



Airborne Wind Energy Systems: A review of the technologies



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ABSTRACT

Among novel technologies for producing electricity from renewable resources, a new class of wind energy converters has been conceived under the name of Airborne Wind Energy Systems (AWESs). This new generation of systems employs flying tethered wings or aircraft in order to reach winds blowing at atmosphere layers that are inaccessible by traditional wind turbines. Research on AWESs started in the mid seventies, with a rapid acceleration in the last decade. A number of systems based on radically different concepts have been analyzed and tested. Several prototypes have been developed all over the world and the results from early experiments are becoming available. This paper provides a review of the different technologies that have been conceived to harvest the energy of high-altitude winds, specifically including prototypes developed by universities and companies. A classification of such systems is proposed on the basis of their general layout and architecture. The focus is set on the hardware architecture of systems that have been demonstrated and tested in real scenarios. Promising solutions that are likely to be implemented in the close future are also considered.

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1. Introduction

Advancement of societies, and in particular in their ability to sustain larger populations, are closely related to changes in the amount and type of energy available to satisfy human needs for nourishment and to perform work [1]. Low access to energy is an aspect of poverty. Energy, and in particular electricity, is indeed crucial to provide adequate services such as water, food, healthcare, education, employment and communication. To date, the majority of energy consumed by our societies has come from fossil and nuclear fuels, which are now facing severe issues such as security of supply, economic affordability, environmental sustainability and disaster risks.

To address these problems, major countries are enacting energy policies focused on the increase in the deployment of renewable energy technologies. In particular:

- Since 1992, to prevent the most severe impacts of climate change, the United Nations member states are committed to a drastic reduction in greenhouse gas emissions below the 1990 levels.

- In September 2009, both European Union and G8 leaders agreed that carbon dioxide emissions should be cut by 80% before 2050 [2].

In the European Union (EU), compulsory implementation of such a commitment is occurring via the Kyoto Protocol, which bounded 15 EU members to reduce their collective emissions by 8% in the 2008–2012 period, and the 'Climate Energy Package (the 20–20–20 targets)', which obliges EU to cut its own emissions by at least 20% by 2020.

In this context, in the last decades there has been a fast growth and spread of renewable energy plants. Among them, wind generators are the most widespread type of intermittent renewable energy harvesters with their 369 GW of cumulative installed power at the end of 2014 [3]. Wind capacity, i.e. total installed power, is keeping a positive trend with an increment of 51.4 GW in 2014. In the future, such a growth could decrease due to saturation of in-land windy areas that are suitable for installations. For this reason, current research programs are oriented to the improvement of power capacity per unit of land area. This translates to the global industrial trend of developing

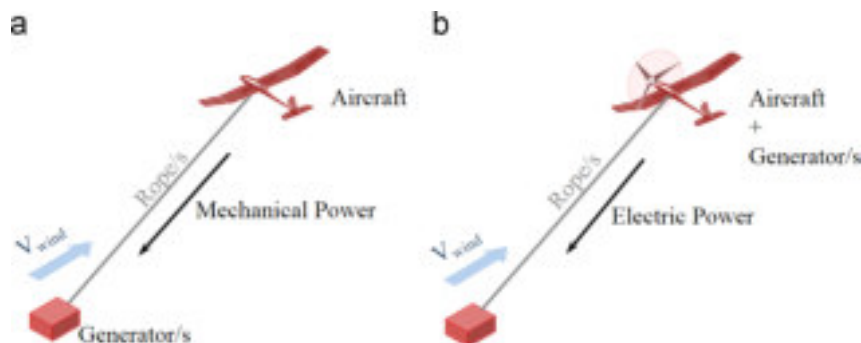


Fig. 1. AWESs. Example of Ground-Gen (a) and Fly-Gen (b) AWESs.

single wind turbines with increased nominal power (up to 5 MW) that feature high-length blades (to increase the swept area) and high-height turbine axis (to reach stronger winds at higher altitudes) [4].

