Various Wind Turbine Technologies

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Abstract

The purpose of this report is to give investors a better idea of which turbine is suitable for a particular setting and to provide a new outlook on vertical-axis wind turbines. Vertical-axis wind turbines are more compact and suitable for residential and commercial areas while horizontal-axis wind turbines are more suitable for wind farms in rural areas or offshore. However, technological advances in vertical-axis wind turbines that are able to generate more energy with a smaller footprint are now challenging the traditional use of horizontal wind turbines in wind farms. Wind technology has grown substantially since its original use as a method to grind grains and will only continue to grow.

Introduction

Wind turbines have come a long way since their original use in mechanical applications. One of the first wind turbines created was the Persian windmill in 700 A.D., shown in **Error! Reference source not found.**, which was used to grind grain and pump water.[1] It was a vertical-axis turbine that could only turn in one direction and would stop completely if the wind blew in the opposite direction, which resulted in an extremely low efficiency.

Figure 1: Persian Windmill[2]

During the 14th century, the traditional smock design that is more commonly known as the windmill was created. The first models were built with wood before the towers were replaced with rock and brick for stability and weatherproofing advantages.[3] Eventually, in the 1870s, the wooden blades were replaced with steel blades, which made the blades more efficient due to the reduced weight of the material and the aerodynamic shaping of the steel.[4] This model, shown in Figure 2, was used until the 20th century.

[1] NTNU
[2] Ullesthorpe Windmill
[3] NTNU, *op. cit.*
[4] *Ibid*

Figure 2: Stembridge Towermill in England[5]

One of the first wind turbines used to generate electricity was created by James Blyth in 1887. It was an 18-meter-tall vertical-axis wind turbine that was able to generate 12 kilowatts (kW) of electricity with a rotor diameter of 17 meters.[6] Figure 3 shows the original design.

Figure 3: James Blyth Wind Turbine[7]

The evolution of wind turbines was slow, especially around the time of the Industrial Revolution when oil was plentiful and energy was a small worry. However, around the 1970s, when oil prices began to rise, so did the popularity of wind turbines and other sources of

[5] *Ibid,* p.7
[6] *Ibid*
[7] Centre for Energy

renewable energy. They began to receive political support through government incentives and grants, which truly allowed the technology to take off.

How Wind Turbines Work

Aerodynamics

The blades of a wind turbine have an airfoil design such that the top half is curved and the bottom half is flat, as shown in

Figure **4**. When laminar wind flows over the thicker, curved section of the blade, the wind initially slows down and then speeds up to match the speed of the relative wind. The increased speed of the wind above the airfoil produces a low-pressure region while the air below the airfoil remains at a higher pressure. This causes a phenomenon called lift, where the turbine blade is lifted perpendicular to the wind flow, towards the low-pressure region. The turbine blade also experiences drag, which is caused by friction along the blade. Drag (D) causes the resulting direction of lift (L) to change, as seen in Figure 5. Both effects of lift and drag cause the turbine blades to rotate around a rotor, which generates kinetic, or mechanical, energy. To determine whether the turbine is mostly affected by drag or lift, the tip speed ratio can be calculated using where v_{rotor} is the velocity of the rotor and v_{wind} is the velocity of the wind.

$$\propto = \frac{v_{rotor}}{v_{wind}}$$

Equation 1: Tip Speed Ratio[8]

If $\propto > 1$, lift force allows the blades to turn faster than the speed of the wind and, therefore, allows the turbine to output more power more efficiently. If $\propto < 1$, the turbine blades spin using drag force, which means that the maximum speed at which the blades can turn is the speed of the wind. The power produced by the wind can be calculated using Equation 2 where A is the cross sectional area of the rotor, ρ is the air density, and v is the wind velocity.

$$P = \frac{1}{2}\rho A v^3$$

Equation 2: Power Production of a Wind Turbine[9]

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[8] Ragheb, 2011
[9] Calculation of Wind Power, 2008

