A Literature Analysis of Offshore Wind Energy

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Table of Contents

Executive Summary

The current renewable energy industry is heavily tipped towards wind power. Efficiency, relatively low maintenance, and reliability are a few of the reasons why wind energy projects are underway across the United States. While the effectiveness of a wind turbine alone is certain, the entire success of wind farms relies solely on the wind itself. Unpredictable, powerful, inconsistent, and relentless are all words that could be used to describe wind. With technological advancements and a global turn to cleaner energy sources, the wind energy industry has become one of the fastest growing industries in the nation. Previously untapped wind sources are becoming some of the most profitable pieces of land and sea. Offshore wind has advantages and disadvantages which will be explored in this analysis. Diurnal and seasonal patterns resulting from the fluctuations in the planetary boundary layer directly affect wind turbine output. Land and sea breezes are critical to the analysis of onshore and offshore wind developments. Extreme weather events must not be neglected when designing and implementing wind farms so that said farms satisfy national safety standards and pose the least possible threat to their environments. There is no better way to understand a turbine's efficiency and the industry than by studying current developments, both onshore and offshore. For this reason, this paper examines existing wind developments to better understand wind industry trends and changes. The report that follows is compiled from tens of reputable journal sources and serves to educate the reader on offshore wind power, as a whole.

Wind Patterns

Wind is the result of differences in air pressure. This difference is caused by the sun, as it heats up different parts of the planets unevenly (National Geographic, 2016). As the warmer spots heat up, air expands and rises higher into the atmosphere leaving behind an area of lower pressure. The cooler spots, on the other hand, end up having a higher pressure, thus the cooler air flows into the warmer spots to fill the void (Wonderopolis.org, 2015). Since the shape of the planet and its orbit around the sun are mostly constant, wind patterns begin to emerge.

Different regions on Earth have their own wind patterns that are controlled by many variables including contact with bodies of water, time of day, geographical location, and season of the year. Some important aspects of a region's wind patterns are the prevailing wind and dominant winds there. The prevailing wind in a region is a wind that blows predominantly from the same direction on the surface of the Earth there (NWS Internet Services Team, n.d.). The dominant winds are similar to the prevailing wind, however, the difference is that they are "the trends in direction of wind with the highest speed" over that location (NWS Internet Services

Team, n.d.). The prevailing and dominant winds in different regions are very much related on a global scale. Since the equator is oftentimes the closest part of the planet to the sun, it is also the warmest, thus it has a lower air pressure compared to the poles. However, due to the rotation of the Earth, there is an excess amount of air at about 30 degrees north latitude and 30 degrees south latitude which causes higher air pressure there compared to the poles (NWS Internet Services Team, n.d.) resulting in global wind patterns shown in figure 1.

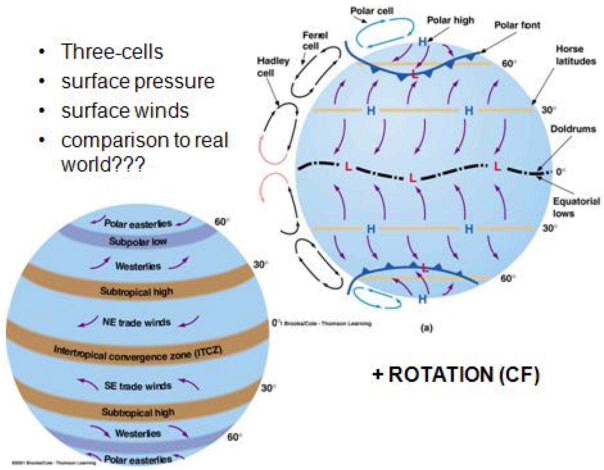

Figure 1: Global Wind Patterns (NWS Internet Services Team, n.d.)

Focusing now on the Northeast US, wind patterns there are predominantly influenced by the Ferrel cell. The Ferrel cell is an atmospheric circulation cell for weather located between 30 and 60 degrees latitude. In this cell, the air flows east and towards the north pole when near the surface, and it flows west and toward the equator at high altitudes (NWS Internet Services Team, n.d.). The prevailing and dominant winds in Northeast regions in the United States are generally from the west and oftentimes come from the southwest during summer months, while during winter months they come from the northwest (National Climatic Data Center, 2015).

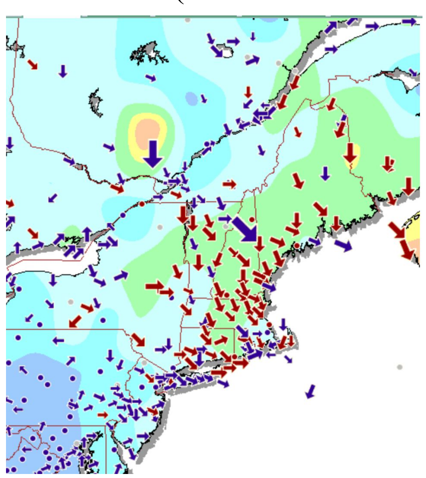

Figure 2: Prevailing Winds in Northeast US (Wind Map, 2020)

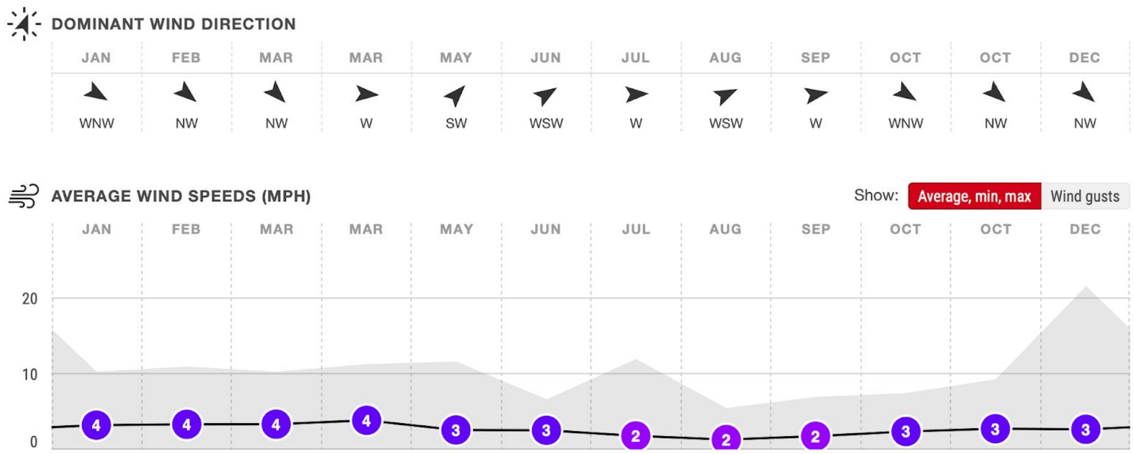

Figure 3: Dominant Wind Direction and Speeds in Brooklyn, New York (Windfinder.com, 2019)

These wind patterns have a big influence on the climate in this region. For example, New York State's climate is greatly influenced by the flow of three air masses. The first is the masses of cold, dry air arriving from the northern interior of the continent. The second is the prevailing winds from the southwest carrying warm, humid air from the Gulf of Mexico (National Climatic Data Center, 2015). The combination of these two air masses result in the dominant humid continental characteristics of the climate there. Finally the third and least influential air flow is the one inland from the Atlantic Ocean which creates the cool, cloudy, and damp weather conditions mostly noticed in the southeast region of the state (i.e. New York City) (National Climatic Data Center, 2015). Although the last airflow plays a smaller role when characterizing climate and weather conditions inland, it does have a significant influence on wind conditions offshore, which is important to consider when developing offshore wind farms.

Land and Sea Breezes

Land and sea breezes are the result of differences in temperature between the land and water. During the day, land heats much faster than water because water reflects most solar radiation and has a high heat capacity whereas land absorbs most solar radiation. This results in sea breeze causing lower pressure over the land than the ocean during the day and thus winds to blow from the water to the land. Land may heat faster than water but it also cools faster than water. Thus, at night, land breezes cause wind to blow from the land to the warm, low pressure water (weather.gov).

