Vessel Emissions in Offshore Wind

by

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Executive Summary

Offshore wind is an emerging industry in the United States and booming in both Europe and China. With a 30GW by 2030 target set by the Biden Administration, the United States is poised for rapid growth in the sector and has an opportunity to use the offshore wind industry to accelerate global vessel decarbonization. Vessels that are currently used to construct and service offshore wind farms burn petroleum derived fuels emitting greenhouse gases such as CO₂, CH₄, and N₂O. These emissions are small in comparison to the net greenhouse-gas-reducing impact of the offshore wind farms, but not entirely insignificant.

The development of offshore wind resources takes place against a larger backdrop of the energy transition and efforts to decarbonize all facets of the economy, including the global shipping industry. Shipping is a significant contributor to the carbon intensity of the global economy and is often considered particularly difficult to decarbonize. Vessels produce roughly 0.9 gigatons, or 3% of global CO₂ emissions via the burning of fossil fuels for propulsion. Offshore wind vessel emissions rely on the same technology as shipping vessels but may be easier to decarbonize due to the nature of their operations and their proximity to the renewable energy sources that they service, the offshore wind farms.

In this paper I examine the emissions impact of decarbonizing vessels that service offshore wind farms in the United States using the national 30GW by 2030 target as a framework. I explore pathways to decarbonizing offshore wind vessels and discuss the implications of decarbonized United States offshore wind sector for the broader maritime industry.

By analyzing offshore wind project development plans, I produce estimates of the vessel related emissions impact of the first 30GW in the United States. Through analysis of 10 scenarios, a range of 26 million tons of CO₂e to 127 million tons of CO₂e appears likely for this buildout. This range is equivalent to between 192,000 and 923,000 cars operating on our roads during each year of the anticipated 30 years of the offshore wind project’s operational life. Key factors influencing the greenhouse gas emissions produced by the buildout will include:

1. Selection of ports used for each project, with ports farther from the projects resulting in increased emissions.
2. Choice of construction strategy, with greater vessel requirements for some installation methods.
3. Selection of operational vessel types.
4. Scale of projects, with greenhouse gas reductions anticipated from larger projects that can drive efficiencies of scale.

Offshore wind vessels are positioned to serve as proving grounds for low emission vessel technologies, with green hydrogen-based fuels as the best candidate technology for deep vessel decarbonization. Vessel developers are designing and constructing hydrogen-ready ships for use in the industry, and European countries are accelerating development of green hydrogen ecosystems that synergize with offshore wind production. These ecosystems are situated to supply hydrogen-ready offshore wind vessels with clean fuel, which may ultimately cause price reductions in hydrogen vessel technology, enabling adoption by the larger shipping industry.
Introduction

The Challenge of Vessel Decarbonization

The International Maritime Organization (IMO) is the United Nations body that regulates shipping on the high seas. In 2018 the IMO set a target of reducing greenhouse gas emissions in the shipping industry by 50% compared to 2008 levels by 2050. In October of 2021, the International Chamber of Shipping, (ICS), an industry consortium responsible for 80% of global shipping, requested that IMO accelerate their decarbonization ambitions, pushing for a net zero target by 2050. With shipping emissions representing roughly 3% of global greenhouse gas emissions, and potentially contributing 17% of greenhouse gas emissions by 2050 if unregulated, reaching these targets would make a major difference in mitigating the worst effects of the climate crisis.

However, even if the more aggressive ICS target is adopted the work of decarbonizing will be challenging. Vessels are considered hard to decarbonize for several reasons related to the massive amounts of energy-dense fuel required by the global vessel fleet each year. Ships run primarily on Heavy Fuel Oil (HFO), Marine Gasoils (MGO) which are blends of distillates, or Marine Diesel Oils (MDO) that are blends of distillates that may include some HFO depending on the blend. Generally, large ships run on HFO or MDO, and small vessels cannot run on HFO. All three categories of common marine fuel are derived from petroleum and release significant CO₂ emissions even when burned by highly efficient modern engines. Several problems stand out in the quest to decarbonize shipping vessels:

1. **Amount of Fuel Required.** The global shipping industry consumes 8.6 Exajoules (about 2.4 million GWh) of energy each year in the form of fossil fuels.

![International shipping emissions trajectories to 2050 with interim targets for absolute emissions reductions](image)
2. **Economics of Zero Emissions Fuels.** New fuels need to prove themselves cost competitive to be adopted by shipping companies operating in a competitive global environment.

3. **Fueling Infrastructure.** Delivery of zero-carbon fuels generally cannot use fuel delivery infrastructure designed for HFOs, MGO, and MDO. New infrastructure will need to be developed to facilitate this, which can be very expensive and politically contentious.

4. **Lack of Governance.** While the IMO regulates international vessel activities, enforcement is difficult.

Not all oceangoing vessels are engaged in shipping. Ferries, military vessels, fishing fleets, and vessels used to service and construct energy infrastructure are all candidates for decarbonization, and in this paper I outline how offshore wind vessels may be situated to lead in adopting low emission technologies.

**Offshore Wind in the United States**

At the time of writing, two offshore wind projects with a combined capacity of 42MW are operational in the United States. Several states have pushed aggressively to develop targets and increase their offshore wind footprint, and in 2021 the Biden Administration joined them by instituting a national goal of 30GW by 2030. The first 30GW will be developed entirely on the East Coast, with New York and Massachusetts staking out leading positions. Other geographies are likely to follow, though have been slower to gain momentum for a variety of reasons, including challenging subsea conditions, Navy opposition in California, and relatively weaker wind resources in the Gulf of Mexico. \(^{vi}\) While NREL estimates a total potential for development of 2,000 GW in United States domestic waters, \(^{viii}\) this analysis is constrained to the established 30GW target.

