Airborne Wind Energy- A Review

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Abstract Airborne Wind Energy (AWE) is a new approach to harvest stronger wind streams at higher altitudes for renewable energy. This paper reviews recent developments in this field. Conventional wind energy and current constrains for its development are discussed and airborne wind energy as an appropriate solution in the literature is reviewed. Different AWE technologies are reviewed and appraised and other related issues such as transmission and curtailment are discussed.

Keywords Airborne Wind Energy (AWE), Synchronous Generator, direct interconnection, Power to gas

1- Introduction

At present, with rising concerns about global warming and limited fossil resources, renewable energy is more popular than ever. In recent decades, renewable energy has seen faster growth than other forms of energy production. Among different non-hydro renewable energies, wind energy has seen the biggest absolute increase. It is anticipated that the share of wind energy in total worldwide electricity generation will be 4.5% in 2030 and that wind power will be the second most significant source of renewable electricity production after hydropower (International Energy Agency 2014).

Despite the rapid development of wind energy in recent decades, it is still expensive and most wind energy projects encounter financing problems (International Energy Agency 2014). Investors are demanding more profit from wind energy projects and researchers are looking for solutions to decrease the total cost of wind energy by reducing cost of construction, repair & maintenance and transmission to grid. According to (The European Wind Energy Association 2009), 91% of a typical wind turbine cost is allocated to the turbine, grid connection and foundation costs forming 75.6%, 8.9% and 6.5% respectively. Airborne wind energy can provide a significant cost reduction in turbine and foundation costs. Also, by using new technologies such direct interconnection and hydrogen production from curtailed winds, grid connection cost will be reduced considerably.

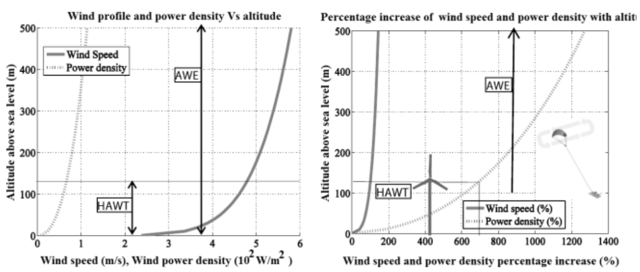
In this paper, different airborne wind energy technologies are reviewed and recent developments in utilizing curtailed winds and a new interconnection scheme are presented.

2- Airborne Wind Energy

An AWE system typically consists of a free flying airborne element such as a kite, glider or floating horizontal axis wind turbine, which is connected to ground through a tether. The first study of airborne wind energy was conducted in 1930 in California, USA, though the first attempt to produce electricity from an airborne wind energy device was in Minnesota, USA; a generator was installed on a balloon and it was capable of producing 350W electrical power (Manalis 1976). Loyd in 1980 reported the first analysis of kite for generating electrical energy. He modeled large-scale power production by means of an aerodynamically efficient kite. According to his work with use of a tethered wing as big as a C-5A aircraft, it is possible to generate 6.7 MW of electrical energy with a 10m/s wind (Loyd 1980).
The primary motivation for developing airborne wind energy systems is accessing stronger winds at higher altitudes. With increasing altitude, the speed of wind increases and winds are more consistent and less turbulent. At altitudes above 200m, wind energy devices can provide the highest capacity factor at lower cost (Archer et al. 2009). According to (1) the wind power density at altitude (WPD_h) increases to the cube of wind speed (Archer 2013). This cubic relationship can be seen also in figure 1 where increase of wind speed and power density with altitude is illustrated. This is the main motivation driving AWE device development; generating wind energy at higher altitude than possible with civil structures. With even small increases in the height of the wind energy device, the generated power increases significantly.

$$WPD_h = \frac{1}{2}\rho V_{w\_h}^3 \quad (1)$$

In (1), ρ is the air density and V_{w_h} is the wind speed at altitude.



(a) (b)

Fig. 1. (a) Wind speed and power density with altitude, (b) Wind density and power density percentage increase with altitude (Coleman 2014).

A. Ampyx Power

Ampyx Power is a Dutch company that is developing a pumping mode AWE system with a tethered rigid wing glider called PowerPlane. Pumping mode AWE is a reciprocating operation which consists of two phases; the pumping phase and recovery phase. During the pumping phase, a tethered glider pulls on the ground station tether drum through the tether. The drum is connected to generator by a drivetrain. With rotation of the tether drum, the generator will rotate, producing electricity. When the tether reaches the maximum length, the glider will change its flight path toward ground station and tether will be rewound onto the drum. This phase is called the recovery phase. Power is consumed during the recovery phase but it is considerably less than generated power in pumping mode. Ampyx Power AWE concept is demonstrated in figure 2 (Sieberling 2013). This company developed a prototype in 2013. The proposed system is a 12 kW PowerPlane which is described as a six degree of freedom rigid wing system. The electrical power take-off for this prototype is a single direct driven electrical machine with grid connection through a power converter (Ruiterkamp et al. 2013). Ampyx Power is planning to develop two 250kW and 3MW prototypes by 2018 (Ampyx Power 2015).

