RENEWABLE ENERGY RESOURCE, TECHNOLOGY, AND ECONOMIC ASSESSMENTS

Appendix I - Task 9: Comparative Assessment of Technology Options for Biogas Clean-Up

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I. EXECUTIVE SUMMARY

The strong and steady winds off the world’s coastlines and shorelines have vast potential to provide clean, sustainable electricity. Off California, the extended fetches along its 840 nm (nautical miles) coastline and across the Pacific Ocean offer unfettered paths for winds right up to many of the state’s largest load centers. Initial assessments found almost 588 GW of wind resource potential within 50 nm of shore at a height of 90-m (included areas were limited to those with >7.0 m/s mean wind speed), with more than 116 GW within 12 nm of shore [1].

While there was more than 7 GW of offshore wind power installed globally by the end of 2013, there is only one offshore wind turbine in all of the United States, a 20 kW research installation off of Maine. The almost complete absence of domestic offshore wind power can be attributed to: (1) the relative newness of the industry and the lack of deep infrastructure to support it, (2) the complexities of maritime planning and regulation, including sensitive environmental considerations, and (3) the technology requirements for adapting and operating wind turbines and the balance of plant to harsh marine environments. These three items – particularly the last – have kept the cost of offshore wind energy high, at 49% [2] to more than 200% [3] greater than that of its terrestrial counterpart.

There is a duality to the roles and impacts of technology in offshore wind power. Marinising wind power requires the application of additional technologies, driving up costs. Technology can also be a major contributor to cost reduction; judicious adaptation of existing technologies and application of innovative technologies can bring down the cost of energy.

Offshore wind power technology is based on its onshore counterpart and almost all terrestrial turbine technologies are applicable offshore, including many advanced concepts under research and development in recent years. In some cases, they are even more relevant offshore because of the drive to larger turbines to offset higher costs for balance of plant, and the need for even greater reliability to alleviate high operations and maintenance (O&M) costs. These include rotor technologies such as passive and active aerodynamic load control; advanced blade manufacturing techniques; drivetrain improvements including direct drive; and novel blade and tower structures. Many of these are discussed in the companion report, “Wind Energy in California’s Future: Barriers, Opportunities, and Research Needs”. Some technology concepts that have been abandoned for terrestrial wind power have seen renewed interest for offshore. These include two-bladed rotors and vertical-axis, stall regulated Darrieus rotors.

Terrestrial and offshore wind turbines can vary dramatically in foundation or method of fixity. The vast majority of offshore wind turbines is in shallow water and use monopiles driven into the sea floor. Gravity-based structures are also used in shallow water, but have less than one-third the adoption of monopiles. These shallow-water foundations are somewhat analogous to common terrestrial wind turbine foundations. As deployments move into transitional depths between 30-m and 60-m, more complex structures such as tripods, tripiles, and jackets have been used.

California’s coast parallels a steep continental shelf, likely necessitating floating platforms for wind turbine installations. Floating platforms for wind power are a nascent technology and are arguably the greatest technical barrier to offshore wind power in California. Paper studies have largely converged upon three general platform configurations. A handful of companies are developing floating wind turbines, but to date, only three full-scale prototypes have been deployed.

Electrical systems have been successfully deployed in shallow offshore wind plants with offshore substations. However, there remain significant opportunities for optimization and improvement,
including higher voltage collection systems and cost-reliability optimized collection layouts. There has been little experience in deep water, which may require floating cabling for both the collection and transmission systems. With plants far from shore, as may be the case in California, HVDC (high voltage direct current) transmission can become economically advantageous. There have been two deployments of HVDC in the North Sea for offshore wind power, with five more under construction.

A preliminary study was performed to gain insight on the potential reliability contribution of offshore wind power to California’s grid. Wind power generation was estimated at three offshore sites over a three year period. The capacity factors over the three years were high, ranging from 53% - 57%. Capacity factors were also calculated over a variety of load conditions, including predefined peak hours during peak months, top load hours, and load deciles. Power production was high under all conditions for two of the sites, with capacity factors over the selected hours exceeding 50%. At one site, the capacity factors over the top 10, 30, 60, and 100 load hours all exceeded 60%. Production under the various load conditions was lower for the third site, but still very good. The high production values indicated that California offshore wind power could have good capacity value and beneficially contribute to the state’s grid reliability.

In summary, shallow-water offshore wind power has been successfully demonstrated and deployed overseas. Offshore wind power in deeper waters is nascent. Engineering solutions exist for the technical barriers to deep-water installations and full-scale prototypes of floating wind turbines have been successfully deployed. However, experience remains very limited.
II. INTRODUCTION

The strong and steady winds off the world’s coastlines and shorelines have vast potential to provide clean, sustainable electricity. Off California, the extended fetches along its 840 nm (nautical miles) coastline and across the Pacific Ocean offer unfettered paths for winds right up to many of the state’s largest load centers. Initial assessments found almost 588 GW of wind resource potential within 50 nm of shore at a height of 90-m (included areas were limited to those with >7.0 m/s mean wind speed), with more than 116 GW within 12 nm of shore [1]. This impressive potential could be a significant contributor to fulfilling California’s energy and emissions goals.

While there was more than 7 GW of offshore wind power installed globally by the end of 2013, there is only one offshore wind turbine in all of the United States, a 20 kW research installation off of Maine. The almost complete absence of domestic offshore wind power can be attributed to: (1) the relative newness of the industry and the lack of deep infrastructure to support it, (2) the complexities of maritime planning and regulation, including sensitive environmental considerations, and (3) the technology requirements for adapting and operating wind turbines and the balance of plant to harsh marine environments. These three items – particularly the last – have kept the cost of offshore wind energy high, at 49% [2] to more than 200% [3] greater than that of its terrestrial counterpart.

There is a duality to the roles and impacts of technology in offshore wind power. Marinising wind power requires the application of additional technologies, driving up costs. Technology can also be a major contributor to cost reduction; judicious adaptation of existing technologies and application of innovative technologies can bring down the cost of energy. This report reviews the state of offshore wind power technology with emphasis on technologies relevant for California’s coast.

II.1. STATUS OF OFFSHORE WIND: GLOBAL AND UNITED STATES

The world’s first offshore wind farm was installed at Vindeby, Denmark, in 1991. It lies approximately 3 km offshore and consists of 11 turbines with fixed-bottom foundations in an average water depth of 4 m and a total capacity of 5 MW [4]. Since that initial project, average plant size, water depth and distance to shore for new offshore wind farms have been increasing. The average capacity of European wind farms installed in 2012 was 286 MW, while the average water depth was 22 m and the distance from shore was 29 km [5].

Globally, offshore wind installations accounted for 2.9% of new wind plants in 2012 [6] with a total of 1,293 MW of new offshore capacity installed that year. The cumulative installed capacity offshore was 5,410 MW at the end of 2012. The majority (over 90%) of offshore wind capacity is located in Europe, with the United Kingdom alone accounting for nearly 3,000 MW. Denmark, Belgium, Germany, the Netherlands and Sweden each have over 100 MW of installed capacity. New European installations in the first half of 2013 totaled 1,045 MW [7]. China and Japan have also installed wind turbines offshore: 390 MW in China and 25 MW in Japan. No wind turbines have been installed offshore of the United States, with the notable exception of the VolturnUS demonstration project in Maine (Section III.5.d). This was launched in June 2013 to become the first offshore wind turbine in the U.S.
II.2. STATUS OF OFFSHORE WIND: CALIFORNIA

There are currently no offshore wind turbines in California. As shown in Figure 13, the National Renewable Energy Laboratory (NREL) produced an estimate of the offshore wind resource at 90 meters above the surface based on data from statewide wind resource maps at 50 and 70 meters [1]. The total resource with an average wind speed of at least 8 m/s is estimated to be 529 GW within 50 nautical miles of the coast. If areas with an average wind speed of 7 m/s or higher are included, the potential resource increases to 588 GW. This is a raw estimate of resource potential and does not account for areas that would be excluded from development due to existing usage, shipping lanes, or environmental protection.

