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Airborne Wind Energy Systems: Current state and challenges to reach the market

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Abstract In this article, the progress of Airborne Wind Energy (AWEs) systems, technology trends and barriers were studied. The concept of AWE technology, the different configurations of the system, the prototypes developed in the world was discussed, giving focus to the research developed in Brazil. The scientific and industrial community in the last decade has been working to allow AWE technology to reach the market in the coming years. AWE systems use wired aerial devices, which are lighter, less bulky and cheaper and allow access to wind energy available at higher altitudes (600m), inaccessible to current tower-based technology. AWE technology is in the research and development (R&D) and testing phase, but it still needs to mature and, therefore, there are many challenges to overcome to reach the market.

Keywords: Airborne wind energy; pumping kite; wired airfoils.

1 Introduction

Transported wind energy is an innovative technology that in the international literature is often referred to by the term Airborne Wind Energy (AWE) (Ahrens et al., 2013). This technology refers to the generation and conversion of wind energy to electricity using wired airfoil devices. These overhead devices can combine both an onboard wind turbine with a conductor cable, and an aerogenerator with wired airfoils mechanically connected to the ground.

Airborne wind energy began to be studied in the 1980s, with the research Crosswind kite power developed by Loyd (Loyd, 1980), which described two ways of generating electrical energy through AWE technology, the lift mode with generators positioned on the ground and the drag mode with generators on board. But it was only at the beginning of the 21st century that AWE technology began to be intensively studied. Figure 1 shows the growing number of research institutions and or industry involved in AWE worldwide.

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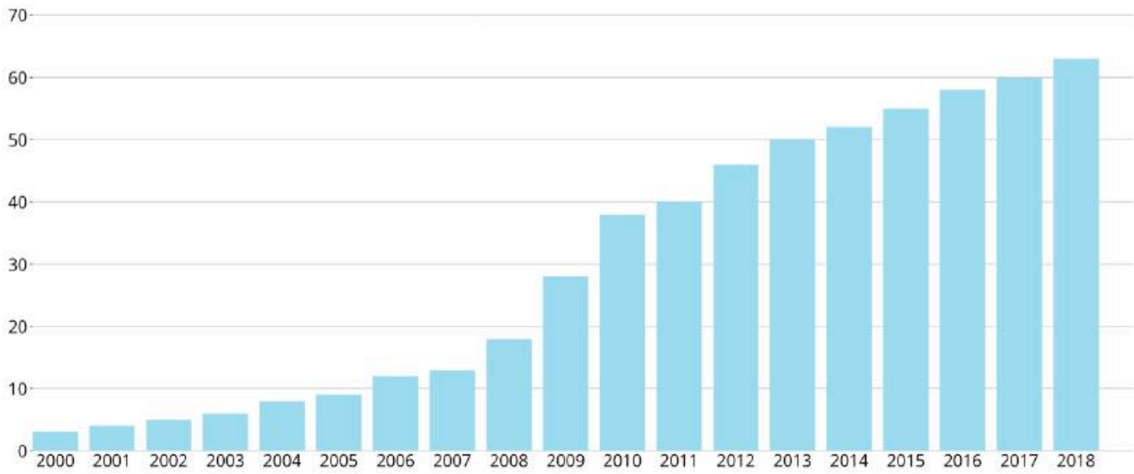

Fig. 1 Number of companies and or research institutions involved with AWE technology. Source: (Schmehl, 2019).

Most research institutions and or industry around the world that have made important technological advances, are using technology using wired airfoils. The strategy used is to fly a kite (the airfoil) in the direction of the crosswind, maximizing the traction on the cable, and consequently the power extracted from the wind. The high altitude airfoil can be maintained by the wind flow, and the cable tension can be used to collect some of the energy that the moving airfoil can potentially extract from the wind.

Comparing the technology of wind turbines with wired airfoils with the technology of conventional wind turbines, it is possible to understand that the goal of AWE technology is to use part of the structure that moves more quickly than a large wind turbine, which are the tips of the rotor blades, and replace them with wings similar to those of a paraglider, kitesurf or similar to a balloon or airplane wings automatically controlled.