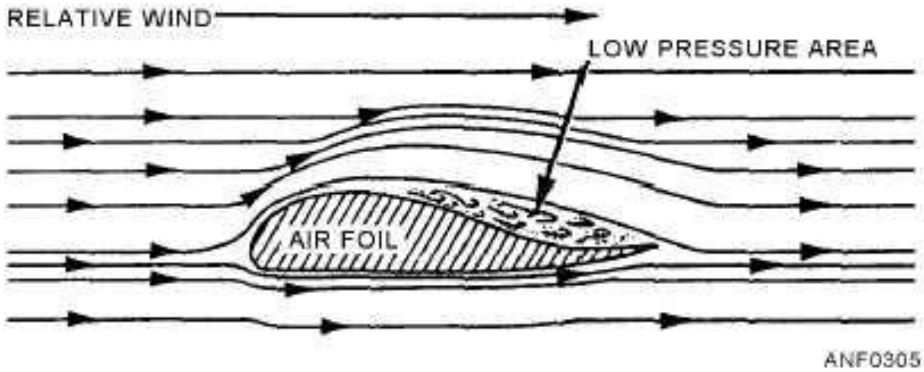

Figure 4: Laminar Flow Over an Airfoil[10]

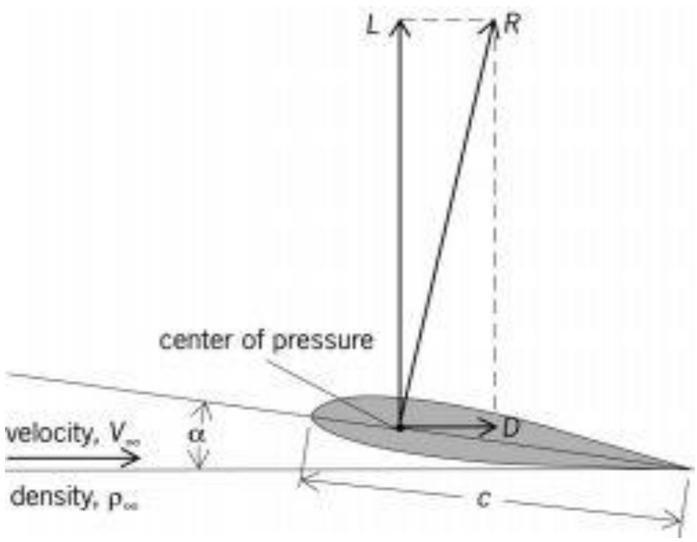

Figure 5: The Effect of Lift and Drag on an Airfoil[11]

[10] Integrated Publishing
[11] The McGraw-Hill Companies, Inc., 2002

Nacelle

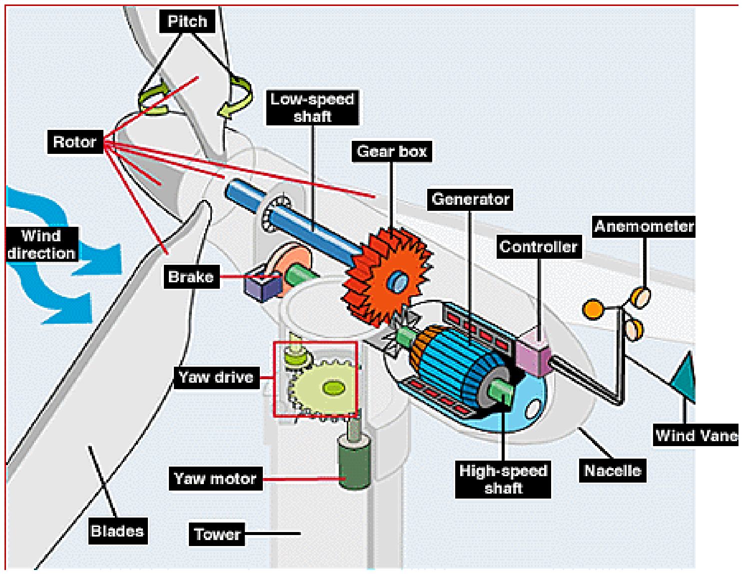

Figure 6: Parts of a Horizontal Wind Turbine[12]

Electricity is produced in the nacelle, which holds the mechanical parts of the turbine that are essential to generating electricity. The generator converts the kinetic energy produced by the turbine blades into electrical energy. As seen in Figure 6, the rotor hub is attached to a shaft that spins at the same speed as the rotor blades. The shaft is connected to a large gear, which causes a smaller gear to turn one hundred times faster The faster-moving shaft is connected to a series of coils, which rotates between two sets of magnets. When the coils experience the alternating north and south poles of the magnets, an alternating magnetic field is produced. The amount of electricity that can be produced is based on two factors as shown by Faraday's law below where N is the number of turns in the coil and $\frac{\Delta\varphi}{\Delta t}$ is the change in magnetic flux over time.

