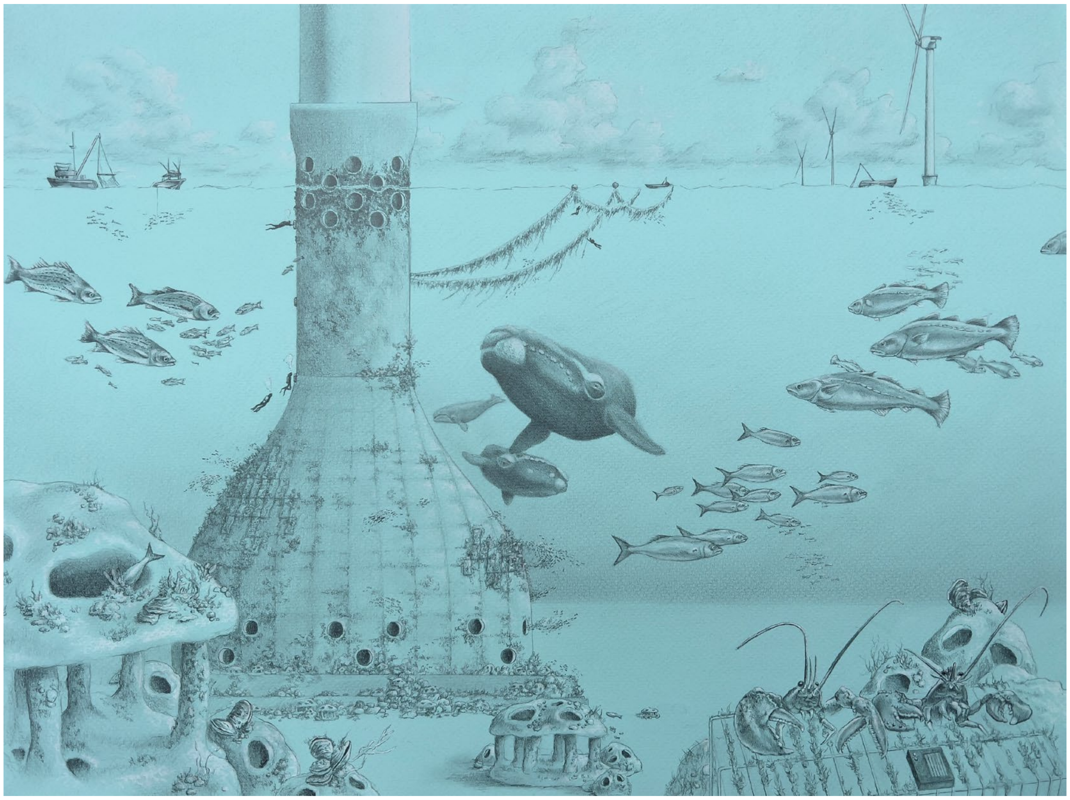

Low-Carbon, Bio-Enhancing Concrete Gravity-Based Foundations for Offshore Wind Turbines

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OffShore Power Research & Education Collaborative

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Preface, Acknowledgements, and Disclaimer

This report, developed during the summer and fall of 2022, was requested by members of the Connecticut House of Representatives on March 25, 2022. Its development is the result of a successful town hall discussion on the merits of concrete Gravity-Based Foundations (GBFs) for Offshore Wind Turbines (OWTs) that was held on March 1, 2022. Concrete GBFs have the potential to provide substantial U.S. jobs, strong environmental benefits, and superior engineering reliability. However, their story and their potential remain largely unknown to decision makers responsible for advancing the U.S. offshore wind industry.

Prior to this Connecticut town hall, members of our team had presented a series of similar workshops, beginning with "Offshore Wind Energy Infrastructures, Jobs and Equity" for the state of Massachusetts on May 14, 2021. This report aims to build on these workshops and to set a benchmark for the critical evaluation of OWT foundations by state and federal decision makers.

We are grateful to Connecticut State Representatives Robyn Porter (Co-Chair of the CT Legislative Committee on Labor and Public Employees), Anne Hughes (Chair of the CT Progressive Caucus, and member of the CT Offshore Wind Commission on Environmental Standards), David Michel (Assistant to the Majority Leader, Co-Chair of the CT Animal Advocacy Caucus, and proponent and member of the CT Offshore Wind Commission on Environmental Standards), and Travis Simms (Assistant to the Majority Leader and Vice Chair of the Transportation Committee) for their invitation to develop this report. We would like to acknowledge the Tufts Office of the Vice Provost for Research (OVPR) for the Springboard Grant that supported our development of the May 14, 2021 Massachusetts workshop and subsequent workshops, and the Tufts CREATE Solutions Initiative supporting part of the workforce portion of this report.

We gratefully acknowledge our colleagues at Seatower for their willingness to share their thinking with us and to critically review the engineering, environment and pricing studies within this paper. It is important to note that this paper was developed without any financial contributions from Seatower or any other commercial entity. Katarina Halldén, who is a co-author on this paper, is a Seatower employee. Her work on this paper was funded through a direct contract paid by Tufts University. Throughout our development of this report and our work on GBFs, we have disclosed to Seatower that our interests in this technology extend to the field of low-carbon, bio-enhancing concrete float-out foundations in general and are not limited to the commercial interests of a single entity. During the work leading up to this paper, we have consulted with concrete GBF-related commercial entities in the U.S., the U.K., Norway, France, and Spain. As we proceed in this space, we will continue to work with a variety of commercial, academic, and government entities who maintain varying perspectives on the GBF design and construction process.

We take full responsibility for the content and discussion herein. Any mistakes, omissions, and opinions within this document are ours alone, and we will be glad to receive further feedback as this document reaches a wider audience.

Eric Hines
Director, Offshore Wind Graduate Program
Tufts University, November 2022

Executive Summary

One of the strongest drivers behind offshore wind (OW) development in the U.S. is the desire to create high-quality U.S. jobs that can support a diverse and inclusive workforce; this is needed to achieve a just and equitable energy transition. Within the offshore wind supply chain that the U.S. hopes to build on its path to 30 GW by 2030, Low-Carbon, Bio-Enhancing Concrete Gravity-Based Foundations (GBFs) for Offshore Wind Turbines (OWTs) have the potential to produce thousands of high-quality U.S. jobs. This is because the construction of GBFs is more labor intensive than steel monopile structures (whose fabrication is highly automated), and there is a greater need to fabricate GBFs close to their installation sites because of their large size and weight. The U.S. commitment of 30 GW by 2030 will require approximately $15 Bn spent on the construction and installation of foundations. Acting as a first mover in the use of concrete GBFs will position that mover to be a major player in the $150 Bn dollar OWT foundation market that will likely emerge between 2030 and 2050.

We estimate the current cost premium for this labor-intensive construction to be on the order of $3 / Megawatt hour (MWh). This marginal cost pales in comparison to the estimated $40.76 / MWh difference between the most expensive and least expensive U.S. offshore wind projects. It also pales in comparison to the approximately $260 / MWh retail electricity cost paid by New England consumers of electricity (ratepayers) over the past few years. For an additional $3 / MWh expenditure, we estimate that each well-designed, well-executed GBF could provide 60 local jobs, while each comparable monopile on a Connecticut offshore wind project is expected to provide only 2 local jobs.

In addition to this impressive increase in local jobs, GBFs can also extend OWT foundation service life to 50-100 years; protect marine mammals through “quiet installation” techniques; enable the current U.S. maritime industry to install OW foundations, provide environmentally friendly opportunities for repair, re-powering, and decommissioning; and enhance ocean biodiversity and fishing stocks through the creation of artificial reefs.

This report addresses each of these issues—jobs, environmental benefits, and service life—using publicly available data. This report aims to advocate for GBFs within the nascent U.S. offshore wind industry as a legitimate alternative to monopile- and jacket-supported structures. The U.S. Department of Energy (DOE) estimates the U.S. OW foundation market to consist of 65% monopiles, 25% jackets, and 10% GBFs or other foundation on the path to 2030.[1] Considering 10% of 30,000 MW to be 3,000 MW, this implies approximately three 67 × 15 MW OW farms constructed with GBFs within the next 8 years. Even though this is a relatively small part of the overall 30 GW goal, it represents an ambitious goal for U.S. concrete GBFs. Achieving this goal would make a substantial impact on U.S. jobs, innovation, and environmental protection.

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[1] U.S. Department of Energy (2022). Wind Energy: Supply Chain Deep Dive Assessment. U.S. Department of Energy Response to Executive Order 14017, “America’s Supply Chains.” February 24. Retrieved on August 28, 2022 from https://www.energy.gov/sites/default/files/2022-02/Wind%20Supply%20Chain%20Report%20-%20Final%202.25.22.pdf

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Introduction

Wind energy is at the forefront of the clean energy transition. With carbon emissions that are just 1% of those from coal, and 2% of natural gas,[2,3] wind power plays a critical role in making our local, national, and global environment safer and healthier. The U.S. Offshore Wind (OW) industry is growing quickly, which means that this is a crucial time to shape the future of OW infrastructure.

Because the U.S. OW industry is new, it has many possible futures. Crucially, there are futures for the industry that fully leverage opportunities to create more jobs, uplift historically disadvantaged communities, treat marine life with respect, and build high-quality infrastructure that can last for generations. These are futures in which turbines and their foundations have longer lifespans, and in which local coastal economies can feel the benefits of these new and exciting projects. However, there are also less-desirable futures for the OW industry—futures in which we don't realize the opportunities to create safety, equity, and sustainability for our communities, our natural environments, our local industries, and our infrastructure. There is urgency in this opportunity.

We have assembled a report for the state of Connecticut that speaks to some of this urgency. In this report, we provide information that we hope will support conversations between public sector decision makers, their constituents, and private-sector actors about a highly technical subject.

This report contains four key findings:

- Jobs: A single GBF can yield an average of 60 direct jobs, while a single monopile base yields an average of 2 direct jobs.

- Environment: GBFs can be designed and installed as "quiet foundations" that drastically reduce environmental impacts on endangered species, such as the North Atlantic Right Whale. Furthermore, advances in bio-enhancing concrete technology enable GBFs to promote and enhance ocean bio-diversity.

- Infrastructure Investment: GBFs can be designed to last for 100 years.

- Carbon Emissions: Construction and installation of a Concrete GBF produces approximately half the CO_2e emissions of an equivalent steel monopile. These emissions can be reduced by an additional order of magnitude thanks to advances in low-carbon concrete technologies.

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[2] Wind Energy Technologies Office. (2022, 16 August). How Wind Energy Can Help Us Breathe Easier. Office of Energy Efficiency & Renewable Energy. https://www.energy.gov/eere/wind/articles/how-wind-energy-can-help-us-breathe-easier. Accessed on 26 August 2022.

[3] Wind energy creates 11 grams of CO_2 per kilowatt hour, while coal creates 980 g/kWh, and natural gas creates 465g/kWh. 11/980 = 1%, and 11/465 = 2%.

Offshore Wind Turbine Foundations

While foundations for offshore wind turbines comprise only 12-15% of the cost of an offshore wind project, they are among the most unique design elements in an offshore wind farm because they physically connect turbines to their specific locations in the ocean.[4] As a result, the design of individual turbine foundations may vary within a farm even though the turbine is the same for the entire farm. The turbine foundation plays a critical part in the design life of an offshore wind farm. The type of foundation will also have downstream effects on the marine environment and on local job creation. As the U.S. progresses toward the Biden-Harris administration's goal of 30 Gigawatts (GW) by 2030, the types of foundations built as a part of the U.S. supply chain will impact how states like Connecticut realize their goals for inclusive and equitable local job creation.[5] Figure I.1 shows an offshore wind turbine supported by a concrete Gravity-Based Foundation. The foundation must keep the turbine stable under wind and wave loads both during operation and during extreme events such as hurricanes.

Figure I.1: Offshore wind turbine supported by a Gravity-Based Foundation, courtesy of Sigurd Ramslie, Seatower AS.

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[4] Stehly, T. and Duffy, P. (2022). 2020 Cost of Wind Energy Review. Golden, CO. National Renewable Energy Laboratory. NREL/TP-5000-81209. Originally published in 2022. Revised, January 2022. Retrieved on August 25, 2022 from https://www.nrel.gov/docs/fy22osti/81209.pdf

[5] White House (2021). FACT SHEET: Biden Administration Jumpstarts Offshore Wind Energy Projects to Create Jobs. Briefing Room statements and releases. March 29. Retrieved on March 26, 2021 from https://www.whitehouse.gov/briefing-room/statements-releases/2021/03/29/fact-sheet-biden-administration-jumpstarts-offshore-wind-energy-projects-to-create-jobs/

A monopile or jacket foundation is embedded into the soil as shown in Figure I.2 through the pounding of piles dozens of meters into the seabed. All three foundation types are designed to provide vertical and lateral support for the OWT under wind and wave loads.

Figure I.2. Offshore wind foundations: Low-Carbon Concrete Gravity-Based; Jacket; Monopile. (image credits: GBF—Seatower[6], AS; Jacket—offshoreWIND.biz[7]; Monopile—Ramboll[8])

Figure I.2 shows three primary types of offshore wind foundations that are known as "fixed" foundations because they are fixed to or rest directly on the seabed (as opposed to floating foundation designs intended for deeper water). The foundations shown here from left to right are: a Low-Carbon Concrete Gravity-Based Foundation (GBF); a Jacket Foundation; and a Monopile Foundation. According to the U.S. Department of Energy (DOE), monopiles comprise just over 65% of the global operating substructure capacity (50.6 GW) for offshore wind. Jackets comprise just under 12% of this capacity, and GBFs comprise just under 2% of the global operating substructure capacity as of August 2022.[9] The DOE also reports the GBFs are expected to climb to just under 7% global market share for projects (88.2 GW) that have been announced.

As offshore wind turbines have grown in size, factory production of monopiles has matured into a highly-automated process. Conversely, the GBF and Jacket supply chains are still maturing

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[6] http://seatower.com/

[7] https://cdn.offshorewind.biz/wp-content/uploads/sites/2/2016/03/29144200/Dutch-Company-to-Oversee-American-Wind-Turbine-Installation.jpg

[8] https://uk.ramboll.com/projects/re/150-monopiles-in-the-north-sea-push-offshore-wind-into-deeper-waters

[9] Musial, W., Spitsen, P., Duffy, P., Beiter, P., Marquis, M., Hammond, R. and Shields, M. (2022). Offshore Wind Market Report: 2022 Edition. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. DOE/GO-102022-5765. August. Retrieved on August 26, 2022 from https://www.energy.gov/sites/default/files/2022-08/offshore_wind_market_report_2022.pdf

and are therefore associated with higher cost and longer fabrication periods. GBFs in particular, however, offer the potential for significant local job creation by utilizing existing domestic supply chains for heavy concrete construction as shown in Figure I.3. They also offer the potential for quieter installation than monopile foundations, which is an important consideration for the protection of critical marine mammal species such as the North Atlantic Right Whale.

Figure I.3. GBFs under construction at the Fécamp project in France.[10]

Finally, GBFs for offshore wind can draw upon decades of experience with GBFs designed to support oil and gas platforms in the North Sea. These so-called "Condeep" platforms were first developed by the construction firm Norwegian Contractors (NC) in the mid-1970s to support the new Norwegian oil and gas industry.[11,12] Weighing hundreds of thousands of tonnes, these platforms were built to float so they could be towed to their installation location and then sunk

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[10] Image retrieved on October 23, 2022 from https://parc-eolien-en-mer-de-fecamp.fr/2021/07/01/les-fondations-gravitaires-selevent-de-plus-en-plus-au-havre/.

[11] Olsen, T.O., Weider, O., and Myhr, A. (2015). "Large Marine Concrete Structures: The Norwegian Design Experience." In Large Floating Structures. C.M. Wang and B.T. Wang (eds.). Ocean Engineering & Oceanography, 3. Springer Science+Business Media, Singapore. DOI 10.1007/978-981-287-137-4_7.

[12] IH Draugen (2022). The Condeep Story. Industrial Heritage Draugen. Finn Harald Sandberg Norwegian Petroleum Museum. Retrieved on August 26, 2022 from https://draugen.industriminne.no/en/2018/05/14/working-on-the-slip/

into place with ballast. Many of these platforms are still in use, as shown in Figure I.4, and have demonstrated the potential to extend offshore wind foundation service life past 50 years.

Figure I.4. The Troll A GBF platform was installed in 1996 and is operated by Equinor. With an overall height of 472 m and weighing 683,000 tonnes (1.2 million tonnes with ballast), it was the tallest structure ever moved by humankind.[13] (image credit[14])

Advantages of Concrete Support Structures

The use of concrete Gravity-Based Foundations (GBFs) offers several advantages over steel structures, as described below:

Long Design Life

Concrete GBFs can be designed to be durable in marine environments and to have lifespans of 100 years or more. This requires careful design of the concrete mix and the reinforcing steel to prevent or limit cracking. Many concrete marine structures have been designed to have ultra-long

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[13] Image credit: https://en.wikipedia.org/wiki/Troll_A_platform. Accessed on 29 October 2022.
[14] Image credit: https://i.redd.it/8ggall830i351.jpg. Accessed on 29 October 2022.

lives including concrete oil & gas platforms, bridges, and piers that continue to exhibit excellent performance after several decades of service.[15,16,17,18,19,20] In contrast, the design life of steel marine structures is more likely to be limited to 25 – 30 years because of corrosion and fatigue. Concrete GBFs are less sensitive to fatigue and open many doors for more sustainable long-lasting infrastructure.

Variety of Concrete Types

The type of concrete depends on the "mix" of cement, cement substitutes, aggregates (crushed or natural rock, and sands), water, and admixtures. Admixtures are materials added to concrete mixtures to change their strength, texture, or the way they set. Depending on the mix design, concrete can be given a wide range of useful properties, including:

- Strength, durability, and porosities similar to granite;
- Lightweight properties. Light-weight concrete is commonly used for structures that are designed to float out to their final location in the offshore wind farm.

In a reinforced concrete structure, the reinforcement is just as important—and often even more important— than the specific mix design. In addition to "passive" reinforcement such as rebar, prestressing reinforcement can be used to put the concrete under consistent compression during its lifetime. This is critical since concrete is better suited to handling compression forces than tension. For example, prestressing reinforcement can provide an order of magnitude increase in the loading under which cracking first occurs.

Prestressing and the amount of passive reinforcement will largely control the stiffness of the foundation since the reinforcing bars and prestressing components carry the tension loads. The levels of prestressing will also control the rate of penetration of chlorides into the concrete that can corrode steel reinforcement. Fibers can also be added to the concrete to control cracking.

Cast Into Virtually Any Shape

One of the primary advantages of concrete is that its shape is controlled by the shape of the formwork into which it is placed. Concrete's structure—particularly at transitions such as notches, corners, or sudden changes in thickness—can be designed to taper gradually and avoid large amounts of stress without significant increases in cost. Admixtures such as

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[15] Moffatt, E. T., Thomas, M., & Fahim, A. (2020). Performance of Concrete in a Harsh Marine Environment for 25 Years. Special Publication, 337, 89-100.

[16] Helland, S., Aarstein, R., & Maage, M. (2010). In-field performance of North Sea offshore platforms with regard to chloride resistance. Structural Concrete, 11(1), 15-24.

[17] Fosså, K. T. (2020). Concrete Mix Design Development for Offshore Structures. Special Publication, 337, 78-88.

[18] Olsen, T. O. (2009). Concrete structures for oil and gas fields in hostile marine environments. CEB-FIB. First Edition, International Federation for Structural Concrete.

[19] Olsen, T. O., Weider, O., & Myhr, A. (2015). Large Marine Concrete Structures: The Norwegian Design Experience. In Large Floating Structures (pp. 157-195). Springer, Singapore.

[20] Polder, R. B., & De Rooij, M. R. (2005). Durability of marine concrete structures: field investigations and modelling. Heron, 50 (3).

superplasticizers and viscosity modifiers control the ease with which concrete flows when it is poured. These admixtures prevent segregation, which happens when gravel is not evenly distributed throughout the concrete mixture. Admixtures also make it possible for concrete mixtures to contain less water which, in turn, produce very strong concrete structures.

Float & Sink Gravity-Based Structure

GBFs operate on a simple and robust principle: They are so heavy that waves, winds, and other forces cannot move them, even under hurricane conditions.

