Peter Siegel

Crosswind Flight using Structured Gliders: The Key to Taking Airborne Wind Energy to New Heights

Humans have long used wind energy to do valuable work, from using sails to capture wind while crossing bodies of water, grinding grains, to pumping water out of the ground. Today, wind turbines tap into more than 1,800 trillion watts of available wind power, generating electricity in an environmentally sustainable fashion as opposed to burning fossil fuels (Cherubini et al. 1464). Wind, however, still only accounts for less than 1% of power generated worldwide, 0.02 terawatts (TW) out of a global energy demand of 12.5 TW (Ritchie and Roser; Delucchi). Since the Industrial Revolution, societies instead have relied on a much cheaper power source, the burning of fossil fuels, which supplies more than 80% of the world’s energy today (Ritchie and Roser). In order to halt the adverse effects of climate change, driven by increased carbon dioxide and other human emissions into the atmosphere, the world needs to turn to alternative and carbon neutral sources of energy, such as wind, solar, nuclear and hydroelectric power.

Wind is gradually becoming a rival to fossil fuels in terms of cost, as companies such as General Electric and Vestas are building taller and taller wind turbines with larger blades that can output more power (Roberts). Although these massive wind turbines increase the amount of electricity collected from the wind, they are unable to compete directly with fossil fuels without the help of large subsidies (Fares). Traditional wind turbine design is nearing an almost perfect degree of refinement and the limits of scaling such systems are reaching their maximum potential. In order to directly compete with fossil fuels, new technologies need to be introduced that disrupt the renewable energy sector.

Recently, an alternative to these massive turbine towers has emerged in the form of airborne wind energy systems (AWES). Instead of being anchored to the ground with a massive tower, an AWES aircraft is connected by means of a flexible tether and aims to collect power from stronger, more consistent winds found at higher altitudes. Additionally, because of the lack of a need for a tall and rigid support structure, the cost of AWES could be significantly reduced. The primary method of harvesting high altitude wind power, adopted by SkySails Power, Ampyx Power, KiteGen and many other AWE companies, involves generators located on the ground, and are known as “ground-gen” systems (Cherubini et al. 1464). Another, less common approach, adopted by the companies Makani Power and Altaeros Energies, uses a “fly-gen” system, where turbine blades are located directly on the aircraft (Cherubini et al. 1470). To date, power generating aircraft resemble either fabric kites controlled using bridles attaching the kite to the tether, or rigid gliders with powered control surfaces. Rigid wing aircraft, because of their increased aerodynamic efficiency, simplified control theory, and increased durability, are likely better suited for large scale power generation offshore, while flexible kites possess key advantages in portability and lower production cost for land-based power generation in remote locations.

Accessing higher altitude winds alone would increase the performance of wind turbines by two to three times, but the greatest advantage of AWE is a special flying pattern that maximizes the apparent velocity of the wind on the aircraft, a result of the work done by researcher Miles Loyd at Lawrence Livermore National Laboratory in California (Cherubini et al. 1474). Utilizing the technique laid out in Loyd’s paper, “Crosswind Kite Power,” would enable AWES to generate one or two orders of magnitude more energy than a comparable ground-based turbine (Cherubini et al. 1472). Because of technical issues such as cable drag and the greatly increased cost and difficulty of designing an aircraft capable of withstanding winds exceeding 100 km/hr, reaching extreme altitudes such as the jet stream at 10,000m may be technically unfeasible as much as it is unnecessary as a result of the enormous advantage of flying crosswind. Although AWES harnessing crosswind kite power face challenges with completely autonomous operation, including takeoff and landing, ground-gen or fly-gen systems using semi-rigid kites or rigid gliders, because of their increased durability and aerodynamic performance, may prove to be the most viable solution to harnessing airborne wind energy. Such systems are most likely to champion the airborne wind energy sector and will have the best chance of displacing our reliance on fossil fuels and costly conventional wind turbines in the near future.

One of the main advantages of AWES is their ability to tap into stronger winds found at higher altitudes. In 1919, German scientist Albert Betz, a pioneer of wind turbine technology, derived an equation governing the amount of power that can be captured by a wind turbine:

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

where the amount of power that can be captured by a wind turbine per unit area swept by the blades, $\delta, \left(\frac{W}{m^2}\right)$ is a function of the wind speed $v, \left(\frac{m}{s}\right)$ and the density of the air going through the blades $\rho, \left(\frac{kg}{m^2}\right)$ (Archer and Caldeira 309). Because wind speeds tend to increase linearly with height and air density increases nearly exponentially, turbines that can tap into wind power at high altitudes have tremendous potential (Archer and Caldeira 309). The benefits of consistent winds on the output power of the wind turbine should not be ignored since, following Betz’s Law, variations in wind speeds will greatly affect the power output. Lower altitudes possess much more variable and weaker overall winds, leading to the inconsistent power output predicted by Betz's equation (Archer and Caldeira 314).