There is no question that the general impact of offshore wind farms on the levels of atmospheric greenhouse gases is to reduce them. However, all sources of energy production have associated emissions, such as embodied carbon from the materials used to create renewable power plants and the emissions required to perform O&M on the facilities. \(^{ix}\) For onshore wind and solar, the associated emissions are relatively low – the carbon impact of driving a truck out to the site of the farm may be the largest impact aside from embodied carbon of the materials. In offshore wind, we must take the emissions associated with O&M more seriously. The maintenance of these sites requires the use of large vessels that generally burn MDO or HFO. With today’s electric vehicle markets, it is comparatively easy to replace a diesel truck with an electric truck to drive to and service the onshore farms. It is much harder to find a low or zero emission vessel to service an offshore wind farm.

A 2021 estimate by Dr. Anthony Gray at Catapult Offshore Renewable Energy predicted a range between 2.31 and 3.97 tons of CO\(_2\)e (CO\(_2\) equivalent) per GWh of energy produced by an offshore wind farm for vessel related O&M, depending on vessel choice and distance to shore. \(^{x}\) The offshore wind CO\(_2\)e per GWh emissions uncovered in this study included construction in addition to O&M, and range from 8.43 to 40.42 tons of CO\(_2\)e per GWh. (These studies differ in their estimates largely because the Catapult study looked only at O&M, and focused on the United Kingdom, which has lower variation in possible distance to staging ports.) For a sense of the scale in emissions difference between these estimates and traditional fossil generation, coal in the United States produces about 1,012 tons of CO\(_2\) per GWh, natural gas 412 tons, and petroleum 966 tons per GWh. \(^{xi}\) Still, in the effort to reach a global net zero, these vessel emissions will play a role. The offshore wind sector may also be a perfect proving
ground for sustainable shipping technologies that have potential to scale and provide larger greenhouse gas reductions.

Offshore Wind Vessel Emissions in the United States

The 30GW by 2030 target provides a convenient framework to study offshore wind in the United States. While it is likely that the United States will develop well beyond 30GW farther in the future, this framework is helpful to understand the near-term carbon impacts of changes in vessel fuels.

Offshore Wind Vessel Background

Construction & Preconstruction

The construction of each new offshore wind project in the United States will use one of two methods. The first construction method, which has been used widely in Europe, involves using a Wind Turbine Installation Vessel (WTIV) to pick up turbine components at port and take them to the wind farm site where it will install them. The second method will use feeder vessels, barges significantly smaller than WTIVs, to pick up the turbine components and bring them to a stationary WTIV that remains at the site of the wind farm. The feeder vessel method is not commonly used in regions with more mature offshore wind industries and is proposed in the United States as a means of working around a piece of federal legislation called the Merchant Marine Act of 1920, commonly called the Jones Act. The Jones Act requires that vessels engaged in domestic marine commerce be built in the United States and crewed by Americans. There are currently no Jones Act compliant WTIVs in the United States, although one is under construction in Brownsville, Texas. With an anticipated requirement for around five WTIVs to service the domestic offshore wind industry through 2030, a shortage of viable shipyards to build these vessels, and lack of investor appetite to take on WTIV construction in the United States, some projects are expecting to enlist foreign flagged WTIVs and use them in conjunction with feeder vessels.

Whichever method is chosen by the developers of each individual project will depend largely on the economics of chartering each type of vessel, and the availability of Jones Act compliant WTIVs. In addition to the barges and WTIVs, a variety of other vessels are used in the development of an offshore wind farm, such as cable laying vessels and survey vessels.

Operations and Maintenance

Operations and maintenance of the offshore wind farms are performed by crews aboard specialized vessels designed to operate within the farms. There are two commonly used vessel types for servicing offshore wind farms, each with different requirements and carbon footprints. These are Crew Transfer Vessels (CTV) and Service Operations Vessels (SOV). While we discuss both of these vessel types as though they are mutually exclusive and no other vessels fill this role, in reality there are some ships that occupy a niche between the smaller CTVs and larger SOVs.

Crew Transfer Vessels are designed to carry crews from the mainland to the offshore wind site, where they can perform the required service on the turbines. They vary somewhat in size but generally can accommodate around 12 technicians and transfer the technicians from shore to the wind farms daily, returning at the end of the day to refuel and let the crew off. These are more commonly used in wind farms closer to shore.

As wind farms began to be built farther from shore, larger vessels were brought into service that could take greater numbers of technicians to the farm to reduce the number of long voyages to the project
site. These ships are called Service Operations Vessels and they are designed to remain at sea for weeks, limiting the travel time for all aboard. Crews live on the ship and perform the required service to the turbines for the duration of the vessel’s time at sea before coming back for extended stays ashore.

Quantifying Emissions

In developing their projects in offshore lease areas, offshore wind developers are required to submit a Construction and Operations Plan (COP) to the Bureau of Ocean Energy Management (BOEM), which plays a large role in regulating the industry. Each COP contains a large amount of information about the anticipated project, including expected emissions impacts. The anticipated vessel emissions information that developers include in project COPs is provided to fulfill requirements of the Outer Continental Shelf (OCS) Air Permits, which are issued by the Environmental Protection Agency (EPA). The OCS permits require that project emissions are calculated within 25 nautical miles of the OCS development activities, and developers have some leeway in determining how to present the results of their emissions calculations. Many offshore wind projects have yet to submit COPs, and still other projects have submitted COPs that are publicly available but have redacted their emissions calculations citing it as confidential. Given the freedom to choose how to present their emissions findings, some of the submitted and publicly available COPs have emissions information that specifically identifies anticipated vessel emissions, and some do not.

