Article 7: Wind Farms

It is typical for tens to hundreds of turbines to be built together in what is called a wind farm. In a wind farm the turbines' supporting infrastructure and operational resources can be shared. The proximity of turbines to one another adds complexity in that they can interact with each other aerodynamically through their wakes, generally reducing the total output of the farm relative to the sum of the outputs if each turbine had operated in the absence of the other ones. This article describes the factors that are considered in siting, construction, and maintenance of wind farms both onshore and offshore. We also discuss the impacts of wind farms on their local environments.

7.1 Siting

Turbines are sited in clusters, typically from 10 to 100, in wind farms. These are projects, with common ownership, coordinated maintenance, and one or more customers. A relatively new, large onshore wind farm in U.S. might host 60 three-megawatt turbines, or a total of 180 megawatts of rated capacity.

A wind developer choosing a site for a wind farm seeks a site with high average wind speed and little variation in the speed. A steady wind direction is also advantageous, because it allows a placement of individual turbines within a wind farm that minimizes the sheltering that occurs when a downwind turbine is sitting in the wake of an upwind turbine. Environmental and societal impacts weigh heavily as well, including wildlife impacts, noise, and aesthetic concerns. Offshore siting decisions take shipping lanes, fishing grounds, and other uses of the sea into account.

The wind at any potential site is best evaluated at the height where the hub of the wind turbine will be located, and (for onshore sites) with the presence of surface obstacles like buildings and trees taken into account. Typically, a temporary meteorological mast is deployed to obtain these measurements, which are compared with data from nearby sites and longer-term records [1]. Later, a permanent mast will be installed at the chosen site to monitor ongoing performance.

Siting Onshore

When there is not already adequate supporting infrastructure, additional infrastructure must be built. For onshore sites this may entail the construction of roads, and for offshore sites this will require ports and ships. The adequacy and accessibility of available transmission lines is especially critical and can affect the timing and size of proposed wind farms.

Siting decisions for onshore turbines often involve negotiations with multiple land owners, who must grant a lease or easement and typically receive royalties for use of the land. If rights to a sufficiently large contiguous plot of land cannot be acquired, a planned farm may become two farms with land between them that is not part of either farm.

Siting Offshore

Offshore wind projects are an increasing fraction of all wind projects. Winds are typically both stronger and more consistent offshore, resulting in a higher capacity factor for the wind farm. Wind turbines can be made bigger offshore than onshore, because onshore turbine size is limited by difficulties with road transport. Wind farms can often be located closer to coastal cities than their onshore counterparts. In some locations, offshore wind patterns are better matched to electricity demand over a typical day; offshore along the U.S. East Coast, for example, wind power generally peaks in the afternoon or evening, near the time when power demand also peaks [2].

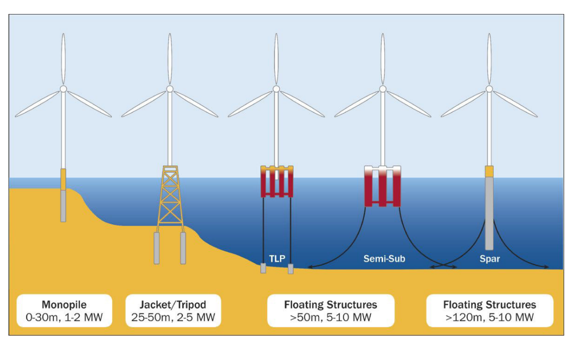

Figure 7.1: Typical foundation types for offshore wind turbines, from shallow waters (left) to deeper waters (right). Source: Bailey, Brookes, Thompson, https://aquaticbiosystems.biomedcentral.com/articles/10.1186/2046-9063-10-8.

Figure 7.2: Photo of the Horns Rev Wind Farm offshore in Denmark, with the complexity of wind turbine wakes made visible by fog. Red circles have been added to identify a turbine in the second through fifth rows behind the leading row of turbines. Source: Vattenfall, https://www.climate.gov/news-features/featured-images/wind-turbines-churn-air-over-north-sea. Red circles added by authors.