In parallel, since the beginning of 2000s, industrial research is investing on offshore installations. In locations that are far enough from the coast, wind resources are generally greater than those on land, with the winds being stronger and more regular, allowing a more constant usage rate and accurate production planning, and providing more power available for conversions. The foreseen growth rate of offshore installations is extremely promising; according to current forecasts, the worldwide installed power is envisaged in the order of 80 GW within 2020 [5].

In this framework, a completely new renewable energy sector, Airborne Wind Energy (AWE), emerged in the scientific community. AWE aims at capturing wind energy at significantly increased altitudes. Machines that harvest this kind of energy can be referred to as Airborne Wind Energy Systems (AWESs). The high level and the persistence of the energy carried by high-altitude winds, that blow in the range of 200 m – 10 km from the ground surface, has attracted the attention of several research communities since the beginning of the eighties. The basic principle was introduced by the seminal work of Loyd [6] in which he analyzed the maximum energy that can be theoretically extracted with AWESs based on tethered wings. During the nineties, the research on AWESs was practically abandoned; but in the last decade, the sector has experienced an extremely rapid acceleration. Several companies have entered the business of high-altitude wind energy, registering hundreds of patents and developing a number of prototypes and demonstrators. Several research teams all over the world are currently working on different aspects of the technology including control, electronics and mechanical design.

This paper provides an overview of the different AWES concepts focusing on devices that have been practically demonstrated with prototypes. The paper is structured as follows. Section 2 provides a brief description of the energy resource of high altitude winds. Section 3 provides a unified and comprehensive classification of different AWES concepts, which tries to merge previously proposed taxonomies. In Sections 4 and 5, an up to date overview of different devices and concepts is provided. Section 6 explains why AWE is so attractive thanks to some simple and well-known models. Finally, Section 7 presents some key techno-economic issues basing on the state of the art and trends of academic and private research.

Differently from other previously published reviews, this paper deals with aspects that concern architectural choices and mechanical

design of AWESs. We made our best in collecting comprehensive information from the literature, patents and also by direct contacts with some of the major industrial and academic actors.

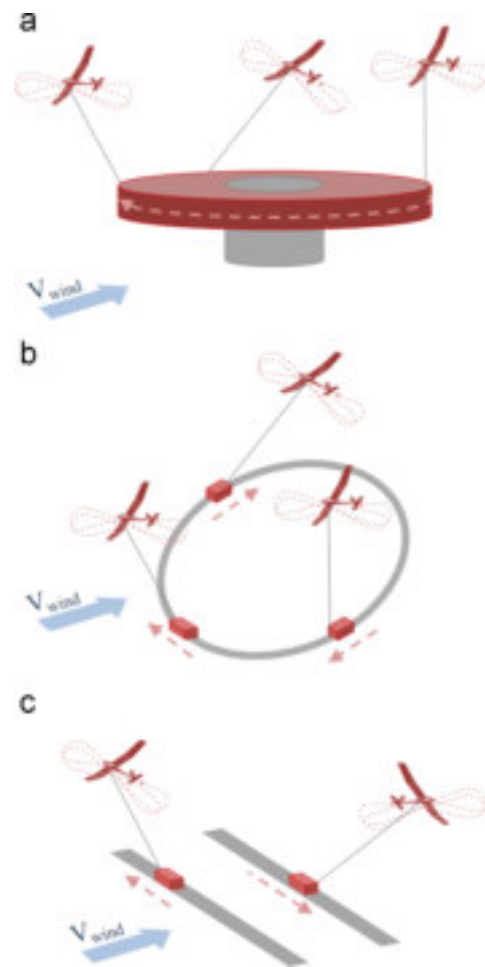


Fig. 3. Scheme of three different concepts of moving-ground-station GG-AWES. (a) Vertical axis generator: ground stations are fixed on the periphery of the rotor of a vertical axis generator. (b) Closed loop rail: ground stations are fixed on trolleys that move along a closed loop rail. (c) Open loop rail: ground stations are fixed on trolleys that move along an open loop rail.