Future offshore wind development in California would be aided by a more thorough characterization of the wind resource at hub height and identification of areas that are preferred or excluded from offshore wind energy development. Currently, measurements of wind conditions at sea are measured near the ocean surface, typically at a height of 5 meters, far below modern wind turbine hub heights of 90 meters or taller. Direct measurements with tall towers and remote measurement techniques such as, for example, floating lidar would measure the wind resource more accurately and capture important characteristics such as shear, turbulence, and extreme events.

Once sites have been identified, the main technical challenge that California’s coast presents is its water depth. While a limited number of shallow water sites might be available, the vast majority of

<table>
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<tr>
<th>Country</th>
<th>Capacity (MW)</th>
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<tr>
<td>United Kingdom</td>
<td>2,947.9</td>
</tr>
<tr>
<td>Denmark</td>
<td>921.0</td>
</tr>
<tr>
<td>China</td>
<td>389.6</td>
</tr>
<tr>
<td>Belgium</td>
<td>379.5</td>
</tr>
<tr>
<td>Germany</td>
<td>280.3</td>
</tr>
<tr>
<td>Netherlands</td>
<td>246.8</td>
</tr>
<tr>
<td>Sweden</td>
<td>163.7</td>
</tr>
<tr>
<td>Finland</td>
<td>26.3</td>
</tr>
<tr>
<td>Japan</td>
<td>25.3</td>
</tr>
<tr>
<td>Ireland</td>
<td>25.2</td>
</tr>
<tr>
<td>Korea</td>
<td>5.0</td>
</tr>
<tr>
<td>Norway</td>
<td>2.3</td>
</tr>
<tr>
<td>Portugal</td>
<td>2.0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>5,414.9</strong></td>
</tr>
</tbody>
</table>
Developable resource would likely fall in deep water. The continental shelf drops off much more steeply on the Pacific coast than the North Sea, where most offshore wind development has taken place, or in the mid-Atlantic states. Water depths of more than 50 to 60 meters are expected to require floating turbines, which are still an emerging technology.

II.3. EXISTING LITERATURE

Several prior reports discuss offshore wind technologies. A comprehensive report by the Department of Energy (DOE) provides a detailed overview of the barriers and opportunities for offshore wind in the United States [4]. The fifth chapter focuses on technology and highlights the differences between onshore and offshore turbine design drivers including corrosion, waves, size constraints and distance from population centers. The contrasts between land-based and marine environments offer opportunities as well as challenges for the development of offshore wind turbines.

The National Offshore Wind Strategy uses the barriers and opportunities identified in the above report to develop an action plan for offshore wind in the U.S. [8]. The primary goals are to reduce the cost of energy and to shorten the deployment timeline for offshore wind, specifically aiming at 10 GW of offshore capacity by 2020 and 54 GW by 2030, with the cost of energy dropping to $0.10/kWh by 2020 and $0.07/kWh by 2030. The strategy identifies key areas for research, development and demonstration.

Navigant Consulting prepared “U.S. Offshore Wind Manufacturing and Supply Chain Development” for the DOE, detailing domestic supply chain opportunities and gaps for offshore wind [9]. It also presents anticipated technological advancements in offshore wind turbines, balance of plant, and infrastructure.

Development of offshore wind capacity in California will require floating platforms to access much of the resource. Butterfield et al [10] identifies many of the engineering challenges faced by floating platforms.

A report by the European Wind Energy Association [11] examines the technologies that will be required for the offshore wind energy industry to move into deeper waters. They believe that floating platforms will be more cost effective than fixed bottom foundations for water depths greater than 50-m. The report includes a list of ongoing projects to develop floating wind turbine platforms with discussion of selected European projects.

Main(e) International Consulting comprehensively assembled descriptions and statuses of floating wind turbine designs and demonstrators worldwide [12][13].
III. TURBINE AND PLATFORM TECHNOLOGIES

III.1. COMMONALITIES WITH TERRESTRIAL WIND TURBINES

Offshore wind power initially employed the same turbines developed for onshore use with minimal adaptations. This provided a proven technological basis for the offshore wind power industry. Offshore and terrestrial turbines remain largely alike, both in currently deployed technology and in advanced technologies under development.

Rotors are largely three-bladed; rotate about a horizontal-axis; oriented upwind with an active yaw drive; and use independent full-blade pitch for power regulation. Blades are fiberglass stressed shells with limited use of carbon fiber. The ongoing trend to larger and larger rotors both on- and offshore has driven innovation research, particularly in four areas: passive load control, active load control, alternative structures, and drivetrains.

Instead of allowing aerodynamic loads to spike up during gusts, load control methods quickly react to lessen loads. This can be an economic means to limiting material utilization and costs as rotors grow larger. Passive load control methods effect this through aeroelastic response, coupling blade aerodynamics to either its composite lay-up (bend-twist coupling) or geometry (sweep-twist coupling). Significant examples of the latter include the DOE-sponsored Sweep-Twist Adaptive Rotor (STAR) project [14] and Siemens’ commercially available Aeroelastically Tailored Blade (ATB) [15][16]. Active load control uses aerodynamic mechanisms on the blade such as flaps/aileron, microtabs, morphing trailing edges, or a variety of other devices [17]. Employing a system of active sensors, aerodynamic devices, and control strategies, it can offer more refined control than passive methods, but at the cost of much higher complexity. Active load control has a long history of research and prototypes, with several concentrated efforts in recent years.

The continual growth of blades and rotors has challenged manufacturing, transportation, and installation. This has spurred innovation in blade structures, including segmented blades [18][19] and spaceframe blades [20][21]. These are intended to not only alleviate transportation difficulties – which are of lesser concern for offshore where blades could be manufactured dockside – but to piece out blades into smaller components that can be manufactured more accurately. Alternative structures for towers such as spaceframes [22] are similarly motivated.

Until recently, virtually all wind turbine drivetrains employed a gearbox to step up the low rotational speed of the rotor to the much higher generator speed. However, most manufacturers are now offering direct drive drivetrains, particularly on their newer, larger turbines. Direct drive eliminates the gearbox, a component with a long history of reliability issues. Long term reliability is particularly important for offshore wind turbines which are costlier and more difficult to access for maintenance, not only because they are on water, but also because of their size.

III.2. OFFSHORE WIND TURBINES

Basic marinisation of wind turbines includes corrosion-resistant coatings, and minimizing openings and air exchange between the environment and interior. Nacelles may be climatized-controlled with dehumidifiers and salt filters, and cooled with heat exchangers [23]. Towers may require strengthening for wave loading [4].

While strong synergies remain between terrestrial and offshore wind power design, economic drivers have pushed offshore technology on to its own path. As shown in the breakdown in Figure 1, balance of plant dominates capital expenditures of offshore wind. This incentivizes innovation.
within the balance of plant sectors, but the most obvious and visible manifestation of this is bigger offshore wind turbines.

