Floating Wind Turbines and Wind Energy Cost Analysis

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Contents

1 Introduction

Largely motivated by concern about emission of greenhouse gasses, engineers and scientists have increasingly turned towards renewable and clean energies. Wind power is currently the leader in renewable energy supply across the globe. However harnessing energy from wind is not a recent invention. Wind has been used to drive mechanical processes such as milling grain since around 600BC in the age of the Persian empire and perhaps even earlier in ancient Egyptian civilizations as well (Jamieson & Hassan, 2011; Hau, 2013). Although wind power has never been used quite as extensively as it is currently at 7.3% of the entire U.S. energy supply (*EIA - Independent Statistics and Analysis*, 2020).

First the fundamental principles guiding wind turbine design will be introduced in Section 2. Then Section 3 will dive deeper into research and progress in increasing wind turbine efficiency and creating wind farms at scale. Sections 4 and 5 will introduce offshore wind turbines and floating wind turbines as well as the particular benefits but also challenges of offshore wind farms. Finally Section 6 will briefly go over the current and projected costs of onshore and offshore wind energy. The efficiency and cost analyses will ultimately lead to the conclusion that offshore wind farms are likely to remain useful sources of *renewable* energy in regions where space and noise and visual pollution are concerns, while meanwhile in regions without limited land supply, onshore wind farms are one of the most cheap and efficient sources of energy period.

2 Fundamental Principles of Wind Turbine Design

There are many different ways that wind energy can be converted into mechanical work. Modern wind turbines which rotate horizontally relative to the axis of the wind flow have proven to be one of the most efficient of these methods. These horizontal axis wind turbine designs are founded on very basic principles. Each turbine uses some number of blades, typically three, to harness the wind's kinetic energy by creating lift, analogous to the the wings of airplanes, which causes the blades to turn. As seen in Figure 1a in Appendix A, the blades are then connected to a low speed drive shaft that is designed to turn at rates of 20rpm-50rpm which is in turn connected to a speed increasing gearbox and high speed drive shaft that is designed to turn at rates of 1200-1800rpm (Wilson & Spera, 2009). The high-speed drive shaft turns an electric generator, producing electricity.

Vertical axis wind turbines, which are primarily driven by drag forces instead of lift forces, in many ways seem to be the more obvious design. One such vertical axis wind turbine design Sigurd Johannes Savonius developed in the 1920s is shown in Figure 1b. Empirical results were the first to show that such vertical axis wind turbines were in fact far less efficient.

There are many considerations when designing wind turbines, but certainly one of the most important guiding principle of wind turbine design is efficiency. Section 3 will explore the efficiency of wind turbines in extensive detail. Other important considerations include durability, cost, noise pollution, ease of construction, and aesthetics. These factors guide the motivations for offshore wind turbines described in Section 4.

3 Increasing Efficiency of Wind Turbines

The most elementary measure of wind turbine performance is the electrical energy output delivered to the customer. It's often important that the emphasis is on energy delivered instead of energy created because inefficiencies in external features of the wind turbine system that transfer energy or simply remote wind turbine location can significantly decrease the total energy that actually reaches its destination. The coefficient of energy or energy recovery factor, which is defined as the ratio of electrical energy output to wind energy input, is given as (Wilson & Spera, 2009)

$$C_E = \frac{AEO_G}{E_W} = \frac{\int_{year} P_O dt}{\int_A \left[\int_{year} p_w dt\right] dA} \tag{1}$$

where

C_E = coefficient of energy or energy recovery factor

AEO_G = gross annual energy output (kWh/y)

E_W = annual wind energy input (kWh/y)

P_O = system output power (W)

t = time elapsed (h)

A = swept area of turbine rotor

p_W = wind power density (W/m^2)

The wind power density p_W is given in terms of the air density ρ and the wind speed U as

$$p_W = 0.5\rho U^3. \tag{2}$$

Equations 1 and 2 make explicit the importance of two obvious factors in wind turbine design; the size of the blades of the wind turbine, and the wind speed of the location of the wind turbine. First the area swept by the wind turbine directly influences the total amount of energy transfer possible from the wind. Second, since the wind power has a cubic dependence on wind speed, the location of a wind farm is also a an important influence on the total wind energy input E_W to a given wind turbine.