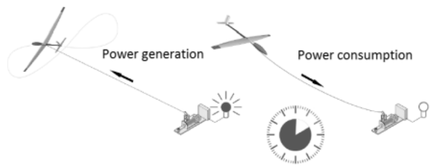


Fig. 2. Ampyx PowerPlane (Ampyx Power 2015)

B. WindLift

WindLift was founded in 2006 and developed a ground actuated kite control system. This American company developed an AWE prototype which utilized a 40m^2 inflatable kite as the prime mover. The kite is tethered to a ground station by three tethers; one main tether that rotates the electrical generator and two steering tethers that provide ground based steering actuation. This system is capable of producing 12kW peak electrical power form winds with speeds between 12 and 40 mph. The ground station of WindLift prototype is shown in figure 3 (Creighton 2012). As can be seen, the main tether is wound onto a drum which is connected to a generator. In the power phase, the kite rotates the generator through the tension in tether. In the recovery phase, the generator operates as a motor, winding the tether onto the drum. The WindLift current prototype uses a 90cm diameter drum, which is connected to 60kW motor-generator built originally for a hybrid electric bus. In the future, WindLift plan to improve the wing characteristics to increase power in generation phase and decrease consumption during recovery phase (WindLift 2015).

C. EnerKite

EnerKite was founded in 2010 in Germany. The core team behind EnerKite has been active in the area of AWE related systems since 2002. In 2008, Aeroix and Festo tested a prototype called 'CyberKite'. This prototype used an innovative hybrid kite designed with a bionic stingray shape and helium supported wings. The development of the control mechanism for this 24m^2 kite ended in 2010 after several hundred hours of testing (Bormann et al. 2013).

After the establishment of EnerKite this company drew on its experiences from CyberKite to develop a new prototype 'EK30'. This AWE device is a 30kW prototype which is driven by a three line ground actuated kite power system. This prototype has been developed as a mobile AWE system mounted on a vehicle and works off-grid using battery storage. It can operate at altitudes between 100 and 300m and uses a 30m^2 wing (Bormann et al. 2013 and EnerKite 2015). The EK30 is shown in figure 4.

EnerKite is planning to develop two new prototypes in 2017 and 2018. EK200 is designed to generate 100kW electricity as a standalone system or within an isolated grid. The wing area of this system is 30m^2 and it will be capable of operating in wind speeds between 3m/s and 20m/s. EK1M is a large-scale commercial product which is planned to be on the market by 2018. This system can generate 500kW electrical energy connected to a power grid. The EK1M is projected to use a 125m^2 area kite and it will operate in wind speeds from 3m/s to 25m/s. The maximum operating altitude for this system will be 300m (Bormann et al. 2013 and EnerKite 2015).

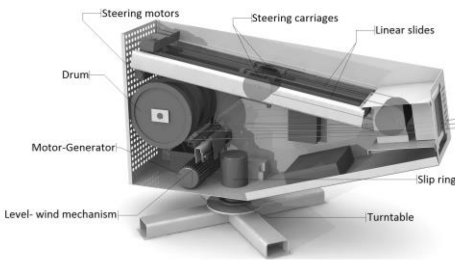


Fig. 3. WindLift ground station (Creighton 2012)

Fig. 4. EnerKite (Bormann et al. 2013)

D. SkySails

SkySails was established in 2001 to develop airborne wind energy devices for ship propulsion augmentation. Between 2001 and 2006, they tested small scale prototypes on various vessels. In 2013 SkySails developed a ship towing kite which is capable of displacing up to 2MW propulsion power. This 320m^2 kite can allow a ship to reduce fuel oil consumption by up to 10 tons per day. This company has extended its interests to electrical power generation. In 2011, SkySails developed a 55kW prototype for producing electrical energy. The prototype is a pumping mode airborne wind energy system, which uses a single motor/generator for electrical power takeoff and kite recovery in the pumping mode cycle. SkySails are planning to develop a 1MW offshore airborne wind energy device, which would use a 400m^2 kite on a 1000m tether. SkySails are considering the development of the first offshore AWE farm with over 7 MW per device (SkySails 2015 and Fritz 2013).