Figure 1. Breakdown of modeled costs of terrestrial and offshore wind power installations. [3]

A larger turbine takes better advantage of the foundation, electrical interconnect, installation, and other infrastructure costs. Onshore turbine sizes have been limited by transportation constraints (e.g., overpass height, road width). In the U.S. in 2013, the average size of surveyed new wind power installations (all terrestrial) was 1.87 MW with rotor diameters of 97-m [24]. Established manufacturers are offering onshore wind turbines with 3.3 MW rated capacity and 130-m diameter rotors. Offshore turbines, on the other hand, can be manufactured and staged dockside and have grown larger, both in rated capacity and rotor diameter. In 2013, European offshore wind turbine installations averaged 3.9 MW rated capacity [25]. The Thornton Bank projects on the Belgian coast have 48 Sinovel 6.2M 126 turbines, which have a rated capacity of 6.15 MW and a rotor diameter of 126-m. 35 Siemens SWT-6.0-154 turbines (6 MW, 154-m diameter rotor) have been installed at the Westernmost Rough wind plant on the UK coast, although they have not yet been commissioned for operation [26]. Prototypes of other 6 MW or larger turbines have been installed onshore, including the MHI Vestas V164-8.0 MW (8 MW, 164-m diameter rotor) [27].

The cost and difficulty of accessing remote, on-water sites make operations and maintenance (O&M) and reliability even greater priorities offshore. Repairs could be delayed for months during seasons of rough weather and seas. Condition monitoring and predictive maintenance can be expected to become more critical. Currently, there is greater emphasis on simpler, more reliable turbine designs. This has driven most offshore wind turbine manufacturers to direct drive drivetrains with permanent magnet generators. The very large sizes of offshore turbines have also yielded other alternatives including hydraulic drivetrains (see Fukushima Shimpuu in Section III.5.c) and designs with single- or double-stage gearboxes and medium speed generators [28].
Some technologies deprecated onshore have reemerged offshore. Fukushima Mirai, Fukushima Hamkaze (Section III.5.c), and Sway (Section III.5.e) are using or have proposed downwind rotors. With the potential for more relaxed noise requirements, two-bladed rotors could be a permissible, more economical alternative to conventional three-bladed rotors. Two-bladed rotors operate optimally at higher tip speed ratios, generating more aeroacoustic noise; however, they are almost as efficient as an equal-diameter three-bladed rotor, with less the weight and cost of one blade. Sandia National Laboratories resumed research on vertical-axis turbines as an alternative for very large turbines on floating platforms [29][30].

III.3. DEPLOYED TECHNOLOGIES – FIXED BOTTOM FOUNDATIONS

Offshore wind turbine substructures can be divided into three categories based on water depth: shallow (0 – 30-m), transitional (30 – 60-m) and deep water (> 60-m). Fixed-bottom foundations can be used in shallow and transitional water depths, but become prohibitively expensive in deeper water, where floating platforms are expected to be more economical. All of today’s commercial offshore wind farms use fixed-bottom foundations. The majority are in shallow water, but more farm are beginning to be located in water deeper than 30 meters.

The most common choice of substructure in shallow water is the monopile, shown at the left in Figure 1. A monopile consists of a single cylindrical pile that is driven into the seabed. The concept is very similar to foundations used on land, although operating at sea complicates construction. Monopiles have a small footprint, limiting their impact on the seabed, although there are concerns regarding the impact of pile-driving noise on marine organisms. The choice of a monopile imposes some limitations of the type of seafloor needed: it must be relatively hard to support the pile but free of rock that would impede installation. As monopiles become longer, their resonance frequency approaches the once-per-revolution frequency of the turbine; in order to avoid damaging excitations the pile diameter must be increased, leading to greater material cost and weight [4]. Around 25 – 30-m of water depth, other foundation types are expected to become more economically attractive.

![Figure 2. Fixed foundations for offshore wind turbines. Compiled by Neddermann [31].](image-url)
Gravity-based structures (GBS) are the next most common type of offshore wind turbine foundation, although a distant second to monopiles. These do not require pile-driving; instead, a wide ballasted base anchors and stabilizes the turbine. Gravity-based foundations require a very level seafloor and a good understanding of the bottom conditions in order to avoid uneven settling and a leaning turbine. A third type of shallow water foundation that has been investigated experimentally but has not been used in a commercial wind farm is the suction bucket. This avoids the weight of the gravity foundation and the deep pile driving of the monopile by excavating a smaller “bucket” in the seafloor below the tower. The bucket is emptied forming a vacuum that holds the foundation in place via hydrostatic forces.

As water depth increases beyond about 30-m, monopiles and gravity-based foundations become much more expensive. Transitional substructures use multiple piles or a lattice structure to provide a wider base that will resist overturning while limiting the increase in material. A jacket consists of a lattice foundation that transitions to a single tower support above the water surface. The lattice reduces the surface area exposed to wave motion while broadening the base of support. Multi-piles incorporate three or more piles joined in a transitional piece that supports the tower and turbine.

To date, monopiles have been by far the preferred substructure for offshore wind turbines. Gravity-based foundations form the next-largest group, but only 16 were installed in 2012 [5] and one in 2013 [25]. At the same time, jackets, tripods, and, to a lesser extent, tripiles are beginning to form a larger proportion of new installations. However, there is some concern that developers are favoring monopiles too much and that the industry is not gaining experience with other substructures quickly enough to drive down cost of energy in the long term [32].

III.4. FLOATING TURBINE CONFIGURATIONS

As depths exceed 60-m, the economic viability of fixed foundations diminishes and floating configurations become more attractive. Floating platforms have been used extensively in the oil and gas industries, but their use with wind turbines is still new with only a handful of prototype
deployments, of which only three have been full-scale. While a broad assortment of floating wind turbine concepts have been proposed over the years, three configurations are generally considered feasible: the spar buoy, tension leg platform (TLP), and semi-submersible. These are illustrated in Figure 4.

As shown in Figure 4, the spar buoy configuration uses a long spar that is hollow and buoyant for most of its length with heavy ballast on the bottom; the center of mass is below the center of buoyancy, keeping the turbine upright. A TLP is a buoyant platform moored by multiple taut, vertical mooring lines, sometimes referred to as tendons. The lines are always in tension, stabilizing the platform. A semi-submersible uses distributed, partially submerged chambers, typically three or four; unlike the spar buoy and TLP, most of the platform volume is near the waterline.

III.4.a. General Comparison of Floating Configurations

In 2011, NREL performed a loads analysis of several floating turbine concepts [34]. A quantitative description of each concept was developed and a loads/dynamics analysis was then performed. The concepts included three variants of the University of Maine/DeepCwind Consortium’s (UMaine) research prototype (Section III.5.d) – a TLP, spar buoy, and a semi-submersible. These variants all employed the NREL 5 MW offshore reference turbine [35] at 200-m water depth. With a common turbine at a common depth, they provide an “apples to apples” comparison between the three configurations. The comparison is imperfect because optimal configuration selection is dependent on site parameters such as water depth and benthic geotechnics; however, these remain useful points
of reference. The three UMaine configurations are presented here as bases for quantitative discussion.

![Figure 5](image1.png)

**Figure 5.** Illustrations of the TLP, spar buoy, and semi-submersible UMaine floating turbine concepts modeled in the NREL loads analysis [34].