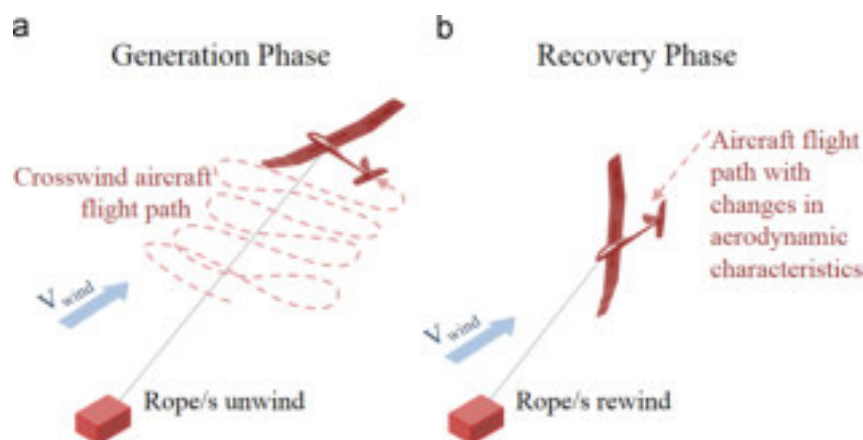


Fig. 2. Scheme of the two-phase discontinuous energy production for GG AWESs. (a) The energy generation phase occurs during the unwinding of the ropes as the aircraft performs a crosswind flight. (b) The recovery phase is performed in order to minimize the energy consumed for the recovery.

2. Availability of Airborne Wind Energy

In the literature, the acronym AWE (Airborne Wind Energy) is usually employed to designate the high-altitude wind energy resource as well as the technological sector. High-altitude winds have been studied since decades by meteorologists, climatologists and by researchers in the field of environmental science even though many questions are still unsolved [7]. The first work aimed at evaluating the potential of AWE as a renewable energy resource has been presented by Archer and Caldeira [8]. Their paper introduces a study that assesses a huge worldwide availability of kinetic energy of wind at altitudes between 0.5 km and 12 km above the ground, providing clear geographical distribution and persistency maps of wind power density at different ranges of altitude. This preliminary analysis does not take into account the consequences on wind and climate of a possible extraction of kinetic energy from winds. However, the conclusions of these investigations already raised the attention of many researchers and engineers suggesting great promises for technologies able to harvest energy from high altitude winds.

More in depth studies have been conducted employing complex climate models, which predict consequences associated with the introduction of wind energy harvesters (near surface and at high altitude), that exerts distributed drag forces against wind flows. Marvel et al. [9] estimate a maximum of 400 TW and 1800 TW of kinetic power that could be extracted from winds that blow, respectively, near-surface (harvested with traditional wind turbines) and through the whole atmospheric layer (harvested with both traditional turbines and high altitude wind energy converters). Even if severe/undesirable changes could affect the global climate in the case of such a massive extraction, the authors show that the extraction of 'only' 18 TW (i.e. a quantity comparable with the actual world power demand) does not produce significant effects at global scale. This means that, from the geophysical point of view, very large quantity of power can be extracted from wind at different altitudes.

A more skeptical view on high altitude winds is provided in Miller et al. [10] who evaluated in 7.5 TW the maximum sustainable global power extraction. But their analysis is solely focused on jet stream winds (i.e. only at very high altitude between 6 km and 15 km above the ground).

Despite the large variability and the level of uncertainty of these results and forecasts, it is possible to conclude that an important share of the worldwide primary energy could be

potentially extracted from high altitude winds. This makes it possible to envisage great business and research opportunities for the next years in the field of Airborne Wind Energy.

