Spring 2024

# Floating Offshore Wind Turbine Analysis and Discovery

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Honors Thesis, Spring 2024

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Abstract

This paper encompasses the challenges and development of four different locations that have been notably leading the FOWT industry. These areas are China, California, Ireland, and Maine. Their obstacles through the permitting cycle and civilian pushback are noted, along with the production and current phases of each location. Furthermore, certain lifecycle phases within of FOWT have been studied in additional sites and will be discussed. In particular, the construction phase, use stage, and end of life. These studies were conducted to optimize the current situation attempting to make it more feasible for industry. Finally, conclusions will be made regarding which of the four locations would be most preferred and what should be included to create the most ideal farm.

# Contents

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# 1: Introduction

The floating offshore wind turbine (FOWT) industry is making strides across the globe from the legislative chairs to hands-on innovative testing.

The first section discusses the challenges with the cradle to gate phase of a FOWT. The United States was analyzed on its barriers that it must cross to get the turbines out of the design phase. To make the renewable energy source more palatable, an analysis on lowering the levelized cost of energy was conducted. All areas of interest had different difficulties and pathways towards launching these farms out of the design phase and were examined.

The second section looked at the designs that each area of interest has been testing with the exception to California. Traditional platform types are also mentioned as most of the designs are based on the three basic models. Optimization within the maintenance phase was researched. A case study from the University of Cincinnati found that lowering production losses lowered the overall cost of the O&M phase.

The third section explored potential end of life disposal as it is currently being overlooked by the industry. The Rigs to Reefs program by the offshore oil and gas industry is a prospective method. This process ensures that the turbines will be sunk and form artificial reefs to help encourage aquatic ecosystem growth.

Lastly, a concluding analysis was done based on preferable location and design. Additionally, explaining why the methods chosen would be the most optimal approach in creating a floating offshore wind farm. Floating offshore wind farms are expected to be the next promising source of energy that can power communities.

# 2: The Launch

## 2.1 Societal Roadblocks

FOWT farms are expected to be a favorable source of energy that can sustainably power neighborhoods. However, roadblocks have been created by society, hindering the energy source from developing further than the early design phase. These barriers are similar from location to location but differ in their pathways to resolution. This is due to specific governmental outlook on offshore wind and how they deem fit to move on.

The first roadblock is the accessibility of obtaining a permit. The process is lengthy and has taken up to 10 years before construction begins due to the massive hoops clean energy must jump through. Within the United States, Biden’s climate agenda of 2023 granted federal permission to move forward in all sectors of renewable energy, backing them with billions of dollars of funding (Tankersley et al., 2023). An example of this process can be shown through New Mexico. New Mexico was not able to install offshore wind, but onshore wind farm coined SunZia. It is 550 miles long and was originally proposed in 2006 by Pattern Energy (Tankersley et al., 2023). In 2023, it was granted its final federal permit and expected to be completed in 2026 (Tankersley et al., 2023). Biden’s agenda is currently facing limitation as Republican legislators are preventing progress by passing laws within their states. These laws make it easier for local communities to fight against renewables. A study in the spring of 2023 from Columbia University’s Sabin Center for Climate Change Law found a 35 percent increase in local ordinances, restricting renewable energy development (Tankersley et al., 2023). Also, there has been nearly a 40 percent rise in “serious organized opposition” of wind or solar projects (Tankersley et al., 2023). The main hesitation from local communities is related to the installation impacting their daily lives.

The second barrier is the workforce needed for construction and development of these projects. Across the globe, the unemployment rate is historically low, and these projects need skilled workers, creating an already small pool to choose from (Tankersley et al., 2023). This type of construction requires tradesman looking to develop a new craft within the niche market. These designs and technology are new to every party involved so old practices cannot be easily translated over. To attempt to combat this issue, energy companies like ReVision Energy in the United States started to train workers inhouse (Tankersley et al., 2023). They offer apprenticeships for new employees to get their electrician license in hopes to encourage employment (Tankersley et al., 2023).

The final issue is supply chain breaks. There are shortages across the entire pathway. FOWT companies are competing with the growing electric car market for materials (Tankersley et al., 2023). This has generated massive wait times for critical items like panel boards and disconnect switches; creating the constant trend of not enough to go around (Tankersley et al., 2023). The United States has been attempting to gain back independence in their supply chain by pulling away from China. This has limited the amount of growth in the construction of floating offshore wind turbines.

In conclusion, permits, declining workforce interest, and supply chain breaks have been limiting the development of the floating offshore wind farms.

## 2.2 LCOE Opportunities

Once permits start to receive approval, the offshore wind farm must be planned efficiently. To determine if a design is going to have a positive effect on society, a unit of measure was declared: Levelized Cost of Energy or LCOE (Díaz & Guedes Soares, 2023). The measurement represents the lifetime cost of an energy source per unit of energy generated (Díaz & Guedes Soares, 2023). The offshore wind industry has seen improvement by decreasing their LCOE but not enough to receive acceptance amongst society. The phases with the most cost reduction opportunities are the installation and logistic phases (Díaz & Guedes Soares, 2023). The logistic phase starts with the modeling of a potential site. Ideally, in a coastal region that has easy access to large ports for construction and good wind patterns. From there, the design of a farm can commence shown through the flowchart in figure one.