These emissions estimates are generally on the conservative end (the upper limit of what the projects would expect to emit). For instance, in their COP emissions calculations the developers of the South Fork Wind project used the worst-case scenario ports, farthest from the project site, in each of the states that they are considering staging their construction equipment. Emissions considered to be produced by vessels are dominated by emissions from transit and maneuvering the vessels, but for the purposes of this analysis and reflecting data availability from developer COPs, vessel emission totals will also include emissions from operations such as crane movement and other turbine installation machinery on board the Wind Turbine Installation Vessels. These onboard operation emissions stand to be reduced through overall vessel decarbonization because leading decarbonized vessels are designed with the ability to tap their zero-emission fuel to provide the power for this type of onboard equipment.

In this paper, vessel emissions for the first 30GW are quantified by extrapolating information from COPs submitted by developers. The developers use a standard methodology developed by BOEM that includes formulas related to main and auxiliary vessel engines, and emissions factors for various types of engines and their associated fuels. To perform the calculations, developers feed proprietary information into a model developed by BOEM called the Offshore Wind Energy Facilities Emission Estimating Tool to calculate their emissions for inclusion in their project COPs. The resulting anticipated emissions for offshore wind projects were pulled from select project COPs and used as the basis for quantifying emissions in this analysis.
**Figures 2 & 3.** Example vessel emissions calculations and emissions factors built into the BOEM Offshore Wind Energy Facilities Emission Estimating Tool.

### Selected COP Documents

**Atlantic Shores**

Atlantic Shores is a proposed 1,510 MW offshore wind project off the coast of New Jersey, developed as a 50:50 partnership between EDF Renewables and Shell.¹⁸ Atlantic Shores was selected because the COP presents a wealth of valuable data, and projects four total scenarios with unique emissions impacts. The four scenarios are generated with two possible options for constructing the farm and two options for windfarm O&M. Construction scenarios include installation using either fixed bottom foundations or gravity-based foundations, and each entails different vessel needs. Operations scenarios include using either SOVs or CTVs. These two types of operations vessels will be discussed in greater detail further in the paper.

**South Fork Wind**

South Fork Wind is a 132 MW proposed wind farm to be built off the tip of Long Island, designed to deliver power to New York. The project is under development by Ørsted and Eversource with an expected operational date in 2023.¹⁹ The South Fork Wind COP presents several emissions scenarios based on different port locations where the construction and major O&M may be staged from. The COP does not present scenarios with different construction methods, as Atlantic Shores does, instead all South Fork Wind scenarios assume fixed bottom monopile installations using feeder vessel barges. The O&M calculations assume CTVs based out of Shinnecock, NY, and jack-up barge and feeders traveling from the major staging port specific to the scenario. South Fork also includes decommissioning emissions estimates, which are not included in the publicly available Atlantic Shores estimates and were not considered for the purpose of this analysis.
<table>
<thead>
<tr>
<th>Project</th>
<th>Scenario</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atlantic Shores</td>
<td>1</td>
<td>Fixed bottom installations and CTVs. O&amp;M based on Atlantic City, Construction based on NJWP, NJ</td>
</tr>
<tr>
<td>Atlantic Shores</td>
<td>2</td>
<td>Fixed bottom installations and SOVs. O&amp;M based on Atlantic City, Construction based on NJWP, NJ</td>
</tr>
<tr>
<td>Atlantic Shores</td>
<td>3</td>
<td>Gravity base installations and CTVs. O&amp;M based on Atlantic City, Construction based on NJWP, NJ</td>
</tr>
<tr>
<td>Atlantic Shores</td>
<td>4</td>
<td>Gravity base installations and SOVs. O&amp;M based on Atlantic City, Construction based on NJWP, NJ</td>
</tr>
<tr>
<td>South Fork Wind</td>
<td>5</td>
<td>WTG O&amp;M based on Shinnecock NY; Major component setup based on Port of New Bedford, MA</td>
</tr>
<tr>
<td>South Fork Wind</td>
<td>6</td>
<td>WTG O&amp;M based on Shinnecock NY; Major component setup based on Port of Providence, RI</td>
</tr>
<tr>
<td>South Fork Wind</td>
<td>7</td>
<td>WTG O&amp;M based on Shinnecock NY; Major component setup based on Port of New London, CT</td>
</tr>
<tr>
<td>South Fork Wind</td>
<td>8</td>
<td>WTG O&amp;M based on Shinnecock NY; Major component setup based on Paulsboro Marine Terminal, NJ</td>
</tr>
<tr>
<td>South Fork Wind</td>
<td>9</td>
<td>WTG O&amp;M based on Shinnecock NY; Major component setup based on Port of Sparrows Point, MD</td>
</tr>
<tr>
<td>South Fork Wind</td>
<td>10</td>
<td>WTG O&amp;M based on Shinnecock NY; Major component setup based on Port of Norfolk, VA</td>
</tr>
</tbody>
</table>

**Figure 4.** Ten scenarios were studied between the two projects Atlantic Shores and South Fork Wind. Each resulted in different emissions outputs based on the operations and construction plans associated with each scenario.

