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Marshaling ports required to meet US policy targets for offshore wind power

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ABSTRACT

We analyze infrastructure needed for offshore wind power targets set by U.S. state and federal policies—specifically, manufacturing, vessels, and offshore wind ports. By examining cost-competitive turbine and project sizes and infrastructure challenges, we identify marshaling ports as a key bottleneck. Through elicitation of requirements from supply chain, port, and vessel experts, we identify the necessary attributes for marshaling ports and calculate the area needed to meet policy targets. US marshaling ports are currently insufficient to meet either state or federal power targets. We calculate state commitments from state contracts and policies: in sum, 40 GW by 2040. Federal targets from the Biden Administration are 30 GW by 2030 and 110 GW by 2050. Either target yields more demand for marshaling area than is currently available or planned. The shortage of marshaling area supply has incorrectly been attributed to lack of suitable U.S. locations. Instead, we attribute it to developers having built ports to support early, smaller projects, and having located them to incentivize state power contracts rather than developing ports for long-term, large-scale, and economically-efficient use. Additional land suitable for marshaling ports exists, but it requires commitment from port authorities and port investors to develop it for this purpose.

1. Introduction

When national goals require deep and system-wide transitions, as does the goal to decarbonize an economy, it is important to analyze the supporting industries, infrastructure, and supply chains necessary to achieve those goals. Such analysis can identify investments or policies needed to mobilize upstream investments and to mitigate industry growth constraints. Conversely, it can reveal that either the goal or the goal's time frame are unrealistic (Poulsen and Hasager, 2016; Poulsen and Lema, 2017; Heptonstall et al., 2012). This article analyzes U.S. infrastructure needed to achieve deployment targets for U.S. offshore wind (OSW) power generation.

The US OSW industry is in the nascent stages of developing a domestic supply chain due to market demand driven by policy directives, declining costs (Wiser et al., 2021), and sociopolitical initiatives for energy system transitions. OSW is regarded as a key contributor to these transitions due to its favorable characteristics: 1) OSW generation produces near-zero CO_2 emissions in operation and over its life-cycle, 2) the resource is close to many of the largest and most concentrated electrical loads in the US (Kempton et al., 2016), 3) in coastal states it is typically the largest commercially available clean energy resource (Lopez et al., 2012), 4) cost-effective capacity of one project is comparable to that of a large-scale nuclear or coal generator, 5) the ocean surface is better than land for wind projects because wind speeds are higher, turbulence is lower, and there is much more area available. OSW technology is therefore scalable, cost-competitive (DeCastro et al., 2019; Poulsen and Lema, 2017; Williams et al., 2017), and can be deployed at a pace fast enough to exceed the replacement rate of retiring thermal generation (Grubert, 2020), and potentially at the pace required for effective climate change mitigation (Kempton et al., 2007; Garvine and Kempton, 2008; Masson-Delmotte et al., 2021).

Capitalizing upon these advantages depends on the development of a supply chain specialized for the technology and its operating environment (Poulsen and Hasager, 2016). Some parts of the supply chain may be readily supplied by the offshore oil and gas or marine construction industries, while other parts must be entirely new (Arshad, 2019; Poulsen and Lema, 2017). The European OSW supply chain has already navigated these requirements and reached maturity, defined by its

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global leadership in OSW installations, its economic evolution into a subsidy-free market, its supply of knowledgeable personnel, its experience in realizing the full life-cycle of OSW projects, and its technological achievements (from large turbine manufacturing to successful deployment of floating OSW) (DeCastro et al., 2019; Poulsen and Lema, 2017).

The US OSW industry and supply chain, on the other hand, is still emergent. Yet, due in part to the above characteristics of OSW and the sociopolitical push to transition away from fossil-fuel based energy systems, both US state and federal agencies have set ambitious quantitative policy targets for OSW generation. Even though supply chain logistics and infrastructure are globally a challenge for OSW deployment efficiency and cost-effectiveness, few studies have been done on OSW supply chain management (Poulsen and Hasager, 2016; Poulsen and Lema, 2017; Arshad, 2019; Blanco, 2009; Heptonstall et al., 2012; Dong and Li, 2020; Stentoft et al., 2016; McKenna et al., 2016; Sarker and Faiz, 2017). Little to no research has been done on this topic for the US industry. Further, the topic of US OSW marshaling port infrastructure—an integral component and a hub for supply chain transfers—remains a significant gap in the literature.

Thus, we examine the US domestic supply chain and, specifically, the port infrastructure necessary for OSW deployment. We then quantify the demand for port supply based on state and federal policy for OSW procurement. We treat state commitments as firm demand and federal targets as projected demand due to the US regulatory and policy framework governing power generation. Unlike European and Chinese counterparts, power generation procurement in the US is primarily the jurisdiction of states and state law, regulated by their public service commissions. The federal government can only implement policy that, in effect, speeds up regulatory approval, incentivizes OSW industry developments and creates market circumstances to support OSW growth. Consequently, we here count state laws and targets for OSW procurement as firm commitments and use the federal goal as a proxy for market growth beyond current state commitments. As of October 2021, states have collectively mandated a procurement of 40 GW of electrical generation capacity on the US East Coast by 2040 (itemized in Table 3). The federal OSW target of the Biden Administration is to install 30 GW deployed by 2030 and 110 GW by 2050 (The White House, 2021).

Our analysis of needed infrastructure will show that, to achieve either firm demand from state commitments or projected demand based on federal targets, a significant bottleneck will be the availability of port area required to marshal components and load them onto installation vessels. Thus, there is a need to invest in constructing port area capable of sufficient deployment to ensure target timelines are met and long-term industry growth is possible.

2. Infrastructure required

To understand the range and magnitude of needed infrastructure, we first analyze the evolving sizes of wind turbines and their components. These in turn determine the infrastructure and correlating equipment required to manufacture components, marshal them to be ready for deployment, load onto installation vessels, assemble in the ocean, and maintain components over their project lifetime. Following the examination of the facilities needed, we analyze their capital cost, and then focus on the port types and areas needed.

2.1. Evolution of offshore wind power

First, we illustrate the evolution of wind turbines, projects, and the underlying infrastructure for the industry. The world's first OSW project, Vindeby, was built in 1991 off the Danish Island of Lolland and operated through 2017. Vindeby consisted of 11 turbines mounted on the seafloor, in shallow waters near shore. Each turbine produced 0.45 MW power at peak, with the tower reaching 37 m from water line to hub and blade length of 17 m. The heaviest component lifted, the nacelle, weighed 27 tonnes, the tower was 20 t, and each blade only 2.2 t. Eleven such turbines made up an OSW project of 4.95 MW (NIRAS A/S 2016). Despite rough weather, the entire project was installed in 11 days. The turbines were manufactured in factories built for land-based wind power, moved by conventional transport, and easily deployed from a conventional port using non-specialized marine construction vessels.

By contrast, as we write, a new commercially-competitive project would range from 800 MW to 1.2 GW—more than 160 times the power of Vindeby. Modern projects are specifying turbines with capacities of 12–14 MW, with hub heights of 138 m and blades of 107 m each. The nacelles weigh 600 tonnes and each blade is 55 tonnes,[1] thus requiring the use of a heavy-lift ocean-going crane. Assuming a 1 GW OSW project uses 12 MW turbines,[2] 83 turbines of such technical specifications would be deployed (1000 MW ÷ 12 MW = 83 turbines). Given the evolution of turbine and project technology, the original infrastructure specifications that were sufficient to build Vindeby are far from adequate for a modern OSW project. Now, a 1 GW project needs a port able to receive, store, move, assemble, load onto an installation vessel—with a deck capable of accommodating component dimensions, and a crane capable of the required lifts—and deploy 83 large turbines at sea over the span of 18-24 months. This port needs to meet more challenging area, access, handling, and load-bearing specifications.

2.2. Overview of infrastructure needed

As turbines and projects have grown by orders of magnitude, the underlying physical infrastructure and supply chain has become larger and more specialized. Today, new project components are built in specialized factories, as opposed to onshore wind factories that have been repurposed for OSW. As there is currently no robust supply chain in the US to support the nascent industry, OSW project developers are reckoning with how to work around the lack of US-based infrastructure. Importing all components from overseas runs into several problems: 1) Europe's offshore wind manufacturing facilities will already be strained to meet its own offshore wind goals; 2) developers have been hesitant to rely on early-stage Asian manufacturing in which they do not yet have confidence; and 3) as the components are very large, additional loading and unloading for trans-ocean shipping adds cost and logistics (Sarker and Faiz, 2017).

The above logic as well as the Biden Administration's employment priorities (The White House, 2021) lead toward investing in and supporting US-based manufacturing of OSW components. Substantial investments in manufacturing will be required to meet state and federal targets, but the known targets (detailed in Section 4) give investors visibility into the pipeline of project orders (McClellan, 2019), and the corresponding return on investments in component manufacturing. US investments can be further facilitated by incentives to build manufacturing in the US, as has been pursued by both the federal government and several states (The White House, 2021; NYSERDA, 2020). Thus, we do not treat manufacturing as a significant barrier, as public policies (state and federal) have already created an offshore power market and are incentivizing US-based manufacturing (discussed in Section 3).

[1] Examples of modern OSW turbine specifications include GE Renewables' Haliade-X (https://www.ge.com/renewableenergy/wind-energy/offshore-wind/haliade-x-offshore-turbine), the Siemens-Gamesa SG 14–222 DD (https://www.siemensgamesa.com/en-int/products-and-services/offshore/wind-turbine-sg-14-222-dd), and the coming Vestas V236-15 MW, to begin testing late 2022.

[2] For scale, a 1 GW wind project is approximately the power capacity of a nuclear or large coal power plant. Given typical offshore wind speeds, varying over time, a well-designed offshore turbine will produce on average about half its maximum capacity. For example, an offshore turbine with 12 MW capacity would have an average output of 6 MW, enough to power 4,000 US households or charge 1,000 electric cars simultaneously.