3. Classifications of Airborne Wind Energy Systems

In this paper, the term AWESs (Airborne Wind Energy Systems) is used to identify the whole electro-mechanical machines that transform the kinetic energy of wind into electrical energy. AWESs are generally made of two main components, a ground system and at least one aircraft that are mechanically connected (in some cases also electrically connected) by ropes (often referred to as tethers). Among the different AWES concepts, we can distinguish *Ground-Gen* systems in which the conversion of mechanical energy into electrical energy takes place on the ground and *Fly-Gen* systems in which such conversion is done on the aircraft [11] (Fig. 1).

In a Ground-Gen AWES (GG-AWES), electrical energy is produced on the ground by mechanical work done by traction force, transmitted from the aircraft to the ground system through one or more ropes, which produce the motion of an electrical generator. Among GG-AWESs we can distinguish between *fixed-ground-station* devices, where the ground station is fixed to the ground and *moving-ground-station* systems, where the ground station is a moving vehicle.

In a Fly-Gen AWES (FG-AWES), electrical energy is produced on the aircraft and it is transmitted to the ground via a special rope which carries electrical cables. In this case, electrical energy conversion is generally achieved using wind turbines. FG-AWESs produce electric power continuously while in operation except during take-off and landing maneuvers in which energy is consumed. Among FG-AWESs it is possible to find crosswind systems and non-crosswind systems depending on how they generate energy.

4. Ground-Gen Airborne Wind Energy Systems

In Ground-Generator Airborne Wind Energy Systems (GG-AWES) electrical energy is produced exploiting aerodynamic forces that are transmitted from the aircraft to the ground through ropes. As previously anticipated, GG-AWESs can be distinguished in devices with fixed or moving-ground-station.

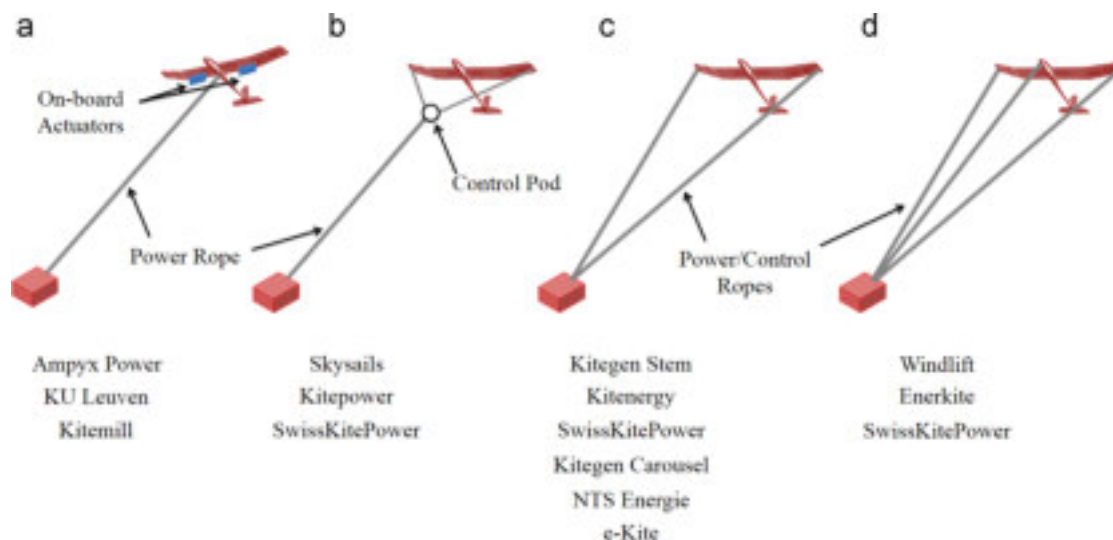


Fig. 4. Control layout of crosswind GG-AWESs. (a) With on-board control actuators; (b) with flying control pod; (c) control through power ropes; (d) with additional control rope.