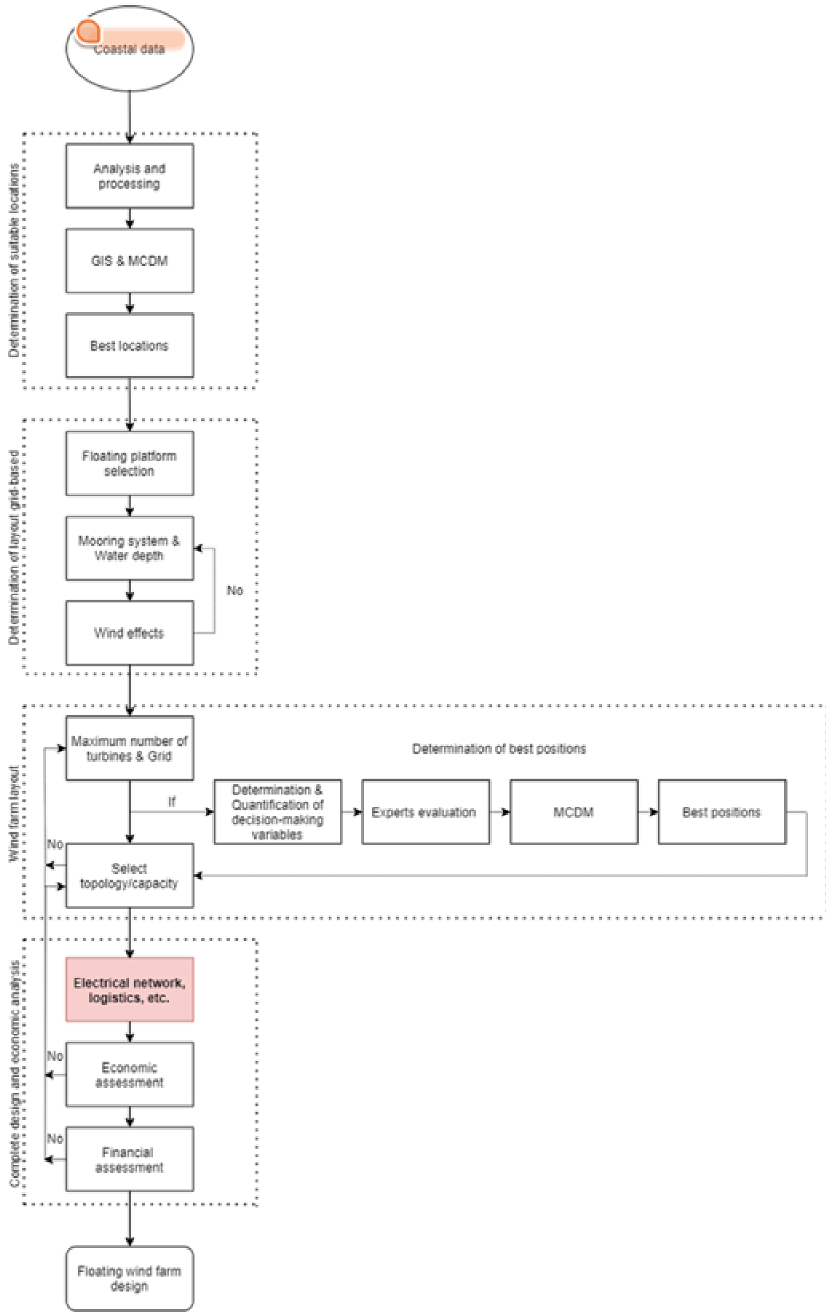


*Figure 2.2.1 Design phase timeline of a FOWT (Díaz & Guedes Soares, 2023)*

Using **Error! Reference source not found.**, planners and investors can handle the design in phases making it easier to track and create milestones lowering the LCOE. To show the benefits of LCOE optimization a case study was performed.

The site was located on Ireland's west coast called the F15 project (Díaz & Guedes Soares, 2023). Based on research, the area has excellent wind resources and good conditions for positioning wind turbines. The platform selection was chosen based off the location. A tension leg platform or TLP was selected (Díaz & Guedes Soares, 2023). TLP are floating foundations moored vertically to the seafloor as shown in Figure 2.2.2.

*Figure 2.2.2 Tension Leg Platform design (Shektaei & Sadati, 2022)*

The platforms are directly assembled in the coastal facilities and towed out to sea without depth being of concern. TLP optimizes the LCOE due to the manufacturing and storage. This sums up to 5-10% of logistic costs from the total investment costs (Díaz & Guedes Soares, 2023).

Once the design and location are chosen, the installation processes begins; components must be manufactured and brought over to the site. These components can be broken up four sections: namely wind turbines, support structures, cables (including array cables and export cables), and offshore/onshore substations (Díaz & Guedes Soares, 2023). These components are manufactured separately with their own supply chains and overseen by a project director. Then, components are given to a port operator who is responsible for the storing of these materials until construction.

The first component that is brought to the site is the namely wind turbines or generators (Díaz & Guedes Soares, 2023). There are subcomponents of the generators shown in Figure 2.2.3.

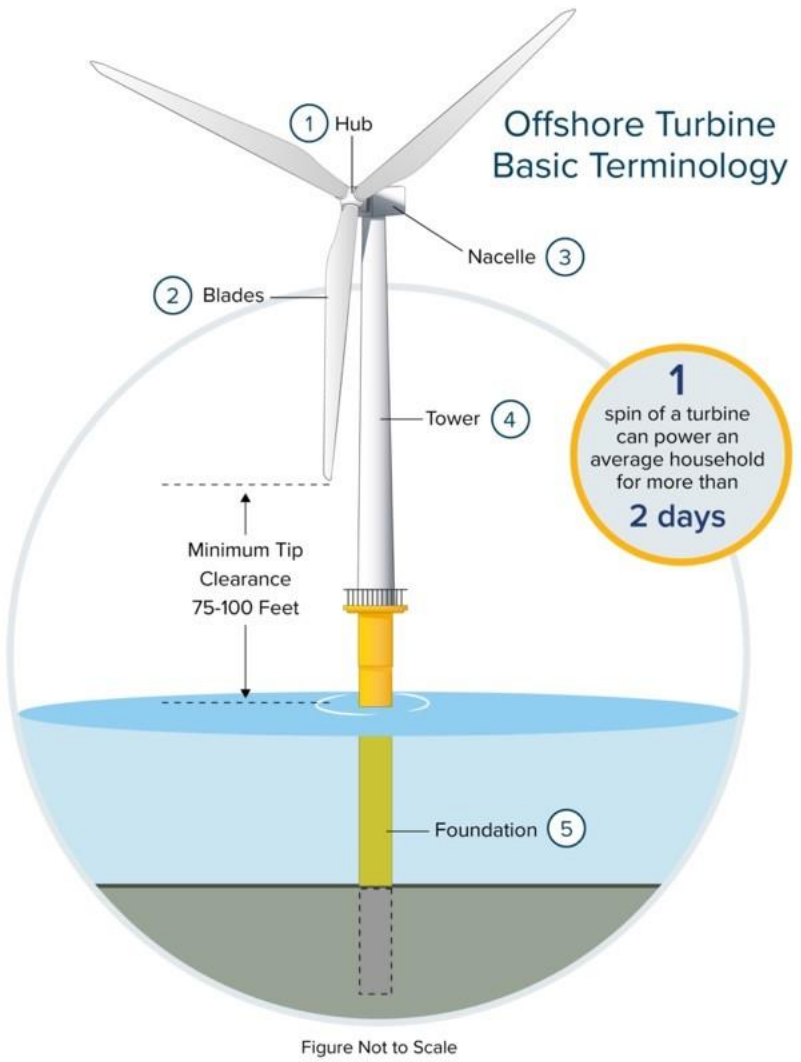


*Figure 2.2.3 Subcomponents of generators (Offshore Wind, n.d.)*

The nacelle is used for power generation and controls. The rotor are the blades and the tower with transition pieces supporting the rotor and nacelle interfacing with the foundation (Díaz & Guedes Soares, 2023). Each of these subcomponents have their own supply chain processes but are delivered to the port where the construction of the generator can begin. The purpose of the subcomponents being installed onsite is minimizing the amount of construction offshore.

The port facilities are divided into manufacturing and mobilization and is critical to the LCOE. The manufacturing port is located close the offshore wind farm and was used for deployment

(Díaz & Guedes Soares, 2023). The mobilization ports are temporary and are used when equipment must be parked. These are most common in developing areas that do not have a manufacturing port nearby or when steel production is needed. However, in floating offshore wind, concrete platforms are commonly used making a mobilization port not essential (Díaz & Guedes Soares, 2023). These ports must have extensive future planning as they need to be able to hold future expansion of the farm.