Most large concrete marine structures, for both oil and gas platforms and offshore wind foundations, have been designed to float out to site. Having arrived at their assigned location, they are ballasted with water, sand slurries, and other materials. This means that heavy materials are placed inside of the hollow concrete bases such that they attain the weight required to sink them to the seafloor and stabilize them permanently. This avoids the need for loud pile driving noises that are harmful to marine life, such as the North Atlantic Right Whale. It also reduces or avoids the need for large installation vessels. This report will explore GBFs as “quiet foundations” in detail in Section III.

Local Manufacturing Jobs

Concrete is a relatively inexpensive material, typically \$100-\$200 per cubic yard; this is about 1% of the cost of steel per unit volume. The primary expenses in building concrete structures include the labor costs for placing and tying the reinforcing materials, and for building formworks. Since concrete structures are typically much heavier than steel structures, they are difficult to move over long distances (like across the Atlantic Ocean) and they are more likely to be fabricated near OW farms. Thus, the selection of concrete GBFs for OW can have a profound effect on the economic benefits to the region near the wind farm. This report will explore local Connecticut labor practices in detail in Section I.

Design Upscaling for Turbine Sizes

Once a GBF design is complete, it can be affordably replicated for different locations and contexts. This is because the design is often driven by stability during tow-out. For example, in the case of a GBF designed to support a 15 MW turbine, increasing the thickness of a wall or increasing the level of prestressing to support a 20 MW turbine in the future would be simple and cost-effective to design because the relative cost of concrete is low compared to steel. Additionally, making a concrete wall thicker would have very little effect on labor costs. In contrast, designing a monopile to accommodate a larger turbine in the future would be comparatively more expensive because of the high cost of steel itself.

High Fatigue Endurance

GBFs are enduring infrastructure: they have longer design-lives than monopiles and are far more resistant to fatigue. Unlike concrete, steel’s surface is vulnerable to corrosion damage. Corrosion reduces the thickness of the steel plate and creates a surface roughness that leads to stress concentrations. Stress concentrations, in turn, increase the risk of significant fatigue damage and the formation of cracks in the steel. Cracks most commonly form where welds connect to the base metal.

In contrast, concrete structures are tolerant of cracking and other forms of damage. When the *tensile stresses* (or stresses related to tension, such as pulling) in concrete exceed cracking stress, then a crack forms. After this happens, the concrete experiences stress at the place where the crack occurs. Provided that appropriate steel reinforcement is used, a crack isn't likely to compromise the structure's integrity. Cracks also make the structure less rigid where they occur, which in turn distributes the tensile loadings more evenly in regions surrounding cracks. Additionally, concrete performs exceptionally well under compression (pushing, as opposed to pulling). As compression increases, the concrete exhibits more *creep* (or long-term permanent deformation of the concrete under sustained load). In other words, concrete also adjusts under compression in a way that does not compromise its structural integrity provided that it has been properly designed. This is also true in instances of fatigue loading, which are the small stresses concrete experiences over time under daily wind and wave loads.

Naturally Low-Carbon (and Able to be Even More Low-Carbon)

The worldwide production of cement (about 10-15% of the composition of concrete) is responsible for about 8% of global Carbon Dioxide equivalent (CO_2e) emissions because we use so much of it. Concrete is the second most used material in the world after water.[21] Because we use so much concrete, however, it is reasonable to question the emissions impact of using concrete GBFs.

The internationally agreed upon metric for assessing the emissions impact of materials is expressed as *grams of CO_2e per kWh of electricity production* (grams/kWh). Using available information about foundations masses, turbine sizes, and capacity factors, the average CO_2e impact of cement in OW foundations is less than 1 gram/kWh, assuming a 25-year design life. This 1 gram/kWh is responsible for about 10% of the carbon footprint of wind energy itself, which is approximately 12 grams/kWh. By contrast, the emissions from producing electricity from Natural Gas averages 490 g/kWh and from Coal average 820 g/kWh.[22]

Thus, the CO_2e impact of cement in concrete GBFs is very, very small relative to the savings from switching away from fossil fuels. Steel foundations have been found to have twice the impact on CO_2e than concrete, and advances in concrete technology have provided ways of further reducing the impact of concrete. This is explored further in Section V.

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[21] Gagg, C.R. (2014). Cement and concrete as an engineering material: An historic appraisal and case study analysis. Engineering Failure Analysis. Vol. 40. May. pp. 114-120.

[22] Life cycle greenhouse gas emissions of energy sources. (2022, August 5). *Wikipedia*. https://en.wikipedia.org/wiki/Life-cycle_greenhouse_gas_emissions_of_energy_sources. Accessed on 25 August, 2022.

Section I: Workforce

Developing a New Paradigm

When most people think about training for the OW foundations marketplace, they think about training for a monopile-centric industry. This is indicative of the extent to which the current paradigm is centered around monopiles. There can be many more job and training opportunities, however, where GBFs are used for offshore wind. In this section, we'll explore how the trades are currently trained for concrete work, barriers to increasing concrete work in the trades in Connecticut, and suggestions for shifting the paradigm.

Much of the discourse around offshore wind *workforce development* refers to work on the water: the assembly and installation of wind farms or the operations and maintenance of these projects. Jobs on the water have the appeal of high wages due to the high-risk nature of this work. Required safety training is one method developers use to protect workers and lower their project risk.[23]

Currently, the required safety training program for anyone working in the offshore environment on OWTs is GWO's Basic Safety Training (BST), which is offered in just two locations throughout New England: Mass Maritime Academy's Buzzards Bay Campus off the southern coast of Massachusetts, and in Groton, CT with the training company ENSA.[24] The training comprises five modules of GWO Basic Safety Training for Offshore Wind: First Aid, Fire Awareness, Working At Heights + Manual Handling, and Sea Survival.[25] The program is specifically for people who are working on open water: assembling, installing, and maintaining offshore wind turbines. For some local trade unions, the expense of BST serves as a barrier to preparing a trained workforce.[26]

Fortunately, not all local OW jobs are on the water. In this report, we aim to shift the focus from water jobs to land jobs. This report will discuss the potential for landside jobs in the manufacturing of foundations.

New England Construction Workforce

In Connecticut, there are currently 2,278 active working members in Carpenters Local 326.[27] In 2021, close to 35% of these active members were minorities. OW construction and maintenance activities offer opportunities to further diversify the trade unions, and to bring safe, equitable employment to those who need it most. In this section, we will review the training and capacity

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[23] Blenkey, N. (2021, August 19). Mass Maritime now delivering training to wind farm construction personnel. *MarineLog*. https://www.marinelog.com/offshore/offshore-wind/mass-maritime-now-delivering-training-to-wind-farm-construction-personnel/. Accessed on 1 August 2022.

[24] n.a. (n.d.) Find a GWO Training Provider. *Global Wind Organisation*. https://www.globalwindsafety.org/trainingproviders/findttraningprovider#. Accessed on 30 August 2022.

[25] n.a. (n.d.) U.S. Offshore Wind Training: Global Wind Organisation. Massachusetts Maritime Academy. https://www.maritime.edu/professional-training/offshore-wind-training. Accessed 14 November 2022.

[26] Interview, Ironworkers Local 7, 7 July 2022

[27] Chris Bachant Interview, Business Representative, Carpenters Local 326, 9 August 2022.

of the current carpentry workforce in Connecticut as it relates to concrete, provide an overview of apprenticeship programs in New England and Connecticut specifically, detail current wages in trade union jobs in Connecticut, and list current programs and initiatives that diversify the trades' workforce in CT and target historically excluded communities.

Concrete and Carpentry in the Trades

There are three areas of work that are considered the "bread and butter" of carpentry: drywall, framing, and concrete. That is to say that *all* carpenters in U.S. union-based training programs, regardless of specific career pathway desires, learn skills necessary to work in these three areas. Concrete itself, however, is a large area of work that encompasses many different kinds of projects in both residential and commercial construction. Union labor is primarily associated with commercial projects.[28] And within that commercial construction category, projects fit into two main categories:

- industrial: for warehouses, factories, and any other manufacturing business[29]
- heavy & highway: for water- and land-based infrastructure, including for roads, freeways, bridges, etc.[30]

The concrete placement process for GBFs fits into the heavy & highway category. As GBFs for OW are massive projects, concrete placement does not proceed inside an enclosed facility but rather at a large outdoor factory adjacent to water. This enables the foundations to be towed out to sea after they have been constructed. The outdoor factory should also ideally be located near a concrete batch plant, which is where the raw materials for the concrete are stored.

All union-trained construction carpenters have been educated in concrete work. However, not all trained carpenters choose to go into concrete work once they finish their apprenticeships. Of the 2,300 active members of the Connecticut Carpenters Local 326, about 850 actually perform concrete work. That's 37% of Southern CT's union-trained workforce. Of those 800 trained concrete workers, about 300 (35%) are trained to do heavy & highway concrete work. To meet the needs of an initial OW concrete GBF project, that number needs to triple to approximately 900 workers. In short, recruitment and training of approximately 600 additional skilled workers is a key priority for concrete specialists in the union trades. OW projects present an opportunity to devote resources to growing this unionized concrete workforce.[31] Unions are working hard on recruitment and diversity initiatives to make sure people who need these jobs most can take them (we'll discuss this more in the DEIJ portion of this section).

Furthermore, as the existing skilled workforce ages and retires, the loss of valuable experience and mentoring capacity can endanger future OW construction if new workers are not trained in

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[28] Chris Bachant interview, Business Representative, Carpenters Local 326, 16 August 2022.

[29] n.a. (n.d.) What is Industrial Construction? Stevens Industrial Construction. https://www.stevensec.com/blog/whats-is-industrial-construction. Accessed on 16 August 2022.

[30] n.a. (n.d.) Heavy Highway Construction. National Center for Construction Education and Research. https://www.nccer.org/workforce-development-programs/disciplines/craft-details/heavy-highway-construction. Accessed on 16 August 2022.

[31] Chris Bachant interview, Business Representative, Carpenters Local 326, 16 August 2022.

time. Jobs in the trades are very physically taxing and can take a toll on one's health,[32] and the construction trades are some of the deadliest jobs.[33] Older construction workers are far more likely to incur a fatal injury than younger ones.[34] Trueblood, Brown, and Harris report that "[i]n 2020, the fatal injury rate in workers 55 or older was 51.1% higher than that of those younger than 55" (2022; 2).[35] Despite a significantly increased rate of fatal injury, the percentage of construction workers 55 years of age and older has increased from 16.9% in 2011, to 21.9% in 2021. The percentage of construction workers under 55 years of age, however, has decreased from 81.3% in 2011, to 78.1% in 2021.[36] While it is difficult to draw general conclusions from these national data, these trends suggests that it may be safer for construction workers to retire before or around the age of 55. These data also suggest that construction workers are aging and/or retiring at increasingly older ages, and that there are fewer younger workers to fill out the workforce. We may conclude, additionally, that there is a strong need for an influx of younger workers.

Finally, while the average fatal injury rate per 100,000 workers is 3.4, that rate more than doubles for carpenters, at 7.8—and increases nearly tenfold for structural ironworkers and steelworkers, at 32.5.[37] This is all to say that carpenters and ironworkers, two of the primary union jobs associated with the construction of GBFs, would benefit particularly from safe, stable, unionized employment—and an influx of younger workers, alongside higher wages and pensions, to relieve an aging workforce.

As heavy & highway construction workers retire, there is an imperative to recruit young people. The question of who ought to benefit from these jobs also raises further questions such as: how does someone enter a union-based apprenticeship or training program to begin with? Who is entering these programs? Are they attracting the people who are most in need of safe, regulated jobs that can form the basis for lasting careers? We will address these questions in the following subsections.

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[32] Graves, J. (2014, 12 September). The Worst Jobs for Your Health. U.S. News. https://money.usnews.com/money/careers/articles/2014/09/12/the-worst-jobs-for-your-health#:~:text=They%20also%20run%20the%20risk,lung%20cancer%2C%20mesothelioma%20and%20asbestosis. Accessed on 22 August 2022.

[33] Bousquin, J. (2020, October 13). Nearly half of America's deadliest jobs are in construction. *Construction Dive*. https://www.constructiondive.com/news/report-nearly-half-of-americas-deadliest-jobs-are-in-construction/586801/ Accessed 13 November 2022.

[34] Brown, S., Harris, W., Brooks, R., and Dong, X.S. (2021, February). Fatal Injury Trends in the Construction Industry. *The Center for Construction Research and Training*. https://www.cpwr.com/wp-content/uploads/DataBulletin-February-2021.pdf Accessed 13 November 2022.

[35] Trueblood, A.B., Brown, S., and Harris, W. (2022, May). Fatal and Nonfatal Injuries in the Construction Industry. *The Center for Construction Research and Training*. https://www.cpwr.com/wp-content/uploads/DataBulletin-May2022.pdf Accessed 13 November 2022.

[36] Harris, W., Brown, S., and Trueblood, A.B. (2022, March). Employment Trends and Projections in Construction. *The Center for Construction Research and Training*. https://www.cpwr.com/wp-content/uploads/DataBulletin-March2022.pdf Accessed 13 November 2022.

[37] n.a. (2022). Fatal and Nonfatal Injuries in the Construction Industry, Chart Data. *The Center for Construction Research and Training*. https://www.cpwr.com/research/data-center/data-reports/ Accessed 13 November 2022.

Union-Based Apprenticeship Programs and Jobs in CT

All carpenters' union locations in the United States have the same training and testing programs. These programs have a multi-step intake process that includes: an initial informational interview, electronic forms, verification of GED or high school diploma, and a more formal intake interview. Apprentices accepted into a program train for 4 weeks per year (1 week after each quarter), for 4 years total. There are two main training facilities for Connecticut union members: one in Wallingford, CT (which serves Southern CT), and one in Millbury, MA (which serves Northern CT).[38] As coastal CT encompasses all potential sites for portside construction, and as it is in the Southern part of the state, this report focuses mostly on trainees attending the Wallingford, CT location. This location is roughly 40 minutes from Bridgeport, 1 hour and 10 minutes from New London, and 30 minutes from Waterbury. We cite Bridgeport, New London, and Waterbury in this report because these are 3 cities where unemployment is particularly high. Workers in these locales would need to have access to a vehicle to reach the Wallingford training facility. Access to a vehicle can be a barrier to safe employment for people who need that employment most of all. Carpenters Local 326 apprentices and demographic data are represented in Figure 1.1 and Table 1.4.

Barriers to Access in CT

Another potential barrier to union apprenticeships—and subsequent jobs—in CT amounts to a discrepancy between wages in different locations. Carpenters' and Ironworkers' Union training centers in Millbury, MA and Dorchester, MA attract many out-of-state trainees from surrounding states, including Connecticut and Rhode Island. This is due to the proximity of these training locations to Boston Area jobs. These jobs, according to both qualitative and quantitative evidence, pay better wages than those outside the Boston Area, and better than those in CT. For instance, union carpenter wages in CT are $36/hr, while in Boston, MA they are $54.61/hr. For union ironworkers, those wages are $38/hr for CT, and $53/hr for Boston.[39] Table 1.1 describes these wages. And while carpenters and ironworkers do not make yearly salaries, we created yearly salary equivalents with some guidance from industry experts.[40] According to our calculations,[41,42]union carpenters can make about $30,000 more per year in Boston than they can

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[38] n.a. (n.d.) Locate the Regional Training Center Nearest You. The United Brotherhood of Carpenters and Joiners of America. https://www.carpenters.org/training-center/. Accessed on 14 November 2022.

[39] The Bureau of Labor Statistics (BLS) reports that, as of May 2021, the mean hourly wage for carpentry jobs is $29 in the Norwich, CT, New London, CT, and Westerly, RI region. Glassdoor reports that, for union carpenters working in the Boston, MA area, the mean hourly wage is $43, with a likely range between $34 and $54 (as of December 2020). Glassdoor reports an average hourly wage of $34/hour for union ironworkers in Boston, with $42/hour on the high-end of a likely wage. BLS reports that, as of May 2021, the mean hourly wage for an ironworker in the Boston-Cambridge-Nashua region is $40/hr. And while there is no available data for the Norwich-New London-Westerly region, state-level data reports a mean wage of $42/hr for Boston, and $33/hr in CT. However, our union contacts report wages significantly higher than this all-around. We use their numbers for our calculations.

[40] Chris Bachant Interview, Business Representative, Carpenters Local 326, 16 August 2022

[41] n.a. (2021, 5 August). Salary vs. Hourly Wages: Definitions and How to Calculate. *Glassdoor*. https://www.glassdoor.com/blog/guide/salary-vs-hourly/#:~:text=Divide%20your%20annual%20salary%20by,This%20is%20your%20hourly%20pay. Accessed on 8 August 2022.

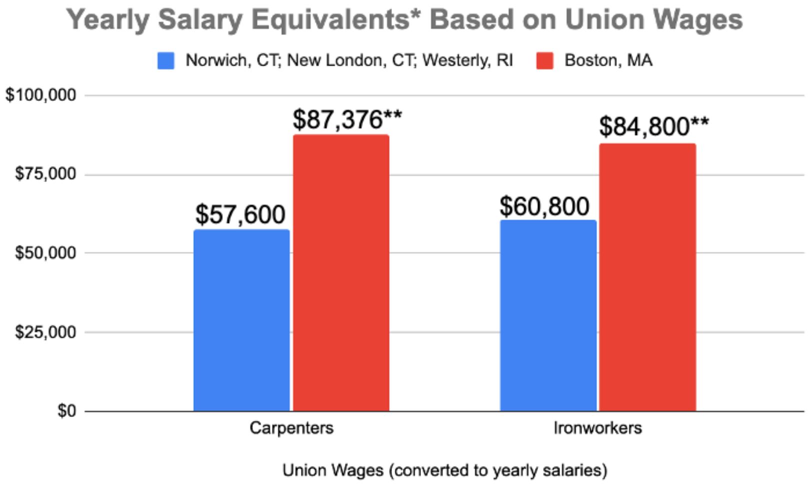
[42] According to Glassdoor, yearly salaries are calculated from wages by multiplying the hourly wage by 8 (assuming there are 8 hours in the average workday), and then by multiplying that number by 260 (which assumes someone

in Connecticut. Iron workers can make about $24,000 more per year in Boston than they can in CT. These wage differences aren't only significant in terms of hourly or yearly pay, they also make a difference for pensions and secure retirement. See Figure 1.1 for more information on these salary equivalents, along with the last two footnotes.

Table 1.1: Wage comparison across regions in New England (BLS, Glassdoor, industry experts, 2021)

	Southern CT (Norwich, CT; New London, CT; Westerly, RI)	Boston, MA
Union Carpenter Wage	$36/hr ($29/hr)	$54.61/hr ($43/hr)
Union Ironworker Wage	$38/hr ($33/hr)	$53/hr ($42/hr)

Note that the numbers in parentheses are from the Bureau of Labor Statistics/Glassdoor, but do not reflect numbers that align with ones our industry contacts provided to us.



* There is no such thing as a salary for carpenters or ironworkers, as they are paid an hourly wage. However, hourly wages alone do not show the extent to which wage differences impact one's yearly take-home. Wage differences add up over time.
** Boston pay is likely to be higher when weekend pay and overtime pay are taken into account.

Figure 1.1: Yearly Pay Differences Between CT Work and Boston Work (Glassdoor, industry experts)

Overall, Connecticut is one of the most unionized states in the country. The rate of unionization in the public sector is high, at 62%. However, that number is lower for skilled workforces that

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works most every weekday, and not weekends). Construction work is different from a typical 9-5 job in several ways: projects aren't consistent (people work at a site until a project is finished), workers often experience time gaps between projects, and there are no paid holidays or sick days. Given these factors, a 9-month salary is an average estimate for trade work, which equates to about 200 working days. Therefore, we used the Glassdoor formula, replacing 260 with 200. It looks something like this:

Yearly Salary Equivalent = Hourly Wage x 8 x 200
This does not include weekend and overtime work, which is more likely to exist in—and increase pay in—Boston, MA.

are both public and private—at 17.1%.[43] We think this lack of unionization for skilled workers may be the root of this wage discrepancy.[44] And we believe that Connecticut, in keeping with its strong union tradition, can boost those wages by offering more union jobs to combined public-private workforces such as the construction trades. This will also offer more bargaining power to the construction trades, which is essential to any equitable workforce. Bargaining power is also essential for a workforce that includes underserved, historically marginalized communities. Here, OW offers the state of Connecticut an opportunity to offer its residents equitable, and sustainable jobs while forwarding the just energy transition. This is especially important because the current Boston construction boom will not last forever. The city has begun to experience a slowdown in developer-proposed projects.[45]

Diversity, Equity, Inclusion, and Justice (DEIJ) in Trade Labor

In this section, we will overview the efforts CT Carpenter's Local 326 has taken to diversify its active membership. We will also expand on some outreach initiatives that have helped to strengthen and diversify the trade workforce.