$$V = -N * \frac{\Delta\varphi}{\Delta t}$$

Equation 3: Faraday's Law[13]

Horizontal-axis wind turbines capture wind that blows at a perpendicular angle to its blades. To ensure that the turbine is constantly facing the wind at the right angle, a yaw mechanism is installed on each horizontal-axis turbine. It works with an anemometer, which

[12] Top Alternative Energy Sources, 2008
[13] Rozenblat, 2008

measures the wind speed, and a wind vane, which senses the direction of the wind, to adjust the direction of the turbine so that it constantly faces the wind.[14]

Onshore Wind

Vertical Axis

Vertical axis wind turbines are closer to the ground and are ideal for catching lower-speed wind in residential and urban areas. Since the rotor rotates around a vertical axis, the blades are able to catch wind blowing from any direction and, therefore, generate electricity without the use of a yaw mechanism.[15] A smaller amount of energy and noise is produced from the turbine, which is perfect for residential homeowners who want to lower their carbon footprint. They typically require less maintenance than a horizontal axis wind turbine, which also makes it ideal for homeowners and business owners. There are currently two types of vertical axis wind turbines in production: Darrieus and Savonius.

Darrieus wind turbines use the airfoil concept described above to turn its blades along a vertical axis. This allows the Darrieus turbine to have a virtually limitless rotation speed. However, it requires a gentle push from a low-powered motor to start rotating. The original Darrieus wind turbines held an oversized eggbeater shape that is held stable by guy wires, as shown in Figure 7. Its gearbox is located close to the ground for easy maintenance, but the entire structure is relatively unstable. A few of the earlier models were destroyed due to high wind speeds that caused the rotors to spin at about 60 revolutions per minute (rpm), well above the rated speed of about 40 rpm, which caused unstable vibrations and inevitable failure.[16]

[14] Layton, 2006
[15] Conserve Energy Future, 2009
[16] REUK.co.uk, 2007

Figure 7: Darrieus Vertical Axis Wind Turbine[17]

The next generation of Darrieus wind turbines held the shape of an H-rotor, as seen in Figure 8. The original H-rotor turbine only had two blades and was supported by guy wires while the more current design uses three. This particular design is the UrWind O2, which has a rated power of 1.7 kW with varying heights of 26, 41, and 61 feet.[18] A single unit generates about 2000 to 4000 kWh/year.[19] In 2010, the average U.S. household used about 11,496 kWh annually, which means that two to three units installed on a residential property is enough to power a single household.[20]

Figure 8: UrWind O2 H-Rotor Darrieus Turbine[21]

[17] Johnson, 2001
[18] UrWind, 2010
[19] *Ibid*
[20] U.S. Energy Information Administration, 2011
[21] Montreal Premiere

Most Darrieus-style vertical axis wind turbines today hold a more helical shape to help smooth out the wind and decrease vibrations for increased efficiency, decreased wear and tear, and decreased noise levels. It was found that the optimal angle of attack of the wind on the blade is between zero and 20 degrees to keep the wind flow laminar, as the change between laminar and turbulent winds would cause vibrations and therefore instabilities.[22] However, to get the optimum angle of attack, the blades need to spin at a sufficient speed, which is why most Darrieus wind turbines are not self-starting.

A few helical designs include the Turby and the QuietRevolution, both shown in Figure 9 below. The Turby is more compact and generates less electricity at a rated power of 2.5 kW[23] compared to the rated power of the QuietRevolution at 6.5 kW.[24] It also has a lower cut-out wind speed at 14 m/s[25] compared to the QuietRevolution at 26 m/s, which explains its lower rated power and has an estimated lifetime of 20 years compared to QuietRevolution's 25 years.[26] Both can be used in urban, suburban, and rural settings due to their flexibility to being placed either on the ground or on rooftops for optimal efficiency.