The selection of the vessels that will transport the materials offshore is essential to lower the LCOE. There is an extreme balance between the leveling cost, minimizing durations, ensuring safe operations, and minimal environmental impact. As the structure in the F15 project is made up of large pre-assembled materials that were constructed in the manufacturing port. The project is optimized lowering the LCOE as compared to other energy source counterparts (Díaz & Guedes Soares, 2023). This is due to the massive size of the prefabricated materials and the serial nature of the installations that mimicking marine oil and gas construction (Díaz & Guedes Soares, 2023). The modern-day challenge of the vessel market is the need for more boats that can transport materials. As the number of wind farms increase, there has been no movement in the creation of transportation vessels. This is causing an increase in price and slowing down expansion.

The management of each of the step is crucial to decrease LCOE to other energy sources. This organization for a cradle-to-gate must be extensively thought out and designed particularly in the early project development phases. This process must be done by trial and error as floating offshore wind farms are in the immature stage of development with limited knowledge across the entire industry. This will take many experts in different fields to efficiently manage the cradle to gate of a floating offshore wind farm.

## 2.3 Locational Analysis Cradle to Gate

### 2.3.1 Maine

In 2021, the Governors Energy Office (GEO) applied for 15.2 square miles of offshore land for 12 wind turbines with floating hulls from the Bureau of Ocean Management (UMaine, n.d.). The University of Maine has been at the forefront of offshore wind research and has been looking into the technology for over 15 years; patenting these hulls (UMaine, n.d.). This came after there was much controversy with the fishing community. Fisherman have expressed that the floating platforms disrupt the ecosystem of clams, lobster, and squids (Tankersley et al., 2023). President Biden is attempting to please both sides of the coin. He saw the opportunity to tap into a huge renewable energy market but also wants to support the community that is directly affected. Biden has mentioned that the US will compensate the fishermen for their losses (Tankersley et al., 2023). In July of 2023, a bill was approved by the Maine legislation for 3000 MW of electricity by offshore wind by 2040 (Sharp, 2023). This amount of electricity can power 900,000 homes, almost half of Maine (Sharp, 2023). Maine's Senator Lawrence has been sponsoring this idea, marketing it as a creation for more jobs and to have a positive environmental impact. However, Governor Mills has not been the greatest advocate for this plan. The bill proposed by the Lawrence came after an earlier bill was vetoed by Mills (Sharp, 2023). Mills is fearful of the labor required to install and maintain these turbines (AP News, 2023). The need for skilled labor could be used to stifle out competition and eliminate thousands of in-state workers from contention (AP News, 2023). Mills also spoke on behalf of the Maine fishermen and the effect on the lobster ecosystems (AP News, 2023).

With the continued advancement in floating offshore platforms, all legislative parties were able to come to an agreement, putting forth the funding needed. These floating offshore platforms can be far enough out that the fishing community would not be affected and not disrupt coastline views of Maine (Tankersley et al., 2023). It is hard however, to get locals to understand this. This topic has been researched at Colby College of how to help communities understand and accept the idea of renewable energy without it affecting them (Tankersley et al., 2023).

One potential location to harness the Maine wind is Sears Island. Although the island is undeveloped, it is a hotspot for tourists, locals, and environmental groups. They are standing in the way of getting the site approved (Tankersley et al., 2023). Even though all groups the share the same values of committing to a future of clean energy, they rather have the government choose a different site. They have stopped the construction of nuclear power plants and gas import terminals on the island (Tankersley et al., 2023). But these groups may lose the fight now as the state is extremely attracted to Mack Port which would be in clear and visible range to Sears Island. The Port is connected to highways and sits beside deep water making it desirable (Tankersley et al., 2023). The island is also owned by the state and is divided into two thirds nature preservation and one third zoned for a potential port (Tankersley et al., 2023).

One supporter of the island site is Habib Dagher who is the founding executive of the University of Maine's Advanced Structures and Composites Center. He has been coined as the godfather of Maine's offshore wind efforts by the New York Times.

There are numerous benefits to his offshore technology, encouraging development in launching the farm. First, US shipyards can be responsible for the concrete production eliminating the need for outsourcing (UMaine, n.d.). Second, bridge construction techniques can be used when creating patented platform (UMaine, n.d.). Extensive training would not be required when it comes to the construction meaning that an old dog doesn't have to be taught new tricks. Third, concrete has a higher resistance to corrosion and less maintenance over time (UMaine, n.d.).

Also, the design chosen can be deployed great distances from shore. The design has received backing from Department of Energy, Mitsubishi Corp, and RWE (German electric company) (UMaine, n.d.).

### 2.3.2 Ireland

The next location of interest is Ireland.  Locals have been expressing concern that the views of Ireland will be ruined by the turbines. They want to see if there is a possibly for floating and not fixed bottom that was originally proposed in 2008 (O'Sullivan, 2023). One area that has been a named a prospective site is MacDara Island shown in Figure 2.3.1 (O'Sullivan, 2023).

*Figure 2.3.1 Birds eye view of MacDara Island (O'Sullivan, 2023)*

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The area itself is an example of an early Christian oratory making it an integral part of the beauty and wildness of the coast (O'Sullivan, 2023). The shallow reefs that encompass the island are a great place for lobsters and crabs to reside. Fishermen would not be able to farm if the ecosystem was disrupted (O'Sullivan, 2023). The drilling done by the turbine construction would cause major disturbance. Additionally, the Mace Head weather station would have to be moved as air movement created by the turbines would disrupt the data collected (O'Sullivan, 2023). The newfound rush from the government has been the target of greenwashing by Blue Horizon (O'Sullivan, 2023). This group is led by Mick O'Meara who wants the floating bottom turbines to be farther out than 60 meters and has been discussing with fisheries about potential designs (O'Sullivan, 2023).

In early 2023, seven projects were fast-tracked through the permitting process and likely to be granted license to intensely survey locations. These projects will be a part of a wind auction bidding to supply energy in a 20-year time frame. The climate action plan by Ireland requires seven GW of renewable electricity, far more than what the country requires (O'Sullivan, 2023). The projects are being developed by Fuinneamh Sceirde Teoranta (FST) and owned by Macquarie's Green Investment Group (GIG) (O'Sullivan, 2023). GIG has compensated 30 local fishermen last year for keeping out of a prospective area due to surveying. This may have been a potential ploy to hide the skeletons in their closet (O'Sullivan, 2023). An Ireland civil engineer SiobHan Kennedy said that FST failed to demonstrate how the government wanted the turbines to be on the same page of environmental protection (O'Sullivan, 2023). Also, GIG has a bad track record of keeping finances in check when it comes to protection of the environment (O'Sullivan, 2023).

Four projects in Ireland were awarded by a wind auction in May 2023 one of them being GIG (Wind Europe, 2023). These structures will have a combined electric capacity of 3 GW (Wind Europe, 2023). The price of the winning bid was much lower than expected (Wind Europe, 2023). They were granted 20-year contract-for-difference or CfD (Wind Europe, 2023). A CfD is a contractual mechanism designed to incentives investments in renewable energy (Low Carbon Contracts Company, n.d.). Three of the projects are located off the East Coast while one is located off the West Cost all of which are to start in 2028. This is ironic as Ireland's climate action plan is to be completed by 2030 (Wind Europe, 2023). The government promises wind operators compensation whenever their project is curtailed due to conflicts in grid congestion (Wind Europe, 2023). Also, the government is fully indexing the operation and maintenance costs to inflation. They also see the need for port infrastructure via supply chain management and have put that as their top priority (Wind Europe, 2023). These projects also must make payments to the marine and coastal communities until the farms start to produce electricity.