2.3. Capital and cost allocation of needed infrastructure

To convey the relative capital cost of OSW-related infrastructure, Table 1 gives approximate costs of the OSW project itself (first row) and the infrastructure needed to build it. These figures are based on discussions with knowledgeable industry professionals (including developers, manufacturers, port managers and vessel operators) by the second author, along with the limited available published information. The first numeric column gives the total capital cost of each major infrastructure facility. The second column is the number of projects that facility might support. The third column, "Rental or cost per project", apportions the total cost across the number of projects (the first column divided by the second). This simple division yields a cost per project, ignoring variations in business models, interest rates, etc.

This approximate and simple cost comparison illustrates several points. By definition, 100% of the capital costs of the OSW project is allocated to that single project. Traditionally, the O&M port has also been dedicated to a single project, but some are now shared amongst several projects. The project cost alone is larger than that of any individual infrastructure facility investment. Installation vessels, manufacturing ports and marshaling ports are significant capital cost infrastructure. Non-intuitively, a single US installation vessel for today's turbine sizes costs more than an entire marshaling port. And because the marshaling port services many projects over a long life, the cost per project is the lowest in the table.

Over the past decade, a key risk to financial return on the vessel investment has been the rapidly increasing turbine dimensions (Sarker and Faiz, 2017; Stentoft et al., 2016). Larger turbines render installation vessels obsolete, in deck size and crane lift, well before their expected lifetime (Poulsen and Lema, 2017). This, and the two-year marshaling timeline per project lead us to estimate only 6 projects per vessel in the table.[3] Such vessels may be subsequently used for older turbines, modified to build bridges, or used for other marine construction.

Newly constructed vessels must continue to grow in size to match the continuing growth of turbines, further increasing vessel cost while reducing useful economic life. Such vessels allow for traditional European deployment methods, which also depend upon large marshaling ports. With two sizeable (>60 ac) and accessible US marshaling ports now committed (NJ Wind Port and Portsmouth), the US may opt to build several more Jones-Act compliant installation vessels capable of supporting traditional European deployment methods. Virginia-based utility Dominion Energy has begun building one such vessel (Ball, 2021). Otherwise, a new method of deployment to address the vessel issue has been investigated by two projects supported by US DOE (one via NOWRDC): designing assembly and deployment methods that shift ocean work to in-port work, streamlining deployment and lowering costs through a much simpler installation vessel and a faster, safer assembly process (Kempton et al., 2017; RCAM Technologies, 2019; Sarker and Faiz, 2017). A third method of deployment has been designed but not yet deployed, using new crane-less lift technologies (Mercure, 2021).

The economic logic of in-port assembly and simplified installation vessels can be seen by comparing the rental of a vessel versus a marshaling port in Table 1, and in the marine construction adage that building at sea costs 5 to 10 times as much as building in port (Kempton et al., 2017). The prospect of such lower-cost deployment demonstrates an additional benefit of large ports with no overhead obstructions, as they allow assembly in-port then carry-out of assembled turbine systems, whether for fixed-bottom or floating turbine systems. Despite the promise, these new deployment methods must be tested before we can determine whether a smaller number of installation vessels will be required in the US than have been in Europe.

Additionally, as will be further detailed in the next section, the marshaling port can be a significant infrastructure and logistical hurdle due to several issues including capital costs and a scarcity of suitable sites. On the other hand, it is one of the least expensive infrastructure needs, whether expressed in total capital cost or apportioned cost per project.

3. Types of offshore wind-related ports

Over the life cycle of an OSW power project, four types of ports are needed. These are described briefly below. (More detail on each port type can be found at Global Wind Energy Council, 2016, pp 37–39.)

1. **Small oceanic ports for survey vessels.** These ports service the launching of survey vessels used for wildlife surveys, seafloor scans, and geotechnical boring. Ports and vessels already exist for these purposes, and may already be sufficient for new OSW use. If not, these ports do not pose significant cost or acquisition and build challenges that would impede further construction.
2. **Manufacturing ports.** OSW components are made on land, but are so large they are impractical to transport over land—e.g., modern blades are 107 m (351 ft), much longer than a semi-trailer maximum length of 16 m (52 ft), and longer than the maximum railroad flatcar length, 27 m (89 ft). Thus, OSW component factories are located within or directly adjacent to a port, so finished components can be moved to the quay via "self-propelled modular transporters" (SPMTs) and loaded directly on a transport ship for transfer to a marshaling port. Subcomponents may be brought to the manufacturing port over land, such as resin and fiber for composite blades, electrical components, steel plate, etc. Thus manufacturing ports may require heavy roadway or rail access. The location and size of factory ports are decided in conjunction with the material supply chain proximity to the factory, component transport to marshaling port or to sea, etc. Manufacturing ports may require up to 60 ac (25 ha) for both the yard and factory areas, but because the separate OSW components can be transported horizontally on deck, manufacturing port location does not require exceptional height clearance—thus, there are many older, unused or underused upriver ports that can be refitted and upgraded to serve as manufacturing ports. The investments in factory and associated quay typically follow booked orders for components from multiple projects (6 years of orders being a typical threshold), which the current US project queue should already be able to support.
3. **Marshaling ports.** Just prior to loading out, all components are collected, stored, and made ready at a marshaling port. Here, components are loaded onto assembly vessels to build the wind project at sea. Our analysis, derived in conjunction with two wind turbine Original Equipment Manufacturers (OEMs), shows that a single 1 GW project with 12–14 MW turbines would occupy 22 ha (54 ac) of such a port for two years during the construction period (House et al., 2020).

   Marshaling ports have the most challenging spatial and load-bearing requirements of all OSW-related port types (required criteria for marshaling ports are detailed in Table 2). Industry planners have stated that no suitable ports exist in the U.S. This claim makes sense only if one is looking for an existing port to modify. By contrast, managers at the Hull marshaling port told the second author that, to find a marshaling port, there is no advantage from starting with a port, that it is equal or better to just start with bare

[3] Unlike vessels, a marshaling port does not have obsolescence risk for two reasons. First, a well-located, 100–200 ac port (40–80 ha) could accommodate substantially larger turbines without port changes. Second, at minimal cost, a marshaling port with road and rail access can be converted to handle other goods, such as containerized freight, break-bulk, or other cargo.

Table 1
Approximate capital costs (total and apportioned per project) of an OSW project and of necessary enabling infrastructure facilities. Assumptions: 1 GW project, 12 MW turbines, 2 construction seasons of 7.5 months each plus mobilization—thus 18-24 months elapsed time for build. Project and construction specifications from Kempton et al. (2017).

Facility	Total capital cost ($ million)	Projects (count)[a]	Rental or cost per project ($ million)	Percent of capital cost/project (%)
Wind project (1 GW)	2700	1	2700	100
Installation vessel[b]	500[c]	6	75	16
Marshaling port[d]	400	25	16	4
Monopile manufacturing port[e]	600	12	50	8
O&M Port	15[f]	1	15	100

[a] Number of projects serviceable over the lifetime of each facility.
[b] Jones Act-compliant vessels built mirroring traditional European design with jack-up and heavy-lift, high-hook cranes.
[c] Cost for a 12–15 MW capable installation vessel is $500M for US build (Partlow, 2021; Schuler, 2021); or $250M - $300M from an East Asian Shipyard.
[d] NJ estimates $400M to build a port for both marshaling and manufacturing (NJEDA, 2021). Note: NJEDA originally estimated $300-400M for a port of 180 ac (73 ha). However, US marshaling port stakeholders have reported that this estimate only covers the first phase of 55 ac (22 ha). We use the estimate to approximate the cost of a port for marshaling only, since building for OSW manufacturing requires about the same load-bearing and surface preparation. The NJ site is representative of a large site with no existing structures to demo or work around; smaller sites and those with conflicting structures would cost more per unit area. Project count conservatively assumes 25 years economic life, two years in port per project, and average of 2 projects simultaneously underway.
[e] Example for monopiles: EEW Rostok manufacturing capacity is 250,000 tonnes/year, one XL monopile is 2,500 tonne. Thus the factory capacity is 100 monopiles/year or about 1.2 GW/year. Paulsboro facility will be approximately $100M for 23 ha port upgrade + $500M for handling, rolling, and fabrication equipment and building. Project count assumes 12 yr operations as deeper water will likely require jackets. (https://eew-group.com/industries/offshore-wind/and pers. comm).
[f] Data from WBOC-TV, “Ørsted Plans to Build Md.‘s First Emissions-Free Offshore Wind Operations & Maintenance Facility in West OC”, 6 Oct 2021, and industry sources. They report $20M for a 120 MW service facility on 2.5 ac, possibly expanding to 5 ac. The Table’s $15M and our scaling draw from discussions with O&M port designers. Cost here does not include 2 crew transfer vessels (CTVs) for a smaller (100–200 MW) project at $5M each.

land adjacent to the water.[4]

It is true that finding sufficiently large land areas adjacent to the water, with no bridges or other obstructions to the sea is challenging. Land adjacent to water is highly valued, and much has been developed as residential property, marketed for water view and access to water recreation. Concurrently, remaining undeveloped land may be environmentally valuable, restricted wetlands, or so soft as to make high weight-bearing problematic. Finally, despite these constraints, states buying OSW-generated electricity often push for a port within their states because of the potential economic benefits and job-creation opportunities. This leads to a proliferation of US plans for ports that are tiny relative to existing European marshaling ports. While small marshaling ports may be useful for the first few projects, they exacerbate logistical inefficiencies, raise costs, and will likely not be useful as turbines grow and as technology evolves to more in-port assembly and/or floating wind.