Figure 9: Turby Vertical Axis Wind Turbine (left)[27] and the Quiet Revolution QR5 (right)[28]

[22] Turby
[23] *Ibid*
[24] Quietrevolution, 2011
[25] Turby, *op. cit.*
[26] Quietrevolution, *op. cit.*
[27] Staedion
[28] Quietrevolution, 2011

Savonius wind turbines use a much simpler concept where the rotors simply cup the wind and use drag force to turn the rotor as shown in Figure 10. Since the rotor is powered mainly by drag force, its maximum speed is that of the wind. This type of wind turbine makes for a cheap and easy do-it-yourself home project because models can be made from items found in local hardware stores. Figure 11 shows an example of a quick, homemade Savonius wind turbine. They are small and quiet, which makes it perfect for residential use.

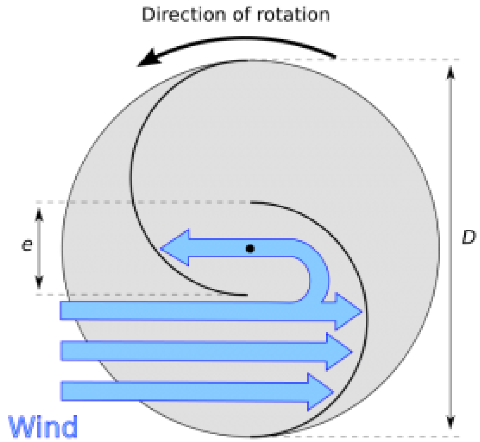

Figure 10: How a Savonius Wind Rotor Works[29]

Figure 11: Homemade Savonius Wind Turbine[30]

Commercially-made Savonius turbines can generate a good deal of electricity. Helix Wind has two products that are Savonius-type wind turbines with a helical shape: The S322 and the S594. Since they are Savonius type wind turbines, they do not need a braking system. The

[29] EnergyBeta
[30] R., 2011

S322 generates about 1,952 kWh/year and the S594 generates about 3,362 kWh/year, but the S594 is almost twice the size of the S322.[31] Both can be used in urban and residential areas that generate greater than 14 mile-per-hour winds with zoning laws that allow installing the turbine to a height of less than 35 feet.[32]

Figure 12: Helix Wind S222 (left) and S594 (right)[33]

Vertical axis turbine technology has been growing at an increasing rate. There are countless designs that are made suitable for almost any type of area so long as the amount of wind is sufficient. It has gotten to a point where vertical axis wind turbines are readily available for homeowners either through purchase or by do-it-yourself design.

Horizontal Axis

Unlike vertical-axis wind turbines, most horizontal axis wind turbines are not suitable for residential uses. According to Equation 2, the velocity of the wind is the most important factor for power production as the cube of the velocity is directly related to power production. For this reason, horizontal axis wind turbines used for commercial energy production are extremely tall so that they are able to capture the faster-moving, laminar air currents. The size of the cross-sectional area is also important as it is directly related to the power produced, which explains the large rotor on each horizontal axis turbine. When the wind blows past the large rotors, the

[31] HelixWind, 2005
[32] HelixWind, 2005
[33] HelixWind, 2005

laminar air currents become turbulent. This turbulence decreases the efficiency of any horizontal-axis turbine downwind. The spacing required between turbines to decrease the effect of turbulence has been about 7 rotor-diameters, but the most recent study done by Charles Meneveau, a fluid mechanics and turbulence expert and mechanical engineering professor at Johns Hopkins University, suggests that they should now be placed 15 rotor-diameters apart.[34] Unfortunately, this suggestion will further increase the already large footprint of a wind farm, which brings into question whether it is truly more efficient.

One of the few horizontal-axis wind turbines that is suitable for residential and commercial areas is the Swift Wind Turbine. It can be mounted on rooftops or can be free standing, as shown in Figure 13. It is about 2.13 meters in diameter and has a rated power of 1.5 Kw.[35] It captures small wind with a cut-in wind speed of 3.58 m/s and generates about 1,200 kWh annually in 5 m/s wind speeds. The Swift Wind Turbine's specifications are comparable to vertical axis wind turbines in terms of footprint and the resulting power generated, so the major deciding factor would be aesthetics.