**Emissions for the First 30GW of United States Offshore Wind**

Data found in the two selected developer COPs shows a range of greenhouse gas emissions outcomes which are explored in this paper on a Tons of CO2e/MWh basis. Of the emissions tracked in the COPs (which include NOx, VOC, CO, PM10, PM2.5, SO2, CO2, CH4, and N2O) only CO2, CH4, and N2O are considered in this analysis to be greenhouse gasses, and the CO2 equivalent of each is listed in the table below.

<table>
<thead>
<tr>
<th>Greenhouse Gas</th>
<th>CO2e</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO2</td>
<td>1</td>
</tr>
<tr>
<td>CH4</td>
<td>25</td>
</tr>
<tr>
<td>N2O</td>
<td>298</td>
</tr>
</tbody>
</table>

**Figure 5.** Greenhouse gas equivalencies for tracked gasses produced by offshore wind vessels. One ton of CH4 has a greenhouse gas potential equivalent to 25 tons of CO2. One ton of N2O has a greenhouse gas potential equivalent of 298 tons of CO2. **xx**

To determine total project lifetime emissions on a Tons of CO2e/MWh basis, some assumptions were required. Each of the projects was assumed to have a 30-year operational lifetime (the project lifetime presented in the Atlantic Shores COP and a common rule of thumb for estimating offshore wind farm operational life). Net capacity factors for both farms were assumed to be 40% **xxi**, which is to say that in an average hour, 40% of the nameplate capacity of each farm was assumed to reach the onshore grid. Generally, estimates for offshore wind gross capacity factor are higher than 40% but net capacity factor captures the entire impact of emissions per usable MWh. Using net capacity factor also enables easier comparisons to onshore generation infrastructure. Emissions from decommissioning activities were not included in the calculations.
<table>
<thead>
<tr>
<th>Project</th>
<th>Scenario</th>
<th>Tons CO2e</th>
<th>Project Size (MW)</th>
<th>Tons CO2e per MW</th>
<th>GWh (Project Life)</th>
<th>Distance to Staging Port (NM)</th>
<th>Distance to O&amp;M Port (NM)</th>
<th>Tons CO2e per GWh</th>
<th>Percentage of Emissions from O&amp;M</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atlantic Shores</td>
<td>1</td>
<td>1,338,942</td>
<td>1,510</td>
<td>886</td>
<td>158,731.2</td>
<td>91.0</td>
<td>17.0</td>
<td>8.43</td>
<td>72%</td>
</tr>
<tr>
<td>Atlantic Shores</td>
<td>2</td>
<td>1,520,610</td>
<td>1,510</td>
<td>1,007</td>
<td>158,731.2</td>
<td>91.0</td>
<td>17.0</td>
<td>9.58</td>
<td>73%</td>
</tr>
<tr>
<td>South Fork Wind</td>
<td>3</td>
<td>1,572,577</td>
<td>1,510</td>
<td>1,041</td>
<td>158,731.2</td>
<td>91.0</td>
<td>17.0</td>
<td>9.91</td>
<td>74%</td>
</tr>
<tr>
<td>South Fork Wind</td>
<td>4</td>
<td>252,674</td>
<td>132</td>
<td>1,914</td>
<td>13,875.84</td>
<td>34.3</td>
<td>66.0</td>
<td>18.21</td>
<td>79%</td>
</tr>
<tr>
<td>South Fork Wind</td>
<td>5</td>
<td>260,488</td>
<td>132</td>
<td>1,973</td>
<td>13,875.84</td>
<td>46.7</td>
<td>66.0</td>
<td>18.77</td>
<td>79%</td>
</tr>
<tr>
<td>South Fork Wind</td>
<td>6</td>
<td>272,332</td>
<td>132</td>
<td>2,063</td>
<td>13,875.84</td>
<td>48.5</td>
<td>66.0</td>
<td>19.63</td>
<td>79%</td>
</tr>
<tr>
<td>South Fork Wind</td>
<td>7</td>
<td>454,286</td>
<td>132</td>
<td>3,442</td>
<td>13,875.84</td>
<td>305.5</td>
<td>66.0</td>
<td>32.74</td>
<td>79%</td>
</tr>
<tr>
<td>South Fork Wind</td>
<td>8</td>
<td>560,820</td>
<td>132</td>
<td>4,249</td>
<td>13,875.84</td>
<td>474.7</td>
<td>66.0</td>
<td>40.42</td>
<td>78%</td>
</tr>
<tr>
<td>South Fork Wind</td>
<td>9</td>
<td>446,602</td>
<td>132</td>
<td>3,383</td>
<td>13,875.84</td>
<td>356.8</td>
<td>66.0</td>
<td>32.19</td>
<td>77%</td>
</tr>
</tbody>
</table>

Figure 6. Summary emissions findings from Atlantic Shores and South Fork Wind scenarios.

Some notable findings emerge from this analysis. The first is that most vessel emissions occur during the operational life of the project, rather than during construction. This may not be intuitive - project construction uses larger vessels that produce significantly greater emissions than the relatively smaller O&M vessels. However, this is offset by the long project life (30 years) over which the smaller O&M vessels are expected to operate. For instance, single year O&M emissions for scenario 5 are about 12.9% of the single year construction emissions for the project, while the total O&M emissions for the scenario are 386.8% of the single year construction emissions.