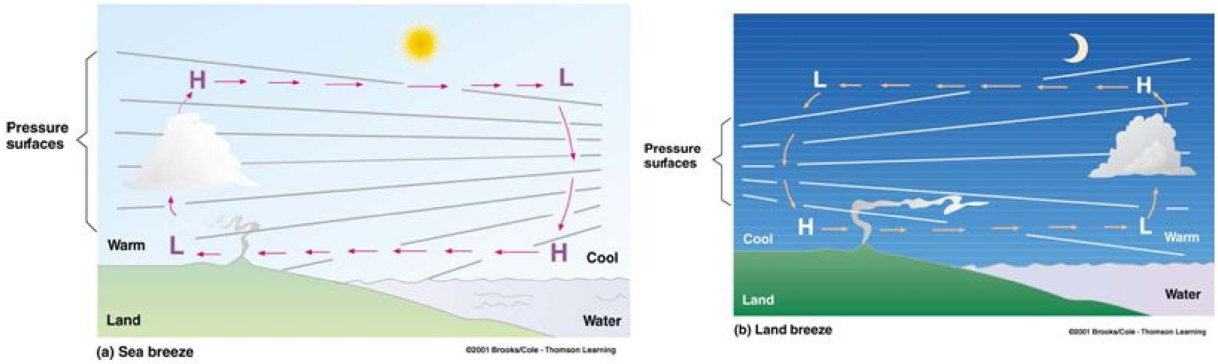

Figure 4: Land and Sea Breezes (NWS Internet Services Team. n.d.)

In New York's case, this effect may be exacerbated by the high density populations and concrete cities which cause urban heat islands in New York City and on Long Island. Land and sea breezes have been notoriously hard to predict but new techniques have emerged that allow us to better predict and thus capture these breezes' energy. Strong sea breezes as far offshore as 90 miles coincidentally occur during peak electricity demand periods from the months of March through September (Seroka et al). Traditionally, renewable energy generation technologies have not been able to handle the ramping up of power generation during peak demand hours forcing us to rely on fossil fuel powered peaking power plants. By capturing strong wind energy from sea breezes, offshore wind farms will be able to combat our power grid's peak loading problem.

Planetary Boundary Layer Phenomena

The planetary boundary layer (PBL) is the portion of the troposphere that is impacted by the characteristics of Earth's surface via rapid vertical exchange processes, primarily by turbulence (Panofsky, 1985). This turbulence determines the dynamical structure of the flow within the PBL. The turbulent flow "contains irregular quasi-random motions spanning a continuous spectrum of spatial and temporal scales. Such eddies cause nearby air parcels to drift apart and thus mix properties such as momentum and potential temperature across the boundary layer" as seen in Figure 5 (Holton & Hakim, 2013). These disturbances result in the transport of heat and moisture away from the Earth's surface, which helps maintain surface energy balance. Additionally, these unresolved turbulent eddies are responsible for transporting momentum to the surface, which maintains momentum equilibrium. This process "dramatically alters the momentum balance of the large-scale flow in the boundary layer so that geostrophic balance is no longer an adequate approximation to the large-scale wind field" (Holton & Hakim, 2013).

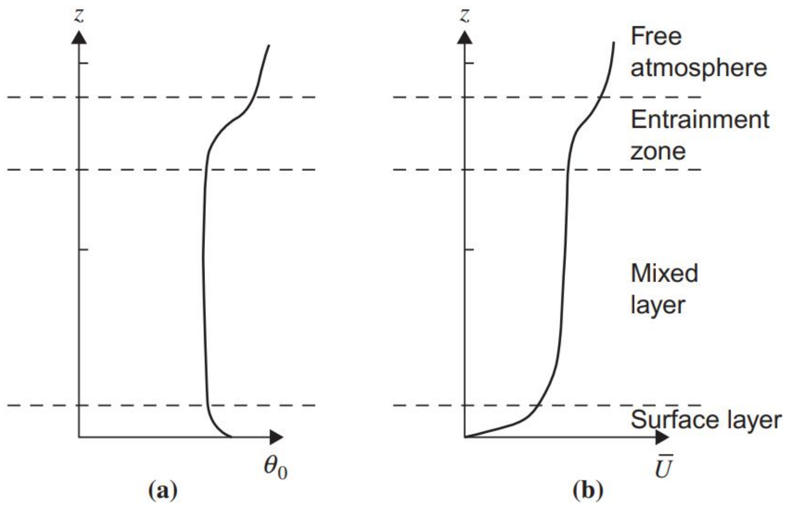

Figure 5. (a) Mean potential temperature, θ_0, and (b) mean zonal wind, U, profiles in a well-mixed boundary layer (Holton & Hakim, 2013).

There are two types of turbulence: mechanical and convective. Mechanical turbulence is caused by powerful winds found close to the ground. Convective turbulence is at its strongest when the atmosphere has been heated from below. Convection is the dominant force throughout the PBL on sunny, light-wind days over land. As wind speeds pick up, mechanical turbulence becomes critical the closer it is to the ground (Panofsky, 1985). The behavior of mechanical turbulence determines the characteristics of the entire PBL, both day and night over land and water, only when strongs winds sweep across a region. The strength of mechanical turbulence within the planetary boundary layer varies with height; an increase in height results in a rapid decrease in mechanical turbulence, as seen in Figure 6. Therefore, convection is the dominant force at the top of the PBL, even when wind speeds are more moderate, because it is able to determine the thickness of turbulence experienced over land. The effects of convection over water are generally negligible, unless the region is experiencing the presence of cold air over warm water (Panofsky, 1985).

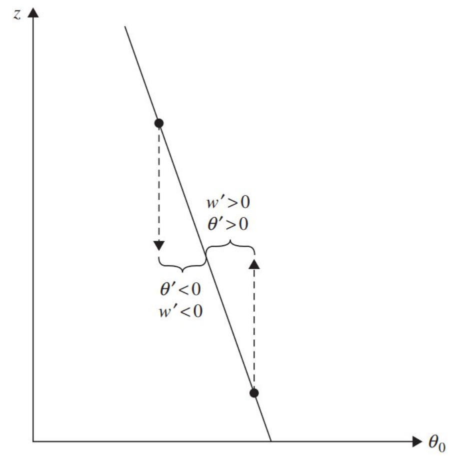

Figure 6. Correlation between vertical velocity (w) and potential temperature (θ) perturbations for upward or downward parcel displacements when the mean potential temperature θ_0(z) decreases with height (z).

As mentioned previously, the characteristics of this phenomena vary strongly from day to night and from land to sea. During the daytime, the thickness of the planetary boundary layer can be defined by either the height of considerable turbulence (h), or the height of the lowest inversion (z), which is also known as the part of the atmosphere affected by surface heating. A "useful parameter in the description of the daytime boundary layers is the Monin-Obukhov length (-L), which is proportional to $\tau^{3/2}$ (τ is the surface stress) and inversely proportional to heat fux" (Panofsky, 1985). On clear windy days, -L is typically 100 m. On clear days with weak winds, -L is usually only 5 m. When z > -L, mechanical turbulence within the PBL becomes negligible as convective turbulence dominates. The region above z = -L is often referred to as the turbulent, or "mixed layer" of the PBL. In this layer, wind direction, wind spread, and potential temperatures are constant with height (Panofsky, 1985).