Some companies such as Sky Windpower, emerging from research conducted at the University of Sydney in 1986, have ambitions of targeting jet streams located between 7 to 12 km above the ground, where the total wind energy is roughly a hundred times greater the current global energy demand (Cherubini et al. 1472). Accessing such altitudes, however, is a problem insurmountable by today's tether technology because of the large drag forces that would affect the cables (Rancourt et al. 906). Sky Windpower went out of business, likely because of the engineering difficulties related to designing an AWES capable of harvesting power from jet streams (Cherubini et al. 1472). Although this news may be considered a major setback for AWES, Cristina L. Archer from California State University and Ken Caldeira from the Carnegie Institution of Washington, Stanford, in "Global Assessment of High-Altitude Wind Power," show that although the highest wind power densities are found between 8,000 and 10,000 m above the ground, there may not be much benefit in pursuing winds higher than 500 m, unless reaching above 2,000 m, because of the relatively constant wind power found between those altitudes (310). Additionally, using global wind data from the Department of Energy and the National Centers for Environmental Prediction, Archer and Caldeira demonstrated that just going from 80 to 500m gives a significant increase in wind power output (310). Their work also highlights the potential of offshore AWES wind power, where wind power maximums are located as low as 1,000 m above sea level (Archer and Caldeira 311). These findings are extremely valuable, because they confirm that irrespective of the immense and possibly insurmountable technological hurdles of harvesting winds from the jet stream, AWES will still gain a major advantage over traditional wind turbines just from reaching altitudes of 500 m or more.

Although airborne wind energy systems emerged from the lure of the 1,800 terawatts of power that could be extracted from high altitude winds, AWES also solve the issue of wind energy growth slowing down because of oversaturation of land covered by windy areas (Fagiano and Milanese 3141). Since AWES are able to reach altitudes with higher wind speeds, they output more power per unit area of land when compared to traditional wind turbines (Cherubini et al. 1462). When compared to traditional wind turbines, AWES excel offshore, where the wind power maximums are located at 1000 m, a height not reachable with conventional wind turbines, but perhaps feasible with AWES. Additionally, costs for installing traditional wind turbines offshore are generally two to three times higher because of the greater massive underwater foundations needed to firmly anchor the tower (Fagiano and Milanese 3142). AWES have the potential to reduce the costs by five to six times in shallow waters between 5 and 30 meters, with even greater benefits in waters deeper than 50 m, where conventional wind turbines simply cannot be installed today (Fagiano and Milanese 3142). AWES do not need a stiff mounting base and would not be affected by vibrations induced by incoming waves, meaning they could be attached on floating platforms, further reducing the cost of installing airborne wind energy offshore (Fagiano and Milanese 3142).

Nearly all AWES designs are comprised of two parts: a ground system and at least one aircraft or wing that is mechanically and potentially also electrically connected to the ground by one or more tethers. Converting the mechanical power of the wind into electrical power is done either with a generator on the ground in what Antonello Cherubini refers to in his paper "Airborne Wind Energy Systems: A review of the technologies," as "ground-gen" systems, or in the air mounted directly to the aircraft in “fly-gen” systems (1464, 1470). Both systems have their strengths and weaknesses, with ground-gen systems excelling with a simpler design that does not require an electrically conductive tether and with “fly-gen” systems main benefit being their ability to continuously generate power.

Systems with a fixed ground generator produce power when lift force of the wind acting on the aircraft is transmitted to the ground system through one or more tethers, rotating an electrical generator as the tether unspools. Energy is produced in this generation phase. To recover the AWES and reset it for another generation phase, power is sent back into the generator, reeling in the tether and bringing back the aircraft to its original position where it is ready to begin another cycle. Flying in a “crosswind,” figure eight pattern will increase the stronger apparent wind acting on the aircraft and therefore its pulling force, significantly increasing the maximum power that an AWES can produce (Loyd 108). For a ground-based generator to produce a net positive amount of power, the amount of energy produced during the generation phase must be less than the energy spent in the recovery phase (Cherubini et al. 1465). Such a feat is done with the implementation of a control system that adjusts the aerodynamic characteristics of the aircraft and/or controls its flight path to minimize the energy spent while reeling in the tether. The main problem ground-gen systems face is their intermittent power output, requiring the use of batteries, capacitors or the deployment of multiple AWES simultaneously to generate a more consistent power output (Cherubini et al. 1465).