### 2.3.3 California

California has become a hot spot within the United States to construct offshore wind farms. The strong consistent winds have been identified as a key resource with up to 112 GW of power for 1.5 million homes (Cart, 2023). The location of the wind farms can be shown in Figure 2.3.2.

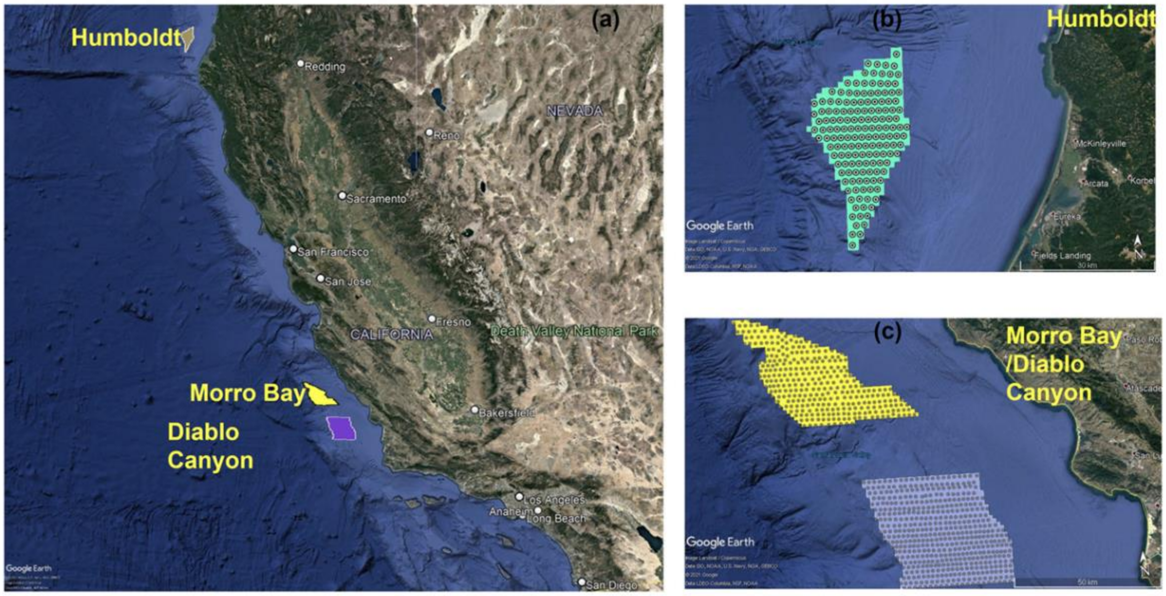



*Figure 2.3.2  Locations along the California Coast (Cart, 2023)*

These areas are Humboldt, Morro Bay, and Diablo Canyon. These areas are officially recognized by the state of California and the Bureau of Ocean Energy Management (Cart, 2023). In a recent auction, five energy companies divided up the 583 square miles of ocean waters (Cart, 2023). Planners are looking to use floating offshore platforms as the strongest winds are about 20 miles off the coast and more than half-mile deep (Cart, 2023). The companies chosen are willing to spend up to five years prepping technical plans and environmental analysis. The waters contain a large fishing habitat with multiple endangered species. Also, the commercial fishing industry generates about 22 billion dollars from this area, sparking conflicts (Cart, 2023). Much of the environmental analysis may not come into fruition until the turbines are installed due to lack of scientific relation and understanding. Following the five year analysis, there will also be a two-year approval process and a five-year construction process. However, urgency is being pushed by the California government as they promised to be fossil fuel free by 2045 (Cart, 2023). The scale of size being pushed is leading companies into a dark wave of uncertainty.

One positive starting to come out of the construction of Humboldt is new jobs projected to be created in the area (Cart, 2023). This will lower the unemployment curve as one out of five people currently live in poverty (Cart, 2023). However, the Yurok Tribe feels as if they have lived through this before (Cart, 2023). They know they have the potential to live through a huge economic opportunity. Conversely, they are not ready to face the potential raised cost of living which is what is steering them away from the idea. The Yurok have been capitalized on before and will not be taken advantage of again (Cart, 2023).

### 2.3.4 China

China accounts for 30% of the world's greenhouse gas as of 2020, most coming from coal power (Haugan, 2020). The Chinese communist party sees electricity as an important pillar of modern society (Haugan, 2020). China's original power grid was built to hold a steady supply of coal (Haugan, 2020). In the past 20 years, they have experienced massive increase in their energy consumption. As a result, China has been looking into ways to break up its energy mix by renewable sources. Communist authorities have the right to oversee the innovation of wind systems to their desired capacity and overcome challenges by implementing policy as they see fit. The interest in wind energy began in 2002 when technology was imported from Denmark and Germany (Haugan, 2020). The boom started in 2008 and led to overcapacity and poor functioning turbines (Haugan, 2020). Governing authorities had to modify the criteria to focus on quality over quantity. This strategy was backed by investment from government and innovation is on the rise. In 2021, China overtook the United Kingdom as the nation with largest offshore wind power capacity (Haugan, 2020). Out of the 10.5 gigawatts of energy capacity available, China holds 8 GW of energy (Haugan, 2020). China is planning to move to floating offshore wind turbines by 2026 with a potential capacity of 477 MW in 2026 (Wyk, 2022). In 2022, China domestically produced and installed a floating wind turbine off the coast of Guangdong Province (Wyk, 2022). In 2023, China is starting to integrate fishing and wind power as one with their new design backed by Shanghai Electric (Wyk, 2022).

# 3: The Design

## 3.1 Platform Design

Floating offshore wind turbines are becoming more popular in coastal areas due to the limits of fixed bottom ocean range. Floating platforms can exceed the 60m threshold opening the exploitation of better wind conditions further offshore. There are also additional benefits including: the ease of construction, less expensive, and less impact visually from land (Ojo et al., 2023). The roadblock preventing the increased expansion of the floating technology is the cost of commercialization and capital expenditure (Ojo et al., 2023). As the push towards green energy increases, innovation will evolve towards large expansion on floating offshore turbines to lower the expenditure needed.

There are three main different types of floating platforms are being used across the globe. They were originally designed from oil and gas markets (Ojo et al., 2023). The first is the tension leg platform, the second is the spar design and lastly, is semi-submersible platform. These can be shown in Figure 3.1.1.

