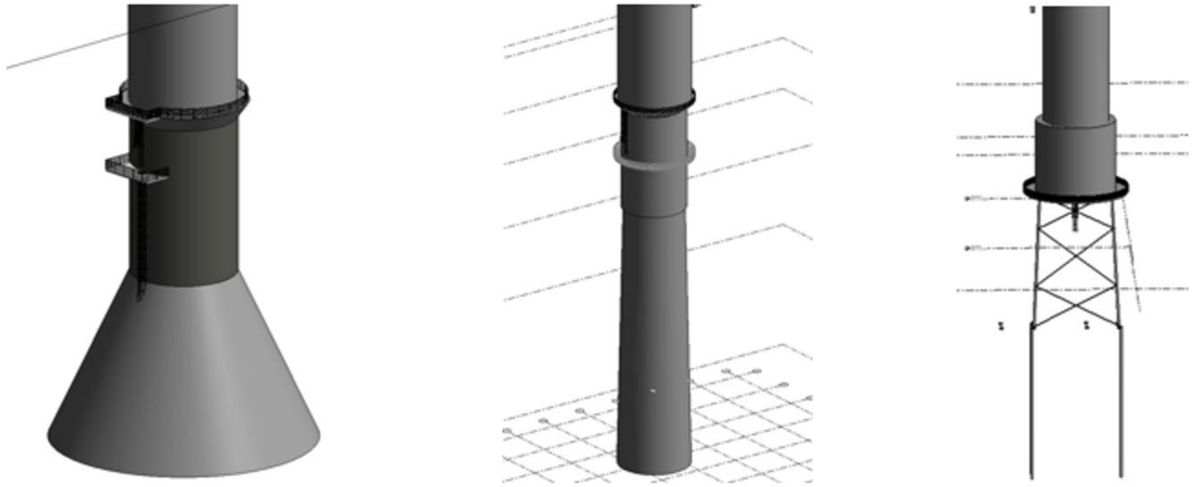
Three alternative design concepts were developed by the student team that met the criteria in the RFP. All three designs included an operations and maintenance facility along with differing approaches for the offshore subsurface system. Each alternative was analyzed with respect to structural, environmental, geotechnical, and construction engineering.

The Proposed Operations and Teaching Facility.

The first alternative considered was a gravity-based foundation (GCF). This would be designed from precast concrete with steel reinforcements and is suitable for sites with depths of up to 30 meters.

The second alternative considered was a monopile foundation. This would be designed as a long, single slender steel member typically installed at a water depth of 10 to 25 meters.

The third alternative considered was a jacket foundation. This would be designed as a lattice-truss structure that can be installed using piles or suction caissons typically installed in depths of 30 to 35 meters.



From Left to Right: Alternative 1: Gravity-Based Foundation, Alternative 2: Monopile Foundation, Alternative 3: Jacket Foundation.

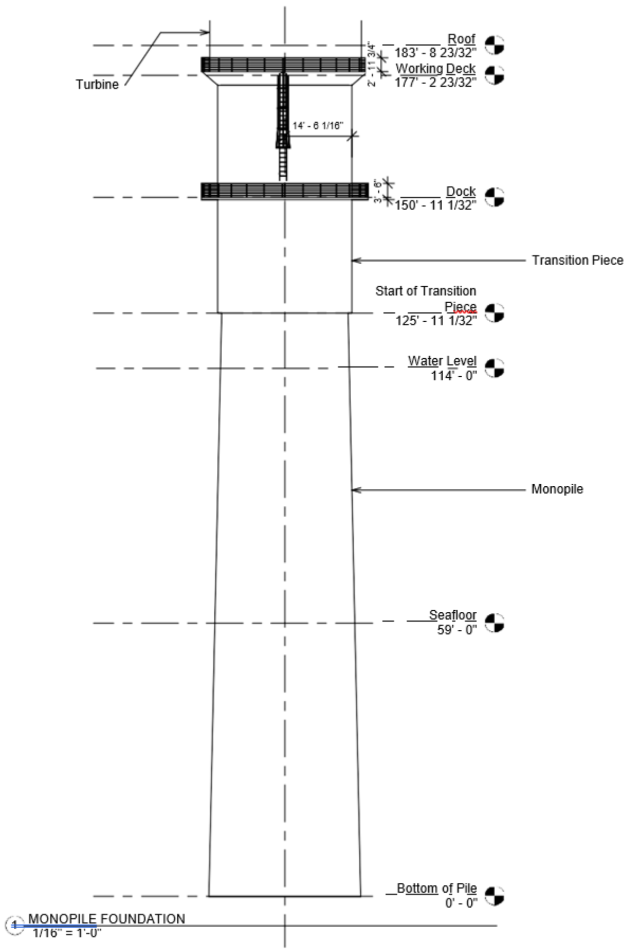
A multi-criteria decision matrix was developed to quantify the merits of each alternative. Input from the client was used to establish the criteria and to apply weights to each criterion in the matrix. The factors that were evaluated include environmental sustainability, social sustainability, economic sustainability, the project schedule, and the team's opinion of probable cost. Offshore wind energy, while having existed since 1991, is a new industry in the USA. As such, the student team was also challenged to identify the various sources of uncertainty for the site evaluations and preliminary design. These included data-based uncertainty, knowledge-based uncertainty, uncertainty in the estimate of probable cost, and the importance of uncertainty in design.