The combination of requirements, cost, state politics, and land development challenges make marshaling ports a likely barrier to growth of the industry, and their lack could additionally preclude the development of fast and low-cost deployment methods.

4. **Operations and Maintenance (O&M) ports.** O&M ports have a smaller geographical reach than other OSW ports. They typically have 1 or 2 small craft serving one project with daily visits. However, with projects further from shore, the conventional model is shifting to using a larger O&M port (say 10 ac, as opposed to 5 ac) and a service operation vessel (SOV) moored on the project site for multiple days, housing a constant crew who service one or more wind projects. In either case, the port operations might include a parts warehouse, offices, a meeting room or small training facility, and one or two craft. In either model, O&M ports are relatively easy to create by modifying existing ports, requiring as little as $10M investment. Even if an O&M port with accompanying service vessels is built to serve only one project, it constitutes an insignificant portion of the total project cost. For floating wind projects, O&M of large-components may best be done by towing the entire turbine structure to the marshaling port for replacement using the same dock and cranes that were used for initial assembly.

Based on the above comparison of needed port types, the marshaling port appears to be the most challenging type necessary for large-scale deployment of OSW turbines. Whereas the other three port types are often re-built from old commercial ports, marshaling port requirements limit site options and indicate that the best future marshaling ports may not now be ports. Additionally, while there are clearer thresholds of business viability for the other port types, marshaling ports are a more difficult venture. Given these insights, we concentrate our subsequent analysis here on marshaling ports.

3.1. Marshaling port requirements

OSW marshaling ports have specific technical and geographical requirements that exacerbate the typical port challenges of efficient management and optimized area capacity (Yang et al., 2019; Jin et al., 2019): 1) the weight of the components—partially spread out by SPMTs—leads to high load-bearing requirements for the port surface and quay; 2) component size and count, turning radius for component movements, maneuvering for partial assembly, and load out to installation vessels determines necessary port area; 3) the logistical sequence—shipments in from manufacturers, wait to receive full turbine sets, then wait for deployment weather windows—determines residence time of sets of components; 4) vessels to ship in components, and more challenging, installation vessels to take components out to sea, determine quay length, channel depth, and—for jack-up vessels—channel bottom weight support; 5) vertical clearance is required for jack-up vessel spuds, as well as for the industry practice of assembling and commissioning the tower with its electrical systems in-port then shipping it out upright. Combining requirements, items 2 and 3, along with the option of adding a manufacturing facility at the marshaling port, all lead to large area requirements. Item 5 and the expectation of more assembly in-port as the industry develops necessitate no overhead obstructions from port to sea.

[4] These Hull managers added that it had been more costly to tear out old fishing piers and inadequate ground reinforcements at Hull than it would have been to build new on clear land with non-reinforced waterside.

Table 2
Offshore wind marshaling port requirements. Based on analysis of offshore wind ports and turbine sizes (Brett and Kempton, 2018), on results from a DOE study of advanced deployment methods for offshore wind (Kempton et al., 2017), on insights derived from House et al. (2020), and from eliciting requirements as described in the text. Note: Assumes 12–14 MW turbines with 107 m blades.

	Minimum Requirement		Rationale
	(Imperial)	(Metric)	
Land area	100–200 ac	40–80 ha	Possible but inefficient with as little as 50 ac (20 ha); the suggested >100 ac (40 ha) allows for larger turbines, higher port handling efficiency, new lower-cost deployment techniques, floating deployment, and/or manufacturing on site.
Channel depth	20–36 ft	6–11 m	Required to accommodate large, specialized installation jack-up vessels (higher number), or to accommodate today's US liftboats (lower number).
Vessel Width	150 ft	46 m	Needed for component storage on deck. Vessel beam plus required clearance defines minimum harbor entrance width.
Max current along quay	5 knots	2.6 m/s	Supply and installation vessels have to turn before or after docking and load out; if current is too fast, vessel has to wait for next slack tide. Note: the "knot" is widely used in practice but is not an SI unit, thus we put it in the Imperial column.
Quay length	1,300 ft	400 m	Today's deployment vessels are 140m length, quay should accommodate at least 2 vessels simultaneously, or one plus supply transport ships.
Tidal range	(Low is desirable)		Mooring and load out is more difficult with a large tidal range; today's typical load out is to vessel when it is up on spuds at quayside.
Laydown area loading	1200 PSF	6 tonne/m^2	Storage and movement of structures, assume loads spread by SPMT or similar (numbers given are required ground bearing pressure)
Quay/lift area loading	3000 - 6000 PSF	15–30 tonne/m^2	Crane loads and assembled towers require the most load bearing, the larger remaining areas of quay require the lower load quantities.
Overhead air clearance	∞	∞	Limit now set by vessel's spud height above waterline, and by assembled towers shipped out upright on deck (now ≈ 120m). In the future, greater clearance will be needed to allow upright transport of the entire assembled turbine structure.
Off-quay wet storage, or dry dock, for assembly	Load =full structure, width =base; wet base assembly may req. quayside depth ≥ travel depth		In-port assembly is needed both for fully built-in-port fixed-bottom or for most floating wind. Assembly areas may require either in-water quayside or dry dock if assembling in port. In-water build or storage requires channel floor reinforcement.
Labor hours			No local restrictions on quayside working hours or nighttime shifts.
Skilled labor			Locally available skilled workforce.

If future deployment of floating wind turbines is contemplated for the same port, the same requirements would apply (adding another reason to require freedom from overhead obstructions). Additionally, for both floating and full assembly of fixed-bottom structure in port, assembly must be accommodated. For example, some floating developers have requested a load-bearing assembly area in the water, just off the quay, with cranes on the quay lifting components to assemble in water. Alternatively, assembly could be done in dry dock, making a gantry crane possible if the dry dock has sufficient width for the floating platform base.

Table 2 summarizes the requirements for a marshaling port designed for today's turbine sizes (assuming 12–14 MW turbine specifications with 107 m blade). These requirements have been developed based on our site inspections of three European OSW marshaling ports, discussions with designers and operators of those ports, sample layouts on US areas by wind turbine OEMs, as well as joint port analysis with two OEMs and four vessel operators (Brett and Kempton, 2018; House et al., 2020).

Note that the criteria of Table 2 do not match the characteristics of existing US Atlantic and Pacific ports and their access channels, since the larger of those ports were designed for Panamax vessels.[5] If the OSW industry redesigned turbines to fit in Panamax-optimized ports and vessels, there would be a greater amount of suitable port area for OSW deployment. However, Panamax dimensions would consequently require smaller turbine components and less efficient, slower, and less safe installation, yielding more expensive electricity. In short, US coastal Panamax-designed ports and channels are not useable for OSW marshaling.[6] More sensibly, OSW ports need to be designed for vessels that can optimally install modern turbines that continue to grow.[7]

In addition to vessel considerations, a forward-looking marshaling port design should consider at least 15 MW turbines with 120 m blades and prepare for future 25 MW turbines with 156 m blades.[8] Foundations for 15 MW and higher are increasingly likely to require jacket foundation structures rather than monopiles, thus requiring substantially more assembly and laydown area per turbine. Larger components disproportionately increase area required for storage and marshaling due to turning radius considerations in port. For example, one OEM working with us calculated that a 35 ac (14 ha) port could only marshal 5 of their new large turbines at a time—not a complete solution for a commercial project, which might deploy 60 to 80 turbines.

[5] Panamax ship dimensions—draft of 13–15 m (42–50 ft), air draft of 40 m (130 ft) and beam of 32.2 m (106 feet)—insure that the vessel can pass through the locks of the Panama Canal.

[6] Gulf of Mexico oil and gas (O&G) yards and ports are already better matched to OSW, as many were designed to accommodate construction and whole-structure load-out of massive O&G platforms. Great Lakes ports can accommodate larger ships but the St. Lawrence Seaway severely limits air draft to 35.5 m (117 ft).

[7] The US installation vessel Charybdis, designed for turbines "12 MW and greater" (likely up to 15 MW) has a beam of 56 m (184 ft) and its class height is over 85 m (280 ft) unloaded, already roughly twice the Panamax dimensions (Schuler, 2021).

[8] Siemens-Gamesa has announced the 15 MW SG 14–222 turbine (although with undersized rotor), and a plausible 25 MW turbine design funded by ARPA-E is being proposed for commercialization (Loth, 2021). We calculate expected rotor areas based on a commercial offshore turbine with high capacity factor, due to its specific rotor area of 3.17 m^2/kW. Given a 6 m diameter hub and this efficient specific area, we calculate blade lengths of 107 m, 120 m, and 156 m, respectively for 12, 15 and 25 MW turbines.

Fig. 1 is an operating and highly successful marshaling port, the Port of Esbjerg in Denmark, which had marshaled approximately 80% of the 15 GW OSW capacity installed in Europe over the 16 years up to the time of this picture, 2017.[9] The turbines shown are 1/3 to 1/2 the capacity (in MW) of those expected to be used going forward in the US. This port was approximately 440 ac (178 ha) of land area devoted to marshaling for the OSW industry at the time of this photograph. As will be itemized, all existing and planned US marshaling ports are together approximately half the area of Esbjerg, yet OSW commitments by US states demand deploying 2.5 times as many MWs of installations in the same number of years. The desirable size and design of Esbjerg is validated by the preference of project planners and vessel operators for using it over closer marshaling ports—Esbjerg is often used to marshal projects 500 km (310 mi) away from the port (House et al., 2020).

Unlike Europe, the US has just one operational marshaling port: the New Bedford Marine Commerce Terminal, in New Bedford, MA. This port is 29 ac (11.7 ha), and was originally designed for the Cape Wind project with turbines of 3.6 MW each. Now, New Bedford has been leased to help marshal the significantly larger 800 MW Vineyard Wind 1 project, with turbines of 13 MW each. Due to limited port area, parts will have to be marshaled among three regional ports to accommodate the project's size and target power-on date. This increases the cost, logistical challenges, and time of the project's installation, while also complicating port availability for other projects set to be deployed within the same region and time period. The need to use three ports for a single project already demonstrates a shortage of US marshaling ports of sufficient area for modern turbine and project sizes.

