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Brief Report

The seafloor footprint of offshore wind infrastructure in the United States Ocean

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Abstract
Increasing numbers of wind turbines are installed in the ocean, yet the total physical area or "footprint" of these structures remains unknown. We projected turbine footprints for U.S. ocean wind energy areas leased as of 2024. Calculations revealed turbines may occupy seafloor (18.20 km^2; turbine foundations plus scour protection area) and water column (6.33 km^2; vertical surface area underwater) footprints of similar magnitude to U.S. artificial reefs installed from 1899 to 2020.

Keywords Built marine structures · Marine infrastructure · Marine urbanization · Ocean sprawl · Seascape ecology

1 Main text

Numbers of built structures are increasing in the world's oceans [1, 10]. Due to an unpredictable global energy market and efforts to harness alternative energy [3, 8], one source of new marine built structures is offshore wind (OSW) development, whose pace and scale is increasing globally[7] Multiple types of structures are installed during OSW development. These include not only turbine foundations but also aprons of rock or artificial material placed around foundations to protect against scour. A previous global analysis found that the footprint of OSW infrastructure was 0.76 km^2 in 2018 and expected to reach 3.10 km^2 by 2028 [1]; at the time, the U.S. had installed little OSW infrastructure. Since then, the OSW industry in the U.S. has gained momentum (and faced recent headwinds), yet the physical area or "footprint" of OSW infrastructure currently and expected to be installed in U.S. ocean waters remains unknown. Here, we calculate the footprint of OSW infrastructure – turbines and their scour protection – for U.S. wind energy leases issued as of 2024 under a maximum buildout scenario. We recognize that this scenario may not come to fruition given external drivers in the U.S.; nonetheless, the footprint estimates provide information on the existing and potential extent of offshore wind infrastructure, which will be valuable figures as society grapples with balancing societal and ecological priorities.

Calculations of OSW footprint revealed that turbine foundations and associated scour protection within leased areas may cover 18.20 km^2 of the U.S. seafloor (Fig. 1; Table S1; Table S2). This value is based on publicly available construction plans, timelines, and specifications for existing and planned wind farms within 44 OSW leases (Fig. 1A-F; Table S1). Some construction plans provided full specifications from which a "measured" OSW structure footprint was calculated,

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whereas others lacked information and required calculation of an "estimated" footprint using a data-driven approach. This analysis assumed monopile style foundations for all existing leases; we also describe how the footprint changes with other foundation types (Text S1).

Our investigation highlighted that the projected seafloor footprint of turbine foundations (0.53 km^2 total; 0.28 km^2 measured; 0.25 km^2 estimated; Fig. 1G) is multiple orders of magnitude smaller than the footprint of scour protection (17.67 km^2 total; 9.86 km^2 measured; 7.81 km^2 estimated; Fig. 1H). Footprints of turbine foundation and scour protection both varied regionally, with the Mid-Atlantic and New England exceeding the Southeast, Gulf of America, and Pacific (Fig. 1G-H; Table S2). The water column footprint of OSW turbines is expected to be 6.33 km^2 (3.32 km^2 measured; 3.01 km^2 estimated; Fig. 1I) and also varied regionally (Fig. 1I; Table S1). OSW structures are already installed or are sited for installation across portions of the ocean with federal or state OSW development leases (Fig. 1A-F; Table S1). The 44 leases as of September 2024 cover a combined seafloor area of 12,865 km^2 (Fig. 1J; Table S2), indicating that 0.14% of the total leased seafloor area may be covered by turbine infrastructure under this buildout scenario.

To place the OSW footprint into context, we compared it to published calculations of the seafloor footprint of another major type of built ocean structure – artificial reefs. We made this comparison because the footprint of artificial reefs in the U.S. was previously quantified [10], and we wanted to understand whether the maximum buildout scenario of OSW would result in a footprint of similar magnitude to that of existing artificial reefs. Moreover, artificial reefs are the only type of open-ocean built structure that occurs in every region of the U.S. Since OSW infrastructure may soon also occur in all regions of the U.S. ocean, a comparison to artificial reefs is both warranted and may be useful for marine spatial planners, ecologists, and other ocean constituents. The artificial reef footprint (including "reefed" oil and gas infrastructure) in the U.S. ocean was estimated to be 19.23 km^2 as of 2020 [10], which is slightly more than the estimated 18.20 km^2 OSW seafloor footprint. The calculated OSW footprint eclipses that of artificial reefs in New England and the Mid-Atlantic, whereas the reverse occurs in the Gulf of America (Fig. 1K,Table S3), due in part to regional policy differences and to the "rigs-to-reefs" program in the Gulf [5]. In the Pacific and Southeast, calculated OSW and artificial reef footprints are similar. When we compared the leased area for OSW development to the area zoned (i.e., permitted) for artificial reefs in the U.S., we discovered that the area leased for OSW (12,865 km^2) is over twice as large as artificial reefs zones (5,811 km^2,[10]) and varied regionally (Figure S1).