Contrastly, only mechanical turbulence that is driven by wind force over land can exist within the planetary boundary layer during nighttime. This is because the maximum cooling that occurs at the surface dampens the turbulence by stratification. At night, light winds result in weakened turbulence and a slowed vertical transfer of momentum, heat, and moisture. During these conditions, the depth of the mixed layer usually is rather small (around 100 m), depending on the wind speed. Heat transfer by infrared radiation becomes relatively important at the top of the turbulent layer and above. Surface cooling is then extended above the turbulent (mixed layer). Therefore "the PBL (the layer modified by surface changes) can be much thicker than the mixing depth (the turbulent layer). Typically, the PBL extends to the top of the surface inversion, but the mixing depth is much smaller. This difference has led to considerable confusion in the definition of the thickness of the nocturnal boundary layer" (Panofsky, 1985). These complications are also increased by the presence of thin turbulent layers, driven by local shear, that are created upon separation from the main turbulent region. The PBL can be known to undergo abrupt changes due to local processes that can occur on some nights. Oftentimes after sunset, there is a tendency for the wind above 100 m to accelerate once the mixing between upper and near-surface air has ceased. During some nights “when the surface cooling is not excessive, the wind shear becomes sufficiently large enough to cause mechanical turbulence through a thick layer, producing increasing temperature, winds, and turbulence at the surface. This destroys the shear, and further cooling at the surface reestablishes the less turbulent conditions that had prevailed previously” (Panofsky, 1985).

Observing satellite imagery over sea surfaces can often show large areas of coherent streaky structures that are caused by instability patterns within the planetary boundary layer. This phenomenon can be identified as boundary layer rolls. In a scientific article titled “A Case Study of Offshore Advection of Boundary Layer Rolls over a Stably Stratified Sea Surface”, researchers have defined these rolls as “elongated vertical circulations aligned approximately in the along-wind direction, consisting of counterrotating vortices, creating areas of alternating up- and downward motion. This vertical wind speed pattern also translates into the horizontal wind field, where lower horizontal winds are seen in the upwind regions and higher in the downwind regions, which makes it possible to observe the rolls in satellite images where wind speed is inferred from backscatter from the roughness elements at the sea surface” (Svensson, Sahlée, Bergström, Nilsson, Badger, & Rutgersson, 2017). These boundary layer rolls have led to considerable increases in vertical fluxes of momentum, heat, and moisture. They have also been attributed to the initiation of both deep convection and storm development.

Studies have shown that advection of land features across a coastline is possible and can affect the conditions offshore for long time periods and large offshore distances. Simulations have determined that boundary layer roll circulations of more than 3 m/s at 100 m height have resulted in the presence of wind speed variations for as long as 11 hours of the day. The horizontal wind speed variations present during this time were found to be at their largest at around these heights. This is crucial for offshore wind technology because modern wind turbines are typically erected around similar heights of 80 to 160 m. This increases the uncertainty of wind speed estimates, which can be of importance for short term wind power forecasts (Svensson et al., 2017). The PBL phenomena is important to consider when analyzing the effectiveness of offshore wind technology at a potential site, because it has a direct impact on the diurnal and seasonal winds that are present within the area.

Diurnal and Seasonal Wind Patterns

To understand the common fluctuations in wind farm output, one must first explore diurnal and seasonal wind patterns around the United States. Diurnal means pertaining to changes that occur during each day. Seasonal refers to the four major seasons, fall, spring, summer and winter, which occur in specific time intervals over the course of one year. Understanding these variations is key in planning for consumer demand during each time period. With more reliable predictions of demand and system output, grid operators can better prepare for peak loads and conserve energy by only powering gas plants, and other sources of energy, when specifically planned.

The aforementioned boundary layer phenomena is known to affect diurnal fluctuations in wind speed. The cycle from daytime heating and nighttime cooling causes higher winds to reside above the earth's surface during evening hours. As low altitude temperatures begin to increase during the morning hours, the winds which previously resided at higher altitudes start their gradual descent to the earth's surface. This phenomena results in daytime gustiness and nighttime peace and calm. (Halblaub, 2014) Naturally, this variation directly impacts offshore wind developments and is studied continuously when surveying a potential wind farm site.

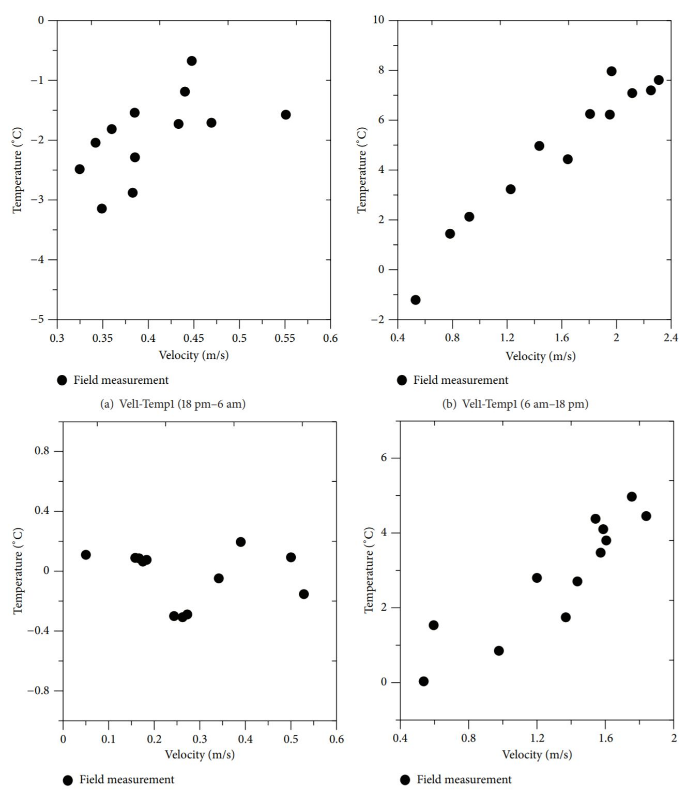

Figure 7. Distribution between wind velocity and temperature. (Kim, K. You, J. You, 2014)

It is in California's best interest to install a wind farm which will output maximum power during the summer months, due to the need for energy to power air conditioning units. This led California to study locations all along its coast, in search of a site with strong winds during the months of June, July and August. The National Buoy Data Center (NBDC) placed 20 buoys off California's shore in 1980. Two said buoys were over 50 miles offshore and were not considered in the following figures. Six more buoys were disregarded as these locations had a capacity factor lower than 30%. The average estimated wind power output, compiled from all the buoys studied, displays a peak around 1 am and a valley near 6 pm, seen in Figure . This diurnal variation is likely caused by the sinusoidal heating and cooling of the earth's surface and near-surface area i.e. boundary layer phenomena. Without another source of power, the grid would be unable to meet consumer demands during the peak hours of 4-7pm. For this reason, wind cannot be the only source of power until a reliable, green, energy storage system is implemented.

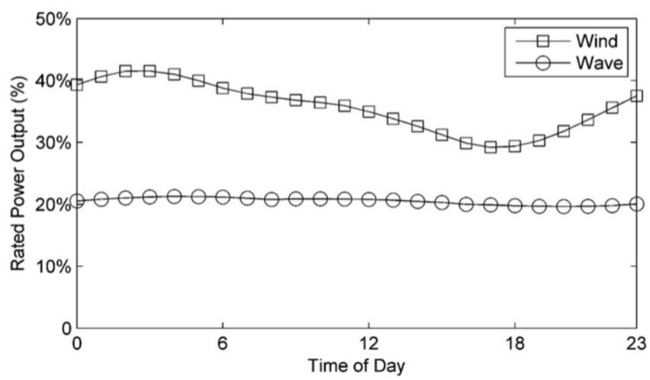

Figure 8. Average rated power output for an offshore wind farm or wave farm for each hour of the day for the summer months for all buoys and all years with quality annual records. (Stoutenburg, Jenkins, & Jacobson, 2010)

The study, carried out by the NBDC, used the logarithmic law assuming neutral atmospheric stability conditions, to estimate the wind speed 80 meters above each buoy. This neutral assumption is actually conservative in respect to wind speed, since the atmosphere is usually stable over the Pacific Ocean off California. The graph below was composed using 11 years of data from Buoy 14, and represents the general trend of most buoy outputs during this period.