3.2. Near-term alternatives to traditional marshaling methods

With the logistical challenges presented by smaller marshaling port areas and the lack of large, Jones-Act installation vessels, planners for US projects have already explored several alternative installation methods to enable and optimize deployment without well-designed infrastructure. For example, the Block Island Wind Farm brought a deployment vessel from Europe (Fred Olsen Windcarrier's Brave Turn), and since the Jones Act prohibits moving components from a US port to build on a foundation, the marshaling port used for Block Island was the port of Halifax, Nova Scotia. Halifax was not designed for marshaling and was sufficient for only five 6 MW turbines for that 30 MW project.[10]

Likewise, for the Virginia CVOW project, Jan De Nul sent a jack-up installation vessel from Belgium to use Halifax, Nova Scotia as the marshaling port. This solved both limited US marshaling port area and lack of Jones Act-compliant vessels. However, the vessel had to make three round trips from Halifax to the offshore Virginia site in order to pick up monopiles and transition pieces, then towers, then turbines and blades. CVOW is 43 km from shore, but the installation ship had to make 6 trips of 1,400 km each to or from a Canadian port–at substantial added cost in vessel and crew time (Buljan 2020).

Another approach to work around the lack of US marshaling ports and vessels is the "feeder barge" system, wherein a large installation vessel stays at the wind project site and does no component transport. Rather, barges or transport vessels carry components directly to the site, some coming directly from US factories, others from US marshaling ports, and the installation vessel picks components off the barges and assembles complete turbines at sea. The feeder barges must be Jones Act-compliant, but if the installation vessel never carries parts from a US port, it need not be. Nor does the installation vessel need a US marshaling port. However, this approach requires transporting components by barge to the ocean site and transferring from barge to

[9] Source: Port Esbjerg Wind Business Area, https://portesbjerg.dk/en/business-area/renewables.

[10] Source: Fred Olsen Windcarrier, 2019. "Case Study: Block Island". https://windcarrier.com/block-island-15.

Table 3

State OSW demand derived from OSW-specific policy commitments and procurements sum to firm OSW demand by state along the US East Coast, as of October 2021. Awarded project names are shown, along with respective power-on dates. The last row for each state shows the state's "Remainder of Commitment," i.e., the difference between the total state requirement and the total projects awarded. (ACP, 2021, 2020).

State	Policy Target (MW)	Target Year	Project Name	Project Size (MW)	Project Power-on Date
Maine[a]	12	2020	Aqua Ventus	12	2023
			Remainder of Commitment	0	
Rhode Island[b]	1000	–	Revolution Wind[c]	400	2024
			Block Island	30	2016
			Remainder of Commitment	600	
Connecticut[d]	2000	2030	Revolution Wind[c]	304	2024
			Park City	804	2026[e]
			Remainder of Commitment	892	
Massachusetts[f]	5600	2035	Vineyard Wind I	800	2023[e]
			Mayflower Wind	804	2025[e]
			Remainder of Commitment	3996	
New York[g]	9000	2035	South Fork Wind Farm	130	2023
			Sunrise Wind	880	2024
			Empire Wind I	816	2024
			Empire Wind II	1260	2026
			Beacon Wind	1230	2026
			Remainder of Commitment	4684	
New Jersey[h]	7500	2035	Ocean Wind I	1100	2024
			Atlantic Shores OSW	1510	2027
			Ocean Wind II	1148	2029
			Remainder of Commitment	3742	
Maryland[i]	1568	2030	Skipjack	120	2023[e]
			MarWin Wind Farm	248	2025
			Remainder of Commitment	1200	
Virginia[j]	5200	2034	Coastal VA OSW Project	12	2021
			Dominion Energy Project	2640	2026
			Remainder of Commitment	2548	
North Carolina[k]	8000	2040	–	–	–
			Remainder of Commitment	8000	
Total Firm Demand	39 880		Awarded as of October 2021	14 218	

[a] (UMaine, 2020).

[b] RI does not have an official OSW policy commitment, but has awarded a 400 MW contract and has announced a request for proposals for up to 600 MW (Kuffner, 2020). Block Island is not included as contributing to the 1000 MW target as its award date of 2009 and power-on date of 2016 place it prior to the timeline for this analysis (2020–2040).

[c] (Ørsted & Eversource. Revolution Wind Project at a Glance. https://revolution-wind.com/about-revolution-wind).

[d] (DEEP, 2019; Substitute HB No. 7156, 2019).

[e] Power-on dates for indicated Massachusetts, Connecticut, and Maryland projects are projected dates as of end of data collection, October 2021. Original dates have been delayed due to federal permitting backlogs (Gheorghiu, 2020; Prensky, 2020).

[f] (DPU, 2020; SB No. 9, 2021; DPU, 2019).

[g] (NYSERDA, 2019, 2021a,b; Bill No. A08429 2019).

[h] (EO No. 92, 2019; Peretzman, 2021, 2019).

[i] (MD PSC Order No. 88192, 2017; MD HB 226, 2013; MD SB 516, 2019; Prensky, 2020).

[j] (Dominion Energy, 2021; HB 1526, 2020).

[k] (EO No. 218 2020).

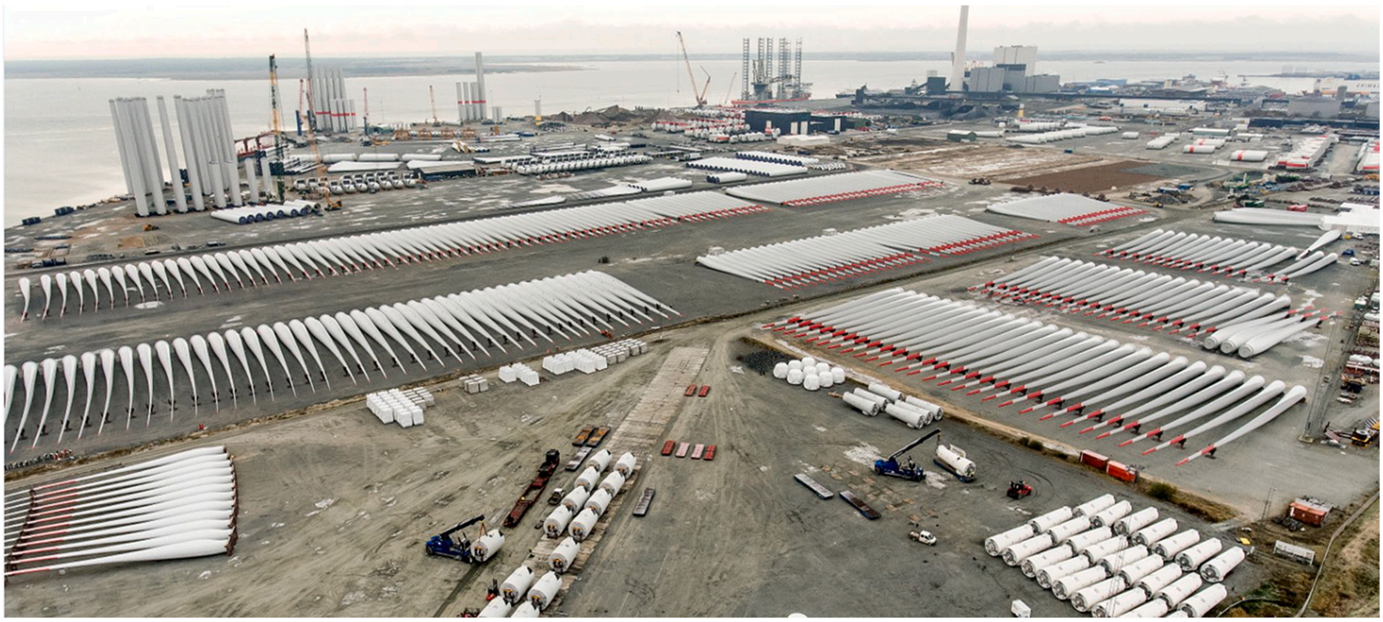

Fig. 1. An example OSW marshaling port, the Port of Esbjerg in Denmark (2017). Blades and some tower sections are in foreground, and tower assembly can be seen in background adjacent to the load out areas. For scale, the blades pictured are 80 m long. (Reprinted with permission of the Port of Esbjerg).

installation vessel, potentially in rough wave conditions, rather than loading one large vessel in port.

While each of these alternative methods are important solutions to move OSW projects forward within tight schedules, they are less optimal than the traditional European method. They result in increased vessel trips, longer travel times, prolonged construction schedules, complicated logistics, increased hazards at sea, and increased construction costs. Sizeable marshaling area remains the ideal method as it reduces logistical constraints, streamlines the supply chain, and allows for industry evolution in both technology and changes in deployment method (i.e. increased in-port assembly and crane-less lift technologies discussed above).

4. Port area demand due to OSW generation targets

Now we are prepared to ask: 1) What is the demand for US marshaling area, given the OSW deployment from US state and federal OSW targets? 2) Is the supply of US ports sufficient to meet this demand? And, 3) if not, can the supply chain make do with modified alternatives to support the burgeoning US OSW industry?

We calculate deployment capacity demand in MW per year based on state and federal targets, as well as the size and power-on date of awarded OSW projects (Table 3). Given MW deployment rates, port requirements, and technology specifications, we derive marshaling capacity demand, expressed in GW/year and translated into marshaling port area (ac and ha). This answers the question of how much marshaling area is needed to meet OSW generation demand driven by policy targets. We will then analyze the supply of existing, planned, and potential marshaling port area to assess whether it is sufficient to support firm and projected demand.