Our findings highlight the rapid pace and expansive scale of artificial structure installation that may come with an OSW buildout in existing U.S. leases, especially when compared to artificial reefs. The first U.S. OSW farms were installed less than a decade ago. Most projects included here are scheduled for completion by or in the 2030s, so these OSW footprint estimates could be realized over the course of *one to two decades* if development proceeds on that timeline. In contrast, the U.S. artificial reef footprint was achieved over *more than a century* [10],1899–2020 analysis). Given our finding that, under a buildout of existing leases, the physical OSW footprint may soon be on par with or eclipse that of artificial reefs, *cumulative* ecological effects of OSW may be as substantial as those of artificial reefs.

Adding OSW infrastructure to the ocean presents potential benefits and risks for marine life and ecosystems [9]. Wind turbines can generate "artificial reef effects," often enhancing or modifying habitat for marine species [2], but can alter hydrodynamic patterns, generate electromagnetic fields and noise, and facilitate invasive species spread [11]. These effects – some of which may be mitigated – can vary during different stages of OSW development (e.g., construction, operation, decommissioning; [11]). Ecosystem effects of OSW may also vary among different turbine types (e.g., monopile, jacket, spar) and can be distinct from effects of other artificial structures, such as artificial reefs, oil and gas infrastructure, and shipwrecks [6]. Future research could explore how to maximize ecological benefits and minimize ecological risks of OSW infrastructure through incorporating nature-inspired designs and optimizing spatial siting. Additional work is also needed to clarify the expected remaining footprint (and ecological effects) of OSW infrastructure under multiple decommissioning scenarios [4]. Finally, given that OSW development may result in an influx of infrastructure into U.S. ocean waters, there is a need a to track the OSW footprint as it grows and to further resolve scientific uncertainty by better understanding associated cumulative ecosystem impacts.

2 Methods

We identified 44 OSW leases (Table S1) using publicly available records from the Bureau of Ocean Energy Management (BOEM) (https://www.boem.gov/renewable-energy/mapping-and-data/renewable-energy-gis-data) and state records as of 1 September 2024. Call areas or wind energy areas (WEAs) were excluded; research leases were included. For each lease, we located the Construction and Operations Plan (COP) if public. Some COPs provided specifications