**Table 2.** Properties of the UMaine floating turbine configurations in the NREL loads analysis [34].

<table>
<thead>
<tr>
<th></th>
<th>TLP</th>
<th>Spar Buoy</th>
<th>Semi-Submersible</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter or width × length (m)</td>
<td>6.5 (column)</td>
<td>6.5 to 9.4 (tapered)</td>
<td>50 (column spacing)</td>
</tr>
<tr>
<td>Draft (m)</td>
<td>24</td>
<td>120</td>
<td>20</td>
</tr>
<tr>
<td>Water displacement (m³)</td>
<td>2,767</td>
<td>8,029</td>
<td>13,990</td>
</tr>
<tr>
<td>Mass, including ballast (kg)</td>
<td>774,940</td>
<td>7,466,000</td>
<td>13,547,000</td>
</tr>
<tr>
<td>CM location of the platform below SWL (m)</td>
<td>19.72</td>
<td>89.92</td>
<td>13.74</td>
</tr>
<tr>
<td>Number of mooring lines</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Depth to fairleads (m)</td>
<td>28.5</td>
<td>70</td>
<td>14</td>
</tr>
<tr>
<td>Radius to fairleads, anchors (m)</td>
<td>30 30</td>
<td>5.2 445</td>
<td>40.87 837.6</td>
</tr>
<tr>
<td>Unstretched line length (m)</td>
<td>171.4</td>
<td>468</td>
<td>835.4</td>
</tr>
<tr>
<td>Line diameter (m)</td>
<td>0.222</td>
<td>0.09</td>
<td>0.0766</td>
</tr>
<tr>
<td>Line mass density (kg/m)</td>
<td>302.89</td>
<td>145</td>
<td>113.4</td>
</tr>
<tr>
<td>Line extensional stiffness (N)</td>
<td>7,720,000,000</td>
<td>384,200,000</td>
<td>753,600,000</td>
</tr>
</tbody>
</table>
Because it does not employ ballast for stability, the TLP is the lightest of the three configurations, by a full order of magnitude over the spar buoy and two orders of magnitude over the semi-submersible. Weight is usually a strong indicator of material utilization and cost. However, the spar buoy is generally considered the least expensive of the three configurations, as it is the simplest and the majority of its weight is inexpensive ballast.

The spar buoy and semi-submersible are self-stable, but the TLP generally is not stable (i.e., will not remain erect) until connected to its moorings, requiring special considerations for float-out, erection, and installation. In a parametric design study of floating offshore wind turbines, Tracy [36] addressed this by making self-stability during tow-out a design requirement. His TLP designs, one of which is included in the NREL loads study as the MIT/NREL TLP, included significant ballast. This eliminated the mass advantage of the TLP, driving the mass of the MIT/NREL TLP to $8.6 \times 10^6$ kg and water displacement to 12,180 m$^3$; both of these values exceed those of the UMaine spar buoy and are on the same order of magnitude as the UMaine semi-submersible.

The TLP also requires the largest diameter and strongest mooring lines since its stability is fully derived from tension in these lines. In turn, the anchoring requirements, including the sea floor composition, are also the most stringent. The UMaine spar buoy and semi-submersible use catenary mooring lines, which take their name from the shape they assume as they extend from the surface to heavy chains on the sea bottom. Catenary mooring lines disperse loads both horizontally and vertically, lessening anchoring requirements and allowing the use of relatively simple and inexpensive drag embedment anchors. Entanglement and collision risk may be greater because they are longer than the vertical lines of the TLP (1.7 and 4.8 times longer for the spar buoy and semi-submersible, respectively) and radially extend out further (15 and 28 times further for the spar buoy and semi-submersible, respectively).

The semi-submersible has the shallowest draft with, by far, the largest mass distributed over the greatest area. These characteristics provide the distributed buoyancy which stabilizes this configuration. The shallow draft and self-stability facilitate construction and deployment; by comparison, the spar buoy can also be towed-out erect, but requires deep water ports, harbors, and channels for its extensive draft, six times greater than that of the semi-submersible. The large, near-surface wetted area of the semi-submersible render it more susceptible to corrosion and wave slapping than the other configurations.
Figure 7 shows modeled fatigue loads of the three floating configurations. Damage equivalent loads were calculated for a range of materials (parameterized by m, the Wöhler material exponent) and are presented relative to those of a land-based turbine. All three platforms perform comparably well for the majority of the loads and are on par with the land based turbine. The exceptions are the higher tower base loads, ostensibly from small angular displacements of the heavy nacelle that generate large moments over the length of the tall tower. The TLP – generally considered the most stable of the three configurations – fares best (this is somewhat an oversimplification, as freedom of motion can also ameliorate loads), although fore-aft tower base bending moments are still 50% greater than that of the land based turbine. The spar buoy incurs the highest loads in fore-aft tower-base bending moment, almost 250% of the land based turbine.

Ultimate (extreme) loads (not shown) roughly follow the same trend. The TLP incurs the lowest loads. Unlike the fatigue loads, ultimate tower base bending moments of the TLP is negligibly greater than that of the land based turbine. The spar buoy again incurs the highest loads in tower base bending moment, more than 150% that of the land based turbine.

### III.5. INDIVIDUAL PROJECTS

While there are no floating offshore wind turbines in commercial production, a number of demonstrators have been deployed [12][13][37]. A selection of these are listed in Table 3, divided by their Technology Readiness Level (TRL) [38], a measure of a technology’s progression toward commercial production. Details on selected projects are provided further below.
### Table 3. Selected full-scale and sub-scale floating wind turbine demonstration projects.

<table>
<thead>
<tr>
<th>Full-Scale Demonstration (TRL 6+, 7)</th>
<th>Subscale Demonstration (TRL 5+, 6)</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>▪ Statoil HyWind</td>
<td>▪ Blue H</td>
<td>▪ Fukushima Shimpuu</td>
</tr>
<tr>
<td>▪ Principle Power WindFloat</td>
<td>▪ Sway</td>
<td>▪ Glosten Associates PelaStar</td>
</tr>
<tr>
<td>▪ Fukushima Mirai</td>
<td>▪ DeepCwind VoltturnUS</td>
<td></td>
</tr>
<tr>
<td></td>
<td>▪ Kabashima Hybrid Spar</td>
<td></td>
</tr>
</tbody>
</table>

### III.5.a. Statoil Hywind

Hywind is a spar buoy off the Norwegian coast of the North Sea supporting a 2.3 MW Siemens SWT-2.3-82 wind turbine. Installed in 2009, it was the first megawatt-scale floating turbine deployed. It was developed by Statoil, an oil and gas company with extensive offshore experience. Several years ago, Statoil contributed data on a conceptual variant of Hywind to the computational modeling community [39]. The UMaine spar buoy of the NREL loads study is based directly on these data. Hywind is therefore largely similar to the UMaine spar buoy and has been the indirect subject of several other computational modeling studies.

Hywind was designed to accommodate a “standard” offshore turbine in depths greater than 100 m. Design maximum wind velocity and maximum significant wave height are 40 m/s and 10.5 m, respectively. It was assembled in the protected waters of Åmøy Fjord and then towed out erect 10 km west of southern Karmøy, Norway. In 2012, it produced 7.4 GWh of energy (37% capacity factor), although it was hampered by extended downtime due to grid faults and 11% lower than expected wind. Statoil estimates that production would have been 8.9 GWh (44% capacity factor) if the grid faults had not occurred. [40]

Hywind employs a novel “stabilizing floater motion” controller to attenuate platform pitch [41]. As a demonstrator, it is extensively sensored. Its design was preceded by 1:47 scale tank testing in 2005, facilitating computational tool development and calibration [41][42].