Figure 13: Swift Wind Turbine Mounted on a Residential Home in Holland, Michigan (left) and free-standing (right)[36]

[34] ScienceDaily, 2011
[35] Swift
[36] Swift

Other designs are more similar to the wind turbines used by major electric companies that are several meters tall and whose rotors are several meters wide. They have three blades that utilize lift to turn the rotor, which generates electricity. Depending on the diameter of the rotor, how tall the turbine is, and how efficiently they run, the amount of electricity that each turbine can generate varies from 1 kW to even 20 MW. Figure 14 shows an example of a wind farm located in Fluvanna, Texas. Various specifications for selected designs are shown in Table 2Table 4 in the Appendix.

Figure 14: Horizontal Axis Wind Turbine Farm in Fluvanna, Texas[37]

New Wind Farms

Horizontal axis wind turbines may not be the only turbines being used in wind farms from now on. John O. Dabiri, a graduate student in the department of Aeronautical Laboratories and Bioengineering at California Institute of Technology, produced a study that compared the power density of a wind farm using horizontal-axis wind turbines with a wind farm using Windspire vertical axis-wind turbines. The study compared horizontal axis wind turbines with

[37] Boyd, 2012

rated powers of 2.5 and 3 MW with rotor diameters of 100 and 112 meters with the Windspire with a rated power of 1.2 kW and a rotor diameter of 1.2 meters.[38] Figure 15 shows a small collection of Windspire turbines.

Figure 15: Windspire Vertical Axis Wind Turbines[39]

According to the study, the power density of wind farms using traditional horizontal-axis wind turbines today is about two or three watts produced per meter of land area. Since turbulence from upwind wind turbines will significantly decrease the efficiency of downwind turbines, they must be spaced an average of seven rotor-diameters apart. This creates a large area of unused space on the ground and therefore a much larger footprint. In the field tests done by Dabiri and his colleagues, they strategically placed three clockwise-rotating (blue) and three counter-clockwise-rotating (red) turbines to find the optimal power density as shown in Figure 16.

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[38] Dabiri, 2011
[39] Windspire, 2010

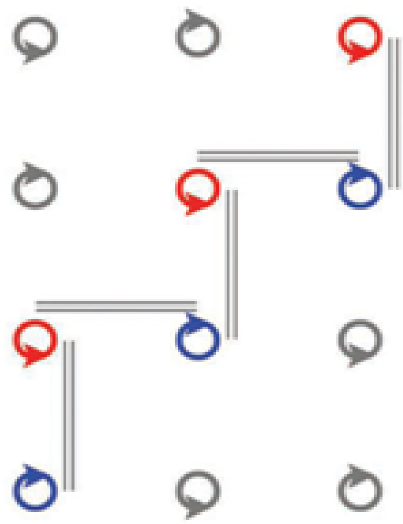

Figure 16: Clockwise and Counterclockwise Configurations of the Windspire Array[40]

They found that a spacing of four rotor-diameters allowed the turbines downwind to recover within 5% of an isolated turbine performance. This allowed for a 48.6 m^2 foot print of a six-turbine array and an overall power density of 6 to 30 W/m^2. It is a marked improvement over the 2 to 3 W/m^2 power density of the horizontal-axis wind turbines and the results suggest that vertical axis wind turbines may be included in future wind farms.

Offshore Wind

Offshore wind turbines are the same as the horizontal-axis wind turbine used onshore, only the rotors are much larger. Wind offshore blows much faster and more laminar than the wind on shore, because there are fewer obstructions such as buildings and hills, so offshore turbines do not need to be as tall relative to their heights as onshore wind turbines. As a result of the faster wind speeds, **Error! Reference source not found.** shows that the slight increase in wind velocity means a significant increase in power production for the offshore wind turbines.

Most offshore wind turbines are installed in shallow water, which is no more than 30 meters deep. Before piles can be driven 24 to 30 meters into the seabed, an assessment must be made to mitigate excessive environmental damages. Recently, more offshore wind turbines have been moving toward the transitional water, which has a depth between 30 and 60 meters. Simple piles will not stabilize these wind turbines against the currents, so tripod-like stands or wider-

[40] Dabiri, 2011, *op. cit.* p.20

base structures must be installed.[41] The eventual goal is to have offshore turbines in deep water, which is greater than 60 meters deep as shown in Figure 17. Research is still being done today.