The power coefficient for the wind turbine is another important measure of wind turbine efficiency. The power coefficient is given as the ratio of power harnessed by the wind turbine blades to kinetic energy input from the wind:

$$C_P = \frac{P}{p_w A} = \frac{P}{0.5\rho U^3 A}. \tag{3}$$

A basic tool in analysis of wind turbine performance is optimum actuator disk theory which models the rotor of wind turbines as a rotating actuator disk or in other words "a rotor with an infinite number of blades" (Wilson & Spera, 2009, p 292). Using optimum actuator disk theory, a theoretical limit on the power coefficient C_P is found to be 0.59, this is often called Betz's Limit. Most modern wind turbines have a power coefficient in the range of 0.4 to 0.5. The discrepancy between the power coefficient of the theoretical limit and modern wind turbines is driven by drag forces as well as the fact that wind turbines of course only have a finite number of blades (Wilson & Spera, 2009).

A puzzling question arises; if more blades increase the efficiency of the wind turbine, why are there only three blades? The answer is simply that the marginal gain of adding a fourth blade increases efficiency by less than 1%, which is not worth the cost of adding the blade. Meanwhile, designs that use two blades incur an efficiency loss of about 3%, and single blade designs have efficiency losses of 7-12% relative to the three blade design (Schubel & Crossley, 2012). While this turns out to make the two blade design more cost effective in some regards, having fewer blades requires faster rotation to generate the same amount of mechanical power, and this both increases stress on components of the wind turbine as well as increases the acoustic noise generated by the wind turbine (Jamieson & Hassan, 2011).

Beyond the number of blades of wind turbine systems, to maximize annual energy output extensive research has been done into optimizing all facets of the wind turbine system ranging from the electrical generator to the shape of the wind turbine blades (Wilson & Spera, 2009; Jamieson & Hassan, 2011; Schubel & Crossley, 2012). However, the detail required for this level of analysis is beyond the scope of this work.

4 Offshore Wind Turbines

In many locations with high population density such as Europe or Japan, it's difficult to find space for wind turbines on land, and furthermore, the best wind conditions are often found off shore anyway. The primary reason that wind conditions are more favorable over water than land is that the roughness of land slows the wind speed and introduces random vertical and horizontal velocity components at right angles to the main direction of flow. The wind gradient, the rate of increase of wind strength with unit increase in height above ground level, is used to quantify the difference between land and water conditions. Wind speeds are zero at the surface between the air and land or water due to the no-slip condition, and increase higher above the ground (Brown, 1985). Over rough terrain, the wind gradient effect causes reductions in the range of 40% to 50% while over open water or ice, the reduction is typically only 20% to 30% (Thompson, 1998). With the amount of energy harnessed by wind turbines proportional to the cube of wind speed, this difference is significant.

One key drawback of offshore turbines is that the production costs of land turbines are sometimes as little as 30% the total capital required to set up equivalent offshore turbines (Jamieson & Hassan, 2011). There are additional costs to connect the turbine to nearby electrical grids, to create the underwater foundation, and simply to do the exact same construction on the water instead of land. Offshore wind turbines are largely pre-constructed to mitigate this last cost. Despite these added costs, offshore wind farms have continued to grow in popularity since the first one was erected in 1991. The vast majority of these offshore wind turbines have been shallow water wind turbines (in water lass than 50m), fixed to the ground (Wang, Utsunomiya, Wee, & Choo, 2010).