4.1. Firm demand: state commitments through generation procurement and policy directives

To project firm port area demand, we tabulate the projects in the development pipeline along the East Coast and the OSW generation targets each East Coast state has set via policy commitments. Table 3 collates these policy commitments and the projects awarded by each state as of October 2021. This data is derived from state legislative policy, executive orders, bid solicitations, requests for proposals, contracts, and press releases across all East Coast states with existing OSW-specific targets. Total MW committed by policy (40 GW) and the subtotal MW of awarded projects (14 GW) are the two sums in the last row of Table 3.

Several states have set intermediate timeline goals (e.g., New York has set an intermediate target of 2400 MW by 2030) and predetermined solicitation timelines.[11] While only the states' end-date targets have been included in Table 3, we have integrated intermediate targets and planned solicitations, where available, into our yearly projections. Based on award, permitting and power-on dates, we plot the expected construction timelines of known and expected projects from 2020 to 2040. We then equally apportion the difference between state policy commitments and the sum of awarded and planned solicitations over the remaining years until the policy target year. Finally, we extrapolate the years a marshaling port would be needed for project deployment by taking its power-on date and allocating the project's MW size as one-half over each of the prior two years (e.g., Ocean Wind I is 1100 MW and has a target power-on date of 2024, so 550 MW marshaled in 2022, and 550 MW in 2023). From the yearly tabulation of state-required OSW MW deployment we will subsequently calculate the port area required to support those state commitments (columns 2 and 3 in Table 5).

The sum of state commitments (40 GW as of October 2021) is likely a substantial underestimate of the state-driven OSW demand from 2020 through 2040, since our "firm demand" tabulation assumes zero new state requirements and zero new market-driven power procurements. In fact the totals in Table 3 have already increased several times during our analysis to prepare this article. It is thus highly likely that state demand will continue to increase and projects will continue to be awarded beyond the current commitments. Additionally, private loads and electric utilities are increasingly likely to independently enter the market regardless of state commitments, further driving demand for OSW power

[11] The New Jersey Board of Public Utilities (NJBPU) plans to issue 5 solicitations from 2020 to 2028. Specifically, 3 solicitations for 1.2 GW each every two years from 2020 to 2026, then 2 solicitations for 1.4 GW each. The New York State Energy Research and Development Authority (NYSERDA) plans to solicit 0.75–1.0 GW annually until 2027 to meet their state policy commitment.

Table 4
Existing, planned, and conceptual ports along the US East Coast that may serve as marshaling ports for OSW deployment. The last three are major European marshaling ports now operating, provided for comparison. All locations have unlimited air draft.

Marshaling Port	Code	Status	Total Area (ac/ha)	Laydown Area (ac/ha)[b]	Draft (m)[c]	Annual Capacity (MW/yr)	Year Available
New Bedford, MA	MA1	In use	29/12	29/12	9	268	Now
Salem, MA	MA2	Planned	42/17	29/12	2–10	185	2024
New London, CT	CT	Planned	35/14	35/14	3–11	324	2022
NJ Phase 1	NJ1	Planned	55/22	30/12	3–5	278	2023
NJ Phase 1 + 2	NJ2	Planned	205/83	63/25	3–5	583	2026
Portsmouth, VA[d]	VA	Planned	101/41	72/29	13	667	2025
Arthur Kill, NY	NY	Concept	35/14	35/14	3	324	–
DE Phase 1[e]	DE1	Concept	331/134	331/134	1–4	3060	–
DE Phase 1+2[f]	DE2	Concept	810/328	810/328	1–11	7496	–
Esbjerg, Denmark[a]	–	In use	440/178	440/178	13	4074	Now
Hull, United Kingdom[a]	–	In use	150/61	109/44	9	1009	Now
Cuxhaven, Germany[g]	–	In use	295/119	243/99	9–13	2250	Now

[a] Esbjerg and Hull published descriptions, plus personal communication between second author and Hull and Esbjerg Port representatives.
[b] Areas from port literature, checked against calculation from linear map measurements (House et al., 2020).
[c] US measurements based on bathymetric NOAA Nautical Navigational charts (Source: National Oceanic and Atmospheric Administration Office of Coast Survey, https://nauticalcharts.noaa.gov/). Esbjerg and Hull estimates derived from direct conversations with respective local port experts.
[d] The current Portsmouth design shows 44 ac (18 ha) reserved for monopile manufacturing and storage, leaving a turbine laydown area of 57 ac (23 ha) (DEME/JVitale, 2020). Given the competition presented by an under-construction monopile facility with monopile storage yard in Paulsboro NJ, Portsmouth may find its area more valuable for marshaling, and thus may expand to the full 101 ac (41 ha) in the future.
[e] DE Phase 1 assumes purchase or lease of Oxychem property plus Dredge Spoils Management Area 1 (DMSA 1) and the vacant area west of DMSA1. Both phases labelled "conceptual" because no commercial development is now planned.
[f] DE Phase 2 would require purchase or lease of DMSA2, DMSA3A and DMSA3B and bordering, unused area. (House et al. (2020), Table 1, page 40).
[g] While various sections of the Cuxhaven Port are in use by shipping companies, some of which are not OSW-related, we attribute the majority of the total area to possible laydown area as it can be re-purposed for this use. We solely exclude a storage yard now leased as storage for Siemens-Gamesa blade manufacturing, and thus not as easily re-purposed. (Source: AFW-Cuxhaven, German Offshore-Industry-Centre (DOIZ), https://en.offshore-basis.de/infrastructure/terminals-and-berths).

generation.[12]

Demand from state and private interests will also begin to yield projects in other US coastal regions, requiring additional US port area outside the present analysis. As we write, US existing contracts and state requirements only on the East Coast, per Table 3. Because of ramp-up time required, projects built through 2025 are likely to only be in that region. But substantial OSW resources do exist in the Gulf of Mexico, the West Coast, and the Great Lakes, and the US Department of the Interior has already begun the Wind Energy Area designation process for both the West Coast and the Gulf as of 2021.

Port considerations vary somewhat by region. In the Gulf, there are many large existing laydown areas with high load-bearing capacities already built to construct and ship out offshore oil and gas platforms. By contrast, the West Coast will have to find and build areas for large marshaling ports with air draft, as well as incorporate the floating platform requirements shown in Table 2. Thus, the post-2025 ramp-up of OSW generation and corresponding port area demand will presumably include Gulf, West Coast, and Great Lakes as well. We do not here project the relative distribution of OSW project and port construction by region.

4.2. Projected demand: federal targets of 30 GW by 2030 and 110 GW by 2050

Given the likelihood of increased demand beyond current state commitments analyzed previously, as a second metric we here project future demand based on federal OSW targets. On March 29, 2021, the White House and four US Cabinet Departments—Interior, Energy, Commerce, and Transportation—announced OSW targets, calling for 30 GW to be built by 2030, and 110 GW by 2050 (The White House, 2021). This joint announcement included several executive agency missions to support the new OSW targets, including expanding available lease areas on the outer-continental shelf, and completing the review of at least 16 Construction and Operations Plans (amounting to 19 GW worth of OSW projects) by 2025. This multi-agency action to catalyze an expansion of OSW generation demonstrates a shift in Administrative agenda throughout the federal government, newly-oriented towards ameliorating regulatory roadblocks and expediting deployment. Such a shift is a positive market signal to private interests and OSW developers. It also lends a higher level of confidence in our annual state-driven demand projections, as project plans currently and soon to be under review are unlikely to undergo the same delays imposed during 2017–2020.

We will henceforth refer to the two sequenced federal targets (30 GW by 2030 and 110 GW by 2050) as projected demand, and use as an example of how state and private demand will likely grow after today's short-term commitments. These are national targets, potentially expanding the geographical range of OSW projects and of supporting infrastructure. These targets also imply a higher projected demand for OSW-related infrastructure (including marshaling ports, vessels, and manufacturing). Neither the state or federal targets are a ceiling; total demand will be driven by some combination of technology development, lower costs, private investment, social dynamics (stakeholder acceptance, climate advocacy, political agendas, etc.), and various policy mechanisms (new OSW commitments, investment tax credits, carbon taxes, etc.).

To quantify projected demand, we extrapolate the yearly builds (in MWs) required to meet the federal targets. First, we regard the first five years of firm (state) demand (2020–2024) as contributing to the federal goal. Recall that the first years have been derived from awarded (not extrapolated) project sizes and construction timelines. During this near-term period, there is no need to distinguish state from federal MWs to measure demand for marshaling area, as the only market driver for OSW projects are contracts to buy power—which, in the case of OSW, are primarily driven by state power generation policy. Post-2025, our "projected demand" is a linear increase to 2030, then a constant build rate, both lines projected in order to meet the federal cumulative targets (30 GW by 2030 and 110 GW by 2050).

Based on the state and federal commitments, we next evaluate sufficiency of existing and planned infrastructure, particularly that of

[12] Dominion Energy has demonstrated this additional utility-driven market demand, as they released a solicitation for 2 GW of OSW generation before the Commonwealth of Virginia established an OSW target.

Table 5
Firm and projected demand for construction of OSW in MW/year, based on state and federal policies, compared with port supply. For each MW figure in columns 2 and 4, the corresponding port area requirement is shown in the next column in acres. Port supply is in column 6, and the projected shortfall between supply and projected demand is in column 7. Column 8 shows the ports available each year (taken from Table 4). The lowermost two rows show the total MWs for firm and projected demand from 2020 through 2040, and the total acre-years (ac-yrs) over the same time period. Data is as of October 2021.