In October 2013, Statoil abandoned plans for developing a 12 MW pilot plant of four 3-MW turbines off of Maine after difficulties negotiating with the state. They are currently developing a proposal for a 30 MW pilot wind plant of five 6-MW floating turbines off the coast of Scotland. They were awarded the necessary lease in November 2013.
Table 4. Properties of the Hywind demonstrator.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbine rated capacity</td>
<td>2.3 MW</td>
</tr>
<tr>
<td>Turbine weight</td>
<td>138 tons</td>
</tr>
<tr>
<td>Draft hull</td>
<td>100 m</td>
</tr>
<tr>
<td>Nacelle height</td>
<td>65 m</td>
</tr>
<tr>
<td>Rotor diameter</td>
<td>82.4 m</td>
</tr>
<tr>
<td>Water depth</td>
<td>200 - 220 m</td>
</tr>
<tr>
<td>Displacement</td>
<td>5300 m$^3$</td>
</tr>
<tr>
<td>Mooring</td>
<td>3 lines</td>
</tr>
<tr>
<td>Diameter at water line</td>
<td>6 m</td>
</tr>
<tr>
<td>Diameter of submerged body</td>
<td>8.3 m</td>
</tr>
</tbody>
</table>

Figure 7. The Hywind demonstrator during tow-out and deployed [43].

III.5.b. Principle Power WindFloat

The WindFloat is a semi-submersible developed by Principle Power, Inc. as a “turbine agnostic” platform for any conventional wind turbine of 3 MW to 10 MW rated capacity [44]. A full-scale demonstrator was deployed 5 km offshore of Portugal in October 2011 with a Vestas V80-2.0 MW turbine.
Table 5: Properties of Principle Power’s WindFloat.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power rating</td>
<td>3.0-10 MW</td>
</tr>
<tr>
<td>Rotor diameter</td>
<td>120-170 m</td>
</tr>
<tr>
<td>Turbine hub height</td>
<td>80-100 m</td>
</tr>
<tr>
<td>Hull Draft</td>
<td>&lt; 20 m</td>
</tr>
<tr>
<td>Operational Water Depth</td>
<td>&gt; 40 m</td>
</tr>
</tbody>
</table>

The WindFloat has a closed-loop hull trim system that moves ballast between its buoyancy chambers with changes in wind velocity [45]. Heave plates at the bottom of the buoyancy chambers provide damping. Conventional moorings are used with four catenary lines to drag embedment anchors. The WindFloat is designed to be towed-out fully assembled with its turbine using only conventional tugs. It is expected to scale non-linearly such that an increase in turbine size from 3 MW to 6 MW would necessitate no more than a 30% increase in hull weight.

Principle Power was awarded Phase I and Phase II funding by the DOE for the WindFloat Pacific Demonstration Project, a 30 MW wind plant 15 miles offshore of Oregon. Five WindFloat platforms with Siemens 6.0 MW turbines are planned for completion by 2017.

Figure 8. An illustration of the WindFloat (left). The WindFloat demonstrator (right). [44]
III.5.c. Fukushima FORWARD

The Fukushima Floating Offshore Wind Farm Demonstration Project (FORWARD) comprises three floating wind turbines and a floating power substation 21 km offshore of Fukushima Prefecture, Japan [46][47]. Mirai is a semi-submersible made by Mitsui Engineering & Shipbuilding. It is paired with a Hitachi 2 MW downwind turbine with an 80-m diameter rotor and a 65-m hub. It was floated out in June 2013. Kizuna is a 25 MVA substation on a novel spar buoy connected to a 66 kV transmission cable. Unlike traditional spar buoys which are slender throughout their length, Kizuna has mid and lower hulls for vertical damping. Its installation was completed in October 2013.

Shimpuu is a V-shaped semi-submersible with a Mitsubishi Heavy Industries MWT167H/7.0 turbine. The turbine is notable for its large 7.0 MW rated capacity and its hydraulic drivetrain. Assembly of Shimpuu has been completed, and installation and commissioning are expected to be complete by December 2015 [48]. Hamakaze is planned as a spar buoy with a Hitachi 5 MW downwind turbine. Like Kizuna, it will incorporate subsurface hulls along its length. Completion will likely be beyond 2015.

![Figure 9. The Fukushima Kizuna substation (left) and Fukushima Mirai 2-MW semisubmersible (right) [48].](image)
III.5.d. DeepCwind VolturnUS

VolturnUS is a semi-submersible prototype at 1:8 scale of a 6 MW design [49]. It was deployed offshore of Maine in June 2013 by DeepCwind, a consortium based at the University of Maine. It is the first and only grid connected offshore wind turbine in the United States. The VolturnUS project was designed specifically to correctly replicate scaled global motion. Accordingly, it uses a 20 kW turbine modified to 12 kW to achieve the desired peak scaled thrust force. Its site meets wind and wave conditions as needed to simulate load cases specified by the American Bureau of Shipping Standard for Building and Classing Floating Offshore Wind Turbines. It is moored at close to its targeted scaled depth. VolturnUS has a concrete hull and composite tower.

III.5.e. Sway

The Sway concept is a spar buoy, but with a number of departures from the usual spar buoy configuration. Instead of catenary moorings, it uses a single rigid member to moor. The spar buoy
is paired to a downwind turbine, but instead of a conventional yaw bearing and/or drive at the nacelle-tower interface, it yaws passively by rotating the combined spar buoy, tower, and nacelle about a subsea pivot. Fixing the spar buoy, nacelle, and tower relative to one another allows guy wires to be used without interfering with the rotor. The guy wires provide structural support, reducing tower requirements, weight, and cost. Sway states that their design is also adaptable to catenary moorings and upwind turbines. [50]

A 1:6.5 scale demonstrator with a 14.9-m diameter rotor and 29-m tower/buoy was deployed in 2011 [51]. The demonstration project suffered a setback in November 2011 when wave heights reached 6.3 m, allowing water to enter through the inlet for the power cable and sinking the prototype. The prototype was recovered and testing resumed in 2012.

At full-scale, Sway is expected to have 2.5-10 MW capacity, with a rotor diameter up to 124-m, and a support structure up to 210-m in length. A 2.6 MW demonstration project was planned for 2013, but it does not appear to have proceeded.
specialized vessel, the PelaStar Support Barge [53]. The barge will also be a critical element of installation (including connecting the tendons to the anchors) and maintenance. In an earlier calculation, Glosten estimated that a 500 MW wind plant of 91 5.5-MW turbines requiring 49 nautical miles of on-water transit (in each direction) could be completed in 8 months with one support barge [54].

As the basis for the DeepCwind TLP, PelaStar has benefited, albeit slightly indirectly, from the 2011 DeepCwind 1:50 scale test campaign. In early 2013, the Energy Technologies Institute (ETI) began funding work on PelaStar with the ultimate goal of deployment of a full-scale demonstrator at Wave Hub, a grid-connected demonstration site 16 km offshore of Cornwall, UK [55]. The ETI funding had an initial £4M for FEED (front-end engineering design) with potentially £21M more for construction and deployment of the demonstrator. The FEED effort included [56]:

- Design of the full-scale demonstrator at Wave Hub.
- 1:50 scale testing in the MARIN Offshore Basin. This was performed over three weeks on a five-arm design with a model of the NREL 5-MW reference turbine. Tests simulated full scale conditions of 55 m water depth, 7.5 m tidal range, and 8.2 m extreme significant wave height [57]. Testing was completed in June 2013. Note that this effort was distinct from the earlier DeepCwind tests.
- A parametric design study over a range of UK site conditions including water depth, wave conditions, wind conditions, tidal range, and sea bottom composition.
- Planning for the construction, deployment, and testing of the demonstrator.