The design of offshore wind turbines closely parallels the design of land based wind turbines. These offshore wind turbines are in fact often just ”standard land based wind turbines that have been ’marinised’ with additional anti-corrosion measures and de-humidification capability introduced” (Jamieson & Hassan, 2011, p. 131). Since wind speeds are usually higher offshore, these wind turbines tend to have heavier and larger blades so that the turbine can generate more electricity operating at lower rotational speeds. The primary structural differences, though, lie at the foundation of the wind turbine. The first design choice for the foundation of the wind turbine is to choose between a fixed or floating base. Fixed based wind turbines are much more common and relatively simple to construct. The underwater foundations are either a tubular, lattice, or hybrid structure, and are constructed very much alike to how land turbines are constructed with the added difficulties of underwater operation. On the other hand, the first and only commercial wind farm using floating platforms was recently constructed in 2018.

5 Floating Wind Turbines

For the same motivations driving wind turbines to move offshore, wind turbine development is looking to move to deeper waters. Specifically, in many locations, Japan being a prime example, there is a paucity of shallow water and furthermore wind conditions may be better yet in locations where only deep water is available. Thus floating wind turbines are of interest because their fixed counterparts are impractical to construct at depths approaching 50m since they require massive underwater supports which are costly and difficult to put into place. Most forms of floating wind turbines only require a few fixed anchors that are significantly easier to set in place than building an entire 50m support structure, and furthermore, floating structures might in fact allow for more longevity (Liu, Li, Yi, & Chen, 2016). There are three main types of floating wind turbines (Tomasicchio et al., 2018)

- Spar-Buoy (SB) type
- Tension-Leg Platform (TLP) type
- Semi-Submersible type (SS)

The three types of floating wind turbines are depicted in Figure 3 in Appendix B.

Each type of wind turbine is tethered to the ocean floor either directly via anchors embedded deep into the ocean bed or to concrete blocks which rest on the ocean floor. Thus even deep water wind turbines prefer shallower waters. Currently offshore wind turbines are not even considered in water depths exceeding 300m (Liu et al., 2016).

The Spar-Buoy (SB) type of wind turbine has a long cylindrical body, often partly filled with water, that extends deep beneath the surface of the water, and it is this body that is tethered to the ocean floor. This makes the SB wind turbines tend to be more stable than the alternatives.

The Tension Leg Platform (TLP) wind turbines have a floating platform whose edges are tethered. Typically in TLP designs the tethers have high axial stiffness and are relatively taut so the wind turbine does not move significantly. TLP designs were first used in oil rigs which require a much larger platform than wind turbine TLPs do.

Though the Semi-Submersible (SS) design may look similar to the TLP design in Figure 3 in Appendix C, they are in fact quite different. SS designs have a platform that is made of large vertical tubes which are partially filled with water and connected with braces. These semi-submerged columns are often similar in material to what is used as the cylindrical body in Spar-Buoy designs. The SS tethering lines are typically not as taut as in other designs since the semi-submersible structure is already stable, thus the mooring in the ocean floor typically is less extensive (Liu et al., 2016). The SS design also benefits from the 'wave cancellation effect', the phenomenon where wave forces acting on the submerged columns with different phases are canceled due to phase shift (Liu et al., 2016).

The last type of floating wind turbine worth mentioning is pontoon wind turbines which consist of many different turbines collected together on a single floating pontoon. Pontoon designs can be combined with any of TLP, SB, or SS platforms. Pontoon designs benefit from the multiple wind turbines being anchored together both allowing more stability and often requiring fewer supports fixed to the ocean floor per turbine. Pontoon designs are in more nascent and exploratory stages. (Boo et al., 2016).

6 Cost Analysis of Wind Energy

The cost of energy is typically measured in either kWh or MWh which is the amount of energy used to consume either 1,000 or 1,000,000 watts of power for one hour. To understand the costs of wind energy, its necessary to have an appropriate baseline of energy costs in general. Costs of various energy sources are given in Figure 2 in Appendix C from the 2019 Lazard annual Levelized Cost of Energy Analysis. Levelized costs are those found by comparing energy produced over the entire lifetime of the energy source to cost of the energy source over its lifetime (includes construction maintenance, etc.).