	Firm Demand		Projected Demand		Planned Port Supply		
Year	Deployment Demand (MW)	Area Demand (ac)	Deployment Demand (MW)	Area Demand (ac)	Area Supply (ac)	Projected Shortfall (ac)	Planned Port Sequence[a]
2020	12	1.3	12	1.3	29	28	MA1
2021	0	0	0	0	29	29	MA1
2022	125	13.5	125	13.5	64	51	MA1; CT
2023	2637	285	2637	285	94	−191	MA1+2; CT; NJ1
2024	3024	327	3024	327	114	−213	MA1+2; CT; NJ1; VA
2025	2825	305	3361	363	186	−177	MA1+2; CT; NJ1+2; VA
2026	6292	680	3697	399	219	−180	MA1+2; CT; NJ1+2; VA
2027	3162	342	4034	436	219	−217	MA1+2; CT; NJ1+2; VA
2028	2980	322	4370	472	219	−253	MA1+2; CT; NJ1+2; VA
2029	2735	295	4707	508	219	−289	MA1+2; CT; NJ1+2; VA
2030	2560	276	5043	545	219	−326	MA1+2; CT; NJ1+2; VA
2031	2530	273	5043	545	219	−326	MA1+2; CT; NJ1+2; VA
2032	2565	276	5043	545	219	−326	MA1+2; CT; NJ1+2; VA
2033	2142	231	5043	545	219	−326	MA1+2; CT; NJ1+2; VA
2034	2141	231	5043	545	219	−326	MA1+2; CT; NJ1+2; VA
2035	1552	168	5043	545	219	−326	MA1+2; CT; NJ1+2; VA
2036	520	56	5043	545	219	−326	MA1+2; CT; NJ1+2; VA
2037	520	56	5043	545	219	−326	MA1+2; CT; NJ1+2; VA
2038	520	56	5043	545	219	−326	MA1+2; CT; NJ1+2; VA
2039	520	56	5043	545	219	−326	MA1+2; CT; NJ1+2; VA
2040	520	56	5043	545	219	−326	MA1+2; CT; NJ1+2; VA
Total (MW)	39 880		81 444				
Total (ac-yr)		4307		8796	3801	−4995	

[a] The port sequence column uses codes from Table 4. Both Massachusetts and New Jersey have two phases of port area availability. When only the first phase is available, the code is MA1 and NJ1. When both phases are available, the codes are MA1+2 and NJ1+2.

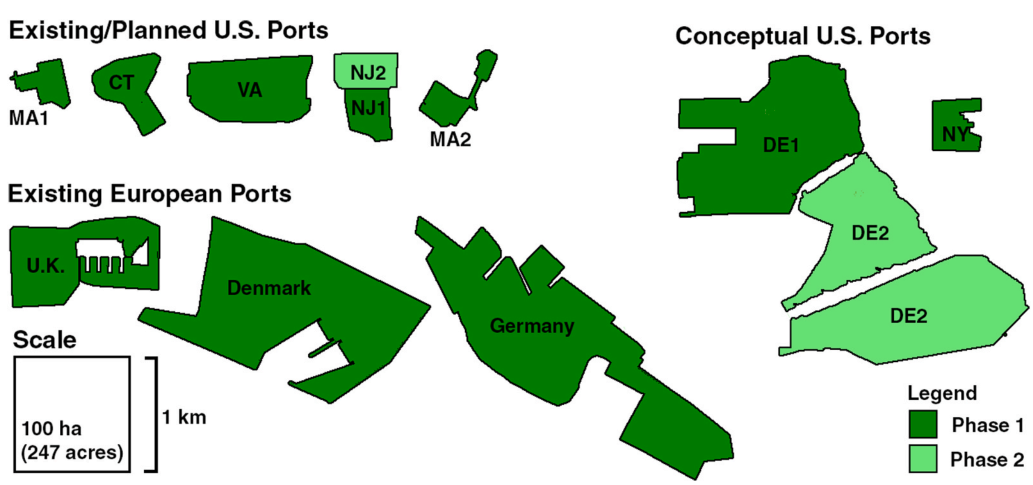

Fig. 2. Relative sizes of the available laydown areas of US marshaling ports (existing, planned, and conceptual) and in-operation European ports in Table 4. Hull in the United Kingdom, Cuxhaven in Germany, and Esbjerg in Denmark are the most heavily-used European marshaling ports. The lighter shade represents potential expansion or Phase 2 developments.

marshaling ports, as related to supporting OSW deployment demand.

5. US marshaling port capacity

Table 4 shows existing and potential US marshaling ports meeting criteria of Table 2. All are along the East Coast and near project commitments, due to early engagement in the OSW industry from East Coast States. The US has just one already built and available marshaling port (New Bedford), three planned and announced ports (New London, Portsmouth, and the New Jersey Wind Port which will be constructed in two phases), and two detailed studies of potential marshaling ports, not certain enough for us to label "planned" (House et al., 2020; Davis and Dougherty, 2019). The latter two are located in New York and Delaware, and are both labelled "conceptual". Three operating European marshaling ports are included for comparison. Ports listed in Table 4 meet the air draft and other criteria of Table 2, excepting minimum laydown area.

Table 4 shows marshaling ports by name; the US ports' "Code" column shows the two-letter code used subsequently in figures and tables. The fourth column gives each port's total area dedicated to offshore wind and its laydown area (a port with a laydown area smaller than its total wind area has dedicated some area to wind manufacturing, thus not available for laydown). The second from rightmost column converts the laydown area into MW capacity of the project (assuming 12–14 MW turbines and 54 ac (22 ha) to deploy a 1 GW project over 18 months, per Section 2). The rightmost column of Table 4 is the year of availability provided by port planning documentation..[13] The last two columns will be integrated into the analysis in the following section comparing market demand for marshaling area with port area supply.

Fig. 2 illustrates relative sizes of each port, both US and European, by showing each to scale in outline form. The existing and planned US ports are substantially smaller than their European counterparts, due to several factors: limited port area without overhead obstructions, pressure on OSW project developers to show local economic development, contracts requiring electricity delivery on schedule, and looming expiration of tax credits (US marshaling port constraints discussed in detail in Section 3). This combination has resulted in decisions to build on land that is local and available, rather than planning larger, more cost-effective, and adaptable ports that a port authority or port developer would invest in. This seeming inefficiency makes some sense with reference to Table 1; given that the wind project is a $2700M investment, if a port is essential, adding, say, $150M for a small port adds 6% to the project's capital cost, raising electric costs slightly in exchange for gaining port certainty for the developer plus an economic benefit for the state.

Despite these current US motivations, an offshore wind developer arguably is a suboptimal party to develop a marshaling port, and they have not done so in Europe. The project developer has a shorter time perspective and different investment priorities—again leading to building of smaller ports, and ports only adapted to today's deployment methods and turbine sizes. Private port operation businesses or port authorities, with 30-year time horizons, might prove to be better owner-operators of marshaling ports.

To serve the existing and near-term projects during the 2020–2024 timeline, only MA1, CT, and NJ1—with a combined area of 94 ac (38 ha)—will be available as marshaling ports by 2024 (MA2 likely will not be available until late 2024). This translates to a maximum OSW deployment capacity of approximately 0.9 GW per year on the East Coast. Post-2024, MA2, NJ2, and VA will bring the total available area to 228 ac (92 ha), and the max deployment capacity to about 2 GW annually.

Our primary calculation of port demand is based on area per GW as calculated above (and graphed in the next section). As a quick comparison, we compare with European GW and port areas. All current plus planned US marshaling ports are less than 1/3 of the area and thus less than 1/3 of the deployment capacity of the three most-used marshaling ports in Europe. Esbjerg, Hull, and Cuxhaven have a total combined area of 792 ac, (321 ha); if fully used, we calculate that those three European marshaling ports could deploy 7.3 GW annually. Yet, the 2020 OSW build in Northern Europe was a total of 2.9 GW, with an average turbine size of 8 MW (Ramirez et al., 2021). The seemingly oversized total European marshaling area makes sense for several reasons: our calculated port capacity does not account for some ports being more appropriate for closer OSW projects, some years having more or fewer projects to build, the inclusion of some manufacturing storage areas in our measured laydown areas, and the port space reported as available for OSW sometimes being alternated with other maritime trade and construction purposes.

To us, the higher capacity in Europe marshaling ports suggests caution to planners that the needed US port capacity areas that we derive in the next section should be considered minimum requirements. Our port area calculations only assume topside OSW components, and do not account for other project components that could require marshaling for US projects (e.g. monopiles, cables, substations, etc.). While it may be argued that these components do not have overhead clearance requirements and therefore can be marshaled upriver, research shows that mitigating OSW logistical complications and consequent higher electricity costs depends on fewer vessel trips, fewer splits in the supply chain, and decreased distance from manufacturing to the installation site (Poulsen and Lema, 2017; Sarker and Faiz, 2017).

In the following section we quantitatively evaluate the sufficiency of these existing, planned, and conceptual US ports in meeting firm and projected demand for port area, using the two policy metrics—state commitments and the federal target.

[13] We do not include planned offshore wind ports such as Bridgeport and the South Brooklyn Marine Terminal—although both will be helpful for some assembly and storage, they lack the criteria of Table 2 and thus cannot marshal a full project, cannot build or ship out upright towers nor fully-assembled turbines, and cannot berth installation vessels with tall spuds (legs).

6. Analysis of port capacity to meet deployment demand

We have reviewed the infrastructure required to support evolving OSW technology, identified US marshaling ports to be a significant challenge and necessary for the US market, calculated marshaling demand from state and federal targets from 2020 through 2040, and reviewed the planned supply of marshaling port area in the US during the same time period. Now, we can analyze whether planned and existing marshaling area supply will be sufficient to meet deployment demand.