Glosten estimated completion of these efforts in Q4 2013, completion of detailed design in Q2 2014, and deployment of the demonstrator in Q3 2015 [58].

![Figure 12. Illustrations of the PelaStar and its support barge.](image-url)
IV. PROJECTIONS FOR POWER PRODUCTION AND GRID RELIABILITY CONTRIBUTIONS

Over the past decade, discussions of renewable power have gone beyond simple power and energy production, to integration with the larger grid. Grid integration looks at how a grid element (an individual or subaggregate of generation or load) interacts with the rest of the grid (the full aggregate of generation, load, and transmission). This includes a range of issues such as long-term grid reliability and the scheduling of balancing resources at various timeframes. Quantifying this requires looking not only at the amount of, for example, a generator’s production, but its timing along with the simultaneous behavior of the entire rest of the grid.

Conducting a thorough grid integration analysis of California offshore wind is currently not possible; it would require too much data that does not yet exist (e.g., actual California offshore wind power production, California offshore wind measurements at sufficient height and quality for power estimates, specific sites for plant development/installation), as well as a large amount of protected data for the rest of the grid. However, we made a number of reasonable assumptions to develop some preliminary insights into selected grid integration issues, primarily capacity value.

A study period of three years was selected, from 2012 to 2014. This captured some interannual variation in both wind and demand, and provided some interannual redundancy in dealing with practical data quality/availability issues.

IV.1. WIND SPEED DATA SOURCES

California has no sufficiently tall wind measurements offshore for wind power assessment. The National Oceanic and Atmospheric Administration’s (NOAA) National Data Buoy Center (NDBC) operates a small network of offshore buoys reporting quality-controlled, publicly available data [59]. A subset provides hourly surface wind data, with the anemometer at 5-m height (Figure 14) and wind measurements projected and reported at a height of 10-m. This is very low, but can be used as part of a Measure-Correlate-Predict methodology to project to higher heights, as presented in Section IV.2.

As shown in Figure 12 and summarized in Table 7, data from three buoys were used: Point Arena in Northern California; Bodega Bay to the north-northwest of San Francisco; and South Santa Rosa in Southern California, off of the Channel Islands. Buoys further south, off of San Diego were not included because the wind resource is too low to economically support offshore wind power development. Other buoys were rejected because of poor data availability.

The data quality of the three buoys was very good, with Point Arena and Bodega Bay at 97.8% and 99.4% availability. South Santa Rosa was slightly lower with 91.3% availability; while still good, there was an extended gap from most of 5 September 2012 to 24 November 2012. This gap spans a typically high load period (September) and a relatively low wind period (Fall) in California; it must be kept in mind when considering the results herein.

The mean wind speeds from the buoys over the three year study period ranged from 5.91 m/s to 7.23 m/s. South Santa Rosa’s mean wind speed was likely skewed slightly high by the Fall 2012 data gap. However, a review of the 2013 and 2014 annual mean wind speeds confirmed that South Santa Rosa is by far the windiest buoy site of the three. As shown in the wind roses in Figure 13, all three sites had a dominant prevailing wind direction of northwest to north-northwest, as is expected for California coastal winds.
IV.2. POWER PROJECTIONS

A Measure-Correlate-Predict (MCP) methodology was used to project the buoys’ surface measurements to wind turbine hub heights. This coupled two independent data sources and was preferred over direct extrapolation with, for example, power or log profiles because of the buoys’ very low, near surface height (5-m) relative to the target hub height (≥ 90-m). The hourly timeseries from the buoys were linearly scaled to hub-height mean annual wind speeds taken from the NREL Offshore 90-Meter Wind Speed Maps [1][60]. These maps were developed specifically for offshore wind power development, providing annual mean wind speeds up to 50 nm offshore at 90-m height and a spatial resolution of 200-m. The maps were computationally derived with bases and validation from both onshore and offshore measurements. The offshore wind map for California is shown in Figure 12.

The mean annual wind speed for each site was taken as the highest offshore speed at 90-m height within 30 mi of the buoy, but still within 50 nm of the mainland shore. Note then that the wind power site selections were made primarily based on data availability and to span a range of locations along the coast. The selection did not consider numerous factors critical to site assessment for actual project development, including existing uses, environmental sensitivities, bathymetry, proximity to staging sites for construction and installation, proximity to landing sites for electrical interconnection, etc. Although offshore hub heights already exceed 90-m and offshore turbines are continuing to grow larger, wind speeds were not projected any higher to keep estimates conservative. As summarized in Table 7, the mean hub-height wind speeds of the Point Arena, Bodega Bay, and South Santa Rosa sites over the three-year study period were 11.63 m/s, 9.5 m/s, and 9.25 m/s, respectively. In terms of wind power development, these are all high wind sites. Terrestrial sites are typically considered economical for development above mean speeds of 7.0 m/s. Bodega Bay and South Santa Rosa are NREL wind power class 6 and Point Arena is class 7, the highest defined class. Point Arena exceeds the IEC class I (the windiest of classes I-IV) mean wind speed specification. However, note that IEC specifies that offshore turbines should be categorized as class S for “special designs” beyond the more common parameters defined in classes I-IV.

For power projections, a power curve from a wind turbine with a specific power of less than 350 W/m² was used. Specific power is the ratio of a turbine’s rated capacity to its rotor swept area. It gives some indication of a turbine’s performance in different wind regimes (e.g., at a low-wind site vs. a windier site). 350 W/m² is toward the lower end of the common range and is consistent with the relatively large rotors now seen both on- and offshore. Power was normalized as we are primarily interested in generation trends, not actual power or energy. The power curve is shown in Figure 14.

The hub-height wind speed data were corrected for air density variations calculated from the buoy air pressure and temperature data. The corrected wind speeds were then convolved with the turbine power curve to give hourly power generation.

IV.3. GENERATION TRENDS

The wind power generation data were plotted as date versus hour-of-day heatmaps, shown in Figure 15 through Figure 17. Date-by-hour heatmaps are useful for examining diurnal and inter-day or longer (e.g., monthly or seasonal) patterns simultaneously. A few observations were immediately evident from the plots. All three sites spent a significant amount of time at or near rated power (1.0), more so than commonly seen at many of California’s terrestrial wind plant sites. This was expected given the high mean wind speeds across the sites.
For comparison, one year of power production from a California terrestrial wind plant is shown in Figure 18. The power is normalized and the year is intentionally omitted to protect the anonymity of the plant. California onshore sites typically are windiest during spring and summer. Driven either directly or indirectly by sea breezes, onshore wind plants are usually most productive from late afternoon/early evening into the morning, with a lull in mid-afternoon. The three study sites exhibited some seasonal and diurnal trends in power production, but they were not as pronounced as typically expected terrestrial patterns. The study sites exhibited both inter-site and interannual variation. To investigate this further, the production data were broken down further and simultaneously compared to load.

IV.4. GENERATION AND LOAD ANALYSIS

Performing a complete integration analysis requires extensive data for both load and generation across a grid control area, as well as operating parameters and constraints for generation and transmission. Information for variable and/or constrained generators with large installed capacities is particularly important, as is the case with wind, solar, and hydro. Absent this abundance of data, we can still glean significant insight into a generator’s integration impact by comparing it to load alone, the single largest and most variable grid element.

Hourly load data for the California Independent System Operator (CAISO) control area during the study period of 2012-2014 were extracted from the publicly accessible CAISO OASIS data system [61]. It is plotted as a date-by-hour heatmap in Figure 19. As expected, strong seasonal and diurnal trends were present, with the highest load hours distinct in summer and early fall afternoons.