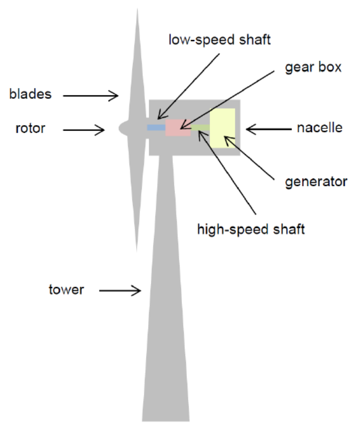
Wind power can be seen to achieve the lowest cost power MWh of any energy source. Furthermore, reports from the 2020 Bloomberg New Energy Finance found that wind power is currently the cheapest source of energy for new constructions for at least two-thirds of the global population. Offshore wind energy, however, is much more expensive at an average of 89$ per MWh. This cost takes into account the higher productivity offshore wind turbines have in result of benefit ting from higher wind speeds.

Although economists know dollars and cents are not the only costs important to consider. The noise of wind turbines often forces wind farms to be distanced from residential areas. In locations with limited space, this may not possible, and either the noise pollution has to become part of daily life or wind turbines have to be abandoned all together. Furthermore, wind turbines may be considered unsightly near city locations. These unfortunate features of wind turbines often force them to be located far from where the energy they produce will actually be consumed, and more importantly, often make it impossible to use them at all. These difficulties constrain the universal usage of onshore wind turbines, but in these cases offshore wind farms offer an, albeit more expensive, alternative.

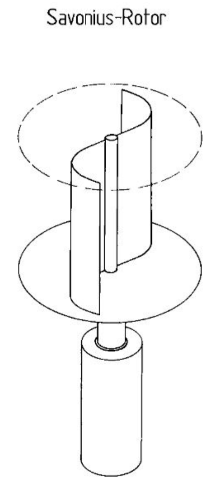
7 Conclusion

Wind energy is one of the most rapidly expanding sources of renewable energy and has the promise of enabling a cost effective green future. The optimization of the modern wind turbine from the most minute details of the wind turbine blades to gearbox rotations has been one the great achievements of modern engineering, and continuing research into wind turbines is pushing the cost of wind energy even lower. Furthermore, research into offshore wind turbines and in particular floating wind turbines holds promising early results, however onshore wind farms remain in most ways superior when limited space and noise and visual pollution are not of concern.

Appendix A



(a) Labelled diagram of horizontal axis wind turbine (Fulcher, 2019)