6.1. Projecting growth through 2040 and beyond

In this section, we examine the results of analysis of both the firm state demand and the projected increase and continuation of demand inferred from the federal goal. Table 5 demonstrates the results of these tabulations, as well as the corresponding marshaling area needed each year to support demand. Based on Table 3, the results of our state-driven annual deployment demand results and corresponding port areas required to meet state commitments (detailed in Section 4.1) are shown in the second and third columns of Table 5. Results of the projection beyond state-driven demand (detailed in Section 4.2) are shown in the fourth and fifth columns of Table 5.

Port acreage and marshaling demand are calculated based on the same technical specifications and construction timeline assumptions used to project the port marshaling capacities laid out in Table 4. But instead of examining planned port capacity, Table 5 shows the results of how many MWs require marshaling as a result of state and federal policies, and answers the following question: how much marshaling area is required to enable the deployment of those MWs?

According to firm demand projections, current state demand reaches its peak in 2026, requiring a marshaling capacity of 6.3 GW, and a corresponding port area of 680 ac. However, what appears now as a "peak demand" for infrastructure also reflects that, as we write this paper, we see only procurements through 2021, most state policy target years currently stop at 2035, and the time from procurement to build is about 5–6 years. Thus 2026 represents a peak in demand only if no further procurements are done beyond current commitments, and no states add to their commitments—so state "firm" demand is likely a low-bound projection. North Carolina, for instance, is an outlier among state targets as it is the only state with a policy target year beyond 2035 (it is 2040), causing the deployment and area demand to seemingly drop from 1.6 in 2035 to 0.5 GW in 2036. Given these trends, we expect new state policies to continue to contribute to demand in the years after 2035. This gives a visual sense of why we use the federal goal as an alternative projection for OSW deployment and marshaling area demand beyond the state commitments.

Firm and projected deployment demand in GW/yr are graphically shown in Fig. 3, where the blue bars represent the projected deployment demand and the orange bars represent firm deployment demand (in GW/yr) based on the assumptions integrated into Table 5. We model 2020–2024 deployment as being solely derived from existing state awards and contracts (presumably most marshaling up to 2024 will be by work-around methods such as feeder barges and deployment out of Canadian ports). Any new state-run solicitations after October 2021 will likely carry power-on dates later than 2025. Given the cumulative capacity of state-derived demand from 2020 to 2024 (6 GW) and port capacity construction parameters, we make a simple projection of a linear increase from state-driven demand in 2024 (3 GW) to a peak port marshaling capacity of 5 GW/year starting in 2030. This linear annual increase in demand demonstrates the OSW marshaling rate necessary to reach a cumulative OSW deployment of 30 GW by 2030. Of course, manufacturing, vessel, and other infrastructure would need to grow correspondingly.

From 2030 onward, we assume a flat rate in demand for project builds at 5 GW/yr (meaning that OSW-related infrastructure continues to manufacture, marshal and deploy at the same annual capacity as achieved in 2030). Therefore, Fig. 3 shows for the remaining 20 years (2030–2050) an annual demand for 5 GW/year of marshaling capacity, that is, 545 ac of port space must continue to be used to deploy projects each year. Based on the 5 GW/year project construction rate, the second federal target of 110 GW is achieved by 2046, four years sooner than the announced federal target year (2050). The cumulative growth of OSW deployment necessary to meet the federal goal is graphically shown in 3 by the black dashed line connecting the black dots for federal generation targets.

To illustrate the relationship between marshaling port supply and port demand, Fig. 4 graphically compares three trends, from 2020 to 2040, all measured in area and derived from Table 5: 1) the existing and planned port areas each year, in green, 2) the port area required to meet firm state demand (orange), and 3) our projected additional port area to be required, based on the federal goal (blue). When interpreting Fig. 4 it is important to remember that the "firm demand" (orange dashed line) is based on the policies and contracts enacted as of October 2021 and is thus a low-bound estimate as discussed above. But whether we consider demand to be driven by state policies, lower OSW electric prices, or the federal goal, our model nevertheless shows, in Table 5, and Figs. 3 and 4, a steady increase in demand for new port area to match the project build demand curves.

The delta between the port supply and either the firm or projected demand in Fig. 4 is the amount of additional marshaling port area needed in each year (projected shortfall is tabulated in the seventh column of Table 5). In Fig. 5, we examine port area supply versus demand through a new metric: marshaling port acre-years. The acre-years metric allows us to consider the marshaling sufficiency problem within the context of stock and flow based on: 1) port area needed—shown in the last row of Table 5—to meet OSW marshaling demand by 2040, i.e. the latest state commitment target year; and 2) the built and planned port area supply, also shown in Table 5.

Fig. 5 can be interpreted as a visual representation of the total marshaling area stock needed over the course of the target time period (2020–2040) given the inflow rate of ac/year demand. This rate yields the total stock of marshaling area development needed at the end of the period in question, which is shown as the lower bar of Fig. 5. The orange represents the firm stock of area needed by 2040, while the blue represents the additional stock of projected area needed beyond state demand (this corresponds with the sum of Table 5 acre-year totals in the third and fifth columns). Conversely, the upper bar reflects the marshaling area that is currently expected to exist during this period. As shown, the supply in green is already insufficient to meet firm demand alone given each port's years of availability. Only after the conceptual NY, DE1, and DE2 ports are added to the acre-year supply does the port area supply meet total demand. However, an important caveat to this hypothetical supply expansion (and the use of acre-years) is that the conceptual ports must be built soon to be sufficient, with assumed new port availability starting in 2025, 2026, and 2030, respectively.

7. Discussion

A key takeaway from the stock and flow problem represented in Fig. 5 is the relationship between years of availability and the supply flow rate. Earlier expansion of marshaling area increases the total flow more than later expansion. The later the investment, the later the construction and availability, meaning a lower flow rate and a consequently insufficient port area over time (acre-years). This is perfectly exemplified by the addition of the NY and DE ports in Fig. 5. To express this relationship in one sentence: Achieving the state or federal OSW deployment targets requires investing in the expansion of marshaling port area sooner rather than later, so that the area is available over more years up through policy target dates and beyond.

Another key clarification of Fig. 5 is that, although supply only just meets demand when all listed ports are included, recall that the market and planning are more advanced on the East Coast and potential port locations in other regions have not been evaluated. We noted that the

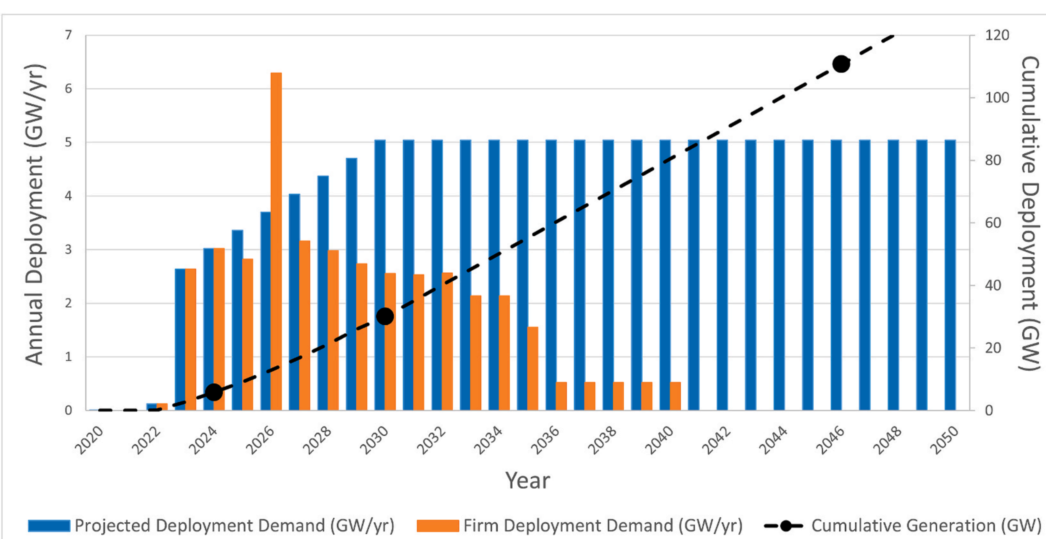

Fig. 3. Projected and firm OSW deployment demand from 2020 to 2050 based on the federal goal and state commitments from Table 5. Blue bars show projected GW/year deployment demand (seen as darker bars on grayscale media), orange (lighter) bars show firm GW/year demand. The left scale is annual demand (bars), and the right scale is cumulative OSW built by that year, graphed by the black dots and black dashed line. The first black dot shows cumulative generation capacity deployed by 2024 based on state-driven demand (5.8 GW). The middle and rightmost black dots show when federal targets (30 GW and 110 GW) are achieved (2030 and 2046, respectively). The dashed line connects the black dots by a polynomial curve fit. Demand data is as of October 2021.

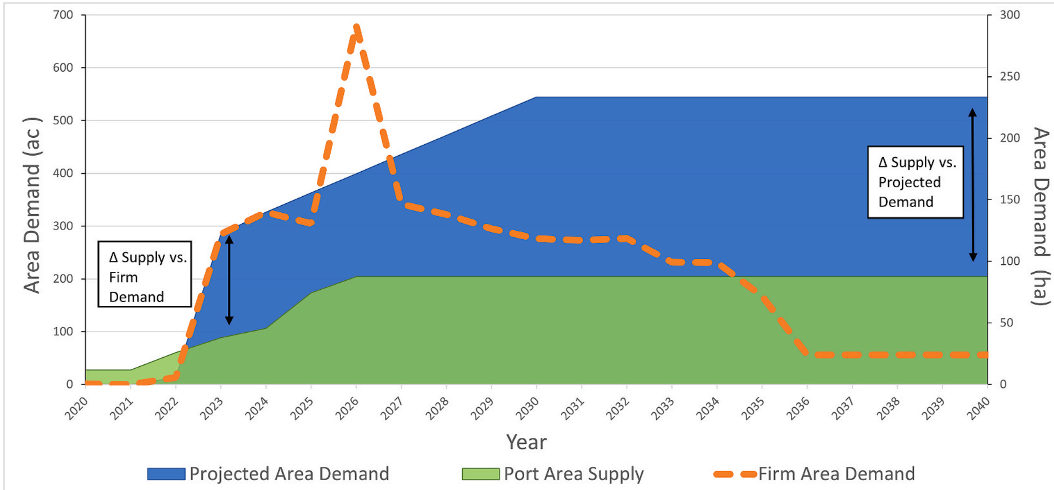

Fig. 4. Existing plus planned supply of port area (solid green/light grey) versus firm demand generated by state OSW commitments (orange dotted line) and projected port demand informed by federal targets (solid blue/dark grey + solid green), from 2020 through 2040. Firm area demand, projected area demand, and port area supply are derived from columns 3, 5, and 6, respectively, in Table 5. Demand and supply data is as of October 2021.