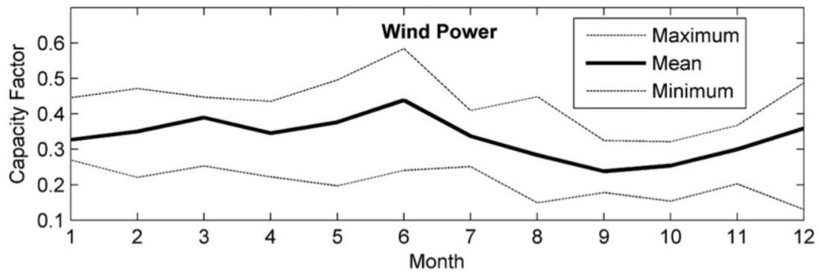

Figure 9. Monthly capacity factors of wind energy for a representative buoy, buoy 14 at Port Arena. (Stoutenburg, Jenkins, & Jacobson, 2010)

As seen in the figure above, there is a clear correlation between a potential wind farm's capacity factor and month. A downward trend in capacity factor was recorded in this specific area, during the summer months. This is a common phenomenon that occurs at most sites.

In the next study, high-resolution numerical simulations were performed from 2002 to 2008, using the atmospheric portion of the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS) (Jiang, et al., 2008). Two major, potential wind farm sites were of interest; Cape Blanco and Pt. Arena. The site off of Cape Blanco is of particular importance because there is a large increase in mean wind speed during the summer months. This is favorable for California as peak load occurs in the summer, as energy consumers use air conditioners. Installing an offshore wind farm in this location could drastically improve the load duration curve in the state of California, as the peak could be mitigated by the addition of wind.

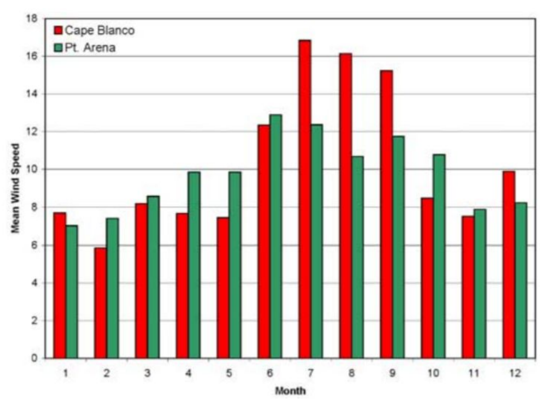

Figure 10. Histogram of the monthly mean wind speed for 2005 at the 90-m level offshore of Cape Blanco and Point Arena. (Jiang, et al., 2008)

The general trend is normally opposite, with higher wind speed during the winter months and lower wind speed during summer. The specific locations chosen in this study are outliers which will benefit California's load duration curve, if chosen as sites for offshore wind plants. While some regions may have strong average annual wind speed, planners may not select those sites if they do not provide power during the peak months of energy usage. A location must have reliable, strong winds during the necessary months to convince investors and governments to move forward with the multimillion dollar project.

Extreme Weather Events

The greatest hindrance for offshore wind development is deep water. The United States' Pacific Coast as well as the coasts of Hawaii and Maine have deep waters that make offshore wind development technologically and economically unfeasible for the foreseeable future. This leaves the country with the Atlantic coastline stretching from Massachusetts to Florida as well as the Gulf of Mexico suitable for offshore wind developments. In this regard, New York State is fortunate to have acceptable depths for wind turbines. Unfortunately, these areas bring along with them their own set of issues, namely hurricanes. Hurricanes present very challenging structural problems for wind farms. Due to climate change, both sea levels and the occurrence of hurricanes and tropical storms have been increasing and are predicted to increase further, exacerbating the greatest developmental obstacles for offshore wind energy development.

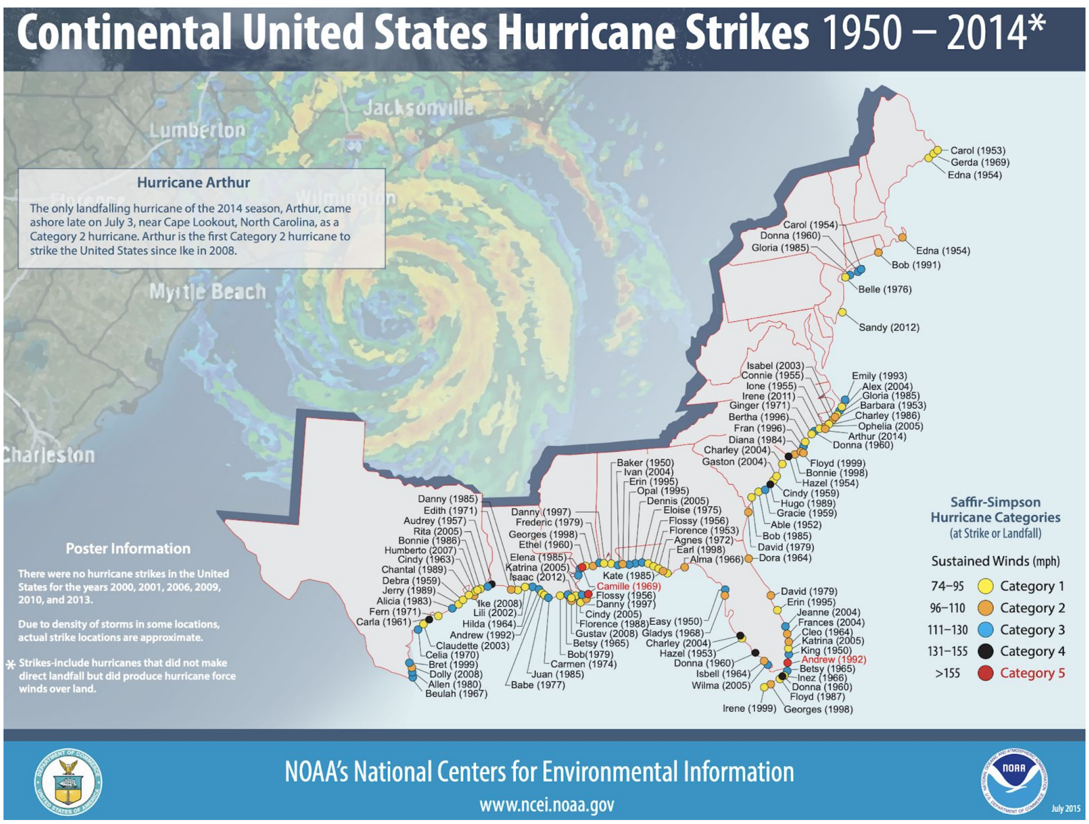

Figure 11: US Hurricane Strikes (NOAA n.d.)

Figure 1. Master Plan Offshore Study Area

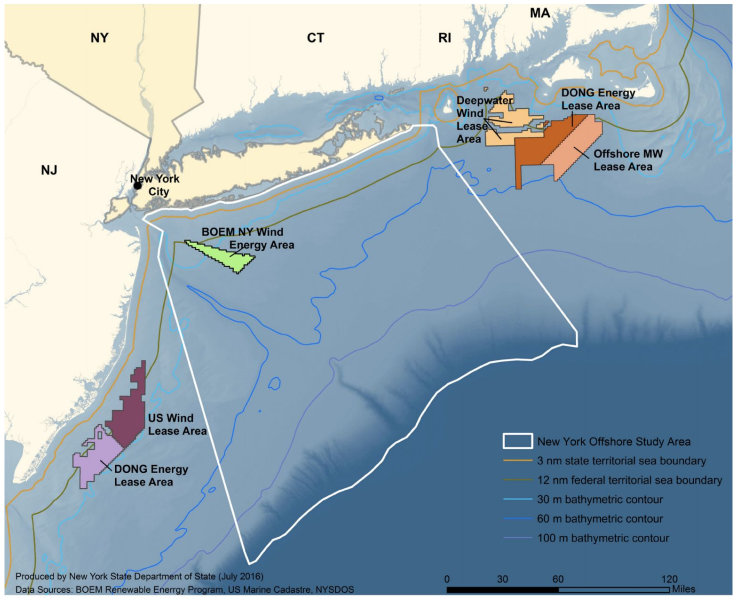

Figure 12: New York State Master Plan Offshore Study Area (NYSERDA n.d.)

New York's goal is to have wind farms at least 20 miles beyond the coast to prevent them from being seen from the shore. New York State has been hit with few high strength hurricanes, while Hurricane Sandy in 2012 was catastrophic on land, it was still a Category 2, something that wind turbines are built to deal with.