The Connecticut Carpenters Local 326 has 2,278 active working members. Of these workers, 238 identify as Black; 8 identify Asian, Hawaiian, and Pacific Islander; 1,484 identify as White; 483 identify as Latino or Hispanic; 5 identify as Native American. Additionally, 2 identify with two or more racial or ethnic categories, and 58 have not reported.[46] As of 2021, close to 35% of these active members are women and/or people of color.[47,48] While we do not have historical race and ethnicity data for Carpenters 326, it is our understanding that local trades unions have been working to diversify their ranks for the last several decades.[49] Leadership within Carpenters 326 is working to recruit such that the diversity of the union matches the diversity of Southern CT, which is closer to 40% non-white in New Haven County[50] and 80% non-white in the city of Bridgeport (Figure 1.3). Figures 1.2 and 1.3 show the demographic data from 2021 on the racial and ethnic backgrounds of active members and apprentices in Carpenters Local 326.

The executive board of Local 326 has prioritized diversity. This board consists of 8-members total: 7 voting members and 1 non-voting president. Through recent changes, the board now has

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[43] Pazniokas, M. (2021, 19 August). Construction trades vote to stay in the CT AFL-CIO. But why did it come to a vote? *The CT Mirror*. https://ctmirror.org/2021/08/19/construction-trades-vote-to-stay-in-the-ct-afl-cio-tensions-in-labor/. Accessed 8 August 2022.

[44] The practice of hiring construction workers as independent contractors, rather than through unions, contributes greatly to this issue. See: Erlich, M. (2021). Misclassification in construction: The original gig economy. *ILR Review, 74*(5), 1202-1230.

[45] Ryan, G. (2022, 12 May). Boston is seeing a slowdown in proposals by developers. *Boston Business Journal.* https://www.bizjournals.com/boston/news/2022/05/12/boston-is-seeing-a-slowdown-in-proposals-by-develo.html. Accessed 3 September 2022.

[46] Chris Bachant Interview, Business Representative, Carpenters Local 326, 16 August 2022.

[47] Chris Bachant Interview, Business Representative, Carpenters Local 326, 12 August 2022.

[48] This data was collected through an internal survey conducted by the executive board of Local 326, working to improve the representation of members from minoritized backgrounds.

[49] Porter, E. (2021, 6 November). Can Progress on Diversity Be Union-Made? The New York Times. https://www.nytimes.com/2021/11/06/business/economy/unions-race-boston.html. Accessed on 22 August 2022.

[50] https://usafacts.org/data/topics/people-society/population-and-demographics/our-changing-population/state/connecticut/county/new-haven-county?endDate=2021-01-01&startDate=2010-01-01

the following demographic breakdown: 4 out of 8 members identify as Black; 1 out of 8 identify Latino/Hispanic; 3 out of 8 members identify as white. 2 out of 8 members identify as women. There is 1 white woman on the board, and 1 Black woman. To date, members of the executive board of Carpenters Local 326 have the most diverse backgrounds of any board in the North Atlantic Council.[51] Ultimately, Local 326 aims to represent, through racial and gender breakdowns of its members, the diversity of Southern Connecticut. The executive board has set a goal for *at least* 50% of union members to be Black or African American, Native American, Hispanic, Asian, and Hawaiian or Pacific Islander.

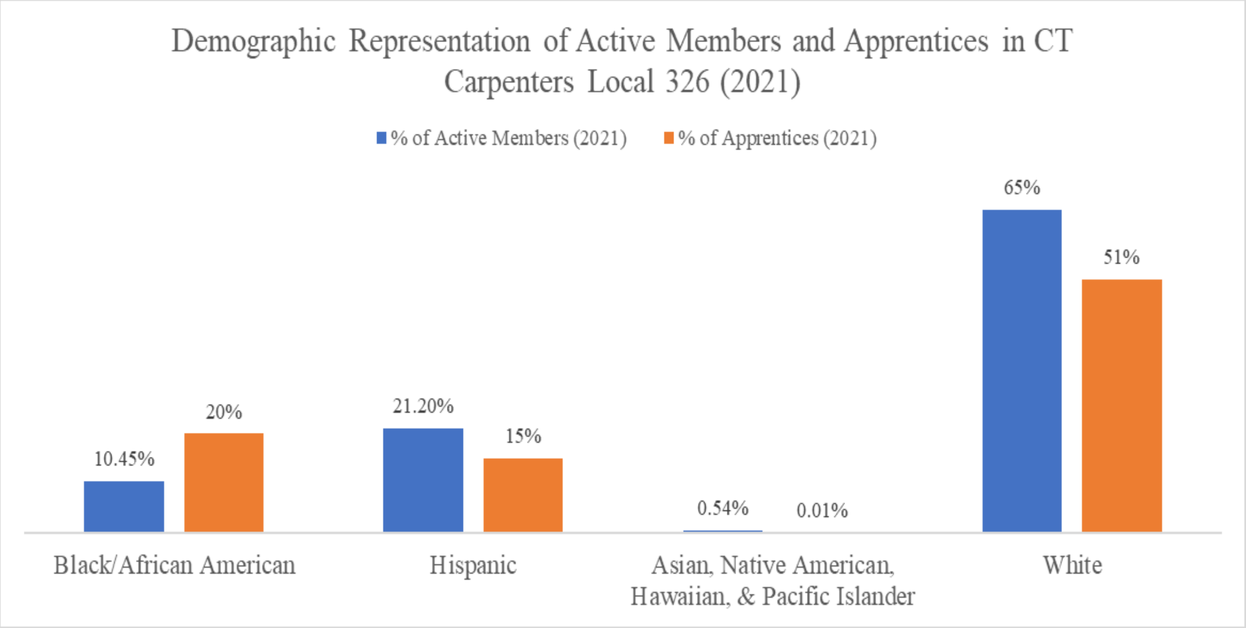

Figure 1.2: Demographic Representation of Active Members and Apprentices in CT Carpenters Local 326.

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[51] Chris Bachant Interview, Business Representative, Carpenters Local 326, 16 August 2022.

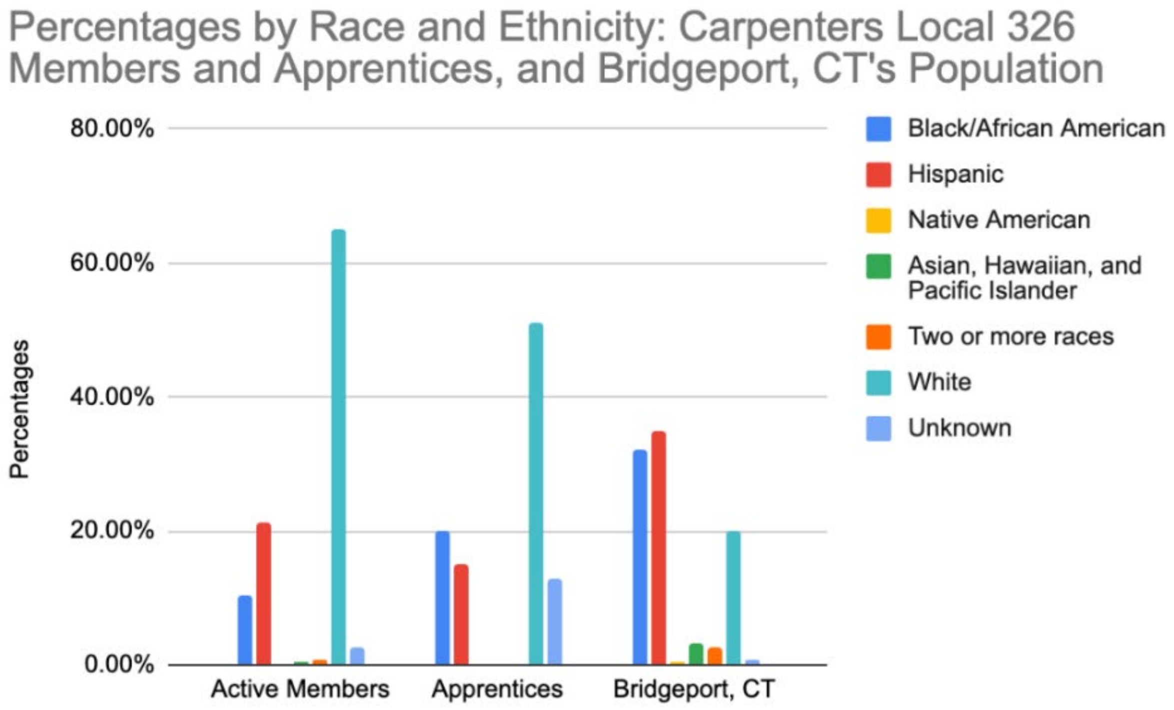

Figure 1.3. Demographic percentages for Carpenters Local 326 (Members and Apprentices) and Bridgeport, CT

Sources: Carpenters 326, 2020 Census

Importantly, apprenticeship numbers reflect progress toward diversifying the workforce. Apprentices tend to come from a more diverse array of racial and ethnic backgrounds because the trades have invested in apprenticeship readiness programs that recruit from underserved communities. In short, apprenticeship readiness programs provide opportunities to people who have been historically excluded from safe, equitable employment. Below, we review a few of these initiatives.

Building Pathways

Buildings Pathways is a program designed to prepare and promote women, veterans, and minorities to enter the Building Trades. The program consists of a seven-week, union-led training curriculum that serves as an introduction to different trades and is intended to provide participants an insider perspective on opportunities across construction. The program is open to women who are Connecticut residents and all applicants to the CT Northwest Regional Workforce Investment Board (NRWIB) who are eligible for WIOA (Workforce Innovation & Opportunity Act) funding.

However, there are a number of requirements that pose barriers to entry for Building Pathways. For instance, the need for a driver's license and access to a car.[52] Additionally, while the seven-week program is free, it runs on business days from 7:00 am to 3:30 pm, which can be prohibitive for people who work full-time. It is also unpaid and therefore does not compensate people who need paychecks while transitioning careers.[53]

Helmets to Hardhats

Helmets to Hardhats is a program designed to transition veterans and active-duty military members to a career in construction. H2H is a national nonprofit program available to veterans in every state.[54] Traditionally, apprentices in the trades make 50% of their full wages—an amount that increases in each of the 4 years of the apprenticeship. However, active and retired military personnel can make full journeyman (post-apprenticeship) wages as soon as they enroll in training. This is because union apprenticeship programs are registered with the U.S. Department of Labor's Office of Apprenticeship (and/or may also be registered with Connecticut's Office of Apprenticeship). This enables veterans to make use of their G.I. bill benefits to enroll in H2H and to begin making a full journeyman salary immediately.

Sisters in the Brotherhood

Sisters in the Brotherhood (SIB) is a program mostly situated around a series of conferences within the larger structure of the United Brotherhood of Carpenters (UBC). SIB provides networking opportunities, trainings, and community for women in carpentry unions across the country. Ultimately, the SIB initiative aims to strengthen the retention of women in the trades.[55]

Additionally, our team is aware of efforts between Local 326 and other community organizations to recruit and train formerly incarcerated people.

DEIJ and Project Labor Agreements

In addition to recruitment by unions, an influx of union jobs and bargaining power, Project Labor Agreements (PLAs) are critical to ensuring a diverse, equitable, inclusive, and just OW workforce. They are negotiated contracts between a developer on a given project and the union trades on construction projects with a budget of $35 million dollars or more. PLAs ensure compensation, timeliness, safety, and diversity for union workforces and—on OW projects, which are likely to have very high budgets—they have the potential to further empower union labor. In Connecticut, where construction is both a public and private workforce, PLAs can ensure competitive wages when unions are employed by large developers. PLAs can also include terms that are mutually beneficial for developers. By ensuring that trade union workers are treated fairly at the outset, PLAs can also protect developers against strikes, provide clear processes for the resolution of labor disputes, enumerate health and safety measures in clear

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[52] n.a. (n.d.) Building Pathways CT FAQ. *BuildConnecticut*. http://ctula.org/staging/wp-content/uploads/2018/07/Building_Pathways_CT_FAQ_7_8_18.pdf. Accessed on 1 August 2022.

[53] ibid

[54] n.a. (n.d.) Carpenter Careers. *Helmets to Hardhats*. https://helmetstohardhats.org/carpenter-careers/. Accessed on 1 August 2022.

[55] n.a. (n.d.) Join the Sisters in the Brotherhood. *The United Brotherhood of Carpenters and Joiners*. https://www.carpenters.org/sib-join-us/. Accessed on 22 August 2022.

terms for all parties, and connect projects that have been previously un- or under-regulated to federal-level legislation.[56]

Chiefly for this section, we'd like to point out that PLAs are one mechanism for diversifying construction—and potentially diversifying OW construction. Vineyard Wind is one example of this. In the Vineyard Wind PLA, 20% of the onshore workers are required to be apprentices. Some of these apprentices can be direct graduates of the regional Building Pathways program, meaning they will be first-year apprentices when they begin work. Additionally, the Vineyard Wind PLA requires contractors to have a workable plan that advances a workforce of 10% women and 20% BIPOC (Black, Indigenous, and People of Color) workers. Vineyard Wind has agreed to "commit up to $500,000 to aid Building Pathways and similar programs to help train and employ local, BIPOC and women apprentices for work in offshore wind."[57] The PLA also includes plans for an Access and Opportunity Committee to meet monthly and oversee DEIJ strategy and progress. While we believe that DEIJ plans in these documents are not as robust as recruitment efforts by unions themselves, they can be an important support for unions in OSW projects.

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[56] The White House Briefing Room. (2022, February 4). Executive Order on Use of Project Labor Agreements For Federal Construction Projects. https://www.whitehouse.gov/briefing-room/presidential-actions/2022/02/04/executive-order-on-use-of-project-labor-agreements-for-federal-construction-projects/

[57] Vineyard Wind Outer Continental Shelf Wind Farm in Lease Area OCS-A-501 Project Labor Agreement, Vineyard Wind, Its Project Prime Contractors-The Southeastern Massachusetts, Cape Cod and Islands Building Trades Council AFL-CIO, et. al., May 2021, pg. 21.

Section II: Economics

Offshore Wind Pricing

In February 2022, Hines and Kates-Garnick reported a weighted mean Levelized Nominal Price (LNP) of $95.36/MWh for nine offshore wind projects on the East Coast in 2022 dollars.[58] While offshore wind costs and pricing can be difficult to compare between projects and vary based on assumptions related to: contract term, contract timeframe, inflation rate and discount rate, capacity payments, the use of the Federal Investment Tax Credit (ITC), and the level of economic benefits; it is well established that U.S. offshore wind prices on average have settled below $100/MWh and currently range from $73.27/MWh to $114.03/MWh.[51]

Consider this range: $73.27/MWh to $114.03/MWh. The maximum difference between projects is $40.76/MWh, or 43% of the weighted mean LNP. Imagining this difference for a 1000 MW wind farm with a contract life of 25 years and a capacity factor of 50% yields a total difference in project cost of approximately $2.1 Billion in 2022 dollars.

This section introduces a pricing study where the cost premium for a low-carbon concrete GBF is approximately 20% higher than an equivalent monopile foundation. Assuming that the foundation accounts for 15% of a wind farm's total cost, this amounts to an approximately 3% increase to the overall project cost, or an increase in the weighted mean LNP from $95.36/MWh to $98.22/MWh.

Consider further that the all-in cost of electricity, including retail generation, transmission, distribution, and fees for a residential rate payer in Massachusetts has been approximately 26¢ per kilowatt-hour (kWh) or $260/MWh over the past few years. Translated into practical ratepayer terms, this additional $2.86/MWh would represent a 1.1% increase to the residential electricity rate mentioned above.

Furthermore, a comparison simply by LCoE or LNP is flawed because it neglects many critical factors including longer design lives, local jobs, and environmental benefits. These matters are discussed further in this paper with the introduction of the term Societal Cost of Energy (SCoE), discussed at the end of this section.

Gravity-Based Foundation Jobs: Sample Calculation

Water-based OW jobs have been the most quantified to date. In this report, however, we shift to quantify and compare land-based manufacturing jobs. For this comparison, we use the National Renewable Energy Laboratory's (NREL's) Jobs and Economic Development Impact (JEDI) Model, the New England Wind Design Construction and Operations Plan (COP), and projections for the proposed EEW monopile facility in Paulsboro, NJ in order to estimate potential monopile jobs. None of these resources, however, provide insight into the number of potential GBF jobs. For this reason, we developed our own calculations, which we present below. When comparing

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[58] Hines, E. and Kates-Garnick, B. (2022). U.S. Offshore Wind Prices (2018-2021). Tufts University. OSPRE-2022-01. February 28. Retrieved on August 26, 2022 from https://dl.tufts.edu/pdfviewer/x633fg18n/rb68xs83b

job numbers from foundations alone, based on the analysis described in this paper, we estimate that a single GBF could yield approximately 60 local jobs for a Connecticut OW project, and a single monopile could yield approximately 2 local jobs for a similar project.

Appendix A1 develops this number of 60 local jobs per GBF in detail as an approximate average of GBF foundations designed in Section IV for 25 m and 50 m water depths. In order to help our reader understand the methodology behind these calculations in Appendix 1, we offer the following simple calculation for an 8,400 tonne (3,500 m^3) GBF that is assumed to cost 20% more than an equivalent 2,000 tonne monopile.

Assuming a cost of $3,000 / t for steel monopile fabrication, a 2,000 t monopile would cost:

($3,000 / t) × (2,000 t / monopile) = $6,000,000 / monopile

Assuming a 20% premium for an equivalent 8,400 t GBF gives a GBF cost of:

($6,000,000) × (1.20) = $7,200,000 / GBF

A GBF with 3,500 m^3 of concrete weighs 8,400 t. Assuming a concrete material cost of $188 / m^3, a steel reinforcing bar material cost of $550 / t, and a volumetric steel reinforcement ratio of 2% yields:

(3,500 m^3) × ($188 / m^3) = $658,000 for concrete; and

(0.02) × (3,500 m^3) × (7.85 t/m^3) × ($550 / t) = $302,000 for steel reinforcement

Subtracting the material costs from the total assumed GBF cost yields a labor cost of:

$7,200,000 - $658,000 - $302,000 = $6,240,000

Assuming an all-in labor cost of $100,000 per job per year:

($6,240,000) / ($100,000 per job per year) = 62.4 job years

Which can be rounded to 60 jobs per year per GBF. This calculation demonstrates that for an overall project premium of 3% (approximately $3 / MWh) most of the money invested in GBFs would go directly to local jobs. Conversely, monopiles fabricated outside of Connecticut would produce approximately 2 local jobs per monopile as discussed in Appendix 1. The reason for this stark difference is that monopiles will be built elsewhere and delivered to Connecticut for each project.

GBF jobs in the Context of a GBF Factory

Table 2.1 considers a GBF factory with similar throughput to the proposed EEW monopile facility at Paulsboro, New Jersey. This Monopile factory is projected to provide 500 jobs and produce 100 monopiles per year once it reaches its second phase.[59] By contrast, a low-carbon GBF factory with similar throughput would create 6,000 jobs per year, assuming 60 job-years per GBF, assigning an all-in cost of $100,000 per year to each job. This can be calculated as:

$$(100 \text{ GBFs} / \text{year}) \times (60 \text{ job-years} / \text{GBF}) = 6{,}000 \text{ jobs}$$

Table 2.1: Comparison of stable jobs for factories servicing the wider offshore wind industry

Factory	Jobs	Throughput
Monopile	500	100 foundations per year
GBF	6,000	100 foundations per year

Local jobs in OW foundation manufacturing

The *local share* of jobs is critical to contextualizing job-years produced from manufacturing different OW foundations. *Local share* is the percentage of local labor and materials that will comprise the manufacturing process. In this section, we describe the JEDI model's assumptions about local share, material costs, and labor costs that yield the number of job-years per foundation. This section contextualizes the JEDI model by describing the process of fabricating monopiles and concrete GBFs.