Criteria	Goal	Weight	Alternative 1	Alternative 2	Alternative 3
Approximate Construction Cost [$]	Min	23%	684,000,000	682,000,000	727,000,000
Transportation Cost [$]	Min	19%	64,320,000	50,400,000	105,600,000
Installation Time [weeks]	Min	21%	13.7	8.9	18.9
Impact of Benthic Habitat [ft^2]	Min	13%	415.5	70	12.5
Depth of Foundation Embedment [m]	Min	16%	3.5	28	23.5
30 m Sound Pressure Level	Min	8%	128	112	94
Total		100%	32.54%	**35.50%**	31.96%

Decision matrix for the three alternatives.

A key step in the alternative evaluation was the student team's formal presentation. A PowerPoint presentation was created that summarized the three options with a focus on the pros and cons of each one. Each student on the team presented a portion of the project through the lens of their technical specialty. CAD drawings of the three foundation designs were presented to describe the technical merits and key differences of each alternative.

The student team ultimately recommended Alternative 2, the monopile foundation, as the best option to meet the client's goals. This foundation will achieve the lowest estimated cost and a longer



Detailed CAD drawing of the Alternative 2 Monopile Foundation Final Design.

lifespan without having to sacrifice structural integrity. With an overall budget of $700,000,000, the monopile project has an Opinion of Probable Cost of $683,000,000. This project has an anticipated duration of approximately three years and two months.

The monopile design makes up most worldwide offshore wind foundations. The method has found success due to its lowered installation time and suitability for lower water depths. The structural support that the monopile provides was found to be adequate for the existing conditions in the proposed project site based on studies and calculations performed by the student team.

With the client's approval, the team proceeded with the final design. Their work product includes a geotechnical report, verification of compliance with applicable codes, structural calculations, drawings, and specifications. The Moment Foundation Analysis and Design (MFAD) software package was used for the foundation analysis. Specifications included bid forms, terms and conditions, and technical sections for key project elements. A student serving as the project manager tracked and coordinated the team's effort and project schedule.

A summary of the construction schedule was developed for the project, as given below.

Task	Start Date	End Date
Permitting, Regulatory Review	6/30/2022	10/10/2022
Project Planning	7/13/2022	12/30/2022
Turbine Manufacturing & Shipping	8/01/2022	8/01/2025
Construction Start	11/18/2024	-
O&M Construction	12/6/2024	3/28/2025
Foundation Install	12/02/2024	3/28/2025
Tower Erection	2/10/2025	4/03/2025
Project Completion	-	8/11/2025

This schedule was also summarized in a Gant Chart, which was included in the presentation to the judges.

A geotechnical report was prepared based on twelve Standard Penetration Test (SPT) soil borings conducted in the offshore lease blocks and one STP boring conducted in the onshore lease block by a private company in February 2022. In addition, a geophysical survey was conducted by the same company to obtain bathymetry data and revealed the water depth in the offshore blocks was 17 to 18 meters at the locations of the proposed turbines. The worst soil conditions were found in Borehole 9, which consisted of three main layers classified by USCS as lean clay (CL) from 0 to 4 meters, clayey sand (SC) from 5 to 10 meters, and lean clay from 11 to 42 meters. Since it is unfeasible to design foundations for the geotechnical conditions of each of the 12 sites, the industry standard is to design one foundation for the worst soil conditions encountered and implement that design at each of the sites. The geotechnical investigation and calculations therefore proceeded using the soil conditions encountered at Borehole 9. A detailed stability analysis of foundations using the MFAD software was also included in the report.

A formal presentation of the final design was made to the client and a panel of judges. The entire student team participated and explained the details of their design and the considerations used in establishing final configuration. A projected construction schedule and final opinion of probable cost were delivered. Copies of the plans, specifications, and a project manual were included in the presentation materials.

Collaboration

Collaboration was emphasized by the class instructors and was critical to project success.

The proposal prepared in response to the client's RFP set the tone for collaboration between team members. A project manager was selected by the students, and the anticipated design activities and project roles were divided among them based upon each student's study emphasis and career interests. However, no individual had sole authority over any aspect of the project and the project manager coordinated these activities.

Perhaps the best example of team collaboration would be the preliminary and final design presentations before a panel of judges. The presentations were seamless and professional with all team members contributing to the slides and speaking to their individual specialty and role.

Collaborative efforts extended outside the team as well and included five professional mentors that were assigned to the team. All mentors were licensed engineers with differing expertise in the four areas of engineering analysis. The mentors helped guide the project and shared advice, grounded in years of experience. The panel of judges included licensed engineers, research scientists, and members of the public. In addition to evaluating the alternatives and design, judges asked questions and offered suggestions for improvement. All these activities were coordinated by three principal instructors for the class, all of whom are licensed professional engineers.