The load and wind power production data from the three sites were broken into month-to-month diurnal profiles, shown in Figure 20. In each profile, the bold lines show the mean across the three year study period and the lighter dashed lines bound one standard deviation around the mean. The standard deviation bounds provide indication of the variability of the generation/load. Load was normalized by its maximum value over the three year period, 46.7 GW.

Hourly mean generation was high across all sites, months, and hours at 40% or well above much of the time. Point Arena hourly mean generation was above 40% for all hours of all months except September, 4:00 a.m. It was at or above 50% from February to July, and December, reaching above 57% for all hours of April and the high load month of July. There were mild diurnal trends in some months, but overall there was not a strong intraday pattern.

Bodega Bay had hourly mean generation above 49% from February to June, and December, reaching 64% in May. It was lower in the mid-summer and fall months, with the minimum ranging from 25% (September) to 37% (November). Unlike Point Arena, Bodega Bay exhibited a diurnal trend over most months with generation declining from very early morning to evening, inverse to load. It was strongest from summer to mid-fall, with the maximum diurnal swing in hourly mean generation ranging from 20 to 27 percentage points. Because of the diurnal variation, Bodega Bay actually had higher hourly mean generation values than Point Arena – 79% and 73% in May and June, respectively – even though Point Arena is a higher wind site.

South Santa Rosa had hourly mean generation above 39% for all months except October and November, reaching to a minimum of 65% and 61% in May and September. South Santa Rosa had the strongest diurnal trends of the three sites, with the maximum diurnal swing ranging from 22 to 32 percentage points in February through October, except May. During those months, like Bodega Bay, generation declined from very early morning to evening, inverse to load. The strong diurnal variation meant that South Santa Rosa had the windiest mean generation hours, even though it was
the least windy of the three sites. Maximum hourly mean generation ranged from 77% to 83% in May, June, August, and September.

At all times, the standard deviation of hourly mean generation was much higher than that of load, indicating more relative variability. This suggested a potential impact on load following, but that would depend heavily on the capacity of offshore wind relative to load, the uncertainty (forecast error) of offshore wind generation, and the behavior of other non-dispatchable generation relative to load.

IV.5. CAPACITY VALUE AND RELIABILITY CONTRIBUTIONS

Capacity value is a generator's contribution to long term grid reliability. Grid operators and utilities use a number of metrics for quantifying capacity value. Here, we use capacity factor over selected load periods, which can, for example, indicate a generator's productivity during high load hours when power is most needed. This is not as rigorous a method as, for example, Effective Load Carrying Capability (ELCC) [62], but it is transparent, intuitive, and has minimal data requirements. Furthermore, the selected load periods for the capacity factor calculation can be calibrated with a method such as ELCC.

The capacity factors at the three sites were taken over various periods, as shown in Figure 22 and Table 8. The periods included:

- Peak periods defined as peak hours (12 p.m. to 6 p.m.) during peak months. Peak months have been defined as either May through September and June through September. Both are presented.
- Peak periods as defined as top load hours over 2012-2014, including the top 10, 30, 60, and 100 hours. These are plotted in Figure 21 with the top hours marked by open circles. The top 100 hours occurred from late June to mid-September. The first, 10th, 30th, 60th, and 100th top hourly loads were 46.7 GW, 44.9 GW, 44.2 GW, 43.3 GW, and 42.8 GW, respectively.
- The study period was also divided into load deciles, in which each decile contained approximately 2,630 hours, with Load Decile 1 containing the 10% of hours with the highest loads and Load Decile 10 containing the 10% of hours with the lowest loads.
- Annual capacity factors and capacity factors for the entire three year study period were also calculated.

Annual capacity factors were high, exceeding 49% for all sites across all years, and reaching 61% at South Santa Rosa in 2012. Across the full three year period, the capacity factors of Point Arena, Bodega Bay, and South Santa Rosa were 57.4%, 53.1%, and 57.1%, respectively. There was both interannual and intersite variability. Bodega Bay was the least productive of the sites even though its mean wind speed over the three year period was higher than that of Santa Rosa (9.5 m/s versus 9.25 m/s). In 2012, 2013, and over the full three year period, South Santa Rosa’s capacity factor exceeded that of Point Arena even though its mean wind speed was much lower (9.25 m/s versus 11.63 m/s). This was likely due to South Santa Rosa’s wind speed distribution, shown in Figure 13, which was skewed toward higher wind speeds compared to the other two sites.

Point Arena and South Santa Rosa were very productive across all the defined periods (peak hours during peak months, top load hours, and all ten load deciles) with capacity factors exceeding 50%. Values for Bodega Bay were lower but still high, with capacity factors exceeding 40% during all the defined periods except the very highest load decile (38.4%). During the top 10, 30, 60, and 100 load hours, capacity factors were notably high, with Point Arena exceeding 50% and South Santa Rosa
exceeding 60%. In terrestrial wind sites, the top load hours are associated with very high temperatures and high pressure systems with stagnant air. Wind production can therefore be low during these periods, particularly when sub-selecting a small number of the very highest load hours (e.g., the top ten). This behavior was not seen in Point Arena or South Santa Rosa, but in Bodega Bay, the capacity factor over the top 10 load hours was lower than when more hours were included. Similarly, at Bodega Bay, the highest load decile had the lowest capacity factor, increased sharply by 10.5 percentage points to the second load decile, and continued to gradually increase into the ninth decile, before dropping slightly to the tenth decile.

The high capacity factors over the various high load periods indicated that offshore wind could beneficially contribute to grid reliability, particularly given the results from the Point Arena and South Santa Rosa sites. Further study and verification could be conducted with additional data, such as taller, more accurate measurements from better designated (more likely candidates for future development) sites, and generation data from the rest of the grid.
Figure 13. Map of California offshore mean annual wind speeds at 90-m height. The Point Arena, Bodega Bay, and South Santa Rosa buoy sites are indicated. [63]
Figure 14. NDBC 3-m discus buoy with an anemometer height of 5-m [59].

Table 7. Summary of buoy locations, data availability, measured mean wind speeds (10-m height), and projected hub height mean wind speeds (90-m height) from 2012-2014.