Monopile Production

Monopiles are immensely large steel cylinders, weighing 1,500- 3,000 metric tons each. For a monopile with a diameter of 10 meters, as is the case in our scenario, steel thickness must be at least 77 millimeters (these details will be described in further detail in Section IV). Thicknesses of 77 mm and greater are at the cutting edge of welding technology and this type of steel welding is not a common practice outside of what is necessary for OW.

Importantly, the two types of welding—the longitudinal piece to combine the rolled steel sheet and the circumferential can welding to make the monopile—cannot take place by hand. Automated welding machines (shown in Figure 2.1) are required to weld at these steel thicknesses.

While several jobs have been created in the construction of monopile factories, there are fewer jobs made than one might initially assume because of automated welding. These practices are important to consider for the JEDI model, because it does not take automated steel manufacture into consideration in its calculations. The JEDI model is based on the IMPLAN economic modeling software which creates industry-specific multipliers from Bureau of Economic Analysis (BEA) data.[60] Because there are no existing economic data in the U.S. to reflect the impact of automated steel manufacturing to produce monopiles, the input data for this model will not reflect this new industry. Monopile factories have yet to be built in the U.S. to generate such economic data for the BEA.

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[59] EEW website. https://eew-group.com/locations/eew-aos/. Accessed on 16 October 2022.

[60] IMPLAN. (n.d.) "What are IMPLAN's Data Sources?" https://implan.com/data-sources/#toggle-id-5. Accessed on 20 August 2022.

Figure 2.1: Automated Welding in a Monopile Factory, SIF Group (2020)

The JEDI model calculates the monopile job-year output from steel weight, cost, and local share of the monopile production process. The job-years calculations for local production of monopiles in CT through JEDI is unreliable, thus we use estimates from planned monopile production facilities at the Paulsboro Marine Terminal (NJ) and at Sparrows Point (MD) to inform the job estimates for monopile production in the US.

Currently, monopile production takes place in Europe, while planned facilities in New Jersey and Maryland are in the early stages of development. Thus, modeling a more realistic local share–the percent of local labor and materials in the manufacturing process–helps us depict a likelier future. By focusing on local share, the factor of automation in foundation manufacturing becomes less critical in calculating foundation job-years. In the JEDI model, local share is a key input to estimate job-years produced in Connecticut. Yet, for Connecticut jobs, the local share for primary steel—the rolled steel that makes up each *can* of the monopile—will be zero. Secondary steel, which makes up the ladders and platform on the foundation, is an opportunity for local manufacturers. Therefore, secondary steel is more expensive than primary steel: it is more labor intensive and cannot be automated in the way of primary steel. Thus, manufacture of secondary steel will yield more job-years than the primary steel required for the cans.

However, secondary steel makes up approximately 4% of the monopile. For a monopile that weighs 1,500 metric tons (a weight that corresponds to supporting a reference 15 megawatt turbine), secondary steel makes up approximately 60 metric tons of that weight.[61,62] Thus, if the entirety of these components is manufactured locally, local manufacture accounts for approximately 4% of all monopile materials.[63,64] To accommodate for the labor intensive nature of this secondary steel manufacture, we assume local share to be 5%. In the following section, we will discuss production processes for GBFs to shed light on assumptions in GBF economic calculations.

Concrete Gravity-Based Foundation Manufacture

While the fabrication of monopiles has matured to largely one manufacturing process, concrete GBFs have a wide variety of potential designs and therefore differing manufacturing processes. In this report, we focus on a design developed by Seatower, a designer of GBFs based in Norway.

Costs of concrete construction are propriety in the OW industry because they would reveal bids to competing developers. However, without specific cost numbers, the calculation of job-years is difficult for OW projects that have a limited history in the US. To overcome this hurdle, we have used the monopile costs as a reference point for costs in that the manufacture of GBF foundations will cost 15%-25% more than an equivalent monopile project.[65] These assumptions are rooted in guidance from industry experts. A 20% foundation difference yields a 2% total project premium for a GBF wind project.

In addition to concrete costs, there are steel costs in GBF manufacture. GBFs, like all reinforced concrete structures, include reinforcing steel and post-tensioning cables. Material and labor cost for this steel are assumed to be the same as the JEDI model's set steel parameters of $3,000 (material and labor) per metric ton.

Lastly, an important limitation of the GBF manufacturing process in the JEDI model is its omission of the work required to set up and take down the manufacturing site. Figure 2.2 depicts the GBF foundation manufacture site in Le Havre, France that is building 71 foundations for the Fécamp Wind Project. These foundations must be built close to the OW site because of their volume and weight, thus requiring a large area for which to conduct the work. Preparing this area to hold the number of foundations necessary for a 1 GW wind farm will require a considerable number of job-years to work in the construction of preparing and taking down the worksite. The job-years calculated with the JEDI model do not reflect the labor required for job site preparation and take-down.

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[61] Petter Karal Interview, CEO, Seatower AS, 22 August 2022.

[62] Sigurd Ramslie Interview, CTO, Seatower AS, 22 August 2022.

[63] To calculate the percentage of secondary steel, we divide 60 metric tons (secondary steel weight) by 1,500 metric tons (total monopile weight), which yields 0.04 or 4%.

[64] In the model, we have used 5% monopile local share to account for the more labor-intensive nature of these secondary steel manufacturing jobs.

[65] Communication from industry experts, Seatower AS, 25 August 2022. We note that using a greater premium of 25% would yield more job-years as the additional costs in GBF manufacture are labor costs.

Figure 2.2: Concrete GBF Manufacture Site for Fécamp Wind Project in Le Havre, France.[66]

GBF jobs in the context of a Connecticut OW Project

In the following section, we'll explain what these numbers mean both in the context of a single offshore wind project, in the context of a GBF factory, and in the context of U.S. offshore wind market growth over the next three decades. The Appendix explains in detail how we got those numbers. Even if GBFs constitute grow to less than half of the U.S. market, there is potential for exponential U.S. construction job growth over the next 20 years, stabilizing at just under 18,000 GBF construction jobs at least through 2050.

While a ratio of 30:1 for GBF jobs to monopile jobs is impressive, it is important to understand these numbers in the context of an actual project. For this reason, it is helpful to imagine an actual Connecticut project, such as Park City Wind, with and without GBFs. Table 2.2 shows that GBFs could create approximately six-times the number of jobs as the same project with monopiles.

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[66] Image credit: https://www.spie.com/en/news/spie-using-its-experience-offshore-projects-develop-renewable-energy. Accessed on 13 November 2022.

Table 2.2: New England Wind Design Case Job-Years, Construction Jobs

New England Wind Design Case	Job-Years	Construction Jobs
Park City as planned in current COP (with monopiles)	770	154
Park City with possible CT low-carbon GBF factory	4,790	958

As a baseline, Table 2.2 lists the jobs for Park City Wind as reported in The New England Wind Economic Analysis.[67] This document specifies a range of 154 direct construction jobs and 70 direct Operations and Maintenance (O&M) Jobs for the 804 MW Park City Wind project.

By contrast, a low-carbon GBF factory with similar throughput would create an additional 804 jobs, to yield 958 jobs as shown in Table 2.2. For a wind project with 67 GBF foundations, 60 job-years per GBF, we calculate 4,020 job years. For a 5-year construction duration, this yields 804 GBF manufacturing jobs. Because the monopile foundations for the Park City project will not be manufactured in Connecticut (New England Wind and Avangrid 2022), we can add the 804 GBF jobs to the report's expected job creation number of 154, which yields a total of 958 jobs. The equation for this calculation is below:

$$(\text{ 60 job-years / GBF })(\text{ 67 GBFs }) = \text{4,020 job-years}$$

$$\text{4,020 job-years / 5 years} = \text{804 GBF jobs}$$

- Operational definition: in this report, the term *jobs* means *jobs that last the duration of the construction activity*.

- Reasoning: there are several confounding factors in the calculation of offshore wind jobs. Perhaps the most prominent is the conflation of jobs and job-years. "Jobs" can have a variety of different meanings, but largely has no set time constraints. "Job-years" refer to the amount of time, generally 2,080 hours, that amounts to one year of work and one salary.

Table 2.2 demonstrates the difficulty in comparing apples to apples with construction jobs over a period of 5 years. The likelihood is that the GBF construction for Park City Wind would take two years or less. This would inflate the number 958 to 2,164 but would not provide a fair comparison. For this reason, most jobs reports focus on job-years.

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[67] New England Wind (2022). Construction and Operations Plan: Lease Area OCS-A 0534; Volume III Appendices; Appendix III-L—Economic Analysis for New England Wind. Submitted by Park City Wind, LLC. Submitted to the U.S. Bureau of Ocean Energy Management. June. Retrieved on October 15, 2022 from https://www.boem.gov/sites/default/files/documents/renewable-energy/NE%20Wind%20COP%20App%20III-L%20Econ_June%202022_PUBLIC.pdf

GBF Job Growth in the Context of Future U.S. Offshore Wind Markets

The potential to build significant expertise and innovation in the service the U.S. offshore wind out to 2050 and beyond is also pertinent to the discussion of a low-carbon GBF factory in Connecticut. Figure 2.3 shows the potential for U.S. job growth in two phases: 1) under Connecticut's initial leadership during the 2020s, where nearly 2,000 permanent jobs are created, and 2) during a second wave of growth at this same factory or elsewhere that eventually reaches a production capacity of nearly 300 GBFs and 18,000 jobs per year. The assumptions and calculations behind this figure are presented in Appendix 1.

Figure 2.3: Possible low-carbon GBF job growth from 2023 to 2050.

Design Life

One of the key challenges for OWT (offshore wind turbine) foundations is ensuring that the structure survives in the harsh marine environment. The amount of time the foundation can safely support the wind turbine is considered the *design life* or the *service life*. There are two key mechanisms of long-term damage that affect the design life of a structure. First, environmental loads, namely the turbulence from wind combined with the waves hitting the structure, lead to a high number of loading cycles acting on the structure. Overtime, these load cycles cause *fatigue damage*, which is the buildup of damage in the structure due to constant stress over its lifetime. This is different from damage or breakage from a single *extreme loading event* such as a hurricane or nor'easter. Another kind of damage occurs due to chemical reactions between the structure and seawater, which cause corrosion of any metals in the turbine's foundation. These two damage mechanisms slowly degrade the structure over time. Because the structure has a finite lifespan, it is crucial for the engineering design process to choose materials and specifications that match the needs of the project.

Due to historical precedent from oil and gas leases and land-based wind farm development, OW leases—and therefore the design life for most offshore wind turbines and foundations—is often set at 25 years.[68] Turbine blades also have a lifespan of about 25 years.[69] Many of the oldest offshore wind farms operating in Europe are just approaching 25 years old, and the industry has begun to investigate lifespan extension.[70] Therefore, it is valuable to consider the potential for different foundations with design lives beyond 25 years.

Concrete structures have displayed impressive lifetimes and fatigue resistance. The oil and gas industry has been using concrete gravity-based platforms for almost 50 years in the North Sea, proving the longevity of concrete foundation structures and the performance of such structures in a marine environment.[71] As a highly fatigue-resistant material, the design life of a concrete GBF can be much longer than 25 years. Due to the durability, concerns about fatigue will not have a significant impact on the design of a concrete GBF, allowing for longer design lives without expending additional material or cost. If a concrete GBF has a sufficiently long lifetime, there is also an opportunity to utilize the foundation multiple times once the initial OWT is decommissioned.

Meanwhile, fatigue typically plays a much more significant role in steel monopile design, particularly for large diameter monopiles in deep waters like those that are expected for the Massachusetts and Rhode Island lease areas.[72] Recent studies have shown that for the large monopiles which are becoming standard in industry, fatigue is a significant concern, primarily due to wave loads particularly when the turbine is not operation (i.e., when it is *parked*).[73] However, there is no simple solution to reducing the effect of wave loads on the structure.

Improving the fatigue life of concrete GBF structures is more easily achieved than it is for monopiles. It is easier to use higher strength concrete or thicken the structure in regions of the structure where the design is controlled by fatigue; neither of these have a significant effect on cost because the dominant cost is that of labor. In contrast, there are limited methods for improving the fatigue resistance of steel monopiles. The primary method is to increase the thickness of the steel tubes (known as cans) that make up the monopile. This option is constrained by the price of steel, as small changes could have an impact on the monopile's cost.

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[68] Ray, S. (2017, November 6). Repowering wind turbines adds generating capacity at existing sites. U.S. Energy Information Administration. https://www.eia.gov/todayinenergy/detail.php?id=33632. Accessed on 23 August 2021.

[69] Gignac, J. (2020, October 30). Wind Turbine Blades Don't Have to End Up In Landfills. *Union of Concerned Scientists*. https://blog.ucsusa.org/james-gignac/wind-turbine-blades-recycling/#:~:text=In%20terms%20of%20durability%2C%20wind,can%20be%20recycled%20or%20reused. Accessed on 3 September 2022.

[70] Ziegler, L., Gonzalez, E., Rubert, T., Smolka, U., & Melero, J. J. (2018). Lifetime extension of onshore wind turbines: A review covering Germany, Spain, Denmark, and the UK. *Renewable and Sustainable Energy Reviews*, *82*, 1261-1271.

[71] Olsen, T. O., & Haugerud, S. A. (2009). Offshore concrete structures. In *Rotorua, New Zealand: The New Zealand Concrete Industry Conference* (Vol. 9).

[72] Njomo-Wandji, W., Natarajan, A., & Dimitrov, N. (2019). Influence of model parameters on the design of large diameter monopiles for multi-megawatt offshore wind turbines at 50-m water depths. *Wind Energy*, *22*(6), 794-812.

[73] Velarde, J., Kramhøft, C., Sørensen, J. D., & Zorzi, G. (2020). Fatigue reliability of large monopiles for offshore wind turbines. *International Journal of Fatigue*, *134*, 105487.

Alternative options to improve the fatigue resistance (such as weld grinding) of steel monopiles are also expensive.

For a monopile, corrosion of the primary steel making up the pile is a major concern. Coatings and cathodic protection are used together to delay corrosion damage and increase the design life of the structure. In the coatings process, the steel pile is coated with multiple solutions, typically made up of epoxies (very durable adhesives, often containing zinc due to its anti-corrosive properties) and polyurethanes (protective plastics) to create a physical barrier between the steel and the seawater. Meanwhile, cathodic protection involves connecting the steel to an external source of electrons (such as a metal or a power source), which prevents the primary steel from corroding for a time.

Neither of these monopile corrosion fixes are simple, and they must be designed by experts in corrosion protection systems. Some of the first offshore wind monopile foundations built in the early 2000s had several issues related to their corrosion protection systems. Ultimately, these early monopile foundations required expensive retrofits to ensure the structures were properly protected.[74] New standards and recommended practice documents mean these same issues should not reoccur in the U.S. market if the designers are competent. While corrosion protection systems are continuing to be developed and improved, they are still an additional system where the consequences of a failure can be a significant expense.

This is all to say that corrosion due to interactions between seawater and metals can be a major source of damage for turbine foundations. Concrete foundations are far safer from corrosion damage than steel monopile foundations. However, concrete foundations do contain reinforcement steel, which acts as a strong and rigid skeleton for the concrete base. This reinforcement steel degrades over time as seawater leaks through the concrete. To avoid this, the concrete surrounding the steel reinforcements can be made thicker and to block the ingress of chlorides.[75] The thickness of concrete required to achieve a more seawater-resistant structure does not render a concrete GBF uneconomical because concrete is a cheap building material. In short, reinforced concrete bases more successfully resist corrosion, requires less maintenance, and have been found to have a significantly longer lifespan than steel monopile bases.[76]

An Economic Model for Decision-Making: Transitioning from LCoE to SCoE

Economic factors control many decisions for the development of offshore wind farms. Currently, the Levelized Cost of Energy (LCoE) is the dominant model used for decision making. LCoE

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[74] Black, A. R., Mathiesen, T., & Hilbert, L. R. (2015, March). Corrosion protection of offshore wind foundations. In *CORROSION 2015*. OnePetro.

[75] Mathern, A., von der Haar, C., & Marx, S. (2021). Concrete support structures for offshore wind turbines: Current status, challenges, and future trends. *Energies*, *14*(7), 1995.

[76] Inspections of offshore concrete structures in the North Sea, 20 years after installation, indicated that the marine concrete is extremely durable and behaves very well when adequate reinforcement cover is provided. Further, inspections showed that the structures lasted past their 20-year design life and the new predicted lifetime of the structures was more than 200 years. Due to its durability, concrete also has fewer costs associated with maintenance (Olsen & Haugerud, 2009).

considers the cost of the design, fabrication, installation, operation, and decommissioning using a design life of approximately 25 years. There are several shortcomings with this approach:

- A short design life is not appropriate for an inexhaustible resource such as wind.

  This is an artifact of the length of typical oil and gas leases, where the resource is often depleted over 25 years. It is also related to an *onshore* wind paradigm, where the rate of technological change (primarily increased turbine size and efficiency) has historically justified a full replacement after 25 years or less of operation.[77,78] Compared to foundations for land-based turbines, offshore wind foundations comprise a comparatively larger portion of the total cost and offer the potential to derive greater economic benefit through longer service life.

- The location of manufacturing, including the value of local labor, is not included in a decision driven by LCoE.

  This is a significant oversight, because on-the-ground experiences of local laborers at OW job sites are one of the top priorities for the U.S. in launching this new industry. Centering local labor is a key part of the just energy transition, and it is advisable to make the energy transition while simultaneously uplifting historically excluded communities.

- Ports, fabrication facilities, and lay down yards used for OW can be repurposed for other industries.

  For instance, they can be repurposed for technology development and transfers, and for businesses that benefit from providing services to these workers and their families.

While outside of the scope of this report, a model for *Societal Cost of Energy* (SCoE), as opposed to LCoE, could be used to capture the full costs and benefits of offshore wind energy in a manner that considers economic impacts more holistically. For instance, the effect on public health of moving to a clean energy economy has been estimated to be on the order of $60 per megawatt-hour (MWh). A further example would be considering the cost of global warming beyond 1.5 degrees centigrade. This is an existential issue that relates to levels of sea-level rise that would radically disrupt life as we know it around the world. For this reason, it is difficult, if not absurd, to attempt to quantify.

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[77] And while turbine blades have a life of about 25 years, blade lifespan is not a reason to maintain a diminished foundation lifespan.

[78] Gignac, J. (2020, October 30). Wind Turbine Blades Don't Have to End Up In Landfills. *Union of Concerned Scientists*. https://blog.ucsusa.org/james-gignac/wind-turbine-blades-recycling/#:~:text=In%20terms%20of%20durability%2C%20wind,can%20be%20recycled%20or%20reused. Accessed on 3 September 2022.

Section III: Environment

Introduction

Connecticut now has the chance to ensure that its offshore wind (OW) energy production is advanced in an environmentally responsible manner by promoting a precautionary approach. This approach will safeguard vulnerable marine habitats and wildlife that otherwise could be threatened. As with all energy production, offshore wind energy will affect the surrounding environment to some degree. It is therefore crucial to mitigate—or, if possible, to avoid—negative impacts and risks, in order to conserve and protect marine ecosystems in areas where offshore wind projects are planned and constructed.

Environmental impacts from offshore wind farms that might have adverse effects on various marine species include: electromagnetic fields from cables, seabed disturbance and release of contaminants from seabed sediments, and increased vessel traffic—including heightened risk of pollution and increased underwater noise. Anthropogenic (human-produced) underwater noise generated during the construction, when noise-intensive pile driving procedures are used to install gigantic steel structures such as monopile or jacket foundations, is identified as a main stressor of high concern for marine wildlife. Noise pollution and its implications on marine species—as well as how these issues can be mitigated or preferably avoided by foundation options and installation choices—will be discussed in the following two sections.