Using either a rigid wing or fabric gliders as the power generating aircraft is one of the most important decisions that can be made when designing an airborne wind energy system. Durability of fabric, with a performance lifetime of around several hundred hours is a known issue, although their decreased weight also means that they possess the ability to generate more power when compared to an equally heavy rigid glider (Cherubini et al. 1467). Rigid gliders on the other hand tend to be more expensive and heavier, although they have the great advantage of having the most aerodynamically efficient design and a long operating lifespan (Cherubini et al. 1467). Additionally, control of rigid gliders in the air is greatly simplified because of the vast experience that the aerospace industry has with modeling and controlling rigid wing aircraft.

A multitude of AWE startups have focused on ground-gen systems because of their simpler design and their ability to take advantage of the increased power generated when flying crosswind in a circular pattern. The Italian company KiteGen was one of the first to test a ground-gen AWES with a successful prototype design consisting of a kite with on board sensors used for accurate kite positioning and two power ropes. Now the company is focused on a new offshore AWES, named “KiteGen Stem” with a claimed power output of 3 MW, rivaling that of most conventional wind turbines (KiteGen Research). The design consists of two ropes wound around generator winches that extend through a 20 m flexible rod called a “stem” and attach to a semi-rigid kite (Cherubini et al. 1467). The “stem” is meant to support the kite above the ground and dampen the high forces that act on the rope during big, unexpected gusts of wind (Cherubini et al. 1467). When the kite takes off the energy production phase starts. Autonomous software controls the kite from the two ropes connecting it to the ground, making it fly in the optimal crosswind flight pattern while generating electricity. The most critical part of the autonomous system is reducing the energy used during the kite’s recovery phase, ensuring that the system produces the largest possible net gain in energy. A special maneuver called “side-slip” or “flagging” is used, where the kite is stalled and pulled down to the ground sideways (Cherubini et al. 1467). After rewinding the rope to a certain length, another special maneuver is used to restore the kite to its power generating position. From its use of the “stem” and a semi-rigid kite design it is evident that KiteGen is attempting to overcome the durability issues involving fabric kites while still taking advantage of the lower weight such systems offer. Its use of two power generation lines, which also act as control lines for the kite are likely one of the best approaches for a ground-gen system because of the lack of a need for a control pod and an electrically conductive tether to power it.

The Dutch company, Ampyx Power, avoiding the complexity of the control software and the durability issues of frameless kites entirely, is instead the first to have developed a ground-gen system that uses a rigid glider (Cherubini et al. 1468). Currently, it is testing two 5.5 m "PowerPlanes," the AP-2A1 and AP-2A2, both aircraft constructed with light and stiff carbon fiber composite shells and backbones, with autonomous software controlling a rudder, elevator and four flaperons (Cherubini et al. 1468). Increasing the simplicity, and hence the durability of their design, only a single rope is used to attach glider to a power generating winch on the groud station. Ampyx power is ahead of most other companies pursuing ground-gen systems, being one of the first companies that has developed an AWES that is capable of fully autonomous takeoff, power generation and landing. In Ampyx's system, the glider first lies on the ground facing the ground station and as the winch starts winding, the glider gains lift and takes off (Ampyx Power). Their prototype has already demonstrated a power production of 6kW with peaks of over 15kW and Ampyx is beginning to develop its first commercial product, a 35 m wingspan AP-4 PowerPlane capable of generating 2 MW (Ampyx Power). Ampyx's rigid-wing glider is another leading example of a ground-gen system because it takes advantage of the well understood and modeled characteristics of rigid-wing aircraft and applies them to airborne wind energy. Additionally, using rigid kites simplifies takeoff and landing software requirements significantly because of the greater control that operators have over the movement of the aircraft.

Because of the superior aerodynamic characteristics of rigid-wing aircraft, recovery phases are likely more efficient than with kite powered ground-gen systems.