E. Makani Power

Makani Power, a Google X company, has developed a unique type of airborne wind energy, which is called an Airborne Wind Turbine (AWT). The AWT is a rigid wing which carries eight propeller/turbines with each connected to motor/generator. During launch, the electrical machines drive the propellers consuming power to bring the system from the ground station to the desired starting altitude. The propellers are then adjusted to act as turbines driving the electrical machines as generators, producing electricity. The generated power is transferred to the ground station through the tether. The tether is made of conductive aluminum wires and high strength carbon fiber core (Makani Power 2015). In addition to power transmission, the tether provides communications between AWT and ground station. Installing electrical power take off machinery on the wing increases the airborne system mass. For a 100kW AWT with 8 turbines the overall weight of power electronics converters and generators/motors on the airfoil would be 70 kg and tether weight will be 320 kg. The optimal tether voltage for minimum mass is 8kv DC (Kolar et al. 2011). Makani Power has tested two 10 kW and 30kW prototypes and currently they are working on an AWT device with 600kW rated power in an 11.5 m/s wind, which operates at altitudes between 140m and 310m with a 145m circling radius (Makani Power 2015).

(a) (b)

Fig. 5. SkySails productions, (a) Ship propulsion system, (b) airborne power generator (Fritz 2013)

F. Sky WindPower

Sky WindPower is developing an innovative type of airborne wind energy device. This system is an autonomous quad-copter, which consumes electrical energy to reach the appropriate altitude for power generation. When the device arrives at the desired altitude, it inflects itself to the wind at a specific pitch angle to allow the rotors to be driven by the wind, consequently generating electrical power and lift simultaneously. Their device, which is called Wind Airborne Tethered Turbine System (WATTS), is nearly ready for customer testing and can generate 240kW nominal electrical power at altitudes up to 2000m with high wind speeds from 9mph to greater than 65 mph (Sky Wind Power 2015). WATTS is designed to operate in off-grid sites such as military outposts, naval vessels, mining operation, oil drilling platforms, agricultural, scientific and research facilities. In addition, WATTS will be capable of performing other roles such as “Eye in the Sky” security systems, remote antenna elevation, atmospheric sampling, weather monitoring, etc. (Sky Wind Power 2015 and Roberts et al. 2007)

G. Academic Research

In several universities, airborne wind energy is under investigation. TU Delft is one of the leading universities working on AWE systems. In 1999, they undertook their first AWE system analysis (Ockels 2001 and 2004). This system consists of a number of wings that are connected to each other by a single tether driving a ground located generator. In 2013, a 20kW rated ground station and kite control system for a pumping mode AWE prototype was developed by researchers in TU Delft (Jehle et al. 2014). Developing novel control methods, ground station and kite design are other issues that are under investigation in TU Delft (Lansdorp et al. 2007, Williams et al. 2008 and Fechner et al. 2015).

In Politecnico di Torino, a prototype called KiteGen has been simulated and tested. Two different topologies have been presented by researches in Politecnico di Torino, yo-yo and carousel configuration (Canale et al. 2010). The yo-yo configuration is the same as pumping mode AWE, while the proposed carousel configuration consists of several airfoils, each one connected to a kite steering unit (KSU) placed on a vehicle moving along a circular rail path. Each airfoil pulls one vehicle on the carousel while the vehicles maintain constant separation from each other on the rail. Electrical power is generated through motor/generators driven by the wheels of each rail vehicle (Canale et al. 2006 and 2007).

Neural network controllers for controlling airborne wind energy systems have been developed at the University of Sussex. The evolution of neural network controllers has been carried out by genetic algorithms. It has been shown that continuous time recurrent networks (CTRNN) are capable of being trained for flying

AWE kites in an appropriate repetitive trajectory even when the length of tether is changing (Furey 2011and Furey et al. 2007).

A two-line kite control algorithm has been developed in KU Leuven. This controller is capable of controlling the lateral angle of kite and feedback is used to stabilize the orbit of the kite. For monitoring of the motion of the kite, polar coordinates are used in four degrees of freedom (Diehl et al. 2001). Optimization of towing kites, developing a non-linear model of predictive control, new approaches for launch and recovery of glider AWE systems and trajectory optimization of AWE devices are other research works which have been carried out at KU Leuven (Geebelen et al. 2012, Houska et al. 2006,2007 and Ilzhoefer et al. 2007). In addition, in (Zanon et al. 2013) the use of two airfoils for airborne wind energy systems on a single main tether has been investigated.