<table>
<thead>
<tr>
<th>Site</th>
<th>NDBC Station</th>
<th>Location</th>
<th>Data Availability (%)</th>
<th>Mean Wind Speed (m/s)</th>
<th>Projected Mean Wind Speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Point Arena</td>
<td>46014</td>
<td>39°14'6&quot; N, 123°58'26&quot; W, 19 nm NNW of Point Arena</td>
<td>97.8</td>
<td>5.91</td>
<td>11.63</td>
</tr>
<tr>
<td>Bodega Bay</td>
<td>46013</td>
<td>38°14'31&quot; N, 123°18'2&quot; W, 48 nm NNW of San Francisco</td>
<td>99.4</td>
<td>6.39</td>
<td>9.50</td>
</tr>
<tr>
<td>South Santa Rosa</td>
<td>46069</td>
<td>33°40'28&quot; N, 120°12'42&quot; W, 50 nm SSW of Santa Barbara, 15 nm S of Santa Rosa Island</td>
<td>91.3</td>
<td>7.23</td>
<td>9.25</td>
</tr>
</tbody>
</table>
Figure 15. Wind roses and wind speed distributions of the Point Arena, Bodega Bay, and South Santa Rosa buoys from 2012-2014. Wind data were measured at 5-m height, then projected and reported at 10-m height by NOAA NDBC.
Figure 16. The normalized power curve applied to the study sites. The reference density is 1.225 kg/m³. This was derived from a wind turbine with a specific power less than 350 W/m².
Figure 17. Normalized wind power production at the Point Arena site from 2012-2014. The data is on the normally observed clock, switching between Pacific Standard Time and Pacific Daylight Time as needed.
Figure 18. Normalized wind power production at the Bodega Bay site from 2012-2014. The data is on the normally observed clock, switching between Pacific Standard Time and Pacific Daylight Time as needed.
Figure 19. Normalized wind power production at the South Santa Rosa site from 2012-2014. The data is on the normally observed clock, switching between Pacific Standard Time and Pacific Daylight Time as needed. There is a data gap spanning most of Fall 2012.
Figure 20. Power production at a terrestrial California wind plant. The year is intentionally omitted to protect anonymity. The data is on the normally observed clock, switching between Pacific Standard Time and Pacific Daylight Time as needed.
Figure 21. CAISO hourly load from 2012-2014. The data is on the normally observed clock, switching between Pacific Standard Time and Pacific Daylight Time as needed.
Figure 22. Month-by-month diurnal profiles of normalized power production at the three study sites and CAISO load. The bold lines show the mean across 2012-2014 and the lighter dashed lines bound one standard deviation around the mean. The data is on the normally observed clock, switching between Pacific Standard Time and Pacific Daylight Time as needed.
Figure 23. CAISO load from June through September, 2012-2014. The top 100 load hours of 2012-2014 are marked by circles.
Figure 24. Capacity factors of the study sites over a variety of periods including (1) peak hours of peak months, defined as 12 p.m. – 6 p.m. from (a) May through September and (b) June through September, 2012-2014, (2) the top 10, 30, 60, and 100 load hours from 2012-2014, (3) by load decile, in which Load Decile 1 is the 10% of hours from 2012-2014 with the highest loads and Load Decile 10 is the 10% of hours with the lowest loads, (4) annually, and (5) the full three year study period from 2012-2014. Normalized load over those periods is also shown.
Table 8. Tabulated capacity factors of the study sites over a variety of periods including (1) peak hours of peak months, defined as 12 p.m. – 6 p.m. from (a) May through September and (b) June through September, 2012-2014, (2) the top 10, 30, 60, and 100 load hours from 2012-2014, (3) by load decile, in which Load Decile 1 is the 10% of hours from 2012-2014 with the highest loads and Load Decile 10 is the 10% of hours with the lowest loads, (4) annually, and (5) the full three year study period from 2012-2014. Load over those periods is also shown.

<table>
<thead>
<tr>
<th>Load (MW)</th>
<th>Load, normalized</th>
<th>Point Arena</th>
<th>Bodega Bay</th>
<th>South Santa Rosa</th>
</tr>
</thead>
<tbody>
<tr>
<td>May-Sep Peak Hours</td>
<td>35,051</td>
<td>75.1</td>
<td>58.9</td>
<td>47.2</td>
</tr>
<tr>
<td>Jun-Sep Peak Hours</td>
<td>36,199</td>
<td>77.5</td>
<td>55.2</td>
<td>41.0</td>
</tr>
<tr>
<td>Top 10 Load Hours</td>
<td>45,619</td>
<td>97.7</td>
<td>65.7</td>
<td>43.6</td>
</tr>
<tr>
<td>Top 30 Load Hours</td>
<td>44,928</td>
<td>96.2</td>
<td>60.3</td>
<td>56.8</td>
</tr>
<tr>
<td>Top 60 Load Hours</td>
<td>44,289</td>
<td>94.9</td>
<td>63.0</td>
<td>54.6</td>
</tr>
<tr>
<td>Top 100 Load Hours</td>
<td>43,761</td>
<td>93.7</td>
<td>62.2</td>
<td>49.7</td>
</tr>
<tr>
<td>Load Decile 1 (Highest)</td>
<td>37,051</td>
<td>79.4</td>
<td>53.8</td>
<td>38.4</td>
</tr>
<tr>
<td>Load Decile 2</td>
<td>31,676</td>
<td>67.9</td>
<td>57.4</td>
<td>48.9</td>
</tr>
<tr>
<td>Load Decile 3</td>
<td>29,120</td>
<td>62.4</td>
<td>56.8</td>
<td>51.1</td>
</tr>
<tr>
<td>Load Decile 4</td>
<td>27,627</td>
<td>59.2</td>
<td>57.5</td>
<td>51.5</td>
</tr>
<tr>
<td>Load Decile 5</td>
<td>26,667</td>
<td>57.1</td>
<td>58.5</td>
<td>54.4</td>
</tr>
<tr>
<td>Load Decile 6</td>
<td>25,753</td>
<td>55.2</td>
<td>58.7</td>
<td>54.7</td>
</tr>
<tr>
<td>Load Decile 7</td>
<td>24,434</td>
<td>52.3</td>
<td>56.4</td>
<td>55.1</td>
</tr>
<tr>
<td>Load Decile 8</td>
<td>23,080</td>
<td>49.4</td>
<td>58.2</td>
<td>57.1</td>
</tr>
<tr>
<td>Load Decile 9</td>
<td>21,747</td>
<td>46.6</td>
<td>57.7</td>
<td>59.9</td>
</tr>
<tr>
<td>Load Decile 10 (Lowest)</td>
<td>20,230</td>
<td>43.3</td>
<td>58.6</td>
<td>59.4</td>
</tr>
<tr>
<td>2012</td>
<td>26,892</td>
<td>57.6</td>
<td>59.7</td>
<td>57.1</td>
</tr>
<tr>
<td>2013</td>
<td>26,754</td>
<td>57.3</td>
<td>54.2</td>
<td>52.6</td>
</tr>
<tr>
<td>2014</td>
<td>26,569</td>
<td>56.9</td>
<td>58.2</td>
<td>49.5</td>
</tr>
<tr>
<td>2012-2014</td>
<td>26,738</td>
<td>57.3</td>
<td>57.4</td>
<td>53.1</td>
</tr>
</tbody>
</table>
V. CONCLUSIONS

Offshore wind power has been well adopted overseas, initially only at shallow depths, but increasingly into deeper, transitional-depth waters. Deep water requiring floating platforms, however, is nascent, with none in commercial production, only three full-scale demonstrators deployed, and a number of other concepts in various stages of full-scale or subscale development. While California may have a limited number of sites offshore for fixed-bottom wind turbines, large-scale offshore development would necessitate floating solutions. Floating platforms, then, are the critical, outstanding technology for California. Numerous other technologies are emerging or under active development that are expected to drive down offshore wind cost of energy. Some are common to or synergistic with terrestrial wind power (e.g., passive load control rotors, spaceframe blades and towers), while others are more exclusive to offshore installations (e.g., two-bladed rotors, alternative drivetrains and generators).

A preliminary study found very high potential for power production from wind power offshore of California. All three study sites exceeded 53% capacity factor over the 2012-2014 study period, with two sites exceeding 57%. Unlike California terrestrial sites, the offshore study sites exhibited diminished or almost no diurnal variation. Capacity factors were calculated over a variety of high load periods, including peak hours of peak months, top load hours, and load deciles. All three sites performed well during these periods, with two exceeding 50% capacity factor across all the defined periods. One site exceeded 60% capacity factor across all the top load hours (10, 30, 60, and 100 hours). These high capacity factors indicated that California offshore wind power would have significant capacity value and would beneficially contribute to grid reliability.
REFERENCES


[23] Siemens Wind Power, “Rising to the Offshore Challenge.”