Noise Pollution

The ocean is an acoustic environment, where marine species depend on sound for almost all the important aspects of their life (e.g., communication, reproduction, foraging, navigation and avoiding predators and other hazards). Anthropogenic underwater noise is therefore a serious issue for most marine inhabitants and may cause both direct and indirect impacts on their lives. The direct impacts from intense underwater noise pollution include tissue damage and injuries such as temporary or permanent hearing loss/impairment, and even death. Indirect impacts decrease the chances of survival for individual animals, as well as for the group as a whole, by causing behavioral changes such as forced movement and disorientation, and by negatively interfering with individuals' ability to communicate and feed. Increased and more prevalent noise pollution from human activities, such as offshore wind energy developments, may consequently pose a severe threat—not just to individual animals but to the whole marine ecosystem, where everything is interconnected. To adequately protect unique and vulnerable marine wildlife, it is important not to focus only on extreme underwater noise levels that cause direct harm to individual animals. A broader approach needs to be taken: the focus should always be on whether anthropogenic noise pollution is **safe** by not causing negative behavioral changes that, in the future, could lead to the extinction of impacted species.

An offshore wind farm emits underwater noise during its construction phases, as well as during its operation. The underwater noise generated during the construction phase is high-intensity and acute if the foundations require pile driving, whereas operational noise is low-level and chronic. Operational noise from a few offshore wind turbines is relatively low, and probably only faintly audible to many marine species. However, concerns exist over the possible impacts on wildlife of low frequency, water-borne noises, and vibrations emanating from 100s or 1000s of wind turbines in operation (i.e., the park effect). This is an area of research that requires further work, but a few highlights can be noted. Piled steel foundations are much more likely to act as underwater transmitters for noise and vibration from turbines through the steel. Concrete structures, on the other hand, have a greater mass and a dampening effect, since concrete absorbs more noise and vibration than steel.

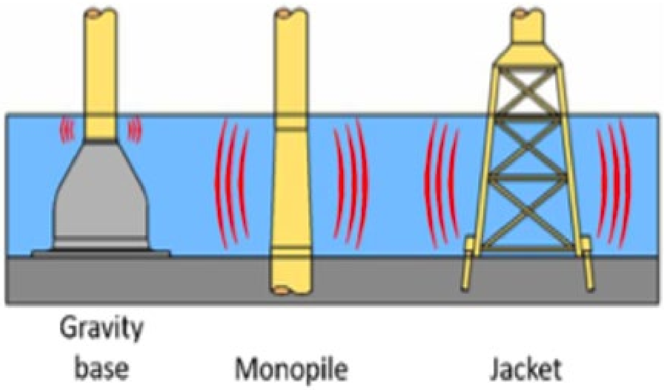

Figure 3.1: Anthropogenic underwater noise and vibrations.[79]

In Figure 3.1, anthropogenic underwater noise and vibrations are transmitted through different foundations during the operational phase of an offshore wind farm. In 2011, the Royal Belgian Institute of Natural Sciences published findings which concluded that wind turbines seated on concrete Gravity-Based Foundations transmit up to 99% less noise to the underwater environment in comparison to wind turbines seated on steel foundations.[80]

While the possible impacts on marine life from operational noise are still not well understood, many studies have suggested that the intense sonic shockwaves from pile-driving monopiles or jackets deep into the seabed, pose a severe threat to fish and marine mammals.[81] This impulsive hammering during the construction phase generates extremely high noise levels that propagate into the water and downward to the ocean floor, as in Figure 3.2.

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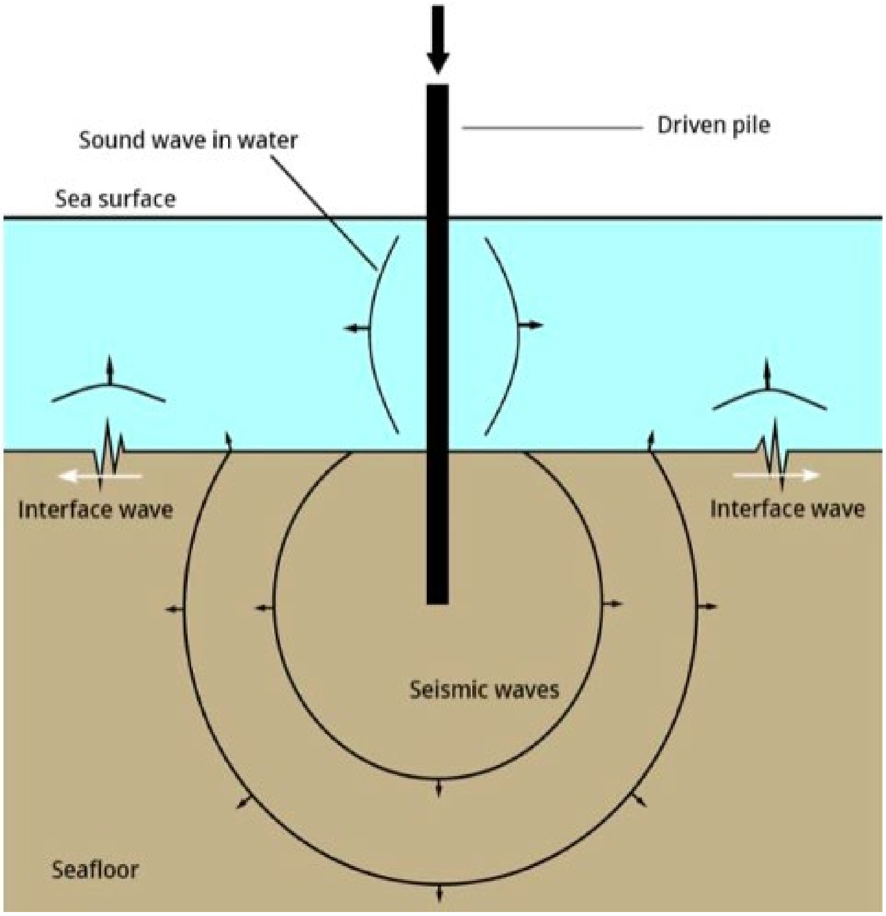
[79] Ilustration by Seatower AC, found in white paper, Mitigating Environmental Impacts of Offshore Wind Power, Halldén, K (2018).

[80] Norro, A., Rumes B. and Degraer S., Characterisation of the operational noise, generated by offshore wind farms in the Belgian part of the North Sea, in: Degraer, S. et al. (Ed.) (2011) Offshore wind farms in the Belgian part of the North Sea: Selected findings from the baseline and targeted monitoring. pp. 17-26, Royal Belgian Institute of Natural Sciences. Brussels, Belgium

[81] Farina, A., (2014) Soundscape and Landscape, Ecology, Springer (2014), Berlin, Germany; Draget, E., (2014) Environmental Impacts of Offshore Wind Power Production in the North Sea, WWF – World Wide Fund for Nature, Oslo, Norway; Wilhelmsson D., Malm, T., Tchou, J., Sarantakos, G., McCormick, N., Luitjens, S., Gullström, M., Patterson Edwards, J.K., Amir, O. and Dubi, A. (eds). (2010) Greening Blue Energy: Identifying and managing the biodiversity risks and opportunities of offshore renewable energy. Gland, Switzerland; IUCN



Sketch by Anthony D. Hawkins

Figure 3.2: Noise levels propagating in water.[82]

In particular, the installation of monopiles has shown to negatively affect the behavior of noise-sensitive marine mammals such as harbor porpoises at distances of at least 20-30 kilometers, or 11-16 nautical miles from the piling source.[83] This is of great concern for the protection of noise-sensitive species such as the North Atlantic right whale, and other vulnerable marine species including fish stock important to the commercial fishing community in the Northeast.

There are no universally established maximum decibel levels for what harms, harasses, and/or affects the behavior of marine species. However, researchers have observed that marine

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[82] Image credit: Popper, A. and Hawkins, A.D., March 2019, Impacts of Anthropogenic Noise on Fishes - Briefing Notes, FSBI. https://fsbi.org.uk/wp-content/uploads/2019/04/FSBI%20Briefing%20Note%20Impacts%20of%20Anthropogenic%20Noise%20on%20Fishes.pdf. Accessed on 13 November 2022.

[83] Tougaard, J., Carstensen, J., Skov, H., Rasmussen, P., (2009) *Pile driving zone of responsiveness extends beyond 20 km for harbor porpoises (Phocoena phocoena (L.))*. The Journal of the Acoustical Society of America. 126.11-4.10.1121/1.3132523

mammals (small cetaceans and large whales) respond, at least behaviorally, to received sound levels as low as 120-130 decibels (dB) re 1μPa or less.[84] The North Atlantic Right Whale shows negative behavioral responses such as reduction or cessation in feeding around 130 dB re 1μPa. Another endangered whale occurring in the area, the Blue Whale, has been documented to alter its acoustic communication when exposed to seismic "sparkers" at 140 dB P-P (peak to peak) re 1μPa[85] and have ceased to call altogether when exposed to sound levels at 143 dB P-P re 1μPa.[86]

Measured piling noise from European OW farms exceed the above-mentioned levels by far. The Belwind OW farm (Belgium), which used piles with a diameter of 5 meters for MW wind turbines, measured 196 dB SPL at 520 meters distance. Gemini OW farm (Netherlands), which used piles with a diameter of 7 meters for 4 MW wind turbines, measured 182 dB SEL at 732 m distance. See Figure 3.3, in which measured Peak Levels (LPeak) and broadband Sound Exposure Levels (SEL) normalized to a distance of 750 meters to the source during impact pile driving at various offshore wind farms in Europe, as a function of pile diameter.[87]

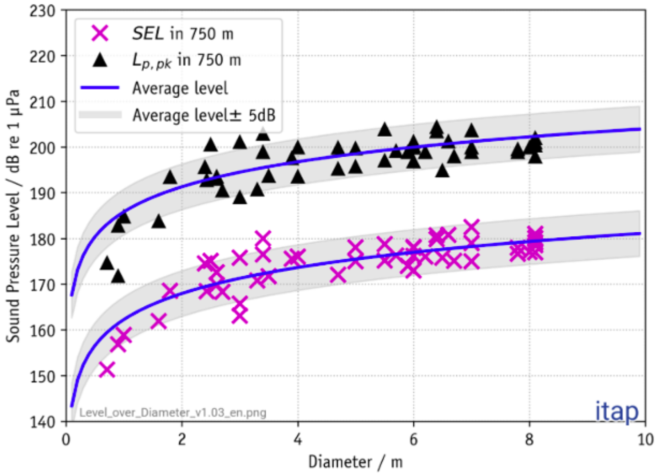

Figure 3.3: Peak Levels (LPeak) and broadband Sound Expower Levels (SEL) during pile driving.[88]

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[84] Observed in e.g. Blackwell, S.B., Nations, C.S., McDonald, T.L., Thode, A.M., Mathias, D., Kim, K.H., et al., (2015) *Effects of Airgun Sounds on Bowhead Whale Calling Rates: Evidence for Two Behavioral Thresholds.* PLoS ONE 10(6): e0125720; Pirotta, E., Brookes, K.L., Graham, I.M. and Thompson, P.M., (2014) *Variation in harbour porpoise activity in response to seismic survey noise*, Biology Letters 10(5): 20131090; Miller, P.J.O., Johnson, M.P., Madsen, P.T., Biassoni, N., Quero, M. and Tyack, P.L., (2009) *Using at-sea experiments to study the effects of airguns on the foraging behavior of sperm whales in the Gulf of Mexico*, Deep-Sea Research I 56:1168-1181

[85] Di Iorio, L., and Clark, C.W., (2010) *Exposure to seismic survey alters blue whale acoustic communication,* Biology Letter 6: pp. 51-54

[86] McDonald, M.A., Hildebrand, J.A. and Webb, S.C. (1995) Blue and fin whales observed on a seafloor array in the Northeast Pacific, *J. Acoustical Soc'y of America* 98: 712-21

[87] Bellmann, M.A., Kühler, R., Matuschek, R., Müller, M., Betke, K., Schuckenbrock, J., Gündert, S. and Remmers, P. (2018) *Noise mitigation for large foundations (Monopile L & XL) - Technical options for complying with noise limits,* Noise mitigation for the construction of increasingly large offshore wind turbines, Berlin, Germany

[88] Bellmann, M.A., Kühler, R., Matuschek, R., Müller, M., Betke, K., Schuckenbrock, J., Gündert, S., Remmers, P., 2018. Noise mitigation for large foundations (Monopile L & XL) - Technical options for complying with noise limits, Noise mitigation for the construction of increasingly large offshore wind turbines, Berlin.

Since the decibel (dB) scale is *logarithmic*, rather than linear. This means that a 10 dB increase corresponds to a 10-fold increase in sound energy, which results in these noise levels being approx. 1,000,000 times more powerful than the potentially harmful 120-130 dB re 1µPa range. Furthermore, increasingly large turbine sizes and water depths will increase the sizes of the monopiles. The construction of enormous XXL monopiles will thus have even stronger implications for the noise radiated into the marine environment.[89]

The most common ways of reducing anthropogenic noise—and its adverse impacts to marine ecosystems during construction—are noise mitigation/abatement measures. Bubble curtains, isolation casings, cofferdams and hydro sound dampers are some of the noise mitigation measures for impact pile driving and with different noise reduction potentials existing between 10 to 20 dB (see appendix 2, Nose Mitigation/Abatement Measures).[90]

However, since there is no universal or widely accepted criterion for what noise level is *safe* for fish and marine mammals, it is questionable whether these mitigation techniques are sufficiently protective. The lives of vulnerable marine species are consequently jeopardized with every new piled foundation that is installed. This issue becomes even more pressing for Connecticut and other states on the US Northeast coast, where offshore wind developers are considering deploying monopiles of sizes never used anywhere in the world - these enormous monopiles would have a length of up to 130 meters,[91] a diameter of over 11 meters and a weight between 2000 - 3000 tons. From a precautionary perspective, it must be asked: Should pile driving be abandoned altogether in sensitive areas with vulnerable marine life like the Northeast coast, if mitigation is not sufficiently protective and less impactful technologies are available?

Quiet Foundations

The precautionary principle established under international environmental law should always be adhered to—to protect vulnerable marine species, while developing a sustainable and successful offshore wind energy sector in the coastal region. Since it will be impossible to guarantee safe noise levels for marine wildlife when pile driving gigantic steel monopiles, the use of "quiet foundations" has significant advantages from an environmental perspective. The installation of so-called quiet foundations, where no deep penetration into the seabed takes place, does not mitigate the negative impacts of pile driving—it eliminates the practice altogether, and so completely avoids intense noise pollution. Although noise mitigation techniques are readily available and used when pile driving, it is unclear if they are sufficient, and it is always more advantageous to avoid negative impacts than to try to minimize them.

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[89] Halldén, A.K. and Smith, T. (2021) *Sea Shepherd Australia – Position on Offshore Wind Farm Development in Australia,* Sea Shepherd Australia, Williamstown, Australia

[90] Koschinski, S. and Lüdemann, K. (2020), Noise mitigation for the construction of increasingly large offshore wind turbines – Technical options for complying with noise limits. Federal Agency for Nature Conservation (Bundesamt für Naturschutz, BfN), Germany

[91] Boslan Engineering and Consulting (2022). *The next generation monopile foundations for offshore wind turbines: Manufacturing, design and handling challenges*. Biscay, Spain. Pg. 12. Accessed on 18 October 2022. https://www.boslan.com/wp-content/uploads/2022/06/BOSLAN_monopile_foundations.pdf

There are different types of quiet foundation methods and designs; GBFs, suction buckets/caissons (i.e., suction bucket jackets and mono suction buckets), floating foundations and vibratory hammering (see appendix 5). However, there are several reasons why the use of GBFs is favorable for Connecticut and thus the focus of this report. As with all quiet foundation types, there is no substantial sound emission from the subsea installation process of GBFs. Furthermore, possible operational low-frequency noise and vibration are dampened by the use of concrete, and the foundations are locally manufactured close to the installation sites. Local manufacturing does not only create job opportunities and tax revenues; it also bypasses the long transportation routes of European-manufactured monopiles, and thus eliminates the adverse impacts of increased shipping traffic.

Connecticut's significant commitment to clean energy, and its development of offshore wind power, puts the environment—as well as present and future generations of humans—first. To ensure that this commitment ends up being an environmental success story, and to avoid environmental backlash against the industry, it is important to refrain from practices that might jeopardize the long-term survival of vulnerable marine species like the North Atlantic Right Whale. Instead of performing potentially devastating experiments on the local marine ecosystem and its inhabitants by using construction methods and installation techniques that produce intense underwater sonic shockwaves, "quiet" installation methods and foundation designs that avoid intense noise pollution altogether are advisable from both a precautionary and a protective approach.

Seabed Installation and Considerations

Monopiles and GBFs differ in how they interact, structurally, with the seabed. These two different foundation types will require different levels of seabed preparation, and may be best suited for different kinds of soil. Since GBFs sit directly on the seabed, installation requires the seafloor to be level so that the support structure is vertical. The seabed is leveled by a process known as *dredging*, which involves the removal of sand, soil, silt, and debris from the ocean floor. This creates a flat pit on the seafloor, and removes any weak soils. In contrast, monopiles are driven down into the soil, and therefore do not require seabed preparation. For sands and clay soils, monopiles are driven directly into the seabed via hammering. If a site has unfavorable conditions such as shallow bedrock, it is possible to install the monopile by drilling through this bedrock. Typically for soils with shallow bedrock, a concrete GBF is a particularly suitable option.

Scour, which occurs when the soil surrounding the monopile or GBF is moved by flowing water, presents a significant challenge for *any* foundation. Scour causes soil around the foundation to erode, which can affect the structure's natural frequency (as discussed in Section IV). Scour puts stress on the part of the foundation that rests on or is touched by the soil and can cause the structure itself to tilt. To prevent this from happening, all monopiles and GBFs must be installed with scour protection, and particularly if soil conditions are susceptible to erosion. For a concrete GBF, scour protection consists of two layers of crushed rocks with suitable size and density. These stones are placed directly onto the seabed. According to the designs presented in this report, this would result in a total footprint diameter (GBF base + 8 meter scour protection) of 51 meters at the shallow water site, and 56 meters at the deep-water site. A similar rock blanket is placed around monopile foundations *after* the monopile is driven into the ground. The footprint of the monopile itself is expected to be about 10 meters in diameter. With scour protection at 5 times the diameter[92], that's a diameter of 50 meters total. This is consistent with the envelope dimensions of the monopiles and scour protection regimes described in the Vineyard Wind 1 (VW1) Construction and Operations Plan, where the monopiles diameters are reported to range from 7.5m to 10.3m and the scour protection areas are reported to range between 1500 m^2 and 2100 m^2.[93]

Assuming that the reported scour protection areas do not include the areas of the monopiles, the overall VW1 scour diameters can be calculated to range between 44.3 and 52.7 m. Based on these numbers, there is no appreciable difference between the benthic disturbance created by GBFs and that created by equivalent monopiles. Some studies have concluded that steel monopiles disturb an even greater area than a concrete GBF for a similar sized turbine.[94] Assuming a 51-56 m disturbed area for each foundation (whether GBF or monopile) yields a benthic disturbance of only 0.060-0.072% of the total area of a wind farm with turbines spaced at 1 nautical mile.

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[92] De Vos, L., Rouck, J.D., Troch, P., and Frigaard, P. "Empirical design of scour protections around monopile foundations. Part 2: Dynamic approach." *Coastal Engineering*. 2012, 60, pp. 286-298. doi: 10.1016/j.coastaleng.2011.11.001.

[93] Vineyard Wind. Draft Construction and Operations Plan. Volume 1. Vineyard Wind Project. September 30, 2020. Submitted to the U.S. Bureau of Ocean Energy Management. https://www.boem.gov/sites/default/files/documents/renewable-energy/Vineyard%20Wind%20COP%20Volume%20I_Section%203.pdf. Accessed on 13 November 2022.

[94] MPA, the Concrete Centre. A Review of Marine Environmental Considerations Associated with Concrete Gravity Base Foundations in Offshore Wind Developments. Marine Space Ltd. In conjunction with ABPmer and Fjordr. September 7, 2012. Version 1.0. https://www.concretecentre.com/Publications-Software/Publications/A-Review-of-Marine-Environmental-Considerations-As.aspx. Accessed on 13 November 2022.

Nature-Inclusive Design/Artificial Reefs

Over the last several years, there has been an increased realization of the importance of designing and construction offshore wind farms that foster the development of marine ecosystems. The geometry and surface materials on these foundations, and the environmental conditions, determine what marine life develops and flourishes. Concrete structures offer great flexibility in geometry, texture, and composition, which making them ideal candidates for artificial reefs.