Saffir-Simpson Hurricane Scale		
Category	Wind speed (mph)	Storm surge (feet)
5	156	More than18
4	131–155	13–18
3	111–130	9–12
2	96–110	6–8
1	74–95	4–5
Additional classifications		
Tropical storm	39–73	0–3
Tropical depression	0–38	0

Figure 13: Saffir-Simpson Hurricane and Storm Scale (Seth, 2017).

Offshore wind farms are designed to be able to withstand Categories 1-3 hurricanes. Following the Saffir-Simpson Hurricane Scale, offshore wind turbines actually produce power optimally in tropical storms with wind speeds up to 55 mph. Past the turbine's cut out speed is when the turbine goes into a protective mode. Just as the wind turbines face into the wind to produce the greatest amount of power during normal operation, the turbine's yaw drive aims to keep the blades facing into the wind during a storm. This reduces surface area and thus stress on the blades. This defense mechanism works well, but once wind speeds reach hurricane category levels 4 and 5, the yaw drive is often not able to react quickly enough to the rapidly changing and unpredictable winds. Winds can be coming from two different directions, putting multidirectional forces on the blades which can lead to damage (Energy.gov n.d.).

The next effect of extreme weather on offshore wind turbines are the violent and strong surges of waves. Hydrodynamic loading can vary greatly from site to site based on its water depth, wave heights and wave periods and in depth analyses of each site location are needed to protect farms. Wave shoaling is an effect well understood in fluid dynamics that occurs when the water depth becomes less than half the wavelength of a wave. Not all offshore wind developments are shallow enough that they have to worry about shoaling, but we must consider it when planning future offshore farms. To combat shoaling effects, it was determined that larger diameter support structures increase the diffraction effect and suppress an increase in wave force from shoaling (Jeong, 2019).

Extreme weather can impact more than just the turbines themselves. Block Island faces a shutdown later this year after sections of the cables installed to bring energy back to land became unburied due to the strong underwater currents after tropical storms (Lee, 2020).

One critique of current offshore technologies is that they have simply taken onshore wind turbine designs and combined them with the borrowed offshore geotechnical knowledge of offshore oil drilling rigs. This approach works and is cost effective but new technologies such as downwind wind facing turbine blades allow the blades to be more flexible and more capable of bending instead of breaking in the high wind speeds of stronger hurricanes (Koh, 2015).

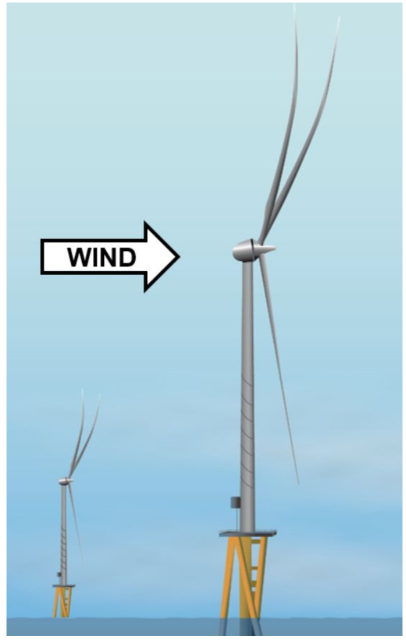

Figure 14: Downwind Wind Turbine Design (Hartman).

New designs specifically designed for offshore applications would also allow wind farms to be built in deeper waters and in areas with stronger and more frequent hurricanes such as the Gulf of Mexico. Further research is needed but with new designs, the scientific community hopes to be able to implement offshore wind farms without having to worry about the destruction of extreme weather events that we deal with today.

Advantages and Disadvantages of Offshore Wind Energy

Wind turbines are enormous engineering assemblies, and are not highly regarded by homeowners for a few reasons. Their appearance disrupts landscapes which were previously untouched by technology before installing a wind turbine, and after look as if they belong on a foreign plant. Standing at around 330 feet tall, these turbines are certainly hard to conceal. In two coastal areas of Denmark, surveys indicated that people were more supportive of additional wind development offshore than onshore. (Landenberg, Dubgaard, Martensen, & Tranberg) Another notable issue is the low frequency hum that is output by a working turbine. Though perhaps hidden under the usual noises of wildlife and automotive traffic, this whir pierces through house walls and can potentially negatively affect human sleeping routines. Offshore wind mitigates both of these major flaws in onshore wind developments.

The general public is much more likely to approve of a giant wind farm that is miles offshore in a location hardly visited by boat traffic and hardly seen by the average beach goer.

The notorious low frequency hum is impossible to identify over the sounds of waves crashing on beaches or boat docks. Not to mention, wind is more reliable and constant without any barriers or interruptions to prevent the full force of weather patterns from reaching the spinning blades of a turbine. Studies also suggest that restricting areas of ocean for a wind farm protects the marine ecosystem while also adding an artificial habitat for sea life to thrive in.

A few obvious downsides exist with offshore wind energy; one being maintenance. Though less maintenance is needed as technology improves in design and manufacturing, addressing issues on land-based turbines is measurably easier than addressing the exact same issue on a much larger wind turbine at sea. Another notable hurdle is in transmission. Generating large quantities of energy at a site is one thing, but transporting this high power requires extensive installations of massive power lines, which means running long, durable, expensive wires along the ocean floor. This is a high cost, high reward procedure that is completely necessary to build an offshore wind farm. Consequently, wind farm projects often incur large initial costs for the connection of the location to the nearest step-down unit and the manufacturing of the turbines. These issues are not necessarily unique to offshore wind energy, and the many benefits of placing wind farms offshore arguably heavily outweigh the negatives. This niche within the overall industry is destined for growth during the approaching decades.

Existing Onshore Wind Developments in NYS

Wind farms are a collection of wind turbines put in the same place to generate electricity. In New York State, the first wind farm came online in 2000. It was the Madison Wind Farm based in Madison County. The next came online the same year in Wyoming County, it was named Wethersfield Wind Farm. The following year, a third wind farm came online named Fenner Wind Farm; it was also based in Madison County. The three wind farms had a combined generating capacity of 48.15 MW (New York State Energy Research and Development Authority, 2019). Today, New York State has a generating capacity of 1,987 MW (U.S. Department of Energy, 2020).

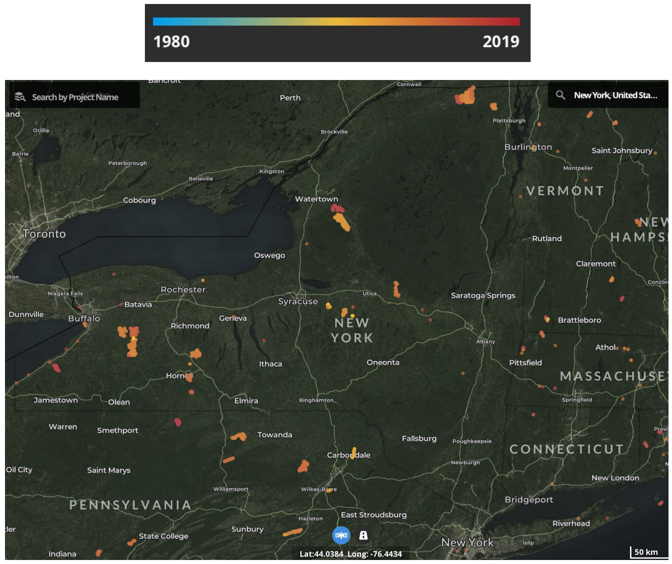

Figure 15: Map of current Wind Turbines in New York State (Hoen, 2018)

Wind farms can generate anywhere from 17 to 39 times as much power as they consume compared to 16 times for nuclear and 11 times for coal (Global Wind Energy Council, 2017). It also only takes a wind turbine 3-6 months to make up for the energy that goes into producing, operating, and recycling the wind turbine after its 20-25 year lifetime (Global Wind Energy Council, 2017). These economic facts as well as many other economic and non-economic incentives have driven New York State to invest in wind power. In 2016, New York State established a Renewable Energy Standard, where 70 percent of the state's electricity would come from renewables including wind (New York State, n.d.). In 2019, wind power in New York State made up about 3.66% of the power in the electric grid (U.S. Department of Energy, 2020). It also generated 4,849 GWh that year (U.S. Department of Energy, 2020). Compared to the years before it, energy generation from wind has been steadily increasing.