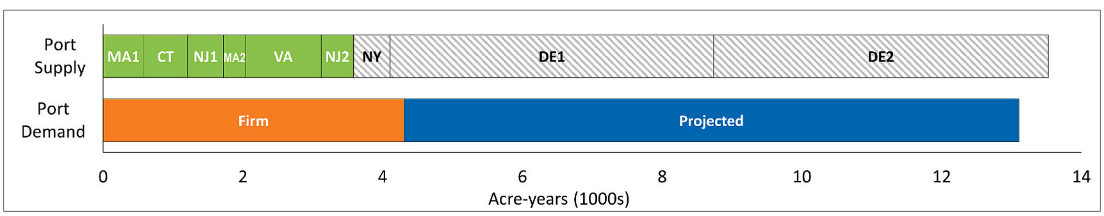

Fig. 5. Port demand and supply in acre-years (ac-yrs) from 2020 to 2040. Acre-years are the area of each port multiplied by the number of years the port is available from 2020 through 2040. The upper bar (green) shows existing (New Bedford, MA) and planned port supply (New London, CT; Salem, MA; New Jersey Phases 1 and 2; and Portsmouth, VA). Conceptual port supply are in grey hatch (Arthur Kill, NY and Delaware Phases 1 and 2). Total demand is in the lower bar, with orange for firm demand, and blue for projected demand through 2040, like prior figures. Demand and supply data are as of October 2021. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web or PDF version of this article.)

Gulf of Mexico is prime for port area expansion. Thus Figs. 4 and 5 show that the claim cited in Section 3—that there are no suitable sites for marshaling ports in the US–is clearly incorrect. Suitable sites are indeed scarce, but there can be sufficient sites if we search by suitability rather than by linking to the next power contract.

We have answered the question of how much marshaling port area is needed to meet firm and projected demand, and when the area will be needed. As for the sufficiency of existing and planned port area, in the very near term (2021–2022) the available port supply is sufficient to support the marshaling demand derived from state policy commitments. Annual demand during these years does not exceed 125 MW, and thus only relies on a max area of about 14 ac. Following 2022, however, there is an immediate port area shortfall. From 2023 to 2035, state procurement demand far exceeds our measured marshaling port supply.

This does not mean that wind project deployment will not occur in the near-term. The alternatives to traditional marshaling methods discussed in Section 3.1 will be used, but with disadvantages. When port area or vessels are insufficient, feeder barges, non-US installation vessels, and small or non-US ports will be used to insure that projects are built to meet contracts. But these methods are suboptimal in cost, construction time required, delivery risk, and hazard at sea. The non-US marshaling port method obviously requires more steaming time for the expensive installation vessel. The feeder barge approach requires barge transport and off-loading in the ocean, with more transfers, more time and handling, risk of delays,[14] and risk of handling accidents. Both suboptimal ports and feeder barge methods increase time and cost in project construction. For example, Lautec estimates that a full offshore turbine (foundation and topside) can be installed in 32 h with an installation vessel, versus 50 h for feeder barge system (Lautec ESOX model, https://esox.lautec.com.).

The final disadvantage of these alternative, work-around approaches is perhaps most important in the medium and long-term. Opportunities for improved methods exist with more assembly in port and simpler installation vessels, made possible by large ports and turbine support structures designed for in-port assembly and upright transport (Kempton et al., 2017). The same port specifications for more in-port assembly will also allow floating deployment. Finally, although developers currently plan two construction seasons for US projects of approximately 800 MW, a larger port plus a robust component supply chain could allow one-season builds, with considerable reduction in cost.[15] These factors and opportunities explain the industry's mid- to long-term preference for large marshaling ports meeting the characteristics in Table 2. As adequately-sized marshaling ports lower cost and speed deployment,

[14] The loadout and installation phases pose the most risk of constructions delays (Barlow et al., 2015), and these operations are more difficult at sea with feeder barges with more transfers.

[15] Europe has achieved 1-season builds since 2009–2010 via larger marshaling ports, a strong supply chain, and the use of two installation vessels to install projects with turbine counts similar to US projects, albeit mostly with smaller turbines.

they thus contribute to meeting climate and decarbonization goals and are therefore a key factor in meeting stated federal and state policy objectives.

8. Conclusion and policy implications

Transitioning energy systems away from fossil fuel generation is fundamentally necessary to mitigate climate change, and OSW technology is a key contributor to that effort. Policies designed to reduce fossil-fuel emissions by setting OSW generation capacity targets have been increasing in size and number by US coastal states and now by the US Federal Government. Achieving these targets as scheduled will require a rapid and early build-out of a robust supply chain and infrastructure, including manufacturing of components, installation vessels, and several types of ports.

We find a marshaling port area shortage that will limit the future of the US OSW industry, impeding efficient and cost-effective OSW project deployment, delaying construction schedules, and constraining logistics. Marshaling ports are difficult to site due to their demanding specifications, and states have thus far depended mostly on re-working existing ports that are much smaller than recommended (Table 2), are located within their borders, and create local jobs. Other larger sites exist, but are either not built for OSW projects, have current high-value uses, or are undeveloped land requiring investment to make them a port, and one suitable for marshaling OSW.

We have analyzed requirements for modern OSW turbines (12 MW - 14MW), and today's cost-effective project size (about 1 GW), thereby finding that each such project requires an area conservatively of at least 54 acres (22 ha) over two years. This is conservative in that even larger marshaling ports are preferred—like those in Europe—for the purposes of streamlined supply chains, reduced vessel time, less logistical complexity, and corresponding cost minimization. Larger ports will allow for multiple projects at the same time, larger quay area and access, on-site manufacturing, one-season project builds, alternating OSW with other port uses, and the marshaling of other components beyond the topsides. They also enable future technologies including larger turbines, more in-port assembly, and floating wind power. We show that it is likely more economical and conducive to technology development to build marshaling ports meeting the requirements of Table 2, rather than the current siting of small marshaling ports within each state that contracts for OSW power.

Based on our assessment of port area, our calculations show that the supply of US marshaling port infrastructure will be insufficient for firm state demand by 2023 and far short of that needed for projected demand through 2050. We find that existing OSW demand, projected OSW growth, and the development of a sustainable domestic industry and supply chain will depend on early action of government, port authorities and/or port investors to plan and develop suitable marshaling ports.

Glossary

- ac - Acre, an area measure equivalent to 4,046.9 m^2 or 0.405 ha.
- beam - The width of a ship at its widest point.
- break-bulk - Cargo consisting of large pieces moved as wholes, for example components of a wind turbine or other large machinery. Contrasted with containerized freight or bulk cargo such as grain or salt.
- capacity factor - The ratio of average power production (of a wind project or any other generator) divided by the maximum power rating.
- draft - Distance from a vessel's waterline down to its keel. Air draft is the distance from its waterline up to its highest point.
- GW or Gigawatt - 1,000 MW (MW), or one billion Watts. The approximate size of a modern offshore wind project as bid today in the United States.
- ha - Hectare, a metric area measure equal to 10,000 m^2 or 2.47 acres.
- jack-up vessel - A marine heavy construction vessel with legs or "spuds" that can be jacked downward, thus lifting the hull out of the water and creating a stable, seafloor-supported, base for loading from port or construction at sea. Offshore wind installation vessels are usually jack-up vessels. In the US petroleum industry, a jack-up vessel is called a liftboat.
- knot - A navigational unit of speed equal to imperial 1.1508 mi/h or metric 0.5144 m/s.
- marshaling port or marshaling harbor - A port built for offshore wind turbine parts to be collected, then when enough of each part are ready, loaded onto an installation vessel and taken out to be assembled in the ocean. See jack-up vessel.
- MW or Megawatt - 1,000,000 W, a unit measuring the maximum power produced by a wind turbine at its full design wind speed.
- monopile - A large steel pipe driven into the ocean bottom, to which a wind turbine tower is attached, thus supporting the entire turbine.
- OEM - Original Equipment Manufacturer, in this industry, the company that designs and manufacturers a particular brand of offshore wind turbine.
- Offtake agreement - A power purchase agreement or other legally-binding agreement to buy power from a generator such as an offshore wind project.
- OSW - Offshore Wind power.
- Port authority - A governmental or quasi-governmental public authority, created by one or more states, to finance, build and operate ports and other transportation infrastructure in their region.
- SPMT - Self-Propelled Modular Transporter, a tractor-trailer sized flat bed that can be linked in assemblies to make a very high load-bearing transporter, with high maneuverability.
- quay - A port's loading and unloading area adjacent to the ship channel. Pronounced/ki:/.
- tonne - Metric ton, equal to 1,000 kg, or 2,205 pounds.

CRediT authorship contribution statement

Sara B. Parkison: Conceptualization, Methodology, Investigation, Formal analysis, Visualization, Writing – original draft. **Willett Kempton:** Conceptualization, Methodology, Writing – original draft, Investigation, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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