According to Fagiano et al. (2010) in conventional wind towers, 20% of the surface at the tip of the rotor blades contributes 80% of the electrical power generated. This is because the speed of the tip of the rotor blades is higher and, consequently, the effective wind speed is higher on the outside of the blades.

Replacing the conventional wind turbine tower with a cable considerably reduces material consumption (reducing the cost of construction, installation and transport) and allows the airfoil to be operated at high altitudes (up to about 600 meters), where there are stronger and more frequent winds, which are inaccessible to conventional tower-based technology. Because it can operate at high altitudes, this new technology can be economically viable even in locations where conventional technology is not viable due to the presence of insufficient winds at low altitudes (Mendonça, 2017). This aspect allows, for example, to reduce costs associated with long transmission lines, with the installation of generating units closer to large consumption centers. From an environmental point of view, AWE technology reduces visual impact, produces less noise and allows airfoil operation to be diverted from bird migration routes, which is not possible in conventional technology without interrupting operation.

In this article, the progress and trend of wind energy technology (wind turbine X wired airfoils) were discussed. The concept of AWE technology, the different configurations of the system, the prototypes developed in the world was briefly discussed, focusing on the technological development developed in Brazil. Although several studies have been carried out on the development and status of conventional wind energy technology, few have been done for AWE technology and none has presented the progress and recent trends in airborne wind energy technology.

2 Advances in wind energy technology

The role of wind energy is to provide competitive, reliable and clean energy to stimulate economic growth and reduce greenhouse gas emissions, while creating jobs and increasing energy security.

Wind energy is developing in this direction and has been transforming the energy sector. The installed capacity of wind energy increased from 17.4 GW in 2000 to 591 GW in 2018 (REN21, 2019). According to REN21 (2019), the energy generated by the force of the wind is 5.5% of the world energy generation in 2018. Technological improvements in the wind sector have reduced the costs of producing energy at competitive prices and the technology has changed since the first wind farms in the world in 1980 as shown in Figure 2, doubling the average size of the rotors and producing more energy (OECD/IEA, 2013).

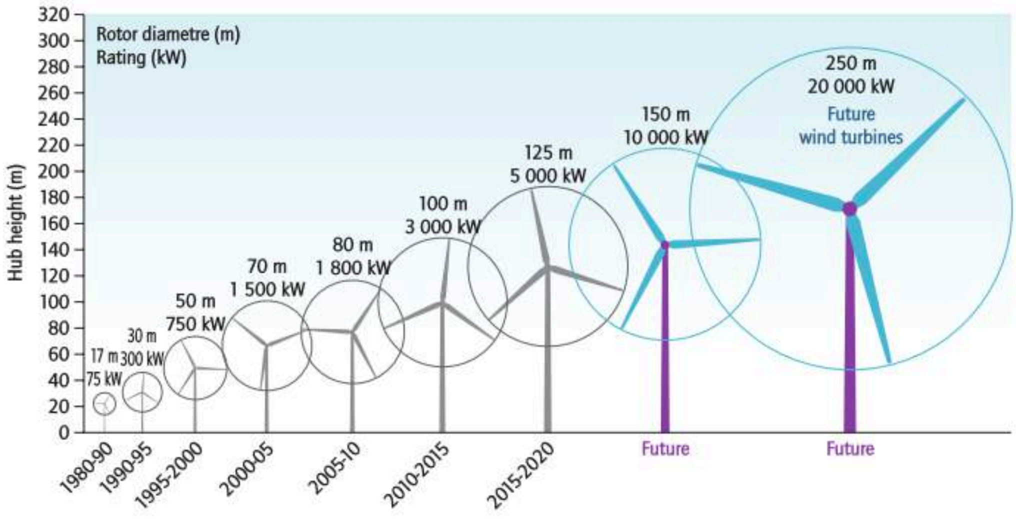

Fig. 2 Scalability expected for a wind turbine. Source: (OECD/IEA, 2013).

According to Thresher et al. (2007), the main incentive to increase the size of a wind tower is to take advantage of the wind shear, placing the rotors at high altitudes in order to take advantage of stronger and more stable winds.

However, according to Fagiano et al. (2010), the wind potential available at high altitudes cannot be tapped at competitive costs by conventional tower-based wind technology.