A second finding, perhaps more intuitive, is that the distance to port has a major impact on the emissions of a project. Examining the six scenarios of the South Fork Wind project, we see a range from 18.21 to 40.42 tons of CO₂ per GWh of energy delivered to the onshore grid. This is caused by a difference in distance to the port used for staging of major equipment, including construction and periodic O&M using a jack-up vessel and feeder barges. While the highest emitting scenario (Sparrow Point, MD) seems unrealistic as a final choice for the project, it is possible that some offshore wind farms in development will face capacity constraints at local ports while competing with other developers for port space and be forced to stage materials at distant ports.
Figure 7. From South Fork Wind Farm COP Appendix L – Air Emissions Inventory. Most project emissions are generally assumed to take place within the wind farms and immediate surrounding area (25NM radius), but this can vary significantly based on which ports are used to supply the construction and the O&M vessels. Using the Norfolk Terminal instead of the Port of New London could add around 700 miles of roundtrip transit each trip.

The Atlantic Shores data offers a third finding from this analysis – that SOVs are expected to emit slightly more than CTVs, though they are relatively similar overall. The SOV scenarios 2 and 4 respectively emit 3.9% and 4.5% more CO\textsubscript{2}e than their CTV counterparts. The Atlantic Shores data also reveals the emissions impact associated with using tugboats to deliver gravity-based foundations to the project site – scenarios three and four have higher emissions than the fixed bottom scenarios 1 and 2, largely because of the use of these additional large vessels. Taking a closer look at the data, this difference becomes more stark – fixed bottom installation has 67,114 tons of CO\textsubscript{2}e associated with foundation installation while gravity-based foundation installation produces 249,748 tons of CO\textsubscript{2}e.

A final finding is that the size of a project has implications for vessel emissions per GWh. Efficiencies driven by scale are commonly observed in energy development projects and are largely derived from the need to only perform certain activities a fixed number of times regardless of project size. For instance, Atlantic Shores is about ten times larger than South Fork Wind but will not require ten times the number of export cables (it will require one or two, South Fork will require one). These efficiencies play out in operations and maintenance as well, with larger projects able to have a comparatively low number of vessel trips per MW compared to smaller projects.

It is useful to compare these numbers to the emissions associated with conventional thermal generation that these farms stand to displace (principally coal and natural gas). While the emissions from offshore
wind vessels should be considered as we move towards a decarbonized world, the overall impact compared to the alternatives is a massive reduction in greenhouse gas emissions.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Tons of CO2e per GWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Offshore Wind Vessels</td>
<td>8.43-40.42</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>413</td>
</tr>
<tr>
<td>Petroleum</td>
<td>966</td>
</tr>
<tr>
<td>Coal</td>
<td>1012</td>
</tr>
</tbody>
</table>

**Figure 8.** United States Energy Information Administration – average emissions associated with generation at fossil fired thermal plants. There is variation within each of the listed fuel sources (natural gas combined cycle plants emit less than natural gas combustion turbines, for instance) but the order of magnitude remains similar.xxiii

These ten scenarios were extrapolated to examine a range of total likely impacts for the vessel emissions related to the first 30GW of offshore wind. While the range of outcomes in the table below shows variation from 26.6 million tons of CO2e, up to 127.5 million tons of CO2e, it is likely that emissions will fall on the lower end of this spectrum. Most of the MWs of capacity that will comprise the first 30GW will be delivered from projects significantly larger than South Fork Wind and will therefore draw on efficiencies of scale. Additionally, the higher emissions scenarios in the South Fork Wind COP represent very inefficient port locations relative to the project site – for economic reasons it is likely that most projects will find closer port space and turn to distant ports as a last resort. Finally, these estimates in the developer COPs are meant to be conservative – in creating these calculations, the planners assume operations associated with the worst-case scenario.

**Figure 9.** Range of possible outcomes for the vessel emissions impact of the first 30 GW of offshore wind in the United States.

The emission values expressed above in tons of CO2e can also be thought of in terms of cars on the road. To perform this conversion, the emissions above were annualized over 30 year project lifetimes, and EPA estimates on average annual automobile emissions in the United States were usedxxiv. Under these assumptions, the best-case scenario buildout from a greenhouse gas perspective (scenario 1) would emit greenhouse gasses equivalent to 192,625 cars on the road in each year of operation. This is roughly equivalent to all the registered automobiles in Vermontxxv. The highest emitting scenario (scenario 9)
would produce emissions equivalent to 923,617 cars on the road in each of the 30 years, roughly equivalent to all the automobiles registered in Utah. Again, it is important to reemphasize that these offshore wind projects will be displacing fossil fuel power generation and will on balance drastically reduce greenhouse gas emissions. These estimates on vehicle equivalents serve to underscore the opportunity in decarbonization of the vessels.

Other Emissions
While it is outside the scope of this paper, it is important to realize that other inputs into offshore wind farms have carbon impacts that should be considered. For instance, offshore wind farms sometimes rely on helicopters to perform survey work from overhead, which burn carbon intensive fuel. In terms of the vessels themselves, the analyses discussed so far do not constitute a complete Life Cycle Analysis (LCA) of the carbon impacts of offshore wind vessels. Full LCA would make considerations for embodied carbon such as the carbon emitted manufacturing the steel used to create the vessels.

Another weakness in the data, is the absence of a full evaluation of ships transit emissions from non-US ports. Atlantic Shores, for instance uses a one-way trip distance of 250 nautical miles for vessels coming from European ports, whereas the true distance would be closer to 3,000 nautical miles. New build vessels constructed in East Asia (where most large ships are built and where the global offshore wind industry will likely source many vessels in the coming years) could take over 10,000 nautical miles to reach the East Coast of the United States. These international trips are generally one time only, with the ships sent over for the duration of project construction.