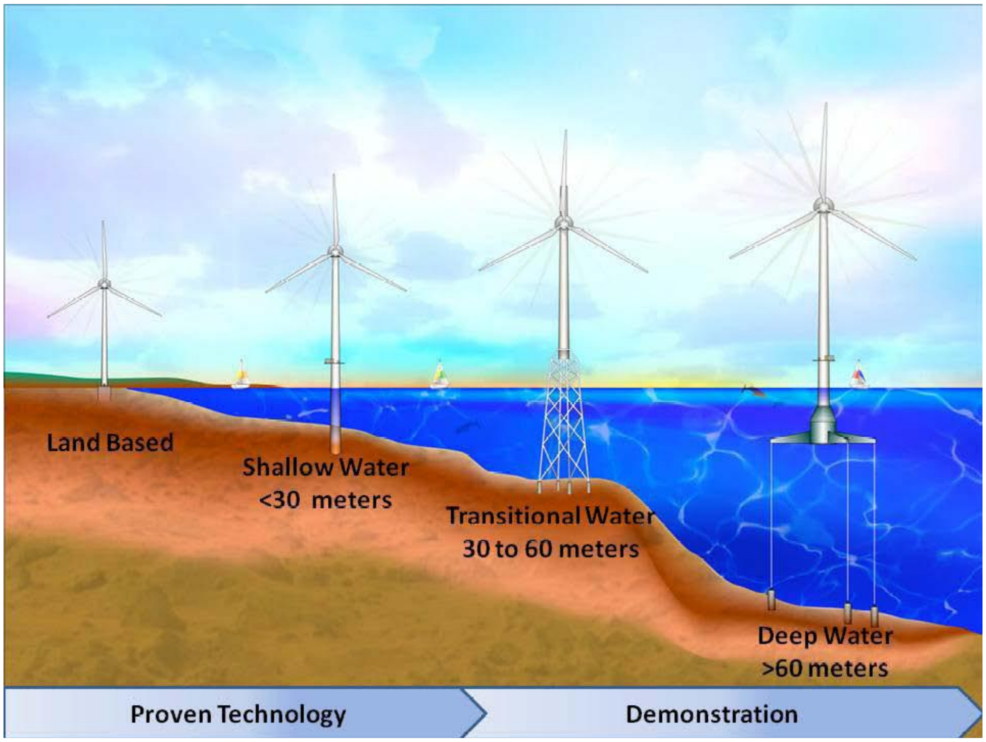

Figure 17: Offshore Wind Turbine Depths Depicted by the National Renewable Energy Laboratory (NREL)[42]

The United States' first offshore wind farm will be located in federal waters 4.7 miles offshore from Cape Cod in Massachusetts.[43] The Cape Wind Project will include 130 3.6 megawatt wind turbines that will cover about 25 square miles of federal water.[44] It is estimated to produce a maximum of about 468 MW, and the average expected production is expected to cover about 75% of the electricity demand of Cape Cod, Martha's Vineyard, and Nantucket.[45] The project received federal approval in 2010 and is now going through more approvals before construction can begin. It can be estimated to look similar to the offshore wind farm in the North Sea in Figure 18.

[41] Union of Concerned Scientists, 2010
[42] Musial & Ram, 2010
[43] Bureau of Ocean Energy Management, Regulation, and Enforcement, 2011
[44] *Ibid*
[45] *Ibid*

Figure 18: Offshore Wind Farm in the North Sea near Germany[46]

Challenges for Wind Power

A few challenges that these wind turbines face are the criticisms of the noise, aesthetics, bird deaths, efficiency, and an overall "not-in-my-backyard" attitude. Noise is caused by mechanical movements of the parts inside the nacelle and from aerodynamic turbulence caused by the rotations of the blades.[47] Common complaints are the annoyance of sound during the day and the deprivation of sleep during the night. The Institute of Noise Control Engineering in Europe has helped create the Wind Turbine Noise conference held every other year since 2005 where representatives from the UK, France, Italy, USA, Netherlands, Sweden, Denmark, Australia, Japan, and many others come together to discuss how to solve the issue of noise.[48] Topics include sources of noise, designs modification, noise modeling, effects on individuals, vibrations from wind turbines, etc.

Aesthetics has always been and will always be a challenging factor for wind turbines. Everyone has differing opinions on the topic and in the end, it comes to a "not in my backyard attitude." There are people who believe in clean energy and enjoy the idea of wind turbines, but

[46] Associated Press, 2010
[47] Sadberge Parish Council
[48] Wind Turbine Noise, 2011

it becomes a different story when they are able to see and hear them at all hours of the day. Unfortunately, since most commercially-used wind turbines are very tall and have very large rotors, they get in the way of the natural landscape.