3 Advances in Airborne Wind Energy technology

In the early 1980s, Miles Loyd had the idea of building a wind generator without a tower, using a flying kite connected to the ground by a cable, like a kite (Loyd, 1980). It was from Loyd's inventions that the concept of airborne wind energy or airborne wind energy was developed.

At the beginning of the 21st century, research on renewable energy sources promises a future free of fossil fuels (Kåberger, 2018), but some forms of renewable energy remain out of reach, as is the case with AWE technology, which is still in phase research and development.

Researchers from sixty-three research groups and or industry are developing various types of wind turbines that can produce clean energy from untapped winds at high altitudes (Schmehl and Tulloch, 2019).

AWEs systems can be classified as:

- **ground generator system** - In this system, electric energy is produced on the ground through mechanical work done by the traction force, transmitted from the airfoil to the generator on land through one or more cables, which produce a rotational movement that makes the generator work. This operation, called pumping kite, can be differentiated between systems with fixed or mobile station devices on the ground.
- **airborne generation system** - In this system, electric energy is produced in the airfoil and transmitted to the ground through a special cable with a dual purpose: to keep the airfoil at a controlled height and to accommodate electrical cables that transmit the energy. Systems with

airborne generators produce electrical energy continuously during operation, except during takeoff and landing maneuvers in which energy is consumed.

Figure 3 presents the first demonstrative prototypes with AWE technology in pumping kite mode.

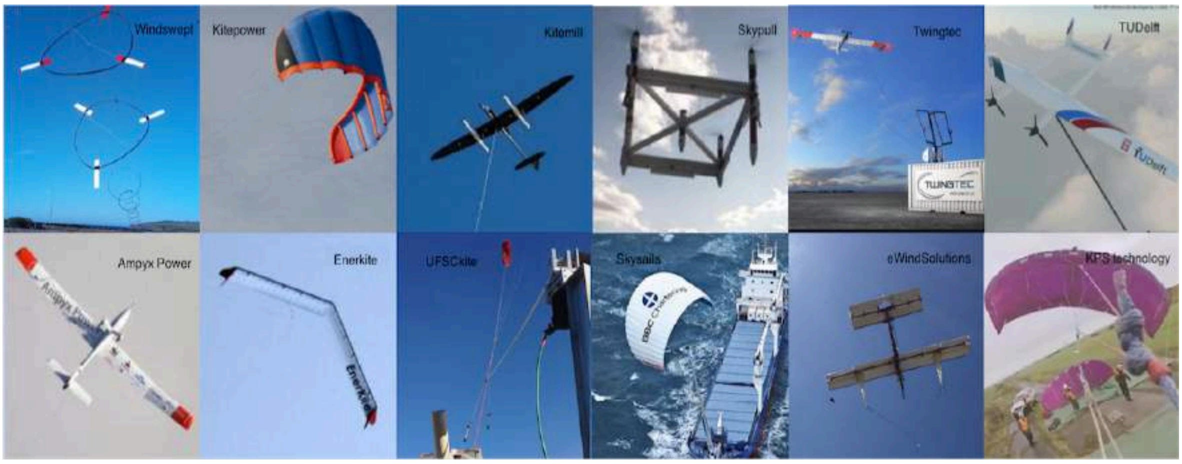

Fig. 3 AWE technologies in pumping kite mode under development. Source: Adapted from (Schmehl and Tulloch, 2019).

Currently, airborne wind energy technology is under development and testing with special permissions for companies and research groups. The local aviation authorities provide these permits. Next, Table 1 presents the main properties of the prototypes in pumping kite mode in demonstration.

Table 1 AWE prototypes in pumping kite mode in demonstration

Prototype category	Organization	Generated power	Size	Weight (kg)	Number of Cables
Flexible wing (ground-based generation)	TU Delft	20KW	25 m2	20	1
	Kitepower (startup TU Delft)	100KW			
	Skysails (kite wind propulsion system, saving 2MW of diesel engine	200 KW	320 m²		
	Kite Power Systems (KPS)	twin-kite system	7 m	45	1
	UFSCkite	12KW	17m2	2	1
	Kitenergy				
Semi-rigid wing (ground-based generation)	EnerKite	30KW to 500 KW	11 m	20	3
Rigid wing (ground-based generation)	eWindSolutions (USA)				
	Kitemill	kind of drone	3.7 m	4.5	1
	Ampyx Power (control center)	90 kW	5.5 m	35	1
	Twingtec	100 kW	3 m2	15	2
	Windlifi				
	Windswept		2 m2	-	-
Rigid wing (airborne generation)	Makani Power – GoogleX	600 KW			