Pathways to Vessel Decarbonization
As discussed previously, most commercial vessels burn HFO, MDO, or MGO, all derived from crude oil. However, several pathways are being pursued to decarbonize global shipping fleets including Liquified Natural Gas (LNG), and green hydrogen fuels. While I only address these two fuels in detail, the history of commercial vessel transport has shown technical viability of many types of propulsion. Some of the technologies not discussed in this paper because of low economic feasibility or geopolitical concerns include biofuels, wind, electrification, and nuclear propulsion.

LNG
LNG is a fuel created by liquefying natural gas, which is primarily methane. To stay liquified, LNG must remain at -162 degrees Celsius (-260 degrees Fahrenheit) to prevent the fuel from boiling into its gaseous form. This process causes the fuel to occupy significantly less volume, to the point where it can be effectively carried on vessels. However, the carrying vessel must be able to maintain the low temperature and must be large enough to house the insulated containers to hold the LNG, and therefore it is unlikely that LNG is a viable technology to be used on small vessels such as CTVs or SOVs. LNG propulsion also has safety concerns relative to HFO, MDO, and MGO which limit the vessel types and operational profiles that may be willing to adopt the fuel.xxvi

LNG is the most widely used alternative fuel to the HFO and MDO fuels in use by large commercial vessels today. We have seen a steady rise in the number of LNG powered vessels with 20-40% increases annually in the fleet size since 2010. At the start of 2020 there were 175 LNG fueled ships operating globally in addition to the global fleet of around 600 LNG carriers which are generally powered by LNG.xxvii
There is some ambiguity about the precise emissions impact of LNG used in shipping. The Energy Transitions Commission claims that LNG reduces vessel emissions by 9-12% compared to other fossil alternatives. An industry LNG association, Sea-LNG, claims that LNG has the potential to reduce GHG emissions up to 23%. Even under this industry favored best-case assumption, a complete conversion of the fleet to LNG stands to reduce vessel emissions to only 77% of what they otherwise would have been.

Refueling equipment, known as bunkering infrastructure, has been developed at many global ports but is still unavailable in most ports around the world due to high development costs and the relatively niche position that the fuel still holds outside of direct transport via LNG carrier ships. Given the relatively small emissions impact of converting to LNG (compared to true zero-emission fuels), LNG cannot be considered a viable pathway for decarbonizing vessel emissions. Additionally, development of LNG bunkering infrastructure creates a lock-in problem in which investors who develop the infrastructure are incentivized to accelerate the LNG industry, preventing us from truly decarbonizing vessel emissions for the life of the infrastructure.

Hydrogen-Based Fuels

As opposed to LNG, which provides potential for limited emissions reduction, hydrogen-based fuels present a pathway that can functionally eliminate GHG emissions (though hydrogen combustion does still produce some emissions, such as NOx). Because these fuels are based on hydrogen, the source of the hydrogen is critical for the lifetime emissions associated with the fuel. There are two dominant pathways to produce hydrogen. The first produces what is known as grey hydrogen and involves separating the hydrogen atoms out from natural gas – 95% of hydrogen globally is produced this way, and this produces significant GHG emissions. The second popular method to produce hydrogen is using electrolysis to separate hydrogen atoms from oxygen atoms in water, producing harmless oxygen emissions. The main inputs into electrolysis hydrogen production are water and electricity, and if the electricity used to produce the hydrogen has no associated emissions (solar, wind, etc) it is considered green hydrogen. Green hydrogen or other zero emission hydrogen (such as hydrogen produced via electrolysis and using zero emission nuclear energy) is the necessary input required to achieve zero GHG emissions shipping through hydrogen-based fuel pathways.

There are several challenges to implementing green hydrogen-based fuels in the global shipping industry, including capital investment into engines and fuel cells that can use these fuels, investments in bunkering infrastructure, and the buildout of renewable energy that would be required to supply clean electricity for fuel production. Despite the challenges, some assessments see potential for these fuels to take over by mid-century. The International Renewable Energy Agency (IRENA) has recently published a study suggesting that hydrogen-based fuels could decarbonize 80% of global shipping emissions by 2050. The most commonly discussed hydrogen fuels are green hydrogen itself and green ammonia created using green hydrogen as a feedstock.

Green hydrogen itself can be used as a fuel through two main pathways. It can be blended into fuel mixtures that can be run through existing engines that have been designed to handle hydrogen mixtures. It can also be run through a fuel cell to produce propulsion – several vessel operators have adopted fuel cells to run their vessels already.
A back of the envelope calculation can shed light on the scale of the challenge for developing green hydrogen renewable energy supplies that would be required to power the global shipping fleet. Taking as assumptions that the global shipping fleet consumes 8.6 exajoules of energy, average vessel engine efficiency may be around 45%, hydrogen fuel cell efficiency is at 60%, transmission and distribution electricity losses are 5%, and electrolyzer efficiency is at 80%. Solar has a capacity factor at 27% and wind has a capacity factor of 40%. We find that either 1,004 GW of solar energy or 673 GW of wind energy would be required to produce the green hydrogen that would be necessary to power the global shipping industry in 2020. With projected growth in global shipping, these numbers will increase in the future. For reference, the United States had a total installed solar capacity of 121 GW at the end of 2021. While the scale of renewable energy required to decarbonize shipping through green hydrogen fuels is daunting, synergies between green hydrogen and offshore wind projects show promise in accelerating simultaneous development of these resources.