Sweden's largest offshore wind far, Lillgrund Wind Farm is one of 14 offshore wind farms in Europe where GBFs are used. This offshore wind project has been an environmental success story so far.[95] If offshore wind foundations can provide predictably reliable benefits to marine ecosystems and communities, then there will be greater support for the development of a larger portion of the nation's enormous offshore wind resource. Figure 3.4 presents a vision for GBFs as artificial reefs that enhance ocean bio-diversity and help restore depleted fishing stocks.

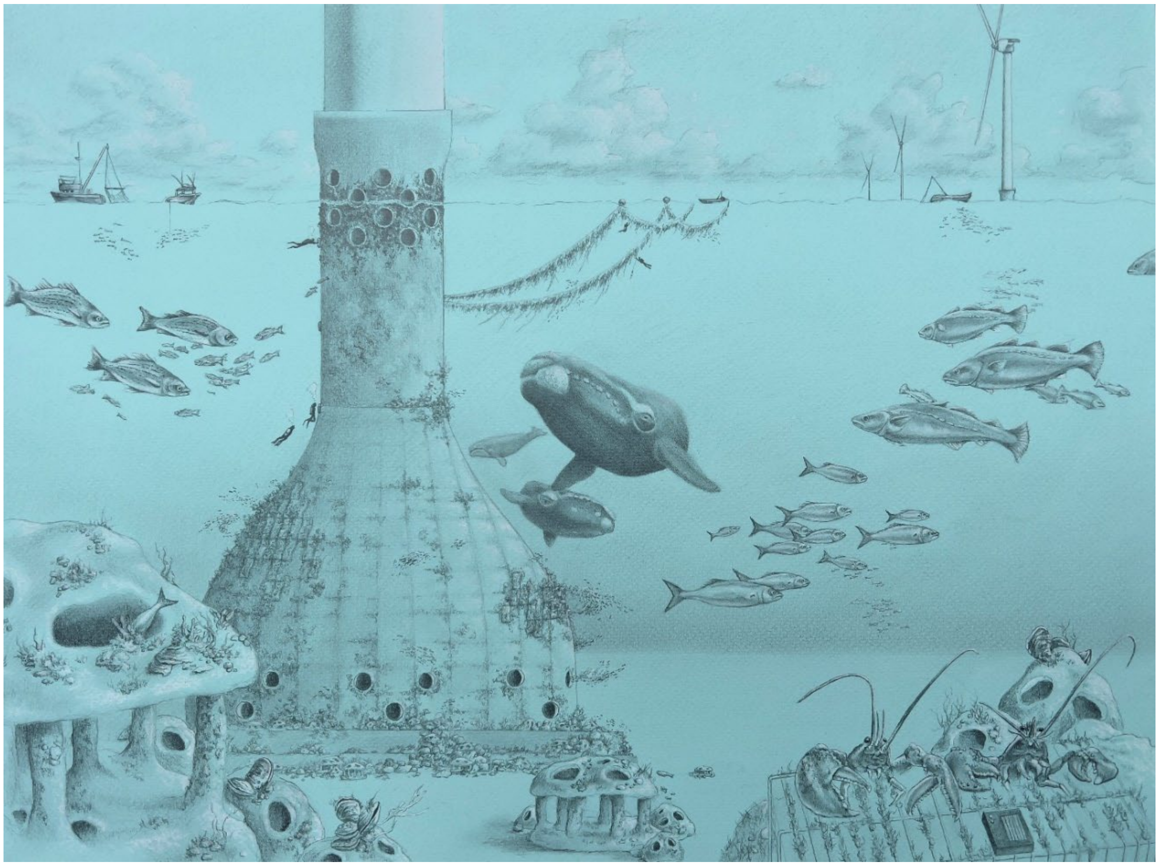

Figure 3.4: GBFs as artificial reefs that enhance bio-diversity. Original artwork commissioned by Tufts University. Artist: Cameron Barker

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[95] Bergström, L., Lagenfelt I, Sundqvist F, Andersson I, Andersson M H, Sigray P, 2013. Study of the Fish Communities at Lillgrund Wind Farm – Final Report from the Monitoring Programme for Fish and Fisheries 2002–2010, On behalf of Vattenfall Vindkraft AB. Swedish Agency for Marine and Water Management, Report number 2013:19, 134 pp, ISBN 978- 91-87025-43-3

Section IV: Technical Case Studies

Introduction

In 2021, Mathern et al. provided detailed lists of GBFs in the offshore wind industry to date.[96] Table 4.1 lists selected commercial scale GBF projects in the North Sea since 2008. Several of the reported water depths in Table 4.1 reflect the values reported by Esteban et al. in 2019.[97] While several earlier GBF projects were constructed in locations with less than 20 m water depths, the more recent Blyth Demonstrator and Fécamp projects are situated in water depths of 30 m and deeper.

Recognizing that the U.S. market presents near-term opportunities to construct offshore wind farms in water depths ranging from 25-60m, this section draws comparisons between designs for a monopile and a GBF foundation for two offshore sites off the coast of the Northeast U.S. For this study, we have selected a 25 m depth and a 50 m depth, as described in the following section.

Table 4.1. Selected commercial scale offshore wind farms with GBFs. (continued on following page)

Project	Operation Year	Size	Water Depth	Developer
Fécamp	2023	497 MW	30 m	EDF Renewables, Enbridge Inc., WPD[98]
Blyth Demonstrator	2017	41.5 MW	38 m	EDF Renewables[99, 100]
Tahkoluoto	2017	40 MW	9 m	Suomen Hyötytuuli[101, 102, 103]
Kårenamn	2013	48 MW	6-20 m	RWE[104]

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[96] Mathern, A., von der Haar, C., and Marx, S. "Concrete Support Structures for Offshore Wind Turbines: Current Status, Challenges, and Future Trends." *Energies*. 2021, 14, 1995. https://doi.org/10.3390/en14071995.

[97] Esteban, M.D., López-Gutiérrez, J.S., and Negro, V. "Gravity-Based Foundations in the Offshore Wind Sector." Journal of Marine Science and Engineering. 2019, 7, 64; doi: 10.3390/jmse7030064.

[98] Developer trio kicks off construction of 500-MW Fécamp offshore wind farm. https://renewablesnow.com/news/developer-trio-kicks-off-construction-of-500-mw-fecamp-offshore-wind-farm-701127/. Accessed on 13 November 2022.

[99] Blyth Wind Farm. https://www.edf-re.uk/our-sites/blyth/. Accessed on 13 November 2022.

[100] Blyth Offshore Demonstrator. https://www.bamnuttall.co.uk/case-study/blyth-offshore-demonstrator/. Accessed on 13 November 2022.

[101] Thkoluoto Offshore Wind Farm. https://hyotytuuli.fi/en/wind-farms/tahkoluoto-offshore-wind-farm/. Accessed on 13 November 2022.

[102] Photo of the Day: Tahkoluoto Foundations Waiting for Vole au Vent. https://www.offshorewind.biz/2017/05/09/photo-of-the-day-tahkoluoto-foundations-waiting-for-vole-au-vent/. Accessed on 13 November 2022.

[103] Finland opens its first offshore wind farm. https://windeurope.org/newsroom/news/finland-opens-its-first-offshore-wind-farm/. Accessed on 13 November 2022.

[104] Offshore Wind Farm Kårenamn. https://se.rwe.com/en/locations/wind-farm-karehamn. Accessed on 13 November 2022.

Rødsand 2	2010	207 MW	6-12 m	RWE[105]
Thornton Bank	2009	30 MW	13-20 m	C-Power[106]
Lillgrund	2008	110 MW	4-13 m	Vattenfall[107]

Analysis Sites and MetOcean Data

The design of an offshore wind turbine depends on the environment in which it will exist. For this reason, we include site-specific environmental conditions in our design, which are needed to estimate the wind and wave conditions around the foundation. This site-specific wind and wave information is called *MetOcean data*.[108] We used MetOcean data from two kinds of study sites: one at 25 meters of water depth, and one at 50 meters of water depth. The locations of these sites can be seen in Figure 4.1, an edited map from the Northeast Ocean Data Portal. We selected these sites because their data corresponds with actual locations that exist near current offshore wind lease areas.

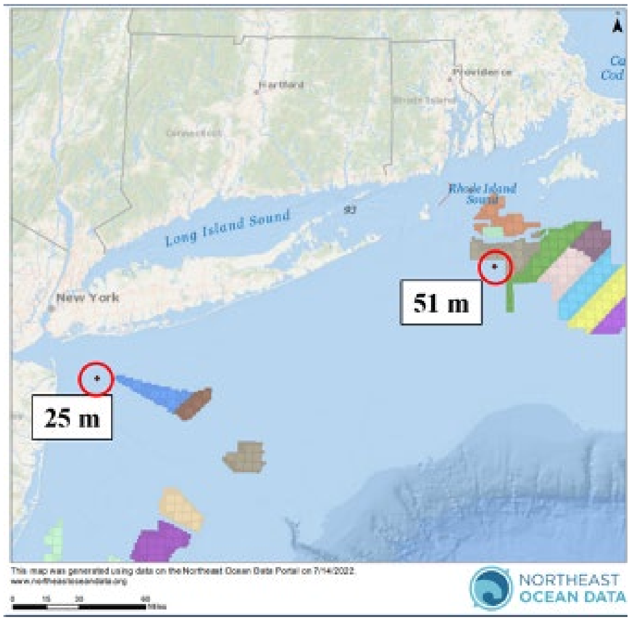

Figure 4.1: Edited map from the Northeast Ocean Data Portal, MetOcean.[109]

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[105] Offshore Wind Farm Rødsand 2. https://se.rwe.com/en/locations/wind-farm-rodsand/. Accessed on 13 November 2022.

[106] The pioneering Thornton Bank is finally taking shape. https://www.rechargenews.com/wind/the-pioneering-thornton-bank-is-finally-taking-shape/1-1-853913. Accessed on 13 November 2022.

[107] Lillgrund—the largest offshore wind farm in Sweden. https://powerplants.vattenfall.com/lillgrund/. Accessed on 13 November 2022.

[108] MetOcean datasets are publicly available from NOAA's National Data Buoy Center (NDBC): https://www.ndbc.noaa.gov/. Each site is intended to represent typical offshore environments in the Northeast US.

[109] Image Credit: https://www.northeastoceandata.org/. Accessed on 13 November 2022.

Design Considerations and Governing Standards

Offshore wind foundation designs are governed by International Electrotechnical Commission (IEC) standards 61400-1 and 61400-3 and many other industry documents. These standards outline 23 total load cases (or cases of stress on the turbine's foundation) spread across 8 different turbine conditions.[110,111] These cases cover the varied loadings that a wind turbine will face over its operational life. Not all load cases will have a significant impact on the design of offshore wind turbine foundations.

The design of monopile foundations and concrete GBFs are driven by different design objectives. This is because they are made of different materials and are shaped quite differently, which also relates to how they are manufactured and how they must be installed. For example, fatigue design requirements can be fulfilled in concrete GBFs much more easily and for lesser cost than for monopile foundations.

For all structures—including, but not limited to, offshore wind foundations—there are three main conditions that must be considered: Ultimate Limit State (ULS), Fatigue Limit State (FLS), and Serviceability Limit State (SLS). These limit states describe various conditions under which the turbine must be assessed to ensure proper performance.

ULS describes the loading conditions which could cause failure due to an extreme, uncommon event, such as a large gust of wind. FLS describes the conditions which contribute to long-term damage due to a combination of many smaller loading events that consistently act on the structure over its lifetime. These events could be, for instance, the effects of repeated waves loads on the structure. Finally, SLS describes conditions which might cause unacceptable deformation of the structure which can cause component breakage. This means that the structure bends, breaks, or tilts to a point where it is no longer operating effectively. These limit states control the design of a foundation to varying degrees depending on the foundation type and environmental conditions, because some limit states will not be of major concern for some designs (for example, fatigue concerns and the FLS usually do not control the design of a concrete GBF because concrete is fatigue resistant and it is not as costly to improve its performance under the FLS as compared to steel monopiles).

Our preliminary designs for both the monopile and GBF focus primarily on the ULS. The design process for each foundation type is further explained below and in Appendix 3, including design considerations unique to each foundation.

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[110] Further, simplifications to the full set of International Electrotechnical Commission (IEC) load cases are outlined in Arany et. al. See next footnote for citation.

[111] Arany, L., Bhattacharya, S., Macdonald, J., & Hogan, S. J. (2017). Design of monopiles for offshore wind turbines in 10 steps. *Soil Dynamics and Earthquake Engineering*, *92*, 126-152.

Reference Wind Turbine

The foundation designs created in this report are designed to be used for the International Energy Agency (IEA) 15 MW reference wind turbine (RWT)[112] such that the wind turbine generator and tower could be placed atop the foundation designs. RWTs are detailed wind turbine designs that are publicly available for research and educational purposes. We selected the IEA 15 MW RWT for this report because it is the most recently published and largest capacity reference wind turbine available. The turbine specifications were not altered, but the relevant properties were utilized in the design of the foundations. In some cases, this may make the designs a bit different from what would be expected in designs using real turbines. For example, the diameter at the base of the tower for the 15 MW RWT is 10 meters which may be a bit high according to conversations that we have has with many designers as well as a review of what is currently being used for the largest available turbines.

GBF Design

The concrete GBF designs presented in this report are modeled after the Seatower Crane-Free gravity-based structures.[113] This type of GBF is attractive because it can be floated out to site, reducing the need for large wind turbine installation vessels (WTIVs) or specialized cranes. A simple float-out like this is less expensive and logistically easier, whereas transportation by barge and installation by crane can be costly.

Following the Seatower design, the designs used inthis report features a thin slab of concrete beneath a conical section which leads to a vertical cylindrical shaft. We modified the Seatower design slightly so as to allow for an all-concrete foundation, as opposed to a hybrid concrete-and-steel design featuring a steel vertical shaft. This modification allows us to avoid a concrete-to-steel connection under the waterline, which could be problematic for the structural integrity of the foundation. The resulting designs bring the concrete shaft up to 15 meters above mean seawater level.

Primary considerations in our concrete GBF design are the ultimate limit state (ULS) and floating stability. Due to concrete's fatigue resistance and durability, the fatigue limit state (FLS) design requirement is assumed to be satisfied by simple mix design and reinforcement selections. Therefore, ULS is therefore the primary loading case that was used for this GBF design.

The concrete GBF designs uses a normal strength concrete.[114] A key difference between steel and concrete is that concrete has extremely poor *tensile strength*—that means that concrete breaks more easily if pulled in opposing directions. For this reason, concrete must be post-tensioned to avoid experiencing tension during operation. Post-tensioning in concrete is

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[112] Gaertner, E., Rinker, J., Sethuraman, L., Zahle, F., Anderson, B., Barter, G. E., ... & Viselli, A. (2020). *IEA wind TCP task 37: definition of the IEA 15-megawatt offshore reference wind turbine* (No. NREL/TP-5000-75698). National Renewable Energy Lab.(NREL), Golden, CO (United States).

[113] You can find more information about these on the Seatower website main page: http://seatower.com/

[114] The allowable stress ranges are predetermined according to design codes. The design of the GBF was chiefly concerned with meeting the allowable stress range under the ULS loading conditions.

accomplished using steel strand or tendons that are used to introduce compressive stress in the concrete.

After we created designs that satisfied allowable stress limits under the ULS loads, we checked the structure for floating stability to be sure that it was possible to float the GBF out to sea, and to sink it at its designated site.[115] The final design consideration for the GBF is tilting or overturning. Since the foundation is not fully embedded into the seabed, the structure relies on its own weight to resist the overturning effect from wind and wave loads. For each design, we computed the weight of required ballasting according to the ULS loading with a *safety factor of 1.5*. Ballasting is additional dead weight that is added to the inside of the GBF structure in order to keep the foundation stable. This means that the structure can withstand 1.5 times the highest expected loading that would occur without tilting over.

Monopile Design

Our focus for the monopile design is again the ultimate limit state (ULS), using the same methods found in the 10-step monopile we referenced earlier.[116] This preliminary design used a monopile with a constant diameter of 10 meters, extending from the bottom of the pile up to the bottom of the tower, with a 10-meter base diameter. Every 5 meters, there is a weld around the circumference of the monopile which connects each individually manufactured can. Another manufacturing constraint on the monopile design is a diameter-to-thickness ratio of 130, which means that the steel comprising a monopile with a diameter of 10 meters *must* be at least 77 millimeters thick. This is simply so that the structural integrity of the monopile remains intact during manufacturing and staging.

We initially estimated the embedment length of the monopile using equations from the paper referenced above. The embedment length is the amount of the monopile that is driven into the soil underground. We then used the Reese & Matlock p-y curves[117] for loose soils—this determines the pressure of the kind of soil (the kind of soil we imagine is at our offshore wind site) against the pile. A primary design objective here is to make sure that the turbine will not tilt significantly from its place in the soil to more than 0.5 degrees at the top of the tower. Finally, we checked the steel embedded in the soil for *yielding* (or bending). Taking all of this into account, we determined 35 meters to be a sufficient embedment length for both the 25- and 50-meter water depth cases.

At this stage of the preliminary designs, a full fatigue analysis has not been completed. Future iterations for more advanced designs will require a full analysis. The monopile presented in this work is intended to represent a preliminary design that would occur early in the process. It would take dozens of multi-physics time series analysis of the whole turbine system to do a full fatigue

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[115] We found that the float-out stability required only minor adjustments to the geometry; we achieved these adjustments by tweaking our design around the Seatower design's geometry.

[116] Arany, L., Bhattacharya, S., Macdonald, J., & Hogan, S. J. (2017). Design of monopiles for offshore wind turbines in 10 steps. *Soil Dynamics and Earthquake Engineering*, *92*, 126-152.

[117] Matlock, H., & Reese, L. C. (1960). Generalized solutions for laterally loaded piles. *Journal of the Soil Mechanics and foundations Division*, *86*(5), 63-92.

analysis and optimize the thickness of the monopile along the whole height. The monopile design work is ongoing and these values represent reasonable starting points.

Presentation of Estimates

Figure 4.2 and Figure 4.3 show the envelopes of the GBF and monopile designs for 25-meter and 50-meter water depths respectively. These figures show each structure twice, with a section view on the left and an elevation view on the right. Table 4.2 presents the estimated material quantities that go into each foundation design, and Table 4.3 presents the ballasting load required for the GBF during float out and after installation, in addition to the floating draft height during float out.

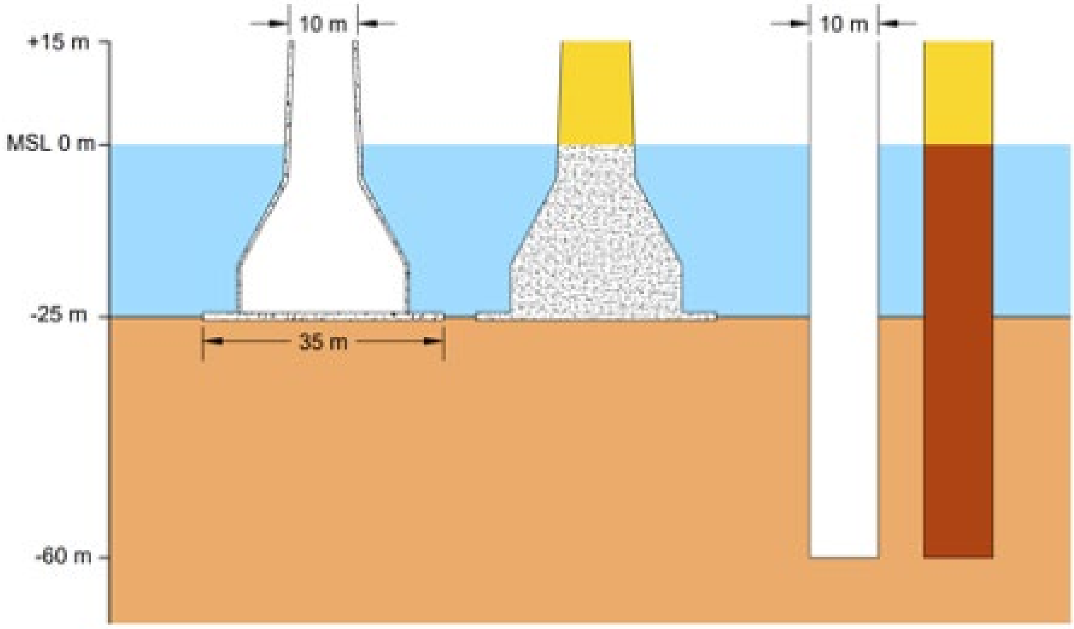

Figure 4.2: Envelopes of GBF and monopiles designs, 25-meter water depth.