Over time, as with offshore drilling for oil and gas, gradual movement into deeper waters can be anticipated, because nearer-to-shore sites will have been developed and because there will be sites where winds are superior. Figure 7.1 shows a possible march of platform types, outward from the coast.

7.2 Interactions Between Turbines

Turbine spacing is an important factor when laying out a wind farm; it will determine the total number of turbines that a site can accommodate. If the turbines are unnecessarily far apart, the land is used inefficiently. If the turbines are too close together, the turbines experience large fluctuating loads from the wakes of other turbines, which increases the farm's maintenance costs and reduces its power output. Wind farms are designed to mitigate these wake-turbine interactions, as well as wake-wake interactions.

A well-known photo of a Danish multi-row offshore wind farm (Horns Rev 1) on a day when atmospheric conditions permitted exceptionally visible wakes is reproduced in Figure 7.2. Relative to the first row, the wind impinging on the second and subsequent rows is much more complicated.

If a dominant wind direction exists on the site, a farm's turbines may be positioned in fewer rows facing the wind, with larger numbers of turbines in each row. The turbines may also be spaced more closely along the rows than between rows. Successive rows of turbines can also be either aligned or staggered. In an aligned layout, where all turbines sit directly in the wakes of other turbines, the turbines after the first row experience a lower incoming velocity and thus generate less power [3]. In a staggered layout, output power is larger because the turbines experience only a part of the wakes of other turbines, but the wind loading across the turbine blades is more unequal, which increases the stresses on the blades and other turbine components and increases maintenance. Figure 7.3 shows an idealized staggered layout for a prevailing wind.

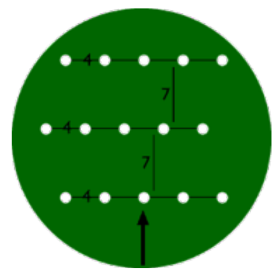

Figure 7.3: A representative staggered configuration of turbines (shown as white dots) relative to the prevailing wind direction (black arrow). The numbers are distances, measured in diameters of the circle traced by the tip of a blade – roughly twice the radius of the blade. So, the turbines here are spaced 4 diameters apart in the direction transverse to the prevailing wind and 7 diameters apart in the direction of the prevailing wind. Source: Guided Tour on Wind Energy, 2011, DWTMA; Delft University of Technology, http://mstudioblackboard.tudelft.nl/duwind/Wind%20energy%20online%20reader/Static_pages/park_effect.htm.

7.3 Construction

Roads may be the first priority in the construction of an onshore wind farm, in order to enable transport of materials to the site. Figure 7.4 displays a pair of trucks transporting a blade through an intersection, which is clearly a tight fit; sometimes roads are created solely for this purpose.

Construction of turbine foundations, drainage, and the electrical network proceeds in parallel. The electrical network includes transformers, power cables, switchgear, and data lines for the control center. Transformers at each turbine raise its output voltage, then the outputs from the farm's turbines are combined, and then the voltage is raised a second time so that the farm's power matches the voltage of the local power network [4]. The cables connecting the turbines to a substation or grid interconnection can run either underground or above ground on posts. While overhead cables are cheaper, they complicate the access of trucks and cranes to the turbines for construction and maintenance and make the system more prone to storm damage. Additionally, above-ground cables and supporting posts are not visually appealing, which can affect project approval.

The foundation and mooring for an offshore turbine are significantly more expensive than for an onshore turbine. We do not discuss offshore construction issues here.

7.4 Operation and Maintenance

The operation of a wind farm is run from a control center that processes information gleaned from meteorological equipment and a network of sensors at each turbine. Site operators monitor the operation of the turbines and can override the automated control system. Increasingly, a third party (neither the equipment manufacturer nor the wind power developer) provides the control center.