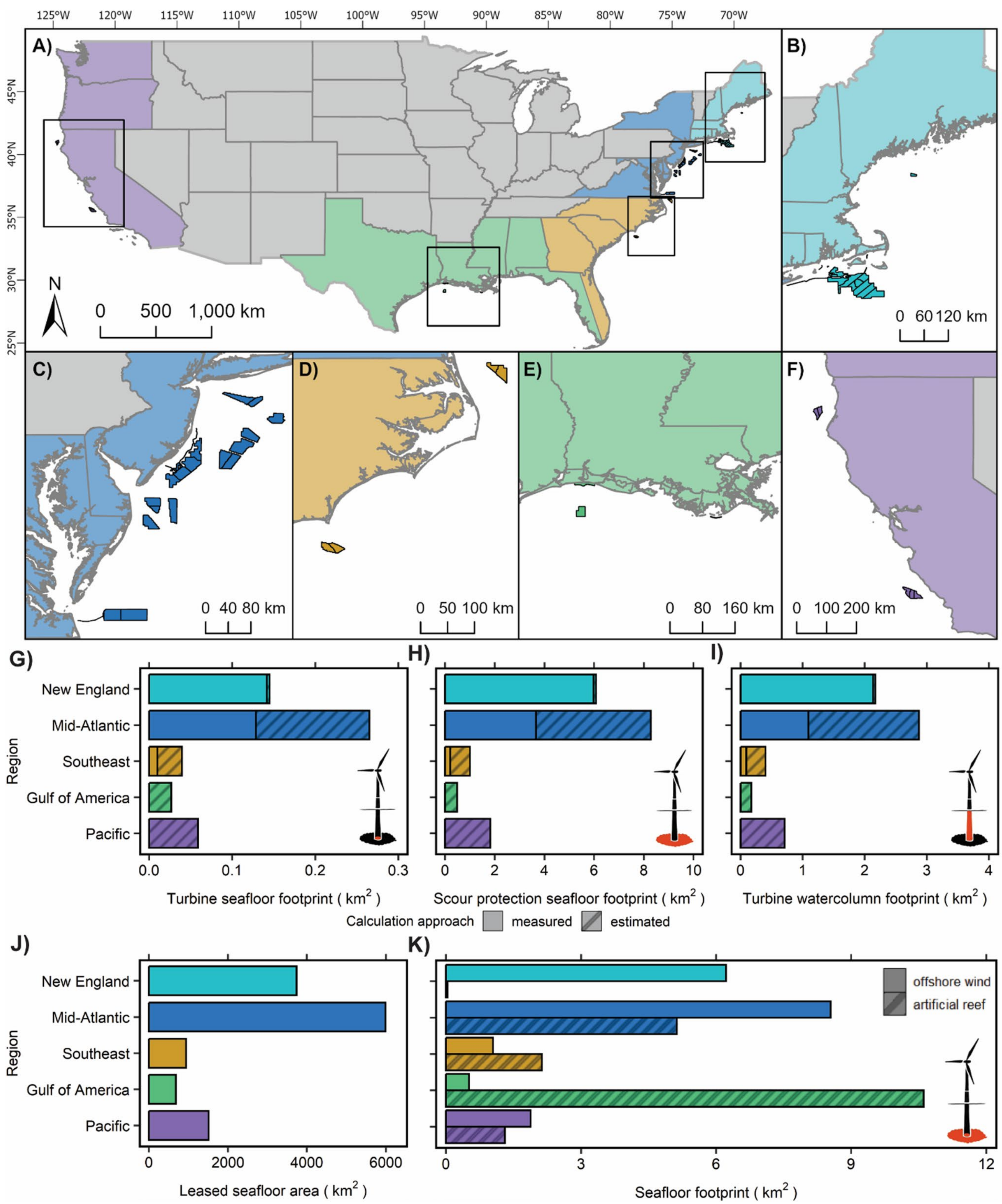

Fig. 1 Locations of offshore wind (OSW) energy leases (dark polygons) in **A**) the US and by region: **B**) Northeast, **C**) Mid-Atlantic, **D**) Southeast, **E**) Gulf of America, and **F**) Pacific. Footprint (km^2) of OSW infrastructure for: **G**) seafloor area covered by turbines, **H**) seafloor area covered by scour protection, and **I**) water column surface area of turbines by geographic region. Shading in G-I indicates the footprint calculation approach (measured = solid, estimated = hashed). **J**) Leased seafloor area for OSW development by region. **K**) Comparison between seafloor footprint (km^2) of OSW infrastructure, including both the turbine and scour protection, versus artificial reef structures [10]. Pattern in K indicates structure type (offshore wind = solid, artificial reef = hashed). Color in all panels indicates the geographic region. Wind turbine illustrations depict the component of wind infrastructure (red color) used for footprint calculations. Turbine illustrations by Alex Boersma

for multiple turbine foundation types (monopile, jacket, etc.). We assumed that all projects included herein will use monopile foundations given their near-universal use for in-progress OSW farms in the U.S. However, we also calculated how the footprint may change if jacket or floating turbines are used instead (Text S1). In general, footprints of monopile, jacket, and floating turbines are within an order of magnitude of one another, although there is uncertainty (Text S1). As such, we used monopile estimations for the Block Island Wind Farm (five jacket-style foundations built), Aqua Ventus (two floating turbines planned), the State of Maine research lease (floating turbines planned), and other leased areas in the Pacific (floating turbines likely).

We searched COPs for the number of turbines planned, turbine diameter, and scour protection radius or area. Where ranges were provided, we recorded the maximum value. Depth values for each lease area were necessary for estimating vertical surface area. For leases on the Atlantic coast, we obtained the median depth for each lease area from the TNC Marine Mapping Tool (available: https://www.maps.tnc.org/marinemap/). For the three leases in the Gulf of America, precise depth data were unavailable, so the median depth was assumed to be 20 m (a depth characteristic of this region of the Gulf). For leases on the Pacific coast (n = 5), for the State of Maine research lease, and for the Aqua Ventus lease in the Gulf of Maine for which floating turbines are planned or likely, depths were great enough that, if used to calculate vertical surface area for assumed monopile foundations, they would have substantially influenced our estimate. We therefore adopted a placeholder depth for these areas of 37 m, the average depth of all other leases where depth was known. We calculated per-turbine footprint values for the turbine foundation alone, the scour protection alone, and the total, all assuming circular footprints. We calculated water column footprint (i.e., vertical surface area) by assuming each turbine was a straight-walled cylinder with height equal to the median (or assumed median) water depth in the lease. While most monopiles are slightly tapered such that they are narrower at the surface than at the seafloor (i.e., frustoconical), the decrease in vertical surface versus a straight-walled cylinder is 10% or less.

Some projects did not have publicly available COPs, so we estimated their footprints. We divided these leases into two categories: 1) known turbine number but unknown turbine specifications (e.g., diameter) and 2) unknown turbine number and turbine specifications. For the latter category, we assumed the density of turbines in the lease area would be the mean from projects where it was known (0.33 turbines per km^2, standard deviation = 0.08, n = 24) and used this value to estimate the total number of turbines that will be built in these areas. For both categories, we assumed turbine diameter would be the mean value from projects where it was known (12.27 m, standard deviation = 1.86, n = 20) and applied this value to estimate total seafloor footprint of foundations. For estimating scour area, we used a data-driven approach that acknowledged the positive correlation between seafloor depth and scour protection radius (Pearson $r = 0.60$, $p = 0.005$). For the 20 leases where seafloor depth and scour protection radius were known, we fit a simple linear regression model between those factors. The resulting equation was *Scour radius = 0.46*Depth + 17.78*. Using this equation and previously obtained depth values, we estimated scour radii for wind projects where it was unknown.

When finalized, most OSW farms will include offshore substations (OSSs). We excluded OSSs, since their quantity is negligible compared to the turbines themselves and since the number, size, and structure of OSSs will vary among projects. We also excluded transmission cables and accompanying armoring because developers endeavor to bury cabling where possible and the degree to which each transmission cable will require exposed armoring is uncertain.

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Declarations

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