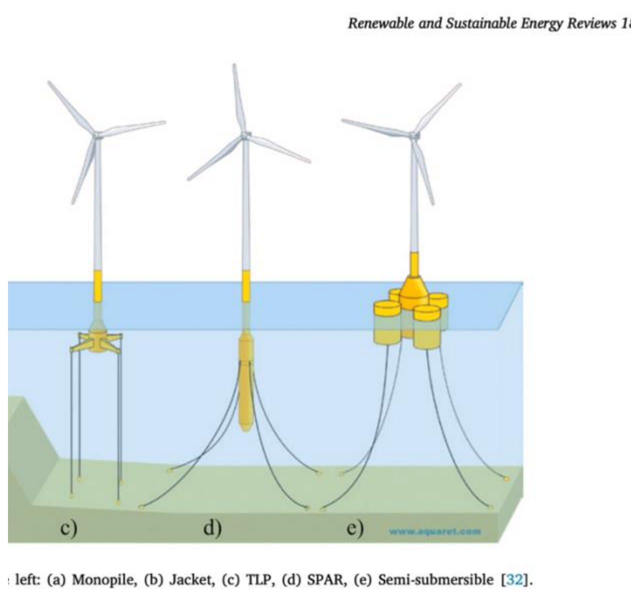



*Figure 3.1.1 Three main floating platforms used in industry: TLP, Spar, Semi-Submersible (left to right) (Asim, 2022)*

Each platform has their own stabilization mechanism: mooring, ballast, and waterplane respectfully (Ojo et al., 2023). The ballast spar design has a floater below the water surface that moves the center of gravity below the center of buoyancy (Ojo et al., 2023). This stabilizes the turbine by counteracting water movements. In the mooring tension leg platform system, the mooring lines experience high tension to balance out ocean movement (Ojo et al., 2023). The waterplane semi-submersible has a second moment of waterplane area with respect to the rotational axis creating a restoring moment to offset the rotational displacement (Ojo et al., 2023).

There are benefits and challenges of each of these platforms. The first one explored will be the spar system. The spar system has low operational risk with a simple fabrication process (Ojo et al., 2023). It has inherited stability due to the ballast design meaning it can take severe sea conditions (Ojo et al., 2023). As the ballast design is simple, it is also cheap. However, the installation cost of the system is high. There must be a specialized vessel used in installation (Ojo et al., 2023). The deep-sea waters create limited port access causing the assembly to be offshore and challenging. The ballast system lastly creates a large seabed footprint.

The second design is the semi-submersible. There is minimal risk to installation and operation in different weather conditions (Ojo et al., 2023). The heave plates shown in **Error! Reference source not found.** reduces the potential of overturning from sea conditions.


*Figure 3.1.2 Semi-submersible design elements. (Du, 2023)*

The system also is insensitive to soil conditions (Ojo et al., 2023). Challenges are in the fabrication process. The manufacturing is non-industrialized requiring labor intensive practices and long lead times (Ojo et al., 2023). The semi-submersible can be built in one piece meaning it cannot be done offshore and requiring skid facilitates.

The final platform is the tension leg. The benefit of this platform is that it is light creating a cheaper material cost (Ojo et al., 2023). The simple structure can be constructed off or onshore. The mooring lines are small and have a small seabed footprint creating versatile water-depth flexibility (Ojo et al., 2023). The cons of this platform are the complexity of mooring anchoring system making it the most expensive out of the three (Ojo et al., 2023). The high tension presents a high operational risk of mooring failure. There needs to be a great amount of investigation into the seabed conditions to ensure the high-tension mooring can be used.

## 3.2 LCOE Spar Design

In 2022, a comparative study was conducted regarding different angles of a spar design and their levelized cost of energy through regions in Great Britain and Ireland (Ojo et al., 2023). There were four different designs studied as shown in Figure 3.2.1.

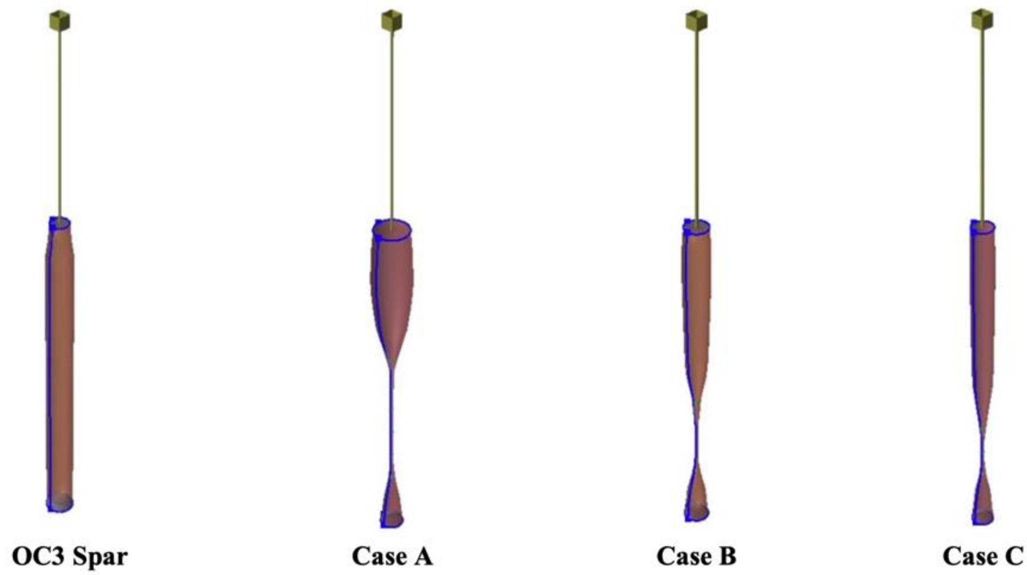



*Figure 3.2.1 Four design cases studied (Ojo et al., 2023)*

OC3 Spar is the original design of the system and over-dimensioned for safety reasons. This means within the study it would have the highest mass amongst the other cases (Ojo et al., 2023). Case A has a five-degree pitch angle, Case B a seven degree, and Case C is a 10 degree. The LCOE is the optimal financial parameter to investigate these designs (Ojo et al., 2023). To reduce the LCOE, the CAPEX or capital expenditure can be reduced as the designs become optimal. The amount of steel needed for each case decreases as the pitch angle increases as shown in Figure 3.2.2.

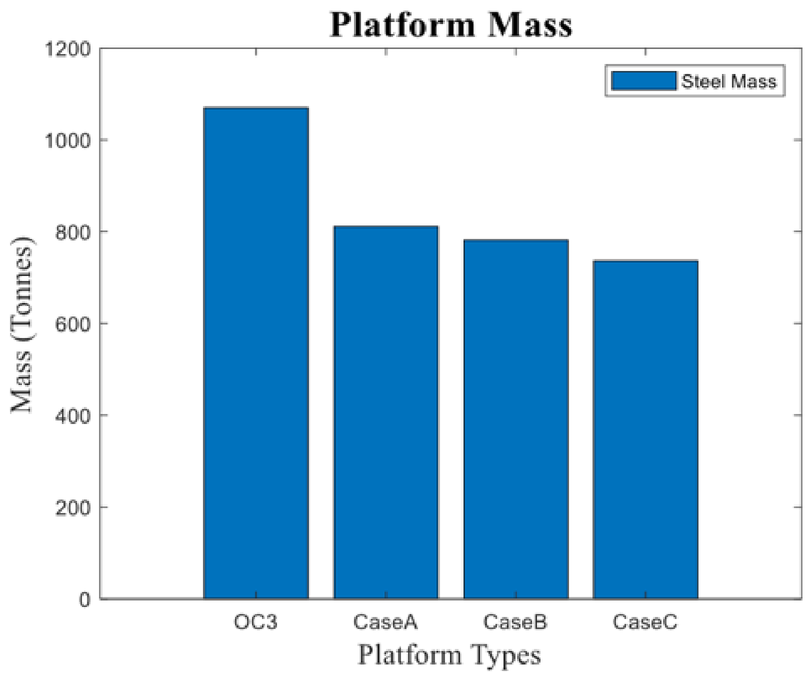



*Figure 3.2.2 Bar graph indicating the amount of steel needed for each design (Ojo et al., 2023)*

There were two different sized wind farms investigated, 30 MW and 60 MW (Ojo et al., 2023). As the angle increased, the platform material cost decreases in both wind farm sizes. As the angle increased, the platform material cost decreases in both wind farm sizes as shown in Figure 3.2.3.