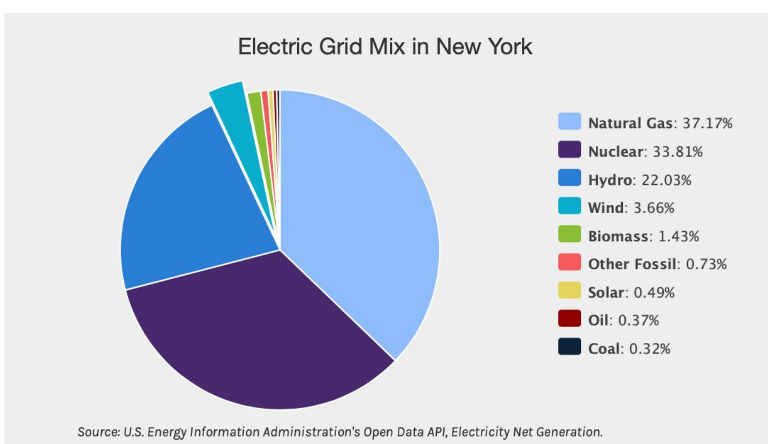

Figure 16: Electric Grid Mix in New York State (U.S. Department of Energy, 2020)

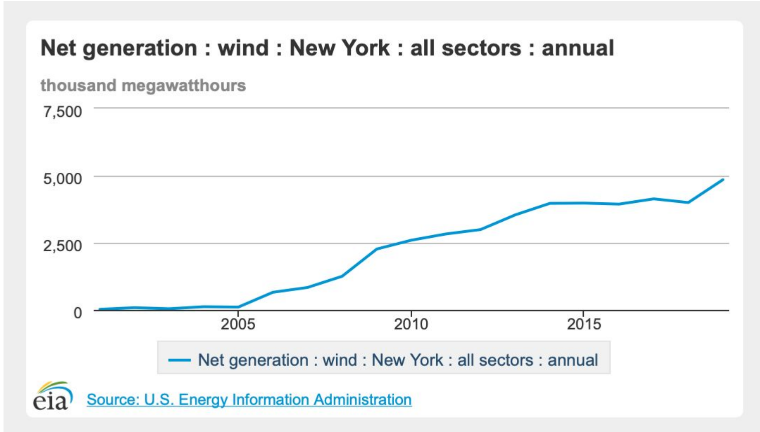

Figure 17: Annual Net Energy Generation from Wind in New York State (U.S. Department of Energy. 2020)

New York State's mission is to reform the energy vision, by making energy more affordable for all New Yorkers, by supporting the growth of clean energy innovation, and by empowering New Yorkers to make more informed energy choices. Their clean energy and climate goals are to reach an 85% reduction in greenhouse gas emissions by 2050, to achieve 100% clean electricity by 2040, and to generate 9 GW of offshore wind energy by 2035 (New York State, n.d.). These goals are heavily reliant on renewable energies like wind energy, and specifically offshore wind energy.

Current Offshore Wind Developments

Wind power is now firmly established worldwide as the leader among renewable energy technologies. New York State alone produces a significant amount of wind power within the United States. While temporary and local setbacks may still occur, the overall growth rates of wind technology's presence worldwide have been sustained at a high level of roughly twenty percent per year. Continuing this momentum has inspired engineers to think bigger, resulting in the idea to move site wind farms offshore (near the coast), and work towards creating even larger turbine sizes. What makes these offshore turbines so attractive comes from the fact that land-based turbines may have reached a size plateau due to transportation and erection limits. Offshore machines, on the other hand, are less constrained, and models currently in development are projected to be innovative 10 MW units of 150 m diameter (Tester, Drake, Driscoll, Golay, & Peters, 2012).

New York State (NYS) has been conducting research, analysis, and outreach since 2016 in order to evaluate the potential for offshore wind energy. The New York State Energy Research

& Development Authority (NYSERDA) has used these four years of hard work to develop the NYS Offshore Wind Master Plan. This comprehensive roadmap encourages the development of offshore wind in a manner that is sensitive to environmental, maritime, economic, and social issues while addressing market barriers and aiming to lower electricity costs (New York State Energy Research & Development Authority, 2017).

NYSERDA's Master Plan has set a bold goal for New York State to meet. It states that by 2030, NYS will help develop 2,400 MW of offshore wind energy, which is enough to power up to 1.2 million homes. As of 2017, there were already six Bureau of Ocean Energy Management (BOEM) Wind Energy Area sites within NYS that were available to contribute to this goal, see Figure 18. Together, these sites have the capacity necessary to meet the state's goal of 2,400 MW of offshore wind energy generation. It is important to recognize that these areas will also be available to support the renewable energy goals of other nearby states. The cost associated with long-distance transmission to New York might increase the cost of NYS offshore wind operation substantially (New York State Energy Research & Development Authority, 2017).

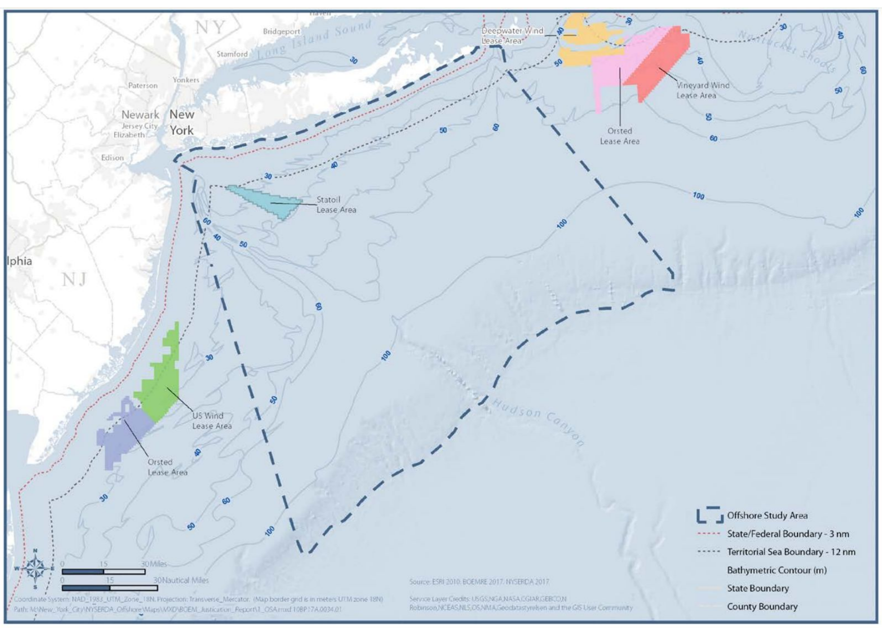

Figure 18. Existing BOEM Lease Areas capable of supplying offshore wind to New York State (New York State Energy Research & Development Authority, 2017).

Due to the nature of offshore wind energy, it is understandable for a single Wind Energy Area to meet the demands of multiple states, becoming a regional resource. In order to ensure an adequate and competitive supply of areas are available to meet New York's demand at the lowest cost, it is critical that NYS continues the identification and leasing of new Wind Energy Areas.

The potential sites shown in Figure 19 have the potential to lease at least four new Wind Energy Areas within each Area for Consideration. Each of these sites are capable of supporting at least 800 MW of offshore wind. Because of the great energy potential that each site possesses, NYS has determined that they have the best potential to be the most cost effective and desirable areas for future wind development off New York’s coast (New York State Energy Research & Development Authority, 2017). The Area for Consideration from Figure 19 encompasses 1,061,802 acres and is more than 21 miles away from land at its closest point. Using the analysis from the Visibility Threshold Study, the State set a minimum distance of 20 miles for the Area for Consideration in order to ensure that, for the vast majority of the time, turbines would have no discernable or visible impact for a casual viewer on the shore. By increasing the distance between the NYS shoreline and the turbines, the potential for turbine visibility is further reduced. The proposed future sites present the fewest overall conflicts with ocean users, natural resources, infrastructure, and wildlife. This has been concluding since “BOEM’s identification and leasing of new Wind Energy Areas within the area the State proposed would increase competition, drive down ratepayer costs, and provide ample capacity to meet New York's 2,400 MW goal of offshore wind by 2030, even if some portions of the area remain undeveloped, are only partially developed, or serve other markets in part or in whole” (New York State Energy Research & Development Authority, 2017).