A new power take off method for pumping mode airborne wind energy has been developed at the University of Limerick. This AWE prototype does not reverse the generator to perform the recovery task, but rather this is performed by a fractional scale recovery motor. In this arrangement, the two pumping mode operations are separated and performed by optimally specified electrical machines for each task. Using a non-reversing generator is more suitable for power generation and delivery to grid especially at large scales. Furthermore, direct interconnection of AWE generators and distributed control for the flight of tethered kites have been developed at the University of Limerick (Coleman et al. 2013 and 2014) and remains an active area of research.
Currently, six universities consisting of TU Delft, KU Leuven, TU Munich, ETH Zurich and University of Limerick and four industrial partners are cooperating in the AWESCO ITN, a Marie Skłodowska-Curie action under the Horizon 2020 framework program of the European Union (AWESCO 2015). This network is focused on the development and optimization of AWE technology and methods and will ensure the continued development of AWE within the EU.

3- Dispatch and curtailment

Dispatching generated power is a challenge in dealing with airborne wind energy systems especially with offshore devices. Conventional wind energy technology deploys power converters in each unit where the generated power is converted to DC and recovered to gird compliant AC for supply to the distribution network. Using power converters for each unit will increase rate of failure and cost of systems, as according to (Spinato et al. 2009) the converter has the third highest failure rate among wind turbine subassemblies. In offshore airborne wind energy devices, the failure rate and cost would be even more because of high expenses of offshore repair and maintenance and the novelty of the technology. In (Pican et al. 2011) a new approach, called direct interconnection, has been proposed and tested for offshore wind energy systems. In this method, power converters are removed from the individual power devices and the generators are synchronized directly onto an offshore power bus by means of a synchronization controller. After synchronization, overall generated power is dispatched to on-shore station. In an on-shore station, a back-to-back converter provides a grid-code compliant AC output from the interconnected offshore bus. This approach has been analyzed for pumping-mode airborne wind energy systems in (Coleman et al. 2014) and conventional wind turbines in (Pican et al. 2011) with very good results.

In a curtailment situation, wind is available but the grid operator does not allow the wind farm to dispatch the generated power to the grid. A wind turbine or AWE system might be curtailed when the transmission system is under loaded due to lack of demand. In this situation, the system is subjected to overvoltage conditions and network operators try to relieve this by decreasing power production on the network. Curtailment may also happen for other system reasons such as frequency control or market based protocols (Bird et al. 2014).

During curtailment conditions, it may be possible to store energy locally rather than ceasing operation or reducing/curtailing generated power. Different methods for storing curtailed wind energy exist such as pumped hydroelectricity storage (PHES) (Deane et al. 2010) and compressed air energy storage (CAES) (Beaudin et al. 2010). Power to gas (P2G) is a new approach, where curtailed wind energy is converted to methane gas which can be sold for gas network consumption, transportation, heating, etc. P2G systems convert electrical energy to hydrogen through an electrolysis process. The produced hydrogen is then converted to methane by reaction with CO_2 .The required CO_2 could be achieved from different resources such as ambient air, thermal power plant exhaust or biogas. The overall efficiency of power to gas conversion is between 55 and 80 percent depending on the efficiency of the electrolysis and methanation processes (Ahern et al. 2015). Winds in higher altitudes are more consistent and hence AWE systems can operate more often than conventional wind turbines. Since it is not always possible to dispatch generated power to grid, using power to gas technology would be very helpful technology for utilizing curtailed winds.

4- Conclusion

Different AWE technologies have been reviewed. In some technologies, soft wings provide the mechanical prime mover while some others are using rigid wings to harness wind energy. AWE systems with rigid wings are more efficient and easier to control. In the case of soft wings, researchers are developing new kite models and construction methods to improve their efficiency. Using a pumping mode operated ground station is the most popular electrical power take-off method. In some cases such as Makani AWT and Sky WindPower WATTS, generators are mounted on the wing. In these cases, high voltage tethers, increased weight and mechanical strength of cables for transmitting power from wing to ground station are fundamental challenges, especially in large-scale devices.

Dispatching generated power is a very significant factor in the cost of generated power. In the case of offshore AWE systems, dispatch becomes much more important because of the long distance from the shore and the high expenses of offshore repair and maintenance. Direct interconnection is an appropriate solution for reducing the cost of generated power by minimizing the number of power electronic converters offshore. Using curtailed wind energy for producing gas would be a very useful technology to store generated power by AWE devices during the periods when it is not possible to deliver electrical power to the grid.

Various companies and universities are developing AWE systems with many promising commercial products by 2020. Despite the widespread developments of airborne wind energy systems, this technology is still very young and much work remains to move towards commercial devices.

Acknowledgments

This publication has emanated from research supported by the Science Foundation Ireland under the MaREI Centre research program [Grant No. SFI/12/RC/2302] and through the support of the European Commission under the H2020 Marie Skłodowska-Curie action: ITN AWESCO [Reference No. 642682].

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