3.1 Research with AWE technology developed in Brazil

According to AWESCO, the Federal University of Santa Catarina (UFSCkite) is the only entity in Latin America to do research with AWE technology, through the UFSCkite Project (Schmehl, 2018). At the UFSCkite laboratory, prototypes of AWE systems were developed, which consist of a ground generation unit, equipped with a mechanical structure for automated landing and take-off and a flight unit consisting of a flexible 17 m2 airfoil equipped with an embedded flight control unit. Each ground unit is equipped with a permanent magnet electric generator with a nominal power of 12 kW, a 45 cm diameter spool for storage of approximately 600 meters of cable, an electrical machine control panel and embedded electronics as well as various devices energy conversion (UFSCkite, 2020). Figure 4 shows the prototypes of the ground and flight units under development and testing in the laboratory.

Fig. 4 Prototypes of the ground (left), flight (cent) units and a field test image (left). Source: UFSCkite (2020).

The project developed at UFSCkite is multidisciplinary (UFSCkite, 2020), with an emphasis on areas with:

- Control - different strategies are developed for flight control, cable traction control and control of the system's operating modes;
- Filtering and estimation - it is necessary to filter the sensor readings and estimate previously unknown parameters, such as the aerodynamic aerodynamic coefficients;
- Supervisory systems - together with the development of prototypes, a SCADA system for human operator interface with the wind turbine and data storage is constantly being improved;
- Embedded systems - ground and flight units have embedded systems responsible for tasks such as sensing, filtering, control and communication;
- Mechanical and aerodynamic design - design of ground and flight units and mechanical structures for landing, take-off and operation of the wired airfoil;
- Power electronics - development of ground units (12kW), as well as the development of a wind micro generation system (60W) for continuous supply to the flight unit containing actuators and embedded electronics illustrated in Figure 5;
- Instrumentation - for the operation of the wind turbine, it is necessary to measure and process information such as wind speed, airfoil position and cable traction;
- Wind measurement - for the exploration of suitable locations for the implementation of AWE technology, a low-cost wind measurement unit in the range of 0 - 600 meters altitude is being developed, based on drone and acoustic tomography. The concept for the development of the measurement unit is shown in Figure 6.

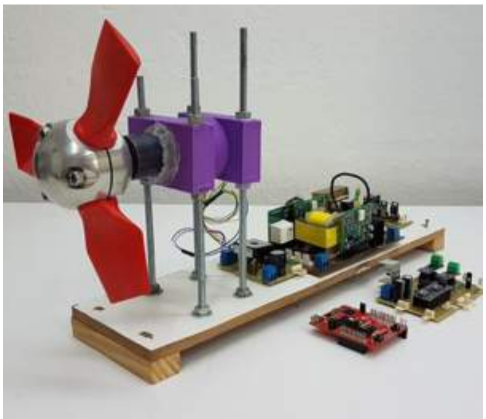

Figure 5: Coupling the 3-bladed turbine to the generator. Source: (UFSCkite, 2020).

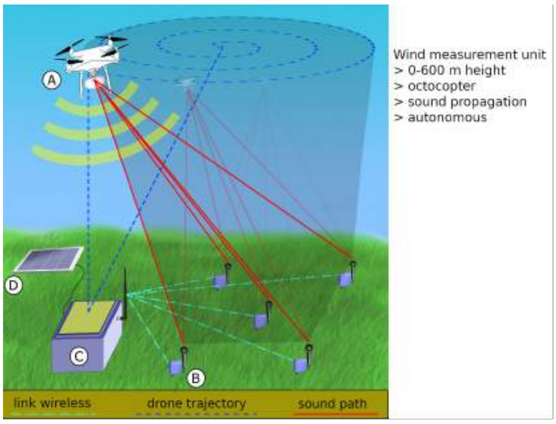

Figure 6: Drone-based viewing unit concept. Source: (UFSCkite, 2020).