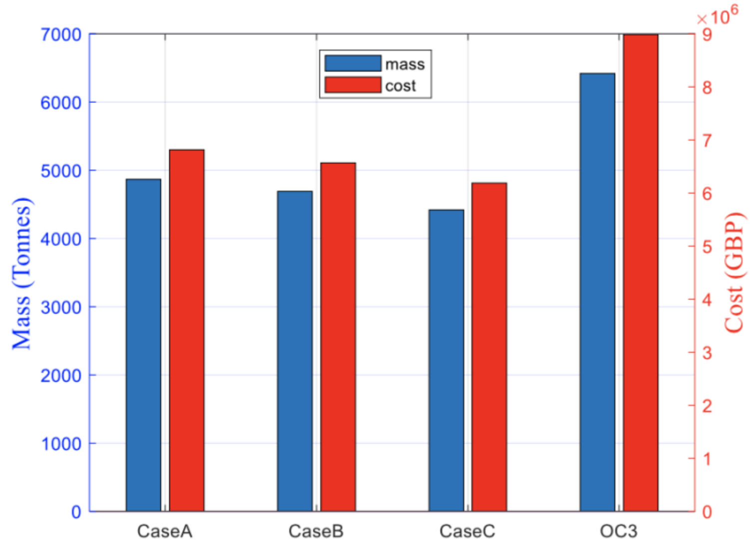



*Figure 3.2.3 Each case compared to the material mass and cost (Ojo et al., 2023)*

The decrease in cost was due to the constraints used each specific cases design hence the reduction in material cost. This material cost is a vital part of total CAPEX cost which helped lower the LCOE (Ojo et al., 2023). However, this study did not investigate the different environmental conditions each of these designs would be able to handle. Increasing the pitch angle is beneficial to cost reduction but the tower may experience more fatigue over time (Ojo et al., 2023). The angle can be high when in a particular landing area when rough conditions are not experienced (Ojo et al., 2023). Lastly, the study also opens the industry eyes that floating platforms can be optimally changed as compared to their fixed bottom counterparts. As more design and sensitively analysis is conducted the cost of the farms will reduce making floating platforms appealing to the growing renewable market.

## 3.3 O&M Optimization

The operations and maintenance (O&M) are roadblocks within increasing the development of offshore wind farms. This is due to the remoteness, rough sea conditions, and logistic challenges taking up 20-35% of lifecycle costs (Feng et al., 2021). The maintenance cost can be divided into a visible and invisible sections (Feng et al., 2021). The visible costs include transportation, labor, and spare parts. The invisible costs are losses in production (PL) due to degradation and failure (Feng et al., 2021). To optimize invisible costs, the power curving method has been used. This method uses the recent performance of the turbine and compare to baseline or design expectations. The weather forecast of up to three days is also used which tells the designers the future wind distribution required to compute the PL within target maintenance time window (Feng et al., 2021). Identifying the invisible costs brings a new challenge for researchers to tackle but also another opportunity to improve the floating offshore industry. To reduce the PL in real time, vessel routing and maintenance scheduling must be cohesive.

A case study was performed to show the importance of PL within O&M. An offshore wind farm of 27 4MW wind turbines was analyzed (Feng et al., 2021). Eleven turbines needed to be repaired within the next 3 days. There were 2 vessels and 19 technicians that can be used to perform the maintenance. There were three different cases studied. The first case or proposed method considered PL, different wind turbines could have significantly different damage and prioritizing them over others. This can be found out by using the power curving method. Method one does not consider any PL meaning that turbine prognosis is not used. Method two considers PL but divide the maintenance into two clusters, each vessel is assigned to perform the maintenance in one cluster individually. The results of these cases are shown in Figure 3.3.1.

| | Trans. cost | PL | Fixed cost | Total cost |
|---|---|---|---|---|
| Proposed method | 809.4 | **2815.7** | 4800 | **8425.0** |
| Method 1 | 603.1 | 4018.3 | 4800 | 9421.4 |
| Method 2 | 715.2 | 3254.6 | 4800 | 8769.7 |

*Figure 3.3.1 Cost comparison among three cases (Feng et al., 2021)*

The “Trans. Cost” is the visible costs which varied for each case as the movement and travel paths during O&M varied (Feng et al., 2021). The results are clear that the total cost is the lowest when PL is considered. The highest cost when PL is not used. This shows that PL is a large portion of the overall efficiency of a wind farm due to the large power capacity of FOWT. The proposed method was the cheapest due to the routes of the vessels and technicians being properly planned by observing the data of each turbine. In conclusion, PL is a variable within O&M that must be considered and tested when proposing new offshore wind farms.

## 3.4 Prospective Areas Design

### 3.4.1 Maine

UMaine has been leading in the United States and has been the first the patented their offshore technology. UMaine designed the VolturnUS using a floating concrete hull and semi-submersible design (UMaine, n.d.). The design was built and inspired by an upside-down bridge as shown in Figure 3.4.1.

*Figure 3.4.1 Design of the VolturnUS (Abel, 2022)*

The floating hulls are good for deep waters of up to 45m or more (UMaine, n.d.). The hulls will used pre-cased, rectangular concrete platforms with buoyancy dynamics (UMaine, n.d.). There are three mooring lines that are connect the anchors to the structure (UMaine, n.d.). Maine believes that the rectangular bottom is easier on construct and adds more wave resistance motion.

### 3.4.2 Ireland

Along with the political struggles to get the floating offshore turbines into the deep sea, affordability is an additional obstacle facing Ireland (Vigliarolo, 2023). The Dublin based company Gazelle Wind Power wanted to investigate changing the buoyancy methods (Vigliarolo, 2023). The design is smaller, lighter, and 30 percent cheaper than the traditional semi-submersible design (Gazelle Wind Power, n.d.). It responds to waves by using a central counterweight of three arms anchored to the seabed as show in in Figure 3.4.2.