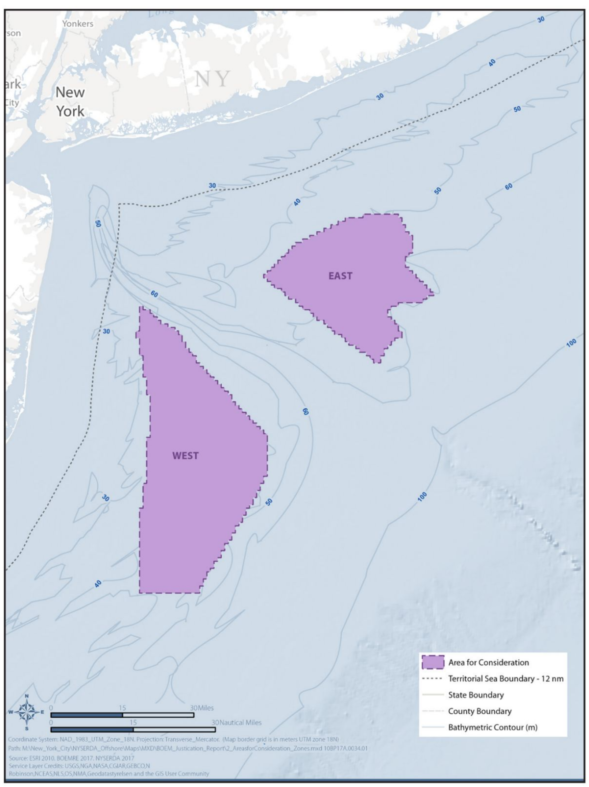

Figure 19. New York State Area for Consideration for Offshore Wind Development (New York State Energy Research & Development Authority, 2017).

Even greater exploitation of offshore siting could provide access to larger and higher-quality wild fields for not only New York State, but the entirety of the East Coast shoreline as well. The NYS contribution to adding more renewable energy technology onto the electricity grid will be a massive step forward for the United States' goal of mitigating fossil fuel pollutants. The current 2,400 MW of offshore wind technology being developed offshore will not only result in greenhouse gas emission reductions and air quality improvement, but it is also projected to amass health benefits valued between $73 and $165 million by 2030 (New York State Energy Research & Development Authority, 2017).

As of the year 2020, the United States of America, has only one fully operational offshore wind farm, located off the coast of Rhode Island. The Block Island Wind Farm has 5 turbines with a total capacity of 30MW, which could power 17,000 homes in New England (Office of Energy Efficiency & Renewable Energy, 2018). If the United States can develop about 86 GW of offshore wind energy by 2050, then it would create 160,000 jobs, cut greenhouse gas emissions by 1.8%, and it could reduce power sector water consumption by 5% (U.S. Department of Energy, 2018).

In 2019, Europe added 3,623 MW net offshore capacity to achieve a total installed offshore wind capacity of 22,072 MW (Wind Europe, 2020). 502 new offshore wind turbines were connected to the grid across 10 wind farms, raising the number of offshore wind turbines across 12 European countries to 5,047 turbines (Wind Europe, 2020).

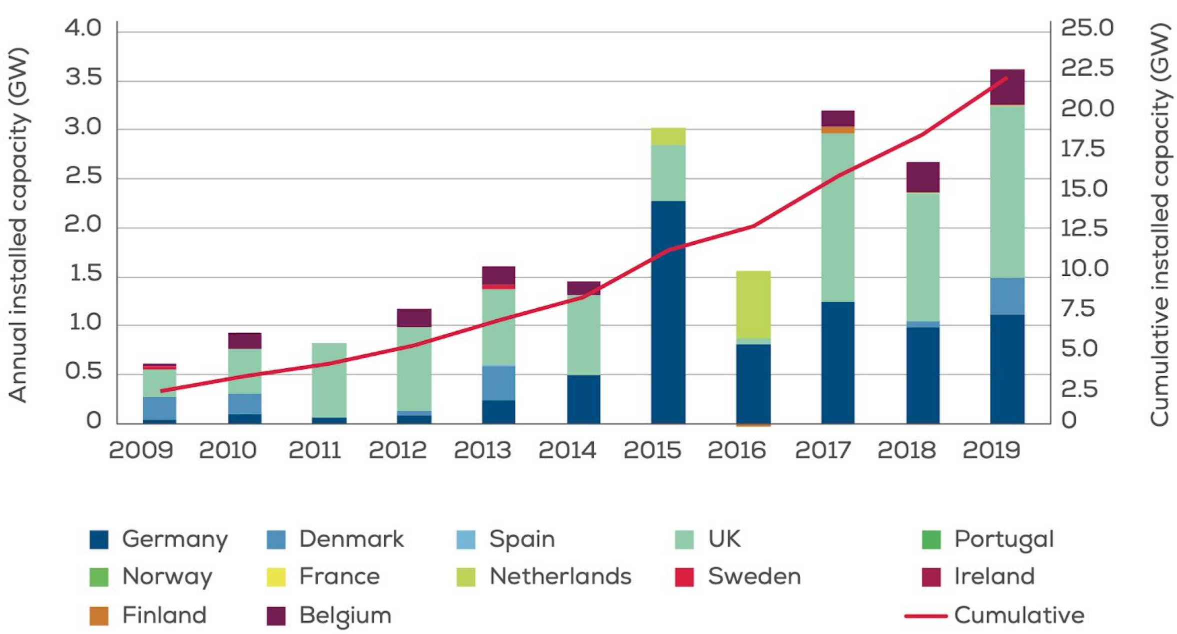

Figure 20: Annual offshore wind installations by country and cumulative capacity (Wind Europe, 2020)

Looking now at the eastern part of the world, China is a leader in offshore wind energy. As the country with the most offshore wind farm projects in Asia, it has 305 of which 43 are currently operating, 12 in which construction progressed enough that the turbines have been connected to the grid and generate electricity, 27 currently in the build phase, 28 which have either been consented or applied for consent, and the rest which are still in the planning phase (4C Offshore, 2020). As of 2020, China has an offshore power capacity of 1288 MW generated by 417 wind turbines (4C Offshore, 2020). China is an excellent representation of the constantly evolving renewable energy sector, as the world becomes more willing to adopt clean energy practices

Conclusions

In order to fully understand the potential that offshore wind power has to offer for states such as New York, it is critical to understand each component that makes this technology so desirable. Recognizing and determining wind patterns in the Northeast U.S. can show which sites have the most potential for future projects, based on the presence of land and sea breezes. On a broader scale, it is also important to recognize how the diurnal and seasonal patterns that result from the fluctuations in the planetary boundary layer directly affect wind turbine output. Key safety concerns must be addressed by recognizing the possibility of extreme weather events when designing and implementing offshore wind farms. Furthermore, analyzing the present and future of New York State onshore and offshore wind developments provides insight for current renewable energy successes for the state, while providing a roadmap that lays out how NYS plans on reaching even greater goals in the future. The examination of existing wind developments also leads to deeper understanding of the wind industry's trends and changes. The future of offshore wind technology in the United States has great potential, and its growth resides in the hands of scientists and state governments who must ensure that new developments adhere to the various aforementioned specifications to maximize the electricity output, reliability, and safety of these sites. This report acts as a brief overview and introduction to offshore wind power and highlights the tremendous potential of structurally sound, well-placed offshore wind farms.