Wind power generation is a complex process with many pieces of equipment, including both moving and stationary mechanical components and a broad array of electrical systems. One reason that wind turbines are clustered within wind farms is to make maintenance less costly. Maintenance crews can move quickly and easily from one turbine to another, whether performing planned maintenance that keeps the turbines operating at high efficiency and availability, or corrective maintenance to repair faults when they arise. (Availability is the percentage of time that a turbine is available to produce power when asked.) Maintenance is typically covered by a service contract with the original turbine manufacturer or a separate company.

The frequency of maintenance will depend upon the type of equipment and its likelihood of failure, the operating history of the equipment, and the age of the plant. Sites experiencing harsh winters or high winds may need more maintenance than sites with less extreme weather. However, since all wind turbines are subject to frequently varying wind, every turbine demands regular maintenance and check-ups a few times per year. Regular maintenance ensures that the gearbox, generator, various bearings, and the braking system are in good condition and are properly lubricated. In addition to reducing the chance of failure, this increases the lifetime of the turbine, just as oil changes help to extend the life of a vehicle. Blades are cleaned to prevent their surfaces from becoming roughened due to buildup of debris and insects; even a small unevenness in the blade's shape has detrimental effects on power output.

Maintenance costs are falling as wind turbines incorporate new techniques. For example, drone-mounted cameras and sensors are now used for evaluating damage to blades, a task that would otherwise be dangerous, costly, and time-consuming – given the awkward location of the blades. Drones delivering an antifreeze fluid supply also simplify the de-icing of blades in winter. "Smart" blades with integrated sensors are enabling advanced data analysis techniques to analyze turbine power output, supplementing visual inspection.

Automation allows maintenance crews to work mostly during the day and to be backed up by remote monitoring crews who evaluate the site continuously for faults and decide when to call out the maintenance crews for urgent matters. In some cases, it may not be advisable to conduct maintenance immediately following the failure of a part. For example, if a turbine fails during the night, it may be safer and more cost-effective to wait until the daytime maintenance crew arrives, rather than employing a 24-hour maintenance crew.

The turbines at a wind farm are not necessarily all roughly alike. There are advantages and disadvantages. Operating only one type of turbine at a farm reduces operator training time and the number of spare parts that must be stocked. Operation and routine maintenance are simplified. Nonetheless, some wind farms deliberately diversify the kinds of turbines installed in order to ensure continued operation when a specific type of turbine needs attention [5] and to guard against common-mode failure. As data acquisition and monitoring become more compatible across the wind industry, the control of a wind farm with two or more turbine types is facilitated.

Figure 7.4: Source: Wind turbine blade, 274 feet (more than 80 meters) long, navigating a turn on its journey from Denmark to an experimental offshore turbine in Scotland. Source: SSP Technology, http://www.ssptech.com/solutions/blades/.

Maintenance Offshore

Maintenance is more difficult for offshore than onshore turbines. Poor weather can necessitate waiting several days or more before a maintenance crew can get onsite for repairs following a breakdown. It therefore pays to make offshore turbines significantly larger. The capacity of a typical new onshore turbine is three megawatts, compared to six megawatts for an offshore turbine, and designs of 12 megawatts and above may be the offshore norm in the near future.

A major consideration for offshore turbines compared with onshore turbines is corrosion. The materials used for the components of an offshore turbine must be corrosion-resistant or they must have robust coatings, increasing costs. Some offshore turbines have a sealed and dehumidified nacelle that prevents moist, salty air from entering.

7.5 Environmental Impacts

Wind farms affect the local environment in many ways. Visual impacts and noise are particularly important, but there are also microclimate impacts on farming, and direct detrimental impacts on other species, notably birds and bats. Indirect impacts are associated with the energy use embodied in the wind farm's components and incurred during its construction.