Another common approach taken by airborne wind energy companies is using a fly-gen system, where electrical energy is produced onboard the aircraft and then transmitted to the ground through an electrically conductive tether. The main benefit of such a system is that it can produce energy continuously while in the air and only expend it during landing and takeoff. Fly-gen systems are able to achieve much higher output than equivalently sized traditional turbines, with Miles Loyd calculating that wind turbines mounted to airborne aircraft could generate up to five times the power if they fly in the described crosswind flying patterns (Loyd 111). Makani Power, a startup acquired by GoogleX aims to take advantage of Loyd’s findings by using a multi-rotor glider with a single conductive tether (Makani Power). The glider takes off vertically reaches the optimal altitude under its own power. It then begins a continuous generation phase where it makes figure eight loops, generating crosswind power, now using the rotors as generators (Makani Power). Landing procedures are also simplified, with the airborne wind turbine touching down on the ground much like a quadcopter (Makani Power). Currently Makani is developing a 600-kW prototype with eight turbines with five propeller blades and a wingspan of 28 m. Makani’s ambitions are set on offshore wind power, where it plans to place a commercial version with 5 MW of power with 6 turbines and a wingspan of 65 m (Gallucci; Makani Power). Makani is partnering with Shell and are preparing to test their 600 kW prototype offshore later in 2019, an achievement which would mark the first offshore test of AWES (Gallucci). Although ahead of many competitors in terms of real-world tests, until several AWES are released as a product it is not possible to determine if Makani’s simplified landing and takeoff procedures and its ability to generate continuous power will put it ahead of the intermittent power generation method used by KiteGen and Ampyx's ground-gen systems.

Some companies are pursing high altitude winds without taking advantage of the added power acquired from "crosswind" flight. Altaeros Energies, a startup founded by MIT and Harvard alumni have developed a lighter-than-air airborne wind turbine, essentially a conventional turbine blade positioned in the center a ducted helium inflated blimp (Samson et al. 2). Like Makani's system, Altaeros's design can send power down to the ground continuously through a conductive tether. The company conducted energy production tests in 2012 and is currently planning to add additional rotors to its system (Cherubini et al. 1472). In addition to being significantly more expensive, the Altaeros design is unable to take advantage of crosswind flying power (Samson et al. 4). Because of Altaeros's decision to simply raise a traditional wind turbine to higher altitude, compromises made in the size of the wind turbine mounted to the lighter aerial blimp likely mean that Altaeros's system is unable of generating more power than traditional wind turbines or AWES taking advantage of crosswind flight.

Rigid and semi-rigid wings have significant advantages over fabric kites and are seemingly emerging as a victor in the AWE community, with Robert Creighton, a founder of WindLift, a company that uses a ground-gen system with a fabric kite stating in 2012 that if the company is not successful with improving aerodynamic efficiency during the regeneration phase with semi-rigid kites, "the need to be able to reel in the kite without expending much energy may ultimately force [WindLift] to adopt completely rigid wings" (Creighton). Seeing as WindLift have since adopted rigid wings in their ground-gen design, kite durability and control during the recovery phase may prove to be a challenge to difficult to overcome for many companies (Windlift). Across all types of AWES, because the aircraft are in a constant state of imbalance, the area where most progress is needed is in developing highly sophisticated and intelligent autonomous software that controls everything from take-off and landing procedures, to crosswind flying patterns. Being able to quickly modify the angle of attack of any fly-gen or ground-gen system is critical because such variations can substantially decrease power output or even make flight impossible (Cherubini et al. 1473). Tethers in all AWES are another culprit because of wear, maintenance and their aerodynamic drag. Because of the shortcomings of tethers, designs that minimize the amount of rope used have a significant advantage.

To date, tens of millions of dollars have been spent so far on AWES, a surprisingly small amount considering the potential impact that airborne wind energy might have on the renewable energy sector (Cherubini et al. 1474). Although only preliminary cost estimates of AWES are possible, it is very likely that production costs will be lower since AWES do not require rigid foundations, large amounts of land, and enormous blades (Fagiano and Milanese 3141). An analysis by Lorenzo Fagiano from Politecnico di Milano in “Airborne wind energy: an overview” projects that airborne wind energy has the potential to displace coal, gas, nuclear solar and current wind technology with its lower costs. However, only once a real product is brought to market will the effectiveness of airborne wind turbines be accurately quantified.