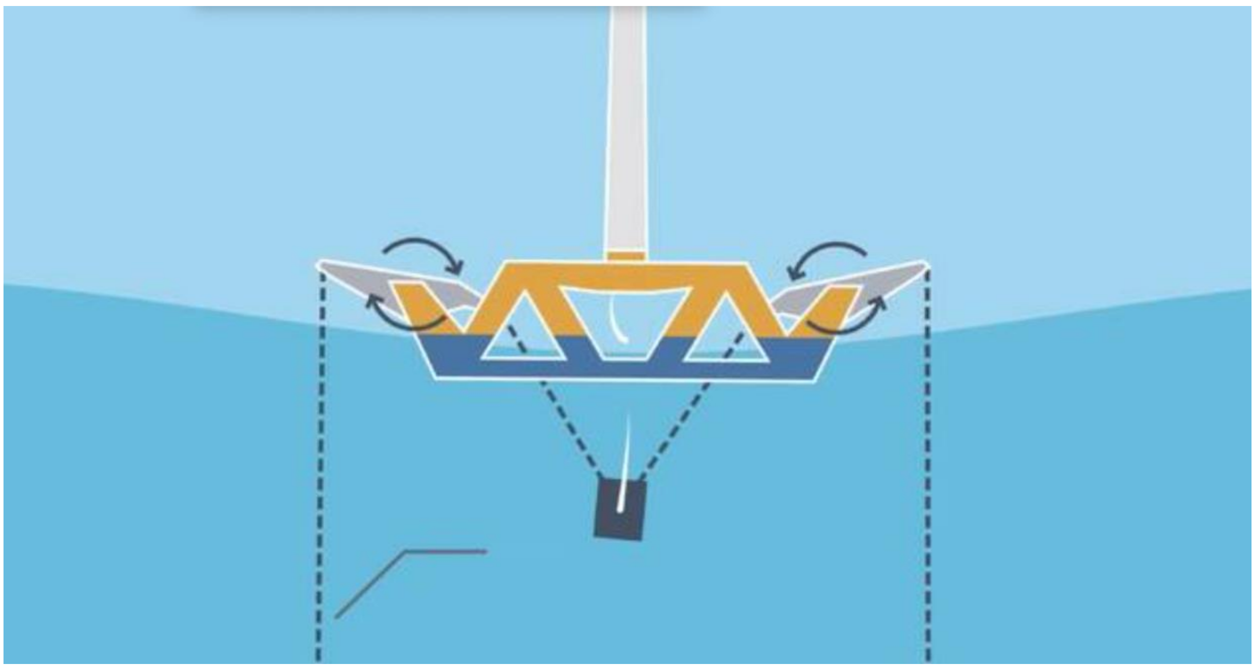


*Figure 3.4.2 The hybrid design from Gazelle (Vigliarolo, 2023)*

Gazelle describes it as having the benefits of a tension leg platform system and semi-submersible. The turbine pitch is less than five degrees letting the platform move with the wind and waves (Gazelle Wind Power, n.d.). This pitch limits the wear and tear that the traditional ten-degree pitch angle has (Gazelle Wind Power, n.d.). The manufacturing and installation of the platform is cost effective as they are light reducing the amount of storing space and easier to transport (Gazelle Wind Power, n.d.). The design has not been fielded and currently still in the testing phase but once put into place every 1 gigawatt of towers deployed would use 71 kt less steel and prevent 100kt carbon emissions (Vigliarolo, 2023).

### 3.4.3 California

As California is still in the design phase, no prospective designs have been publicity released.

### 3.4.4 China

In China, the Shanghai Electric Wind Power group was chosen to construct an offshore renewable energy project (Memija, 2023). This project will contain not only the floating platforms but deep-sea aquaculture as well (Lee, 2023). It will be in the National Sea Ranch Demonstration Zone on Nanri Island (Memija, 2023). The structure of the turbines will be a semi-submersible three column design (Lee, 2023). The hexagonal space in the platform's central area will be used for fish farming as shown in Figure 3.4.3.

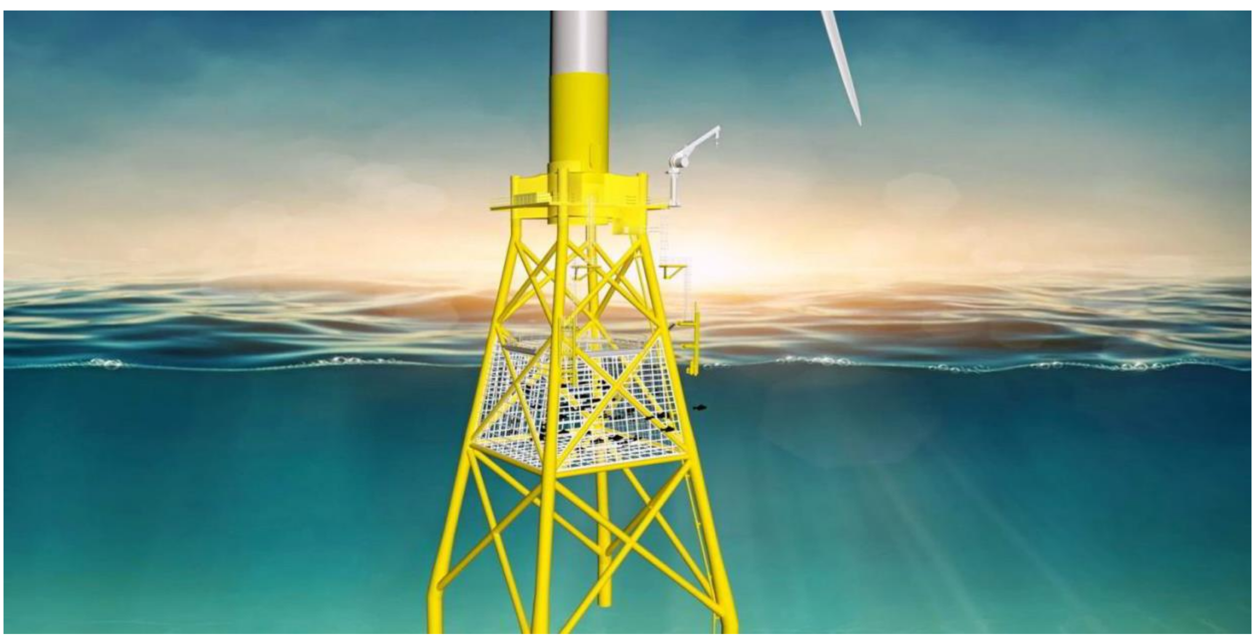


*Figure 3.4.3 Semi-submersible design with aquaculture addition (Lee, 2023)*

The integration of aquaculture in the design of the turbines is currently a key focus in the industry.  The wind farm can generate 96000 kwh of electric which can help power 42500 people daily activities (Memija, 2023).