(b) Vertical axis wind turbine design circa 1925

Appendix B

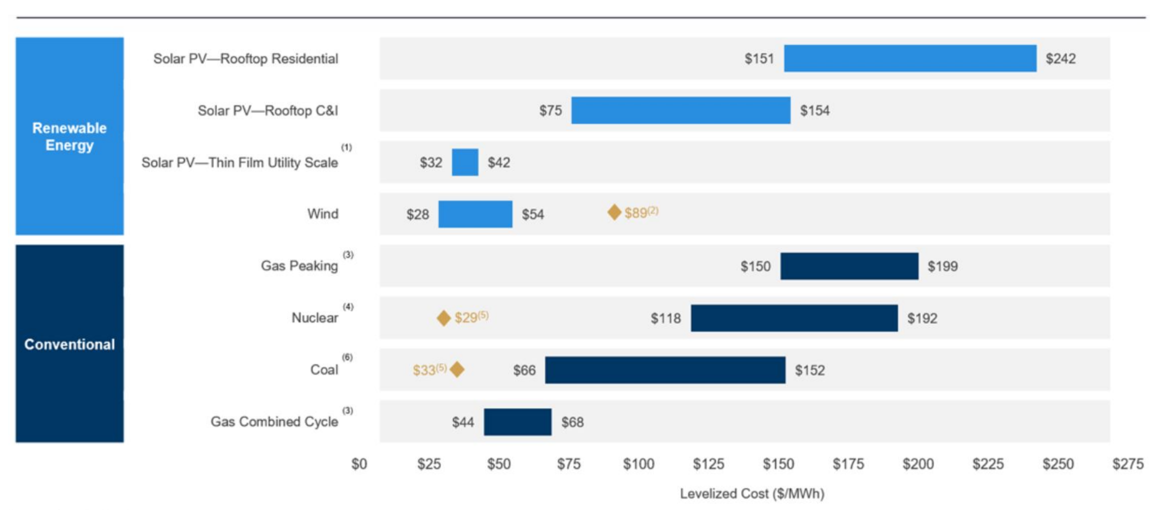


Figure 2: Selected cost of energy by source (Singh, 2019)

Appendix C

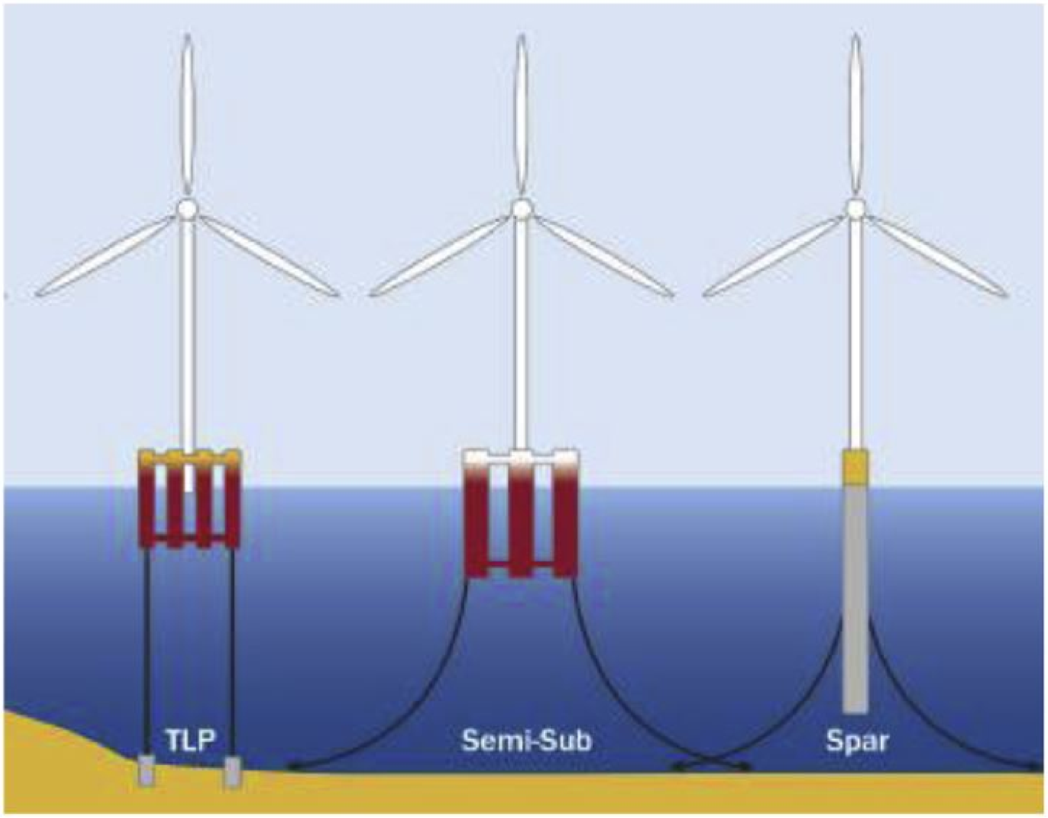


Figure 3: The three primary types of floating wind turbines

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