Visual Impact

The visual impacts of a turbine are both near and distant. Nearby impacts for land-based wind turbines include shadows and flicker. With multiple turbines rotating in a wind farm, the flicker can be more prominent as the blades intercept sunlight at different times. As for the more distant impacts of wind farms, these are sometimes framed as intrusions on landscapes or seascapes and have driven siting decisions in many instances. Onshore, consideration of only the most desirable winds can point to a site on a mountain ridge, but this may be where hikers have their most treasured views. Offshore, at least in the U.S., the distance of a wind farm from land can be pushed upward by political pressure from coastal communities concerned about property values and seascapes.

Wind turbine projects offshore may soon involve 12-megawatt turbines. The blades of one such turbine are 110 meters long and their tower is 150 meters tall, so the tip of a blade straight up extends to 260 meters. If sited 30 kilometers (20 miles) from the shore, the tops of the towers in the daytime, viewed from the shore on a clear day, would be short faint straight lines sticking upward out of the ocean. The lights at the tops of the towers that warn aircraft would be visible from the shore on a clear night. A sense of the size of such a turbine is conveyed by Figure 7.5. The heights listed for the turbines are the distance from the top of a blade pointing straight up to the ground or ocean surface underneath.

Noise

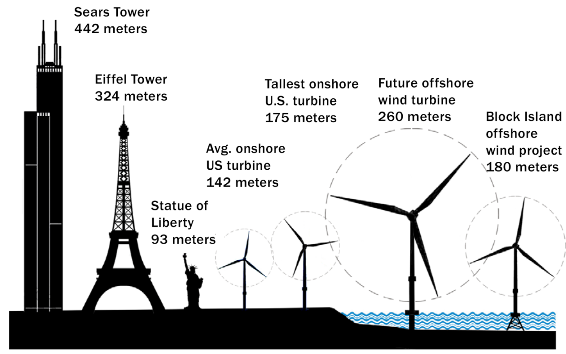

Figure 7.5: Offshore wind turbines are already as large as the largest wind turbines and are slated to become much larger. Wind turbine sizes are compared to the Sears Tower in Chicago, Statue of Liberty in New York City, and Eiffel Tower in Paris. Dashed circle indicates the path of the blade tip. One meter is 3.28 feet. Source: Bumper DeJesus, Andlinger Center for Energy and the Environment.

As the blades of a turbine rotate, they generate pulsating sound at both audible and sub-audible frequencies. The audible component can adversely affect health by producing stress, headaches, and troubled sleep [6]. Since wind farms are generally located in areas that do not have large structures around them (as that would impede the wind), the noise from a turbine propagates easily. Moreover, the noise from a wind turbine is greater when the blades rotate faster. As a result, turbines are designed with a ceiling on their rotation rate.
In Figure 7.6, an auditory impact map from a study of a wind farm in Maine is shown. Here the color scale

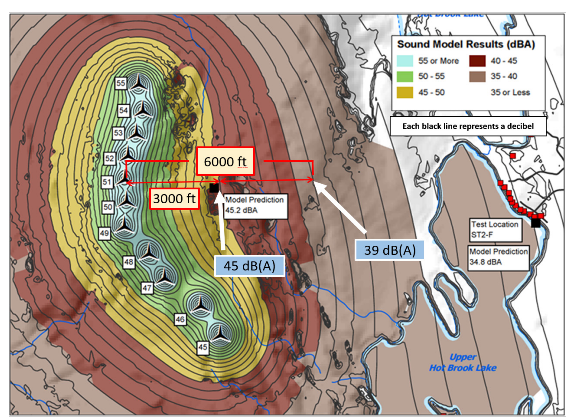

Figure 7.6: Simulations of the noise impact for a hypothetical wind farm along a ridge in Maine. Source: Prepared for VPIRG by Bodwell EnviroAcoustics, https://www.vpirg.org/issues/clean-energy/wind-power/faq/.

is shown in decibels, a measure of sound intensity. The noise level decreases when moving away from the turbines, which form a row down the left side of the map. The decibel contours for 45 and 39 decibels are highlighted and are roughly 3,000 and 6,000 feet (1,000 and 2,000 meters) from the turbines, respectively. This study influenced a decision by the State of Vermont to require that the noise at night from any wind farm built in the state cannot exceed 39 decibels immediately outside any residence.