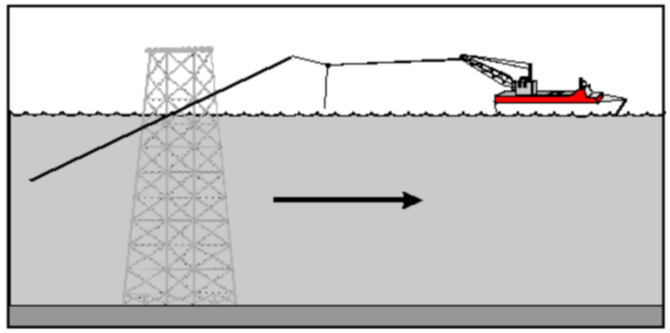
# 4: End of Life

## 4.1 FOWT End of Life Discovery

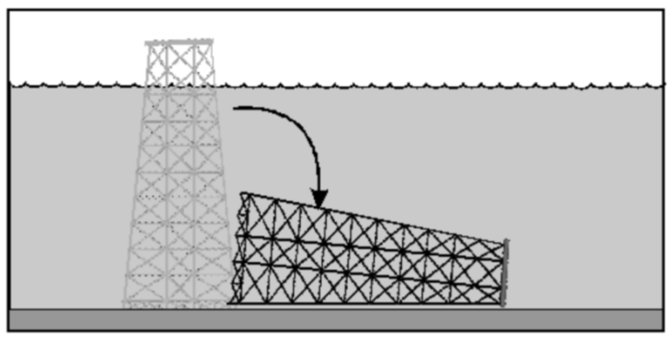
As the urgency is heightened to deploy offshore wind turbine, the end of their operational life has been seen as an issue for the long term. Many end-of-life scenarios have not been realistically tested but can follow a similar approach to the oil and gas industry. A case study was virtually developed by the Norwegian Sway Company (Weinzettel et al., 2009). They developed a full life-cycle assessment of a floating wind farm. To evaluate the grave phase of the farm, the system expansion approach was used. This process breaks down the farm the exact same way it was built, retracing steps (Weinzettel et al., 2009). The tower was transported to a recycling plant. The steel and copper were also recycled and used for either pig iron or copper production (Weinzettel et al., 2009). The blades were the only item that was subjected to landfill (Weinzettel et al., 2009). The ballast mooring system broke down into gravel (Weinzettel et al., 2009). As most of the material is being re-used, the GWP factor of the grave phase is not as impactful as the construction phase.

## 4.2 Oil and Gas Comparison

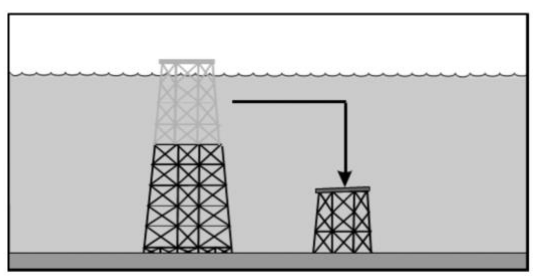
The oil and gas industry uses the term decommissioning to describe the end-of-life phase of offshore rigs. According to the Bureau of Safety and Environmental Enforcement, a Right-of-Use-and-Easement is signed prior to the installation of a plant. This includes the decommissioning process as the extraction of material requires a hole within the earth's crust. The hole must then be plugged to protect the environment and people using the water's surrounding the site (Bureau of Safety and Environmental Enforcement, n.d.). The decommission process' most important element is that the workforce and environment are protected. The platforms are broken up into two sections: topside (visible above waterline) and substructure (below surface and above the seabed) (Bureau of Safety and Environmental Enforcement, n.d.). The topside structure and substructure can be taken to shore to be sold as scrap or recycled to be used in another location (Bureau of Safety and Environmental Enforcement, n.d.). This first process is called Idle Iron within the plug and abandonment agreement (Bureau of Safety and Environmental Enforcement, n.d.). The idle iron refers to any operation that is no longer economically viable on active leases. This first policy keeps facilities from littering into the Gulf of Mexico. The second policy is enforced by NOAA which is the Rigs to Reefs program (Bureau of Safety and Environmental Enforcement, n.d.). The platforms may be sunk in approved places by the Regional Supervisor to create an artificial reef for marine life. Figure 4.2.1 shows the three methods of how reef in place process is done.



The tow-and-place platform reefing method



The topple-in-place platform reefing method



The partial removal platform reefing method

*Figure 4.2.1 Rigs to Reefs Process (Bureau of Safety and Environmental Enforcement, n.d.)*

Currently, there are 515 platforms converted into reefs in the Gulf of Mexico (Bureau of Safety and Environmental Enforcement, n.d.). A mixture of both these processes has the potential to be translated into the practices of floating offshore wind farms. This will minimize labor and transportation costs lowering the GWP factor from the wind farms as well as LCOE.

# 5: Research Analysis

There are clear waters ahead for the FOWT industry as research is prospering and progress is being made in executive offices. After the analyzation of four different areas there is a mixture of strategies that can be taken from each to enhance the industry.

First, is regarding location. The best location with the most governmental ease is China. China from the start of its revamp on renewable energy, it has been able to move forward with any project. The communist government has total control of what can be done and at what caliber. The sea conditions around the country also are desirable for the floating platforms with potentials to harness 477 MW of offshore wind energy. Strategies that can be implicated onto this location involve lowering LCOE. The logistic and installation phase seek the most potential in decreasing. China has full capability of lowering its LCOE due to no conflict of logistics by permitting and community input. This is where other countries struggle as the US and Ireland have a democratic approach to politics. China can choose the best location within the country without backlash from civilians. In addition, the installation phase is a relatively easy process as China has the most steel production in the world. The steel can be made close to site and used in the fabrication of the FOWT. This lowers the LCOE because the lifetime cost of this phase is lower as more energy from the farm would be outputted.

Second, is regarding design. The best design was done by the Gazelle Wind Power Company. They decided to take a hybrid approach of two of most optimal platforms (semi-submersible and tension leg) to create a sufficient design. The construction of the design is cost effective and easy to transport. One downside to this selection is that as the pitch angle is less than five degrees, increasing the mass of steel. As shown in the spar case study, the greater amount of steel, the lower degree angle. But, as the steel is already manufactured in China, it can counteract the amount of steel needed to produce this design. With the ease of transport and the consideration of PL, construction and a maintenance routine will be easy to coordinate.

Lastly, as end of life phasing was not discussed in a case-by-case basis but has opportunity to be efficiently planned out. The rigs to reefs program enlisted by the oil and gas industry is one that can be translated over into floating offshore wind farms. The Gazelle Wind Power platform can be sunk to the seafloor to make an artificial reef for wildlife leaving a positive environmental impact on the area of interest. This also limits the transportation required to breakdown the wind farm as it would be over 60m offshore.

All in all, there are a plethora of opportunities and pathways the FOWT industry can capture. The amount of innovation being studied in each area of interest is just the beginning of how capturing wind offshore can turn into reducing greenhouse gas emissions.

## 6: Final Remarks

In conclusion, four different locations across the globe were discussed and analyzed regarding the progress made on powering communities via floating offshore wind platforms. There were supplementary studies conducted by additional research analysis to help continue enhancing the industry. These studies were within the production, construction, and operating phase of a FOWT. No studies have directly been found to improve the end of use phase of the farms but have possibilities to follow the same path of offshore oil. After much consideration, the ideal location was considered in China with a TLP and semi-submersible design mix. With these two elements decided, the offshore wind industry has tremendous possibly of helping turn back the ticking clock what humans have set off from fossil fuels.

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