Protection of Public Welfare

With public welfare in mind, the team rigorously evaluated applicable health and safety regulations. A partial list of codes referenced includes:

- American Society of Civil Engineers (ASCE) Code of Ethics
- Bureau of Ocean Energy Management (BOEM) – Code of Federal Regulations Title 30, Chapter V
- IEC 61400-1:2019, Wind Turbines – Part 1: Design Requirements

- 29 CFR 1910.269, Electric Power Generation, Transmission, and Distribution
- DNV-OS-J201(2016) – Offshore Substations for Wind Farms
- ASTM F1166-2013 – Standard Practice for Human Engineering Design for Marine Systems, Equipment and Facilities (Section 18.8)
- AWEA, Recommended Practices for Design, Deployment, and Operation of Offshore Wind Turbines in the United States (2012)

Particular attention was given to minimizing safety hazards during and after construction and to ensure the safe movement of personnel and heavy equipment between vessels and the offshore structures. The engineering designs include safe boat landings on the turbine foundations with caged ladders to allow for safe scaling of the structures. The student team also noted the project's proximity to residential areas, both on-land and offshore, as potential areas of conflict for human health and safety.

In addition to engineering analyses, the student team considered the sustainability of the project in terms of the triple bottom line. This includes an assessment of economic, social, and environmental sustainability.

Economic evaluation, which reflected the team's understanding of their fiduciary responsibilities to the local community, was an important factor in making design decisions. The recommendation of Alternative 2 was the least expensive design alternative in terms of both construction and transportation costs while providing a longer lifetime of use.

Social considerations included a recognition that local community members may oppose the development of an offshore wind farm due to the potential social and economic impacts the project could have on the community. These include, but are not limited to, the destruction of natural ecosystems, community disturbance associated with construction, and interference with recreational and commercial fishing. The student team also drew lessons from local industry resistance to a prior offshore wind energy project in the north-eastern USA demonstrating the importance of recognizing the community's concerns and point of view and communicating the project's purpose, schedule, and agreements with other industries.

Environmental sustainability considerations included the analysis of scouring protection and impact to the marine environment from construction and operation of the wind turbine farm. The 30 meter sound pressure level in the decision matrix uses past studies on soundwaves created during installation of a foundation. Before installation, sound propagation will alert all marine wildlife since the monopile driving of Alternative 2 might cause sound waves that can affect sea creatures. After the foundation installation, scouring protection will be implemented by placing gravel or similar material on the interface between the seafloor and the foundation.

Multidisciplinary Activities

It is rare for a civil engineering project to not involve multiple engineering disciplines, and this project was no exception. The instructors built the student teams with the specific intent of covering multiple disciplines and skill sets. Additionally, the client's RFP explicitly identified the multidisciplinary nature of the project and requested that each design alternative will be evaluated with respect to at least four of the following:

- Construction engineering
- Environmental engineering
- Hydrologic/storm water engineering
- Transportation engineering
- Structural engineering
- Hydraulic engineering
- Structural engineering
- Surveying and Geospatial

The makeup of the student team met the need for multiple disciplines, and included students with course emphasis in construction management, structural engineering, geotechnical engineering, and environmental engineering. The mentors and judges also exhibited a spectrum of experience and expertise.

The work product of the team demonstrated their broad capabilities. The team developed detailed CAD drawings of the design alternatives accompanied by extensive geotechnical analysis of the foundational elements. Extensive economic evaluations of the construction costs and ongoing operations were included in the opinion of probable cost. The team also showed sound judgement in assessing the impact on the marine environment as well as more intangible considerations such as community expectations and concerns.

Knowledge and Skills Gained

Perhaps the most valuable knowledge gained by the team in executing the project was exposure to and understanding of best practices for civil engineering projects. Out of necessity, undergraduate work concentrates on the principles and methods of engineering analysis. Experienced professionals know that many of the decisions made and problems addressed in engineering practice are non-technical in nature. Because this was a full “real-world” project as opposed to an exercise, the team was required to perform both technical and non-technical tasks.

The team also learned about the administrative side of engineering. They had to develop cost estimates for the engineering, track time, and do performance reviews of other team members. The team also had to adhere to rigid schedules for design and meet inflexible deadlines. This pushed them to develop their planning skills and the goal-oriented activities that resulted from those skills.

Most problems encountered in undergraduate engineering courses are well defined and have a definite answer. This renewable energy project exposed the students to open-ended problem solving. The team had to develop their research skills, work with incomplete information, and learn to derive necessary information from associates and clients.

There were also technical skills gained during the project. One of the most challenging tasks for the team was learning the drafting skills needed to create engineering design drawings. This meant not only learning CAD and MFAD software, but more importantly, learning the expectations for content and format of professional drawings.

This experience reinforced the value of teamwork and the value that each team member brings to the table; thereby preparing students for their future careers. The success of this design project is the result of students, mentors, and clients working towards a complex objective to benefit and enhance the community.