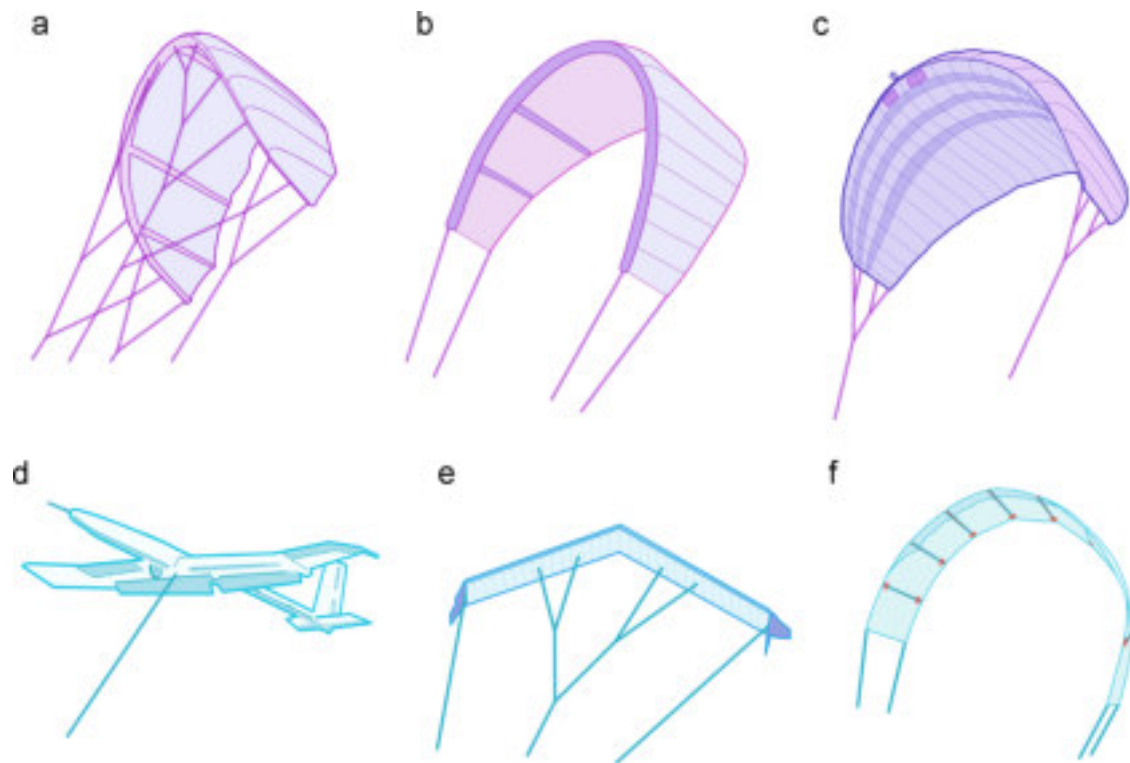


Fig. 5. Different types of aircraft in Ground-Gen systems. (a) LEI SLE (Leading Edge Inflatable, Supported Leading Edge) Kite; (b) LEI C-kite; (c) Foil Kite, design from Skysails; (d) Glider, design from Ampyx Power; (e) Swept rigid wing, design from Enerkite; (f) Semi-rigid wing, design from Kitegen.

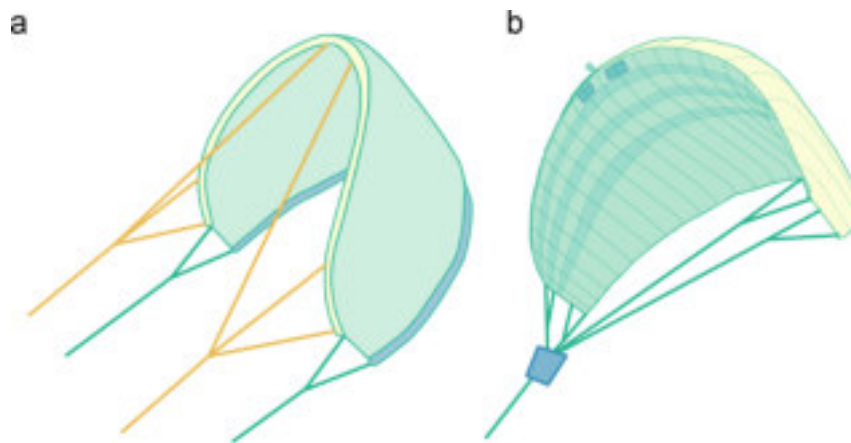


Fig. 6. Control of bridles tension. (a) Control bridles are attached to the leading and trailing edges of a LEI SLE kite. (b) A control pod can be used to control the flight trajectory and angle of attack.