The Offshore Wind Green Hydrogen Nexus

The offshore wind industry is situated to act as a proving ground for green hydrogen production and implementation of green hydrogen fuels in vessels. Excess electricity produced by offshore wind production can be run through electrolyzers to produce green hydrogen which can be processed into green ammonia near the port or used directly as a fuel without the need to develop expensive pipeline infrastructure to move the gas around. This geographic proximity between offshore windfarms and port fuel bunkering locations holds promise that is being explored primarily in Europe. Many in the United States are trying to create green hydrogen ecosystems around offshore wind projects on the east coast, and Atlantic Shores is already contracted to establish a 10MW green hydrogen pilot.

One of the main challenges associated with offshore wind development is interconnection to the mainland grid. As the oceans become more crowded with offshore wind projects and the best interconnection points are taken, this problem will become exacerbated. Additionally, technological advances in floating offshore wind will open new markets for the industry, allowing development farther from shore where cabling will become increasingly expensive. These trends in the broader offshore wind industry open doors to co-development with green hydrogen infrastructure. Green hydrogen can be produced on the turbines or on platforms at sea where the gas can be piped to shore afterwards or left on the platform where it can be used as a fueling station for vessels. This type of application is not in widespread use yet, but forward-thinking developers, regulators, and planners in Europe are mapping out pathways to achieve this type of infrastructure.

One example of development in this space is a project in the Dutch North Sea contracted by German utility RWE. The developer is scheduled to build out the pilot project which will generate offshore wind power at sea, turn the electricity into green hydrogen, and then pipe the hydrogen ashore using existing natural gas pipeline infrastructure. Using existing infrastructure in this manner saves massive costs for hydrogen developers and creates pathways to ease the pain for firms and investors whose gas assets otherwise would become stranded in a decarbonizing world.

Another example of this nexus is under development via a Danish public-private partnership. The project is a wind energy hub island, located 80 km from shore in the North Sea. The island will be surrounded by offshore wind turbines and is intended to have electrolyzers that can produce green hydrogen on site.
Accelerating Global Vessel Decarbonization

Ultimately, the offshore wind and green hydrogen industries are nascent compared to traditional energy industries, and projects harnessing both technologies simultaneously will take years to build momentum and scale to a position where they can become a dominant supply for clean shipping fuels. However, the importance of the technological synergies has been recognized by vessel manufacturers already. Ulstein is a Norwegian vessel manufacturer that is active in the offshore wind space. The firm has designed a green hydrogen powered construction vessel with potential to drastically reduce emissions compared to existing vessel options. xliv Siemens Gamesa recently delivered a green hydrogen-ready vessel called the REM Energy to perform O&M activities on offshore wind farms in Europe.xlv While the ship can run on hydrogen, the absence of a green hydrogen ecosystem in the area will cause it to use its traditional diesel engines in the near term. These examples of low emissions vessel development underscore the viability of using green hydrogen as fuel in offshore wind operations, so long as green hydrogen production can be achieved.

An important factor in offshore wind vessel operations and their unique feasibility in proving hydrogen fuel technology is the operational behavior of the offshore wind vessels. These vessels are used in a relatively small geographic area compared to vessels that are used in global shipping. For instance, offshore wind vessels globally are all clustered in East Asia or Europe, as opposed to the sprawling network of shipping vessels stretching across all oceans. This enables offshore wind vessels to rely more heavily on local fueling ecosystems. For instance, a container ship carrying products from China to the United States would need to either carry enough fuel for the return trip or have access to fuel supplies in the United States before returning to China. If this ship were powered with hydrogen, it would need to have the capacity to refuel its hydrogen tank in the United States before making the return trip. Given the challenges in developing hydrogen bunkering infrastructure, it is unlikely that international trade hubs will all develop the capacity to refuel hydrogen powered ships simultaneously. Shipping vessel operators are less likely to adopt hydrogen propulsion without assurance that infrastructure to refuel will be available along their routes. Any vessels that can rely solely on one hydrogen refueling hub are therefore more likely to adopt. We have seen this logic drive adoption in other vessels that only operate in a local area, such as ferries. xlvi

Because they are uniquely positioned to be leaders in adopting green hydrogen-based fuels, offshore wind vessels may be a key lever to drive down the cost of hydrogen shipping technology. Novel clean energy technologies and industries generally follow cost curves based on deployment — the more that a particular technology is deployed, the cheaper subsequent installations of that technology become. This happens because the industry collectively learns from each development, and at all stages in the supply chain and development process of a novel infrastructure project, firms and individuals seek efficiencies and cost reductions to improve their own competitiveness and increase profit margins. We have seen this effect occur in many industries within the energy sector, including solar, onshore wind, battery storage, and offshore wind.
Ultimately, the costs for these technologies in the early days of their adoption is often too high for widespread use. Only after the price is driven down by early adopters can the technology be brought into widespread use. The same effect is likely in green hydrogen shipping, and offshore wind vessels may be among the best candidates for early adopters that can bring costs down to a point where the broader shipping industry can adopt.

The Opportunity

With the commitment by the Biden Administration to a buildout of 30GW by 2030 in the United States, 30GW by 2030 has become an industry standard assumption for a near-term offshore wind buildout. However, individual state commitments at the time of writing exceed 30GW collectively, and the industry continues to build momentum, leading to a common industry belief that offshore wind development will greatly exceed 30GW in the future. While this paper reflects a range from 26.6 million tons of CO$_2$e to 127.5 million tons of CO$_2$e for the first 30GW, continued expansion of the industry will result in more vessel emissions and therefore a greater impact for decarbonized vessels.