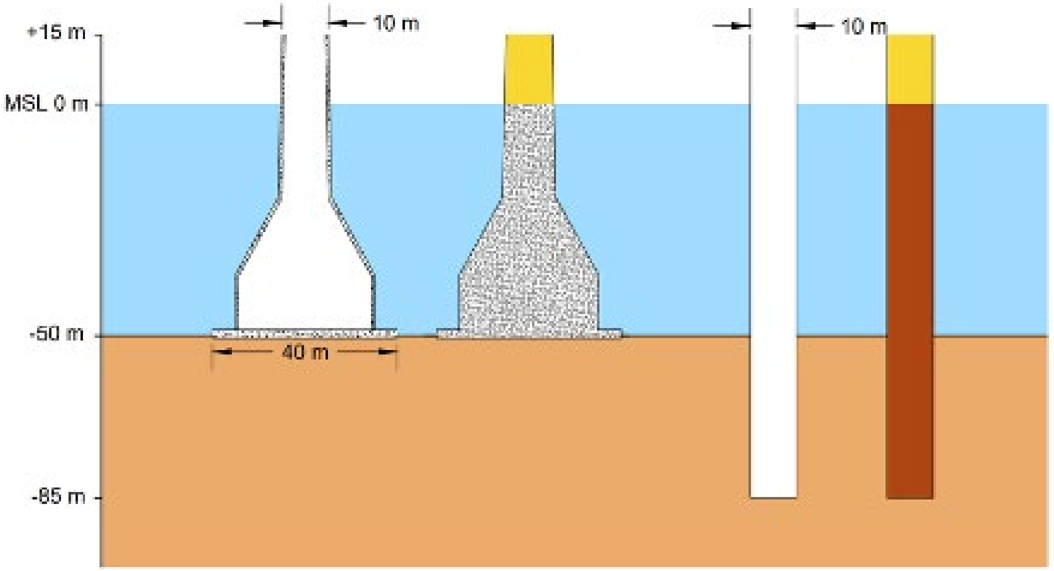

Figure 4.3: Envelopes of GBF and monopiles designs, 50-meter water depth.

Table 4.2: Metric tons of material in each foundation design.

	Mono 25 m	**Mono 50 m**	**GBF 25 m**	**GBF 50 m**
Total Steel (metric tons)	1500	2500	Reinforcement Steel	
Total Concrete (metric tons)	Negligible		6396	9898

Table 4.3: Required Ballasting Weight and Draft Height of final GBF Designs.

	GBF 25 m	GBF 50 m
Ballast during tow (metric tons)	1000	4800
Added ballast once installed (metric tons)	742	2703
Floating draft height (m)	16.7	18.65

Section V: CO_2equivalent (CO_2e) Impact Comparison between Concrete GBFs and Steel Monopiles

In this section, we will present how concrete GBFs have a small CO_2e footprint that is no larger, and perhaps smaller, than the CO_2e footprint of monopiles. The significant CO_2e footprint of concrete comes from the use of cement, and the other primary components (water, sand, and stone) have very little inherent CO_2e footprint.

The production of cement contributes about 8% of the Global Carbon Dioxide equivalent (CO_2e) emissions. This is not because cement is a particularly large emitter of CO_2e (or, to be more specific, CO_2e emissions per kilogram of cement). Rather, it is because an enormous amount of cement is manufactured each year (e.g. 4.4 billion metric tons in 2021). This amount of cement is enough to produce a concrete cube where each side measures 1.5 miles. Concrete is the second most highly-utilized substance (water is the first).[118]

- While the global emissions from cement manufacturing are enormous, the emissions from its use in wind turbine foundations is very small as now illustrated by calculations.
- Before we present the calculation, it is useful to consider a comparison of CO_2e emissions by source of electricity generation, which by international convention is expressed in grams of CO_2e per kilowatt hour (kWh) of electricity generation. One such comparison was presented in a report from the Intergovernmental Panel on Climate Change[119] from which the following values were taken for mean levels of CO_2e emissions.Coal 820 g/kWh;
- Gas 490 g/kWh;
- Utility Solar 48 g/kWh;
- Offshore Wind 12 g/kWh; and
- Onshore Wind 11 g/kWh.

Using these emission values, we find that generating electricity using offshore wind, instead of using a 50/50 mixture of coal and gas, represents a **CO_2e savings of 98%**:

$$1 - 12/(820/2 + 490/2) = 0.982\ (98.2\ \%)$$

Next, we'll calculate the CO_2e impact of cement in offshore wind foundations. The input values and parameters for this example are as follows:

- there are 9898 metric tons of concrete in a foundation for a 15 MW Turbine in 50 meters of water;
- cement is 12% of concrete by mass (a typical percentage for concretes of average strength);
- CO_2e emissions for cement: 0.9 kilograms of CO_2e per kilogram of cement;[120]
- a capacity factor of 50%;

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[118] Gagg, C. R. (2014). Cement and concrete as an engineering material: An historic appraisal and case study analysis. *Engineering Failure Analysis*, *40*, 114-140.

[119] Life cycle greenhouse gas emissions of energy sources. (2022, August 5). *Wikipedia*. https://en.wikipedia.org/wiki/Life-cycle_greenhouse_gas_emissions_of_energy_sources. Accessed on 25 August, 2022.

[120] This is for cement that is manufactured using conventional means, as opposed to more environmentally friendly ways.

- a design life of 25 years.

From these, the following may be calculated:

- there would be 1,187,760 (0.12 x 9,898,000) kg of cement in this foundation
- 1,068,984 (0.9 x 1,187,760) kg of CO_2e from cement in this 9898 metric ton foundation
- a 15 MW Turbine with 50% Capacity Factor over 25 years produces 1.642×10^9 kWh = 15,000 kW x 0.50 x 25 years x 365 days/year x 24 hours/day

With the above values, the calculated CO_2e emission for the use of cement in this offshore wind foundation is

$$\mathbf{0.65\ g / kWh = 1{,}068{,}984 \times 1000 / 1.642 \times 10^9}$$

Similar calculations were done for other turbines in which the mass and turbine rating was known, and these resulted in similar levels of emissions per kWh.

0.65 g/kWh is modest relative to the total CO_2e emissions for offshore wind (12 g/kWh), and extremely low compared to CO_2e emissions from fossil fuels (coal 820 g/kWh; gas 490 g/kWh).

Work completed by the Concrete Centre estimated that CO_2e emissions as 237 tonnes CO_2e/MW for concrete GBfs, 554 tonnes CO_2e/MW for steel jackets and just over 600 tonnes CO_2e/MW for steel monopiles. From this study, we draw the conclusion that concrete GBFs have produced less than half the CO_2e of comparable steel monopiles even without employing specific low-carbon technologies.[121]

Further savings are possible through the substitution of blast furnace slag and fly ash for up to 50% of the cement, extending the design life beyond 25 years, and improving the manufacture of cement through direct carbon capture, use of electric kilns, or use of hydrogen kilns. When combined, these could further lower the CO_2e impact of cement by an order of magnitude.

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[121] Marine Construction. Concrete gravity foundations—carbon footprint study. February 2013. https://www.concretecentre.com/TCC/media/TCCMediaLibrary/PDF%20attachments/CGF_CONCRETE-article-_Carbon_Feb13.pdf. Accessed on 13 November 2022.

Conclusions

When we flip a light switch, we often do not think about the systems behind that action. The power regulated by that light switch is subject to market prices; prices of the materials that create our energy infrastructure; oceans that host wind farms and marine life in tandem, ideally in harmony; people who create and maintain the energy infrastructures that we use; the potential to reshape our social and environmental worlds, simultaneously. The influence of these systems is obscured by both our familiarity with the technology, as well as facts and figures with which we may be far less familiar. In this report, we aim to illustrate the extent to which these elements are related. Flipping a light switch might produce a world in which there are high-quality jobs for people in need, should we understand enough about this system to commit to a paradigm shift.

At the heart of this paradigm shift are a few numbers. It is captivating, from a pure labor perspective, that a single monopile foundation yields approximately 2 jobs and a single GBF yields approximately 60. However, let us refocus our attention on another number: 3%. This is the estimated 3% increase in cost that the state of Connecticut could incur, should it choose to build an offshore windfarm using concrete foundations rather than steel ones.

If we consider the web of relations behind the offshore wind industry, and behind that estimated 3% figure, it comes down to a simple choice. The choice is between a short-term cost-saving measure, or a long-term *investment* in a sustainable job market. How much prosperity could the state of Connecticut usher in by shifting to the concrete Gravity-Based Foundation (GBF) paradigm? And how would that compare to the estimated 3% short-term cost-saving monopile? If we were to successfully put a price on the long-term benefits of the GBF paradigm, we would no longer be speaking the language of the Levelized Cost of Energy (LCoE). We would be speaking the language, as we suggest in the Economics Section, of the Social Cost of Energy (SCoE). In this context, SCoE is an acronym that describes the provision of stable *careers* to communities that need them, and actions to secure economic prosperity in our energy transition.

An area for further research is the question of investment in our community: how can we measure, compare, discuss, and consider the implementation of this investment? These questions are not entirely answerable; however, until we embark on the paradigm shift to concrete foundations. As we release this report out into the world, we are ready to engage in discussions about this paradigm shift with you. Additionally, we are excited to see how this document shifts and takes on new life once it is out in the world, and part of discussions.

Appendix 1: Workforce and Jobs

Workforce

Table A1.1: Demographic data of CT Carpenters Local 326 Active Members, Apprentices compared to Connecticut and Bridgeport diversity.

	Active Members	Black/ African American	Hispanic	Native American	Asian	Hawaiian	Two or more races	White	Unknown
Exec. Board	8	4	1					3	
Active Members *	2,278	238	483	5	7	1	2	1,484	58
Active Member %	100%	10.45%	21.20%	0.2%	0.3%	0.04%	0.09%	65%	2.55%
Apprent.*	164	32	24		2			84	22
Apprent. %	100%	20%	15%		.01%			51%	13%
CT %**		12%	19%	1%	6%	.2%	10%	62%	8%
Bridgeport %***		32%	35%	.3%	3%	.04%	2.5%	20%	.9%

*Survey data collected by CT Carpenters Local #326 in 2021
**2020 Census Data
***2019 Data USA

JEDI Job Categories

In the JEDI model, the jobs created are distinguished by their phase—manufacturing, construction, & installation (MCI) or operations & maintenance (O&M). These jobs are different in how long they last. The MCI jobs are short-term, lasting as long as the construction and installation (~2-3 years), while the O&M jobs are longer-term jobs, lasting as long as the wind turbines and foundations are operating (~25 years). For this report, we focus on the first phase, MCI, which distinguishes job creation into three categories:

1. installation activities, which take place at the site of the offshore wind farm
2. component manufacturing and supply chain/support services, which deal with how parts are created and distributed; and
3. induced

Installation activities comprise workers who will assemble and install the components of the wind farm. They have been separated into the jobs of the various components: Foundation, Scour Protection, Turbine, Array & Export Cabling, and Other. In the manufacturing and supply chain/support services, jobs are listed for manufacturing each component–nacelle, blades, tower, and foundation–in addition to array & export cables, substation, onshore transmission, ports and staging, and other installation, development jobs. Induced jobs refer to the downstream economic impacts due to increased consumer consumption. For instance, induced jobs can encompass jobs such as caretakers of workers' children and food vendors at the job sites.

An important distinction in job-year calculations is where MCI jobs will be located. To date, many of these jobs and economic impact reports have assumed that manufacturing jobs would occur outside the United States due to the lower costs of existing supply chains abroad. Each of the main parts of the wind turbine—the nacelle, the turbine, the blades, and the foundation—can be manufactured and shipped to the site of the wind project and has the potential to create local jobs. Because Europe, and increasingly China, has been developing manufacturing facilities for many of these components, the nascent US industry will likely import these components until they can build a competitive local supply chain.[122] To date, most of the planned offshore projects in the US will use turbines imported from foreign countries.[123] However, the pilings, moorings, and anchoring systems have a history of being manufactured in the US and can continue for OSW.[124]

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[122] Liang., J. (2020). Potential Employment from Offshore Wind in the United States-The Mid-Atlantic and New England Region. Georgetown Economic Services LLC.

[123] Atherton, A., & Rutovitz, J. (2009). Energy sector jobs to 2030: a global analysis.

[124] Liang., J. (2020). Potential Employment from Offshore Wind in the United States-The Mid-Atlantic and New England Region. Georgetown Economic Services LLC.

Job Calculations

In this section, we describe how we calculated job-years per GBF to be 60. This number is derived from two sets of GBF calculations, one calculated for 25-meter water depths and one for 50-meter water depths. The job-year calculations are based on weights calculated in Section IV, which inform foundation manufacture total material and labor costs.

Table A1.2: Weights and Material Costs for GBF

For one concrete GBF:		
Water Depth	25 meters	50 meters
Concrete Weight or Volume	6396 tons or 2665 m^3	9898 tons or 4124 m^3
Concrete Material Cost (Price \$188/m^3)	\$501,000	\$775,000
Steel Weight	2% of 6396 tons = 418 tons	2% of 9898 tons = 648 tons
Steel Material Cost (Price \$550/tons)	\$230,000	\$356,000
Total GBF Material Costs	\$731,000	\$1,131,000

To calculate labor costs for gravity-based foundation projects, we need total costs of these projects. According to industry experts, GBF projects have a 20% premium over monopile projects. Thus, first we calculate the cost of manufacturing a monopile, shown in Table A1.3, to then calculate the total cost of constructing a GBF.

Table A1.3: Weights and Material Costs for Monopiles

For one monopile:		
Water Depth	25 meters	50 meters
Primary Steel Weight	1500 tons	2500 tons
Primary Steel Total Cost (\$3,000/ton)*	\$4.50 M	\$7.50 M

*primary steel cost of \$3000/tons has been verified against proprietary OSW industry data. This cost includes material and labor.

Calculating total monopile construction costs allows us to estimate total GBF manufacture costs. Based on known GBF material costs we can use total cost to calculate GBF labor costs. Assuming each foundation construction worker is paid \$100,000 to take union benefits into account, we produce job-year estimates for a 25-meter GBF and a 50-meter GBF. We average these job years to arrive at 62.7 job-years per GBF, and then round down to 60 job-years per GBF. These values are shown in Table A1.4.

Table A1.4: Calculating GBF job-years

Calculating GBF Labor Costs	25 meters	50 meters
Monopile Foundation Costs	\$4.50 M	\$7.50 M
GBF Foundation Costs (assume 20% premium over monopile costs)	\$5.40 M	\$9.0 M
GBF Material Costs	\$731,000	\$1,131,000
GBF Labor Costs	\$4,669,000	\$7,869,000
Foundation Worker Salary	\$100,000/year	\$100,000/year

Job-years**	46.7 job-years	78.7 job-years

**Job-years refer to one year of work.

The JEDI Model

JEDI is an input-output model developed by NREL researchers based on IMPLAN multipliers. JEDI models the economic impacts of various energy-related construction projects, facilities, and plants. This modeling tool has come to be an industry standard, and therefore is used in many of the reports calculating OW jobs under different scenarios. This is all to say that it forms the basis of OW planning, to the extent that it shapes design choices and, ultimately, who gets the jobs for these massive projects.[125,126,127,128,129,130,131] Notably, these reports have used different versions of the JEDI model as they have become available.[132]

- We used the JEDI model, alongside cost information about steel and concrete, to calculate a single monopile foundation can yield anywhere between 1.13 to 2.65 jobs.
    - 1.13 jobs per monopile if there is no steel manufacture in Connecticut
    - 2.65 jobs per monopile if there is secondary steel manufacture in Connecticut.

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[125] Atherton, A., & Rutovitz, J. (2009). Energy sector jobs to 2030: a global analysis.

[126] Aldieri, L., Grafström, J., Sundström, K., & Vinci, C. P. (2019). Wind power and job creation. Sustainability, 12(1), 45.;
Musial, W., Beiter, P., Stefek, J., Scott, G., Heimiller, D., Stehly, T., ... & Keyser, D. (2020). Offshore wind in the US Gulf of Mexico: regional economic modeling and site-specific analyses. New Orleans (LA): Bureau of Ocean Energy Management. 94 p. Contract, (M17PG00012).;

[127] Liang., J. (2020). Potential Employment from Offshore Wind in the United States-The Mid-Atlantic and New England Region. Georgetown Economic Services LLC.

[128] Speer, B., Keyser, D., & Tegen, S. (2016). Floating Offshore Wind in California: Gross Potential for Jobs and Economic Impacts from Two Future Scenarios (No. NREL/TP-5000-65352). National Renewable Energy Lab.(NREL), Golden, CO (United States).

[129] Zammit, D., & Miles, J. (2014). Potential economic impacts from offshore wind in the United States—the Southeast region. Wind Systems Magazine.; http://www.windsystemsmag.com/article/detail/548/potential-economic-impacts-from-offshore-wind-in-the-united-states--the-southeast-region/

[130] Tegen, S., Keyser, D., Flores-Espino, F., Miles, J., Zammit, D., & Loomis, D. (2015). Offshore Wind Jobs and Economic Development Impacts in the United States: Four Regional Scenarios (No. NREL/TP-5000-61315). National Renewable Energy Lab. (NREL), Golden, CO (United States).

[131] Vigeant. P., Donovan., A., Menard., J. et al. (2018). 2018 Massachusetts Offshore Wind Workforce Assessment. Massachusetts Clean Energy Center.

[132] Note that, in 2021, the JEDI team received an additional grant from the Department of Energy to update their offshore wind model from the previous 2016 version.

In Table A1.5, we detail the parameters of the comparison as well as the total foundation construction costs for each scenario. Notably, the number of local job-years produced with concrete Gravity-Based Foundations is several multiples higher than those from monopiles.[133,134]

Table A1.5: Job and cost comparisons from monopile and GBF structures.

	Monopile		Concrete GBF
Nameplate Capacity (MW)	1,005 MW		
Number of Foundations	67		
	No steel manufacture in CT (0% local share)	Secondary steel manufacture in CT (5% local share)*	Concrete GBF manufacture in CT (100% local share)
Job-years	**76**	**178**	**4020**
Jobs per Foundation	**1.13** = 76/67**	**2.65** = 178/67**	**60** = average between 25m GBFs and 50m GBFs

* Were a monopile factory to be planned for the State of Connecticut with 100% CT labor, we estimate the total number of job years would be approximately 335, with a job-years/MW ratio of 0.33 and a Jobs Ratio of 4.4.
** This averages out to 1.78 job years per monopile which we round-up to 2 job years per monopile.

Through this model, local share is a key input that distinguishes the number of job-years produced from the two foundation types. *Local share* is defined as the percentage of local labor and materials that will comprise the manufacturing process. Monopiles have been prominent foundation types in European wind farms because they are cost-effective in a mature monopile production industry. However, the U.S. is new to building equivalent facilities that can keep costs low enough to be competitive with those imported from the factories established in The Netherlands and Germany, as there are learning curves with these new kinds of facilities.[135,136] While there has been activity to build monopile factories in the US—in Paulsboro, New

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[133] Liang., J. (2020). Potential Employment from Offshore Wind in the United States-The Mid-Atlantic and New England Region. *Georgetown Economic Services LLC.*

[134] Job calculations use the units of job-years to standardize how many hours of work are created. This distinction is important to attend to, as the conflation between jobs and job-years can exaggerate the number of jobs created from projects.

[135] SIF Group. (2020). "How we make a monopile (monopile production process)." *Sif Offshore Foundations.* https://sif-group.com/en/about-us/production-process/. Accessed on 18 August 2022.

[136] EEW Group. (2016). "Monopiles/XL Monopiles/Transition Pieces." https://eew-group.com/products/structural-pipes/monopiles/. Accessed on 20 August 2022.