Another major, yet incorrect criticism is that wind turbines are the major cause of bird deaths. According to the American Bird Conservancy, in the collisions category, wind turbines come in last with a low estimate of 100,000 bird deaths in 2010 and a high estimate of 440,000 in 2009.[49] Glass windows lead the way with a low estimate of 100,000,000 and a high estimate of one million bird deaths. The results are shown in **Error! Reference source not found.**. Other factors of bird deaths include pesticides and toxins, fisheries, global warming, cats, invasive species, disease, and other forms of energy production such as the burning of coal.[50] The major indirect cause of bird deaths is habitat depletion as lands are cleared for residential housing, industrial uses, and other things we use or enjoy.

Collisions with:	Year of estimate	Mortality estimate low	Mortality estimate high
Wind turbines	2009/10	100,000 (2010)	440,000 (2009)
Towers	2008	4,000,000	50,000,000
Power lines	2001	10,000,000	154,000,000
Roads/vehicles	2005	10,700,000	380,000,000
Urban light	2009	31,158,000	
Glass	2006	100,000,000	1,000,000,000

Table 1: Number of Bird Deaths Caused by Collisions in the United States[51]

[49] American Bird Conservancy, 2009
[50] American Bird Conservancy, 2010
[51] American Bird Conservancy, 2009, *op. cit,.* p.25

Conclusion

When most people think of wind turbines, they think of the extremely large windmill-type horizontal-axis wind turbines. However, those are not the only ones that exist. It is true that they are not always efficient, but there are now other options such as vertical axis wind turbines to capture smaller wind that are more efficient. Technology takes time to improve and in a few years, wind turbines may end up being the most efficient source of sustainable energy.

Appendix

	UrWind O2	Turby	QuietRevolution
Type (VAWT)	Darrieus	Darrieus	Darrieus
Swept Area (m^2)	7.29	N/A	N/A
Cut-in wind speed (m/s)	3.9	4	5
Cut-out wind speed (m/s)	N/A	14	26
Rotor Diameter (m)	2.7	1.9	3.1
Weight (kg)	135	136	N/A
Expected Lifetime (years)	20	20	25
Annual energy production (kWh/yr)	2000-4000	N/A	4197 @ 5 m/s, 7000 @ 7 m/s
Rated power (kW)	1.7	2.5	6.5
Total height (m)	7.9/12.5/18.6	6	13
Survival Wind Speed (m/s)	53.6	55	26

Table 2: Specifications of Various Vertical Axis Wind Turbines[52]

	HelixWind D361	HelixWind S322	HelixWind S594	Windspire
Type (VAWT)	Darrieus	Savonius	Savonius	Darrieus
Swept Area (m^2)	3.61	3.19	5.88	7.43
Cut-in wind speed (m/s)	3.5	5	5	3.8
Cut-out wind speed (m/s)	N/A	N/A	N/A	N/A
Rotor Diameter (m)	1.9	1.2	1.2	1.2
Weight (kg)	130	135	605	283
Expected Lifetime (years)	N/A	30	30	
Annual energy production (kWh/yr)	N/A	1962	3362	2000

[52] Author, 2012

Rated power (kW)	1.0	2.0	4.5	1.2
Total height (m)	7-11	3.3	4.87	7.1
Survival Wind Speed (m/s)	N/A	N/A	N/A	47

Table 3: Specifications of Various Vertical Axis Wind Turbines Continued[53]

	Swift	Aeolos	Four Seasons Windpower	ETC Green	Vestas V90
Cut-in Wind Speed (m/s)	3.58	2.5	3	3	
Maximum Speed (m/s)	64.8	45	50	55	42.5
Rotor diameter (m)	2.1	4	3.2	88/99	90
Rated power (kW)	1.5	2	2	2000	3000
Annual energy production (MWh/year)	1.2 @ 5 m/s, 1.9 @ 6 m/s				2724-13301
Weight (kg)	113.398	125	82 (without tower)	245000	402300
Expected Lifetime (years)	20	20			>15

Table 4: Specifications of Various Horizontal Axis Wind Turbines[54]

[53] *Ibid*, p.27
[54] *Ibid*, p.28

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