Bibliography

4C Offshore. (2020). Offshore Wind farms in China. Retrieved from https://www.4coffshore.com/windfarms/china/

Climate New York. (n.d.). Retrieved from https://www.meteoblue.com/en/weather/historyclimate/climatemodelled/new-york_united-states-of-america_5128581

Energy.gov (n.d.). "How Do Wind Turbines Survive Severe Storms?" Retrieved from www.energy.gov/eere/articles/how-do-wind-turbines-survive-severe-storms.

Garben, S. (2017). This Comparison Of Hurricanes' Size And Power Will Shock You. Retrieved from https://guff.com/this-comparison-of-hurricanes-size-and-power-will-shock-you

GE Renewable Energy. (n.d.). 3 MW Onshore Wind Turbine Platform: Retrieved from https://www.ge.com/renewableenergy/wind-energy/onshore-wind/3mw-platform

Global Wind Energy Council. (2017). Wind in Numbers. Retrieved May 7, 2020, from https://gwec.net/global-figures/wind-in-numbers/

Gold, R. (2019). *SUPERPOWER: The transformation of american energy*. Place of publication not identified: SIMON & SCHUSTER.

Halblaub, J. (2014). Daily Wind Changes in the Lower Levels of the Atmosphere. *NOAA's National Weather Service*.

Hartman, L. (2018). Wind Turbines in Extreme Weather: Solutions for Hurricane Resiliency. Retrieved from https://www.energy.gov/eere/articles/wind-turbines-extreme-weather-solutions-hurricane-resiliency

He, Y., Monahan, A. H., & Mcfarlane, N. A. (2013). Diurnal variations of land surface wind speed probability distributions under clear-sky and low-cloud conditions. *Geophysical Research Letters*, *40*(12), 3308–3314. doi: 10.1002/grl.50575

Hoen, B.D., Diffendorfer, J.E., Rand, J.T., Kramer, L.A., Garrity, C.P., and Hunt, H.E. (2018). United States Wind Turbine Database (ver. 3.0, April 2020): U.S. Geological Survey, American Wind Energy Association, and Lawrence Berkeley National Laboratory data release, https://doi.org/10.5066/F7TX3DN0

Holton, J. R., & Hakim, G. J. (2013). Chapter 8—The Planetary Boundary Layer. In J. R. Holton & G. J. Hakim (Eds.), *An Introduction to Dynamic Meteorology (Fifth Edition)* (pp. 255–277). Academic Press. https://doi.org/10.1016/B978-0-12-384866-6.00008-8

Jeong, Kim, & Jeongsoo. (2019, May 6). Wave Force Characteristics of Large-Sized Offshore Wind Support Structures to Sea Levels and Wave Conditions. Retrieved from https://www.mdpi.com/2076-3417/9/9/1855?type=check_update&version=1#cite

Jiang, Q., Doyle, J. D., Haack, T., Dvorak, M. J., Archer, C. L., & Jacobson, M. Z. (2008). Exploring wind energy potential off the California coast. *Geophysical Research Letters*, 35(20). doi: 10.1029/2008gl034674

Kim, Y., You, K., & You, J. (2014, July 20). Characteristics of Wind Velocity and Temperature Change Near an Escarpment-Shaped Road Embankment. *The Scientific World Journal, 2014*, 1-13. doi:10.1155/2014/695629

Koh, J. H., & Ng, E. Y. K. (2015, November 11). Downwind offshore wind turbines: Opportunities, trends and technical challenges. Retrieved from https://www.sciencedirect.com/science/article/pii/S1364032115011752

Landenberg, J., A. Dubgaard, L. Martensen, and J. Tranberg. 2005. Economic valuation of the visual externalities of off-shore wind farms. [Report No. 179]. Prepared for the Danish monitoring program of offshore wind. Food and Resource Economic Institute: Copenhagen, Denmark. 185 p.

Lee, A. (2020, February 10). America's first offshore wind farm faces shutdown after cables 'not buried deep enough'. Retrieved from https://www.rechargenews.com/wind/americas-first-offshore-wind-farm-faces-shutdown-after-cables-not-buried-deep-enough/2-1-753419

National Climatic Data Center. (2015). Climate of New York. Retrieved from https://www.ncdc.noaa.gov/climatenormals/clim60/states/Clim_NY_01.pdf

National Geographic. (2016, April 25). Wind, Wind Information, Facts, News, Photos. Retrieved from https://www.nationalgeographic.com/science/earth/earths-atmosphere/wind/

New York State. (n.d.). Reforming the Energy Vision (REV). Retrieved May 7, 2020, from https://rev.ny.gov/

New York State Energy Research and Development Authority. (2019). Large Wind Farm Developments. Retrieved May 7, 2020, from https://www.nyserda.ny.gov/Researchers-and-Policymakers/Power-Generation/Wind/Large-Wind

New York State Energy Research & Development Authority. (2017). *New York State Offshore Wind Master Plan: Charting a Course to 2.400 Megawatts of Offshore Wind Energy*. State of New York. Retrieved May 7, 2020, from https://www.nyserda.ny.gov/All-Programs/Programs/Offshore-Wind/Offshore-Wind-in-New-York-State-Overview/NYS-Offshore-Wind-Master-Plan

NWS Internet Services Team. (n.d.). Flight Environment. Retrieved from https://www.weather.gov/source/zhu/ZHU_Training_Page/winds/Wx_Terms/Flight_Environment.htm

NYSERDA. (n.d.).“Blueprint for the New York State Offshore Wind Master Plan.” www.nyserda.ny.gov/About/Publications/Offshore-Wind-Plans-for-New-York-State.

Office of Energy Efficiency & Renewable Energy. (2018). Offshore Wind Research and Development. Retrieved 2020, from https://www.energy.gov/eere/wind/offshore-wind-research-and-development

Panofsky, H. A. (1985). The Planetary Boundary Layer. In B. Saltzman (Ed.), *Advances in Geophysics* (Vol. 28, pp. 359–385). Elsevier. https://doi.org/10.1016/S0065-2687(08)60195-8

Seroka et al. (2018, August 30). Sea Breeze Sensitivity to Coastal Upwelling and Synoptic Flow Using Lagrangian Methods. Retrieved from https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2018JD028940

Stoutenburg, E. D., Jenkins, N., & Jacobson, M. Z. (2010). Power output variations of co-located offshore wind turbines and wave energy converters in California. *Renewable Energy*, 35(12), 2781–2791. doi: 10.1016/j.renene.2010.04.033

Svensson, N., Sahlée, E., Bergström, H., Nilsson, E., Badger, M., & Rutgersson, A. (2017). *A Case Study of Offshore Advection of Boundary Layer Rolls over a Stably Stratified Sea Surface*. Advances in Meteorology; Hindawi. https://doi.org/10.1155/2017/9015891

Tester, J.W., Drake, E.M., Driscoll M.J., Golay, M.W., & Peters, W.A. (2012). *Sustainable Energy: Choosing Among Options*. Cambridge: The MIT Press.

U.S. Department of Energy. (2020). Wind Energy in New York. Retrieved May 7, 2020, from https://windexchange.energy.gov/states/ny#maps

U.S. Department of Energy. (2018, April 16). *America's First Offshore Wind Farm* [Video]. YouTube.https://www.youtube.com/watch?time_continue=58&v=gmhdFkrDyzs&feature=emb_title

Wan, Y. H. (2012). Long-Term Wind Power Variability. *National Renewable Energy Laboratory*.

Wind Europe. (2020, February). Offshore Wind in Europe Key Trends and Statistics 2019. Retrieved 2020, from https://windeurope.org/wp-content/uploads/files/about-wind/statistics/WindEurope-Annual-Offshore-Statistics-2019.pdf

Windfinder.com. (2019). Wind and Weather Statistics New York/Brooklyn. Retrieved from https://www.windfinder.com/windstatistics/new_york_brooklyn

Wind Map. (2020). Wind Map - North East United States Observations. Retrieved from https://www.windmapper.com/?Loc=NE.

Wonderopolis.org. (2015). Where Does Wind Come From? Retrieved May 5, 2020, from https://www.wonderopolis.org/wonder/where-does-wind-come-from