Jersey[137,138] and Sparrows Point, Maryland—the jobs and economic impact of these will not reach Connecticut. For this reason, the local share percentage in monopile production is set at 5%. This is a high estimate, as these jobs only comprise secondary steel manufacture to build the ladders and platforms atop the foundations.

GBFS and the Future of Energy Markets

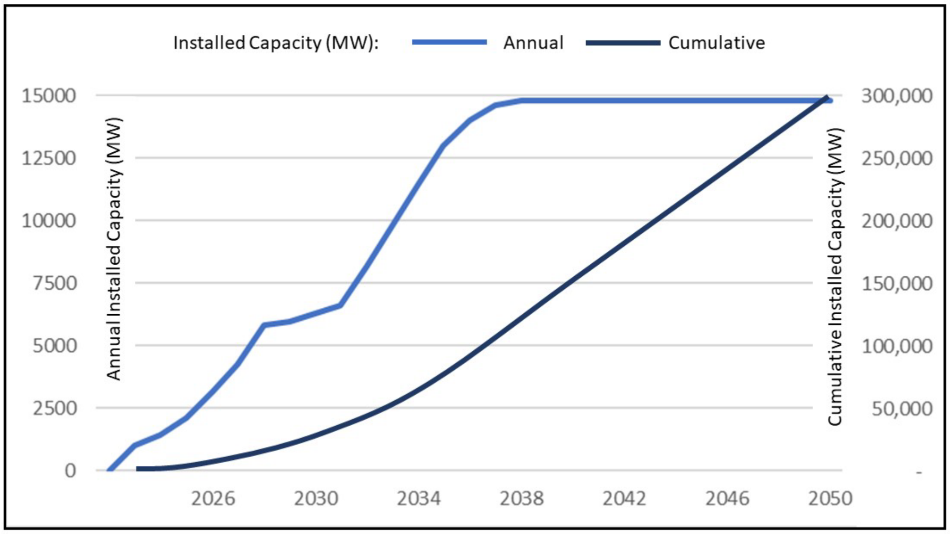

Figure A1.1: Annual and cumulative installed U.S. offshore wind capacity based on goals of 30 GW by 2030 and 300 GW by 2050.

We advocate imagining the entire U.S. offshore wind market as shown in Figure A1.1. This thought experiment assumes the following:

- U.S. OSW installation goals of 30,000 MW by 2030 and 300,000 MW by 2050;
- Turbine size is 15 MW through 2027;
- Turbine size moves to 20 MW in 2028 and stays at 20 MW until 2050;
- Market size increases as shown in Table A1.6;
- GBF market share reaches around 10% in the 2020s and then increases to 40% in the 2030s as costs come down due to innovation and supply chain maturation; and
- Both OSW Market and GBF supply chain fully mature by 2038.

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[137] ibid.

[138] The Paulsboro, NJ factory has almost completed its facility's capacity to do half of its manufacturing projects for the end of 2022, and has plans to be a complete facility by the end of 2024.

Table A1.6: U.S. Offshore wind market assumptions for possible low-carbon GBF factory job growth projections.

	U.S. Offshore Wind					Gravity Based Foundations		
Year	Market Size OWT/Y	OWT Size (MW)	Annual Installed MW	Cumulative Installed MW	Growth Rate percent	Market Share GBFs	GBF Market GBFs/yr	Direct Jobs
2023	67	15	1,005	1,005		0%	0	-
2024	95	15	1,425	2,430	142%	0%	0	-
2025	140	15	2,100	4,530	86%	24%	33	1,980
2026	210	15	3,150	7,680	70%	16%	33	1,980
2027	284	15	4,260	11,940	55%	12%	33	1,980
2028	290	20	5,800	17,740	49%	11%	33	1,980
2029	299	20	5,980	23,720	34%	11%	34	2,040
2030	314	20	6,280	30,000	26%	11%	34	2,040
2031	330	20	6,600	36,600	22%	15%	50	2,970
2032	410	20	8,200	44,800	22%	20%	82	4,920
2033	490	20	9,800	54,600	22%	25%	123	7,350
2034	570	20	11,400	66,000	21%	30%	171	10,260
2035	650	20	13,000	79,000	20%	35%	228	13,650
2036	700	20	14,000	93,000	18%	40%	280	16,800
2037	730	20	14,600	107,600	16%	40%	292	17,520
2038	740	20	14,800	122,400	14%	40%	296	17,760
2039	740	20	14,800	137,200	12%	40%	296	17,760
2040	740	20	14,800	152,000	11%	40%	296	17,760
2041	740	20	14,800	166,800	10%	40%	296	17,760
2042	740	20	14,800	181,600	9%	40%	296	17,760
2043	740	20	14,800	196,400	8%	40%	296	17,760
2044	740	20	14,800	211,200	8%	40%	296	17,760
2045	740	20	14,800	226,000	7%	40%	296	17,760
2046	740	20	14,800	240,800	7%	40%	296	17,760
2047	740	20	14,800	255,600	6%	40%	296	17,760
2048	740	20	14,800	270,400	6%	40%	296	17,760
2049	740	20	14,800	285,200	5%	40%	296	17,760
2050	740	20	14,800	300,000	5%	40%	296	17,760
Total	15,199					33%	5,073	

Table A1.6 lists the numbers assumed in this potential U.S. offshore wind build-out for each year from 2023 to 2050. Significant milestones and their years are highlighted in blue. This build-out results in 15,199 offshore wind turbines, 5,073 of which are supported by low-carbon GBFs, for a total overall GBF market share of 33% and a mature, steady GBF job market with 17,760 jobs starting in 2038. Figure 2.3 shows this potential job growth graphically. From this figure it is evident that this possible job growth is imagined occurring in two phases. The first phase, in the early 2020s represents the initial investment in a GBF factory in Connecticut to service OSW projects procured according to guidelines set by the State of Connecticut. This phase results in the creation of 2,000 jobs that are sustained through the 2020s until the beginning of the second phase, where Connecticut can begin to scale GBF production to meet demands for the entire U.S. offshore wind industry. The plateau in the late 2020s represents a consolidation phase where CT learns from initial project, develops a highly trained core workforce of 2000 employees, and realizes innovations that bring down the cost of GBFs in the U.S. In the early 2030s, growth is assumed to resume at an additional 5% U.S. market share per year until reaching 40% market share in 2036. Thereafter growth continues slightly with the overall U.S. OSW market growth, which is assumed to plateau at the installation of 740-20 MW turbines per year.

Appendix 2: Noise Mitigation/Abatement Measures

1. Big Bubble Curtain (BBC)
   Noise reduction:
   Single: up to 15 dB SEL (depth: 25 m).
   Double: up to 18 dB SEL (depth: 40 m)

2. Isolation Casings
   Noise reduction: 13-16 dB SEL (depth: ≤ 40 m)

3. Hydro Sound Dampers
   Noise reduction: 10-13 dB SEL (depth: ≤ 45 m)

4. Dewatered Cofferdams
   Noise reduction: up to 23 dB SEL (depth: 15 m)

5. Double Piles/Mandrel Piles
   Noise reduction: 16 dB SEL (depth: 10 m)

6. Vibropiling
   Noise reduction: 10-20 dB Leq, 30s (depth: ≤25 m)[139]

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[139] Koschinski, S. and Lüdemann, K. (2020), Noise mitigation for the construction of increasingly large offshore wind turbines – Technical options for complying with noise limits. Federal Agency for Nature Conservation (Bundesamt für Naturschutz, BfN), Germany

Appendix 3: Calculation of Wind and Wave Loading from MetOcean Data

To conduct the ULS analysis, the MetOcean buoy data must be used to characterize the loading conditions at each site according to IEC standards. Table A3.1 details the load cases utilized in the ULS analysis as recommended by Arany et al.[140] This section will describe how each input load was calculated for each site.

Table A3.1: ULS Wind and Wave Conditions

	Site 1: 25 m Water Depth	Site 2: 50 m Water Depth
Wind Conditions	EOG at U_r Extreme Operating Gust which occurs at rated wind speed	ETM at U_r Extreme Turbulence Model wind at rated wind speed
Wave Conditions	$H_{M,1}$ Maximum wave height with return period of 1 year	$H_{M,50}$ Maximum wave height with 50-year return period

Site 1 Wind Conditions

The wind condition for the ULS in shallow waters is the Extreme Operating Gust (EOG) acting at rated wind speed. A gust is defined as acting so quickly that the turbine controls do not have time to react. Namely, pitch angles do not adjust to the higher wind speed, and the thrust coefficient does not adjust. This is important to the wind turbine loading because the thrust coefficient plays a role in how much of the wind force acting on the rotor is transferred into a thrust force acting on the structure.

The EOG is computed as acting at rated wind speed (10.59 m/s) because this is the wind speed where the thrust coefficient is highest. When a quick gust of wind occurs and the controls do not react, the thrust force is acting with the original thrust coefficient. This leads to a higher thrust force when considering the EOG at rated wind speed instead of at higher wind speeds (where the thrust coefficient is lower during normal operation).

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[140] Arany, L., Bhattacharya, S., Macdonald, J., and Hogan, S.J. (2017). Design of Monopiles for offshore wind turbines in 10 steps. Soil Dynamics and Earthquake Engineering. Vol. 92. pp. 126-152.

The ULS wind load is therefore the thrust load due to a gust of wind which occurs at a mean wind speed of rated wind speed. The speed of the EOG is computed according to IEC standards and is described in Equations 1-5.

$$V_{e50} = 1.4V_{ref} \tag{1}$$

Where $V_{ref} = 50\ m/s$ for a class 1B turbine according to IEC standards.

$$V_{e1} = 0.8V_{e50} \tag{2}$$

$$\sigma_1 = I_{ref}(0.75V_{hub} + 5.6) \tag{3}$$

Where $I_{ref} = 0.14$ for a class 1B turbine according to IEC standards.

$$V_{gust} = min\left\{1.35(V_{e1} - V_{hub});\quad 3.3\left(\frac{\sigma_1}{1+0.1\left(\frac{D}{\Lambda_1}\right)}\right)\right\} = 3.98\ m/s \tag{4}$$

Where D is the rotor diameter, equal to 240 m for the IEA 15 MW RWT and $\Lambda_1 = 42$ according to IEC standards.

Once V_{gust} is computed, the gust can be modeled as a deviation from some chosen wind speed, $V(z)$, which is the rated wind speed, 10.59, in this case. The wind speed with a gust is described in Equation 6.

$$V(z,t) = \begin{cases} V(z) - 0.37V_{gust}\sin\left(\frac{3\pi t}{T}\right)\left(1 - \cos\left(\frac{2\pi t}{T}\right)\right) & for\ 0 \leq t \leq T \\ V(z) & otherwise \end{cases} \tag{5}$$

Where T = 10.5 s according to IEC standards.

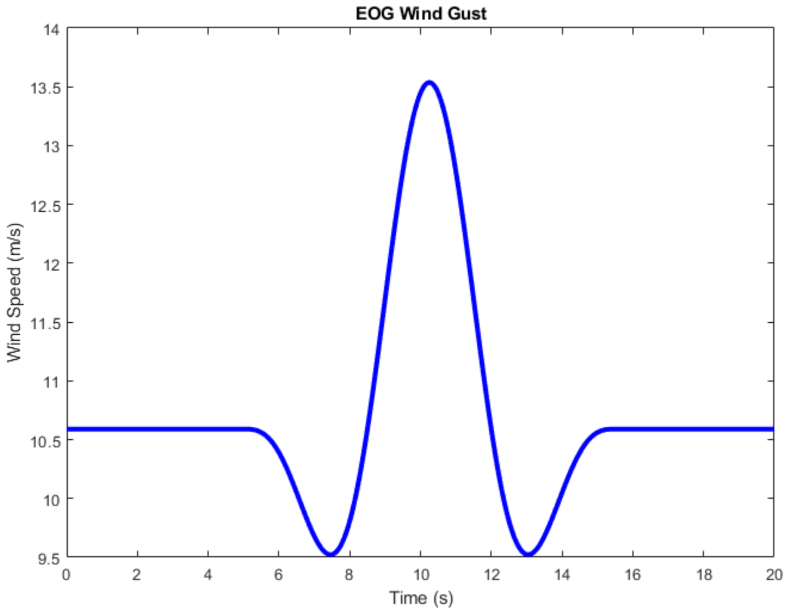

Figure A3.1: Extreme Operating Gust Calculated at Rated Wind Speed

Figure A3.1 shows what the EOG wind speed looks like through time when occurring at rated wind speed. It can be seen from Figure 4 that the maximum wind speed during the period of the gust is 13.53 m/s. This is the wind speed which is used to compute the thrust load due to this gust of wind. Thrust load is computed according to Equation 7.

$$Th = \frac{1}{2}\rho A v^2 C_T = 4.1\ MN \tag{6}$$

Where ρ is the density of air, A is the rotor swept area, v is the gust maximum wind speed, 13.53 m/s, and C_T is the thrust coefficient, which is 0.804 at rated wind speed.

The thrust load is computed to be 4.1 MN, which is about 35% higher than the maximum thrust load experienced by the turbine during normal operation, with no extreme gusts of wind. This is a very high load for the structure, which is expected for the load characterizing the ULS loading conditions.

Site 1 Wave Conditions

The wave conditions for the shallow water site are the 1-year maximum wave height and associated wave period. This is equivalent to the maximum wave height with a 1-year return period. This can be computed according to IEC standards, using MetOcean data from the site in question. The calculations conducted here also reference Nozari's 2021 slides.[141]

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[141] Nozari, Amin. Estimation of Wave Parameters from Metocean data [Powerpoint slides]. Department of Civil and Environmental Engineering, School of Engineering, Tufts University. Spring 2021.

The first step in computing extreme wave parameters is assessing the significant wave height historical data and fitting a Weibull PDF to the histogram of the data. This is because the wave parameters required are a function of the shape and scale parameters of the Weibull fit. Figure A3.2 shows the histogram of the MetOcean significant wave height data with a Weibull PDF fit. The shape and scale parameters fit to the significant wave height data were computed to be:

$$scale\ parameter: \lambda = 1.1808$$

$$shape\ parameter: k = \ 1.9789$$

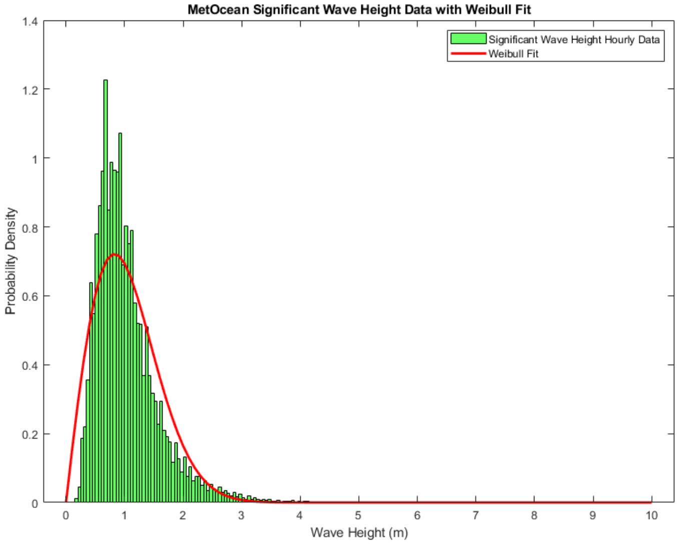

Figure A3.2: Weibull PDF Fit to Significant Wave Height Data

The 1-year maximum wave height and associated wave period are computed from the shape and scale parameters of the Weibull fit. This is described by Equations 8-11.

$$H_{S,50} = \lambda\left[-ln\left(1 - 0.98^{\frac{1}{8766}}\right)\right]^{\frac{1}{k}} \tag{7}$$

Where k and λ are the shape and scale parameters of the Weibull fit, and $H_{S,50}$ is the significant wave height with a 50-year return period.

$$H_{S,1} = 0.80 \times H_{S,50} \tag{8}$$

Where $H_{S,1}$ is the significant wave height with a 1-year return period.

$$H_{M,1} = \sqrt{\frac{ln\left(\frac{3600}{T}\right)}{2}} \times H_{S,1} \tag{9}$$

Where $H_{M,1}$ is the 1-year maximum wave height, and T is the average wave period over the historical data.

$$T_{M,1} = 11.1\sqrt{\frac{H_{M,1}}{g}} \tag{10}$$

Where $T_{M,1}$ is the wave period associated with the 1-year maximum wave height.

For NDBC station 44065, the 1-year maximum wave height and associated wave period were computed to be:

$$H_{M,1} = 6.26\ m$$

$$T_{M,1} = 8.87\ s$$

Site 2 Wind Conditions

The wind condition for a deep-water site under the ULS analysis used in this report is the Extreme Turbulence Model (ETM) acting at rated wind speed, which is computed according to the IEC standards. The wind load is computed by computing some level of standard deviation to the mean wind speed that turbulence creates. The wind thrust load under the ETM at rated wind speed is described by equations 11-14.

$$V_{ave} = 0.2V_{ref} \tag{12}$$

$$\sigma_1 = cI_{ref}(0.072\left(\frac{V_{ave}}{c} + 3\right)\left(\frac{V_{hub}}{c} - 4\right) + 10) \tag{13}$$

Where c = 2 m/s, V_{hub} = 10.59 m/s (rated wind speed), and I_{ref} = 0.14 according to IEC standards.

$$\sigma_{ETM} = \sigma_1\sqrt{\frac{1}{(\frac{6L_k}{U_r}f_{1P,max}+1)^{\frac{2}{3}}}} \tag{14}$$

Where L_K = 340.2 m (based on DNV-OS-J101), $f_{1P,max}$ = 0.126, and U_r = 10.59 m/s (rated wind speed).

$$Th = \frac{1}{2}\rho A(U_r + 2\sigma_{ETM})^2 C_T = 3.55\ MN \tag{15}$$

Site 2 Wave Conditions

The wave loading condition at the deep-water site is the 50-year maximum wave height and associated wave period. This is computed similarly to the wave conditions of site 1. Figure A3.3 shows the significant wave height data for the deep-water site, which is located in 51 m of water. A Weibull probability density function was fit to the data as was done at site 1, and the shape and scale parameters were computed to be:

$$scale\ parameter: \lambda = 1.5917$$

$$shape\ parameter: k = 1.8317$$

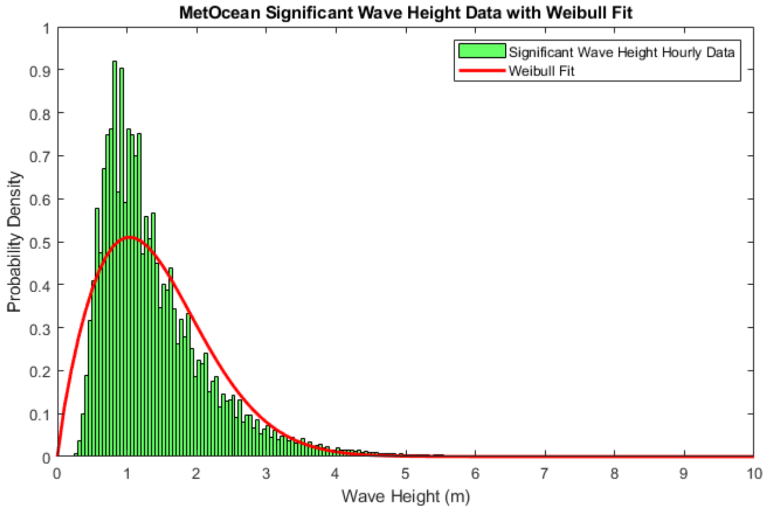

Figure A3.3: Weibull PDF Fit to Significant Wave Height Data

The 50-year extreme wave height is computed according to the following equations.

$$H_{M,50} = \sqrt{\frac{ln\left(\frac{3600}{T}\right)}{2}} \times H_{S,50} \tag{10}$$

Where $H_{S,50}$ is the 50-year significant wave height computed according to Equation 8, and T is the average wave period over the historical data.

$$T_{M,50} = 11.1\sqrt{\frac{H_{M,50}}{g}} \tag{11}$$

For the deep-water analysis site, the 50-year maximum wave height and associated wave period were computed to be:

$$H_{M,50} = 11.32\ m$$

$$T_{M,50} = 11.93\ s$$