While the low-emissions technologies described in this paper will not be in widespread use during the early phases of the first 30GW, they still have high potential to mitigate offshore wind vessel emissions if...
put into service in the coming years. Because most of the emissions occur during O&M, low-emission vessels put into service 5, 10, or even 20 years from now stand to have a significant impact on these projects.

<table>
<thead>
<tr>
<th>Project</th>
<th>Scenario</th>
<th>Tons CO2e/GWh</th>
<th>Percentage of Emissions from O&amp;M</th>
<th>Tons CO2e/GWh given post-construction O&amp;M vessel decarbonization at different times</th>
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<tbody>
<tr>
<td>Atlantic Shores</td>
<td>1</td>
<td>8.43</td>
<td>72%</td>
<td>3.34 4.36 5.38 6.39 7.41</td>
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<tr>
<td>Atlantic Shores</td>
<td>2</td>
<td>8.76</td>
<td>73%</td>
<td>3.40 4.47 5.54 6.61 7.68</td>
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<tr>
<td>Atlantic Shores</td>
<td>3</td>
<td>9.58</td>
<td>64%</td>
<td>4.49 5.51 6.53 7.55 8.56</td>
</tr>
<tr>
<td>Atlantic Shores</td>
<td>4</td>
<td>9.91</td>
<td>65%</td>
<td>4.55 5.62 6.69 7.76 8.84</td>
</tr>
<tr>
<td>South Fork Wind</td>
<td>5</td>
<td>18.21</td>
<td>79%</td>
<td>6.15 8.56 10.98 13.39 15.80</td>
</tr>
<tr>
<td>South Fork Wind</td>
<td>6</td>
<td>18.77</td>
<td>79%</td>
<td>6.35 8.84 11.32 13.80 16.29</td>
</tr>
<tr>
<td>South Fork Wind</td>
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<td>19.63</td>
<td>79%</td>
<td>6.66 9.25 11.84 14.44 17.03</td>
</tr>
<tr>
<td>South Fork Wind</td>
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<td>32.74</td>
<td>79%</td>
<td>11.29 15.58 19.87 24.16 28.45</td>
</tr>
<tr>
<td>South Fork Wind</td>
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</tr>
<tr>
<td>South Fork Wind</td>
<td>10</td>
<td>32.19</td>
<td>77%</td>
<td>11.54 15.67 19.80 23.93 28.06</td>
</tr>
</tbody>
</table>

**Figure 11.** Potential for post-construction O&M vessel decarbonization to reduce overall lifetime vessel emissions from offshore wind farms. This figure shows the impact of decarbonizing O&M vessels at various points after the farms have completed construction (5, 10, 15, 20, and 25 years after construction).

This highlights that development of a low emission vessel industry stands to have significant impact even if not put into service immediately. However, this should not be taken as an excuse to delay investment into low emissions vessels and formation of low emission vessel policy. Proponents of fossil fuels are already eyeing the offshore wind industry as a source of new demand for equipment and fuels, and it will likely require policy intervention to ensure that clean vessel technologies can take hold in this industry.

Policy intervention is likely necessary, though the IMO which regulates global shipping has not enacted regulations designed to shift vessels to hydrogen technology. It is possible that we will see the IMO take more aggressive action to move the sector towards zero emission shipping, as we have seen the organization take progressive steps in the past. In 2020 the IMO instituted regulations capping sulfur emissions from ships operating on the high seas. This step towards their sustainability targets is considered likely to reduce vessel reliance on HFO, but it is unlikely that it will be an effective mechanism for pushing vessels to transition to zero emissions fuels, as low-sulfur fuel oils and sulfur scrubbers installed on existing ships appear to be covering the difference.

Looking to national rather than international policy, one approach that may be effective when considering offshore wind vessels in the United States would be leveraging existing federal subsidy programs to drive the cost down. This technique would prompt early adoption by offshore wind vessel operators and has been followed in the past. The federal government used the Investment Tax Credit and Production Tax Credit to push down solar and wind energy costs and drive adoption. A similar credit could be developed for clean vessel technology, or these existing tax credits could be expanded to include clean vessel technology.
The Loan Programs Office (LPO) within the United States Department of Energy is another promising avenue. The LPO provides loan guarantees for projects meeting their criteria, which reduces the project risk and spurs investment into the project by financiers in private capital markets. The successful application of a loan guarantee from the LPO to a hydrogen fueled offshore wind vessel would inspire confidence and increase the likelihood of additional investment into hydrogen vessel technology.

Conclusion

It is important to recognize that the emissions impact of offshore wind installations in the United States is orders of magnitude lower than the emissions associated with coal and natural gas generation that offshore wind projects are likely to displace. Comparing the range of offshore wind vessel emissions (8-40 tons CO₂e per GWh) to coal emissions (1,012 tons per GWh) and natural gas emissions (413 tons per GWh) makes this clear. Decarbonizing vessels in the offshore wind sector has the potential to have the same impact as removing 190,000-920,000 cars from our roads over just the first 30GW, which is likely the tip of the iceberg for offshore wind in the United States.

The synergy between offshore wind and green hydrogen presents a great opportunity for the offshore wind industry to become a proving ground for decarbonized vessel propulsion technology. By leveraging existing federal programs, the United States has an opportunity to push costs down for clean hydrogen vessel technologies, prompting adoption by offshore wind vessels. Deployment of these technologies in the offshore wind sector would accelerate this process, pushing costs down further, and leading to eventual adoption by difficult-to-decarbonize shipping fleets. This process offers perhaps the most viable pathway to decarbonization of the global shipping industry.
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