Table 2 shows the current and future development of AWE technology in the UFSCkite laboratory.

Table 2: Current development and future research in the UFSCkite laboratory.

2013 a 2018	2019 a 2020	2023
Flight control unit	Plant design for continuous operation	Startup creation
Field tests	Field tests for power curve plottings	Scalability
Onboard generation	Efficiency and maintenance costs	
Ground unit design	Permission for use of air space	
Wind measurement	Wind measurement station tests	

3.2 Current challenges for R&D for AWE technology to reach the market

A recent study called "Study on Challenges in the commercialization of airborne wind energy systems", developed for the European Commission, recognized the power of AWE technology to contribute to increasing the renewable energy mix, and pointed out barriers to its commercialization (EUROPEAN_COMMISSION, 2018). This study provided three main categories of barriers:

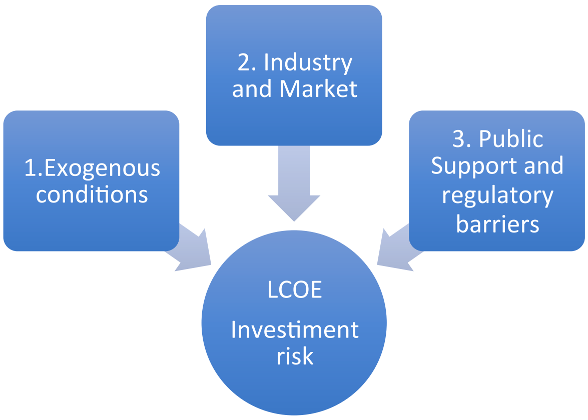

Fig. 6 Categories that can influence the levelized cost of energy (LCOE) and AWEs investment risks. Source. Adapted from (EUROPEAN_COMMISSION, 2018: pp. 69).

Exogenous Conditions barriers - These barriers are related to the potential of resource sites and have been divided into barriers Spatial footprint, Resource potential and Extreme weather conditions;

Industry and Market barriers – The property of addressing industry and market barriers is within the domain of the private sector. These barriers were divided into the subcategories: Component availability, System security and reliability and Economic performance;

Public Support and regulatory barriers – Addressing Public Support and regulatory barriers requires conditions and or support provided by the public domain. These barriers were divided into the subcategories: Social acceptance, environmental impacts, availability of financing and regulatory environment.

At the center of the barriers are the Levelized Energy Cost and the risk associated with investing in AWES projects. Both the LCOE and the investment risk are influenced by a wide range of barriers, directly or indirectly. However, LCOE calculations can discount the risk in the final value of the LCOE, which implies that it is possible to arrive at a single metric. Table 3 indicates the relative importance of barriers for three stakeholders (academic, business and public).

Table 3 Identification of the types of barriers by category of stakeholders, expressed as the relative frequency (%). Source. Adapted from (EUROPEAN_COMMISSION, 2018:pp. 68).

Type of barrier	Academic %	Business %	Public %
	Stakeholders		
System readiness	31	16	10
System safety and reliability	8	9	5
Economic Performance	38	24	19
Social acceptability and environmental impact	0	9	5
Funding availability	15	12	24
Regulatory environment	8	25	29
Exogenous conditions	0	4	10
Total	100	100	100

4 Conclusion

A Wind power technology with wired airfoils is a technology currently under development that has important advantages over conventional wind technology. One of the characteristics of the AWE system is the use of wired aerial devices, which are lighter, less bulky and cheaper and allow access to wind energy available at higher altitudes (600m), inaccessible to current technology based on towers. At this altitude, the wind is stronger and more frequent, and a greater number of locations have the potential for economic viability of this new technology. The scientific and industrial community in the last decade has grown and today numerous companies and universities, mainly in the USA and Europe, are working to allow this technology to reach the market in the coming years. At the Federal University of Santa Catarina, the UFSCkite research group develops a 12KW prototype, currently undergoing tests, and works to build an innovative pilot plant in the next 4 years that operates in a completely automated way, including landing and takeoff of the airfoil. The UFSCkite project's goal is to create a startup to scale the power and transform the pilot plant into a market product.

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