Microclimate

Large onshore wind farms increase the turbulence of the air and decrease the local wind speed as energy is extracted by the turbines, resulting in a unique "wind farm microclimate" [7]. In many cases it is unclear how the farm will affect features of the local environment such as temperatures, heat fluxes, moisture in soil, and rainfall. Simulations suggest that wind turbines increase the transport to the Earth's surface of the drier air high in the atmosphere, which increases evaporation and transpiration [8] and modifies the energy exchanges between the surface and the atmosphere [9]. A study in 2012 conjectured that wind turbines were partially responsible for a 0.7 degree Celsius (1.3 degree Fahrenheit) nighttime warming over 10 years in a large area of west-central Texas [10]; the wind turbines may be disrupting nighttime stratification of cold air close to the ground by mixing it with warmer air above.

Impacts on Wildlife

The effects of onshore wind farms on plants and animals in surrounding areas can strongly affect their siting. The rotation of the blades of a wind turbine can kill birds and bats. Wind turbines can also indirectly influence the migration routes of birds, their patterns in flight, and their choices of habitats for foraging, breeding, and nesting [11].

To mitigate these impacts, wind farms can be located away from migration corridors and nesting and roosting sites. In some instances (more for bats than for birds), wind farm operation is curtailed at certain times of the year and in certain low-wind conditions [12]. Turbines and blades have been modified to make them easier for birds and bats to detect; as the blades get larger, they will become easier to detect, and the incidence of bird and bat fatalities should fall. As for other terrestrial animals, the main negative impacts are during construction.

On the other side of the ledger, there is evidence that wind turbines may actually improve plant growth, since warmer air pushed downwards during the evening hours may prevent dew from forming on the leaves and reduce mold. Livestock often graze right up to the base of a turbine and can use its shadow for shade.

For offshore wind farms, the permitting process may require explicit consideration not only of plant construction but also of plant decommissioning several decades after the installation, with requirements in both cases for specific attention to measures that will minimize disturbance to marine life [13].

Embodied Energy, Land, Material, and Water Use

Water and energy are required to construct and operate a wind farm. Water inputs for wind power are minimal during construction and operation [14] – somewhat lower than for solar power, which requires water for the fabrication of solar cells, and much lower than for power from coal, natural gas, and nuclear power, where the power plants use water both during construction and for cooling when they are operating. The largest energy inputs to a wind turbine occur where the concrete, steel, and other materials are made. Estimates of the energy payback (the time required for the wind turbine to produce as much energy as was required for its fabrication and installation) depend on the specific site but are generally around six months [15]; turbines running at high capacity and in high winds generally have shorter payback times. While running, wind turbines have no air pollution or carbon emissions other than minor on-site emissions associated with auxiliary operations.

By weight, steel, copper, and concrete are the primary materials. Permanent magnets, used in an increasing fraction of new turbines, also use rare-earth minerals such as neodymium, dysprosium, and terbium. While there are supply concerns, the global resources themselves appear to be adequate, relative to projections of future needs for wind power [16].

Because wind turbines must be far apart so that one turbine does not adversely affect the performance of another, a wind farm occupies a lot of land. However, uniquely, a wind farm is compatible with many other uses of the land, including agriculture and animal grazing. Wind farms modify the land significantly less than coal mining, oil and gas extraction, solar farms, or biomass plantations [17].

End-of-Life Considerations

As the wind industry matures, valuable experience is being gained about the trade-off between keeping a component running and replacing it – typically with a component that is more efficient and requires less maintenance. Large-scale replacement, called "repowering," may involve the swapping of major turbine components (the blades, the generator) [18]. An after-market for the replaced equipment is developing, enabling some of the costs of repowering to be offset. Some steel and copper will be reused and some recycled [19].

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