The various airborne wind energy systems discussed have unique situational advantages, and there will likely not be a single design that emerges as the uncontested champion of airborne wind energy. Offshore, where maintenance is more difficult to carry out and where software will must be completely autonomous, rigid wing gliders from Ampyx and Makani bear significant advantages when compared to the control complexity of KiteGen’s semi-rigid fabric kites. Because of their increased portability and lower weight fabric kites will likely be used to generate electricity on land where they may be easily transported to remote locations that don’t have easy have access to energy. Such onshore portable systems, although much cheaper, will likely have to be smaller scale because of the durability issues facing fabric kites. Rather than completely replace conventional wind turbines, AWES will diversify the renewable energy market to suit situations where current turbines will not function as efficiently. It is almost certain that the most successful AWES designs will employ Loyd's crosswind kite power technique because of the enormous improvements it brings to the power output of airborne wind energy systems. If companies can continue making progress with autonomous software and durability of fabric materials and tethers, and if airborne wind energy continues to receive funding from investors, high risk, high reward designs that harness the power of crosswind flight may be the key to meeting goals for offsetting the world's reliance on fossil fuels and combatting the ever-mounting crisis of climate change.

Works Cited

Ampyx Power. "Technology." *Ampyx Power B.V*, https://www.ampyxpower.com/technology. Accessed 17 Apr. 2019.

Archer, Cristina L., and Ken Caldeira. "Global Assessment of High-Altitude Wind Power." *Energies*, vol. 2, no. 2, June 2009, pp. 307–19. *www.mdpi.com*, doi:10.3390/en20200307.

Cherubini, Antonello, et al. "Airborne Wind Energy Systems: A Review of the Technologies." *Renewable and Sustainable Energy Reviews*, vol. 51, Nov. 2015, pp. 1461–76. *ScienceDirect*, doi:10.1016/j.rser.2015.07.053.

Creighton, Robert. "The Benefits of Airborne Wind Energy - IEEE Spectrum." *IEEE Spectrum: Technology, Engineering, and Science News*, 28 Nov. 2012, https://spectrum.ieee.org/energy/renewables/the-benefits-of-airborne-wind-energy.

Delucchi, Mark Z. Jacobson, Mark A. "A Plan to Power 100 Percent of the Planet with Renewables." *Scientific American*, doi:10.1038/scientificamerican1109-58. Accessed 17 Apr. 2019.

Fagiano, L., and M. Milanese. "Airborne Wind Energy: An Overview." *2012 American Control Conference (ACC)*, 2012, pp. 3132–43. *IEEE Xplore*, doi:10.1109/ACC.2012.6314801.

Fares, Robert. "Wind Energy Is One of the Cheapest Sources of Electricity, and It's Getting Cheaper." *Scientific American Blog Network*, https://blogs.scientificamerican.com/plugged-in/wind-energy-is-one-of-the-cheapest-sources-of-electricity-and-its-getting-cheaper/. Accessed 20 Feb. 2019.

Gallucci, Maria. "Alphabet's Wind Energy Kites to Fly Offshore." *IEEE Spectrum: Technology, Engineering, and Science News*, 20 Feb. 2019, https://spectrum.ieee.org/energywise/energy/renewables/alphabets-moonshot-wind-kites-to-fly-offshore.

KiteGen Research. *KiteGen Research*. http://www.kitegen.com/en/products/stem/. Accessed 17 Apr. 2019.

Loyd, Miles. *Crosswind Kite Power*. Vol. 4, 1980.

Makani Power. *Technology | Makani*. https://makanipower.com/technology/. Accessed 17 Apr. 2019.

Rancourt, David, et al. "Design Space Exploration of Gyrocopter-type Airborne Wind Turbines." *Wind Energy*, vol. 19, no. 5, 2016, pp. 895–909. *buprimo.com*, doi:10.1002/we.1873.

Ritchie, Hannah, and Max Roser. "Energy Production & Changing Energy Sources." *Our World in Data*, Mar. 2014. *ourworldindata.org*, https://ourworldindata.org/energy-production-and-changing-energy-sources.

Roberts, David. "These Huge New Wind Turbines Are a Marvel. They're Also the Future." *Vox*, 8 Mar. 2018, https://www.vox.com/energy-and-environment/2018/3/8/17084158/wind-turbine-power-energy-blades.

Samson, J., et al. "A Critical Assessment of Airborne Wind Energy Systems." *2nd IET Renewable Power Generation Conference (RPG 2013)*, 2013, pp. 1–4. *IEEE Xplore*, doi:10.1049/cp.2013.1852.

Windlift. "Windlift Technology | How Our Airborne Power Generation Works." *Windlift*, https://windlift.com/technology/. Accessed 17 Apr. 2019.