Fixed-ground-station GG-AWES (or Pumping Kite Generators) are among the most exhaustively studied by private companies and academic research laboratories. Energy conversion is achieved with a two-phase cycle composed by a generation phase, in which electrical energy is produced, and a recovery phase, in which a smaller amount of energy is consumed (Fig. 2). In these systems, the ropes, which are subjected to traction forces, are wound on winches that, in turn, are connected to motor-generators axes. During the generation phase, the aircraft is driven in a way to produce a lift force and consequently a traction (unwinding) force on the ropes that induce the rotation of the electrical generators. For the generation phase, the most used mode of flight is the crosswind flight (Fig. 2a) with circular or the so-called eight-shaped paths. As compared to a non-crosswind flight (with the aircraft in a static angular position in the sky), this mode induces a stronger apparent wind on the aircraft that increases the pulling

force acting on the rope. In the recovery phase (Fig. 2b) motors rewind the ropes bringing the aircraft back to its original position from the ground. In order to have a positive balance, the net energy produced in the generation phase has to be larger than the energy spent in the recovery phase. This is guaranteed by a control system that adjusts the aerodynamic characteristics of the aircraft [12] and/or controls its flight path [13] in a way to maximize the energy produced in the generation phase and to minimize the energy consumed in the recovery phase.

Pumping kite generators present a highly discontinuous power output, with long alternating time-periods (in the order of tens of seconds) of energy generation and consumption. Such an unattractive feature makes it necessary to resort to electrical rectification means like batteries or large capacitors. The deployment of multiple AWES in large high-altitude wind energy farms could significantly reduce the size of electrical storage needed.

Moving-ground-station GG-AWES are generally more complex systems that aim at providing an always positive power flow which makes it possible to simplify their connection to the grid. There are different concepts of moving-ground-station GG-AWESs (Fig. 3) but no working prototype has been developed up to date and only one prototype is currently under development (see Section 4.3.2). Differently from the pumping generator, for moving-ground-station systems, the rope winding and unwinding is not producing/consuming significant power but is eventually used only to control the aircraft trajectory. The generation takes place thanks to the traction force of ropes that induces the rotation (or linear motion) of a generator that exploits the ground station movement rather than the rope winding mechanism.

Basically, there are two kinds of moving-ground-station GG-AWES:

- ‘Vertical axis generator’ (Fig. 3a) where ground stations are fixed on the periphery of the rotor of a large electric generator with vertical axis. In this case, the aircraft forces make the ground stations rotate together with the rotor, which in turn transmits torque to the generator.
- ‘Rail generators’ (closed loop rail (Fig. 3b) or open loop rail (Fig. 3c)) where ground stations are integrated on rail vehicles

and electric energy is generated from vehicle motion. In these systems, energy generation looks like a reverse operation of an electric train.

The following subsections provide an overview of the most relevant prototypes of GG AWESs under development in the industry and the academy.

4.1. Ground-Gen systems architectures and aircraft

In GG systems the aircraft transmits mechanical power to the ground by converting wind aerodynamic forces into rope tensile forces. The different concepts that were prototyped are listed in Fig. 4; examples of aircraft of GG systems that are currently under development are presented in Fig. 5. They exploit aerodynamic lift forces generated by the wind on their surfaces/wings.

The aircraft is connected to the ground by at least one power-rope that is responsible for transmitting the lift force (and the harvested power) to the ground station. The flight trajectory can be controlled by means of on-board actuators (Fig. 4a), or with a control pod (Fig. 4b), or by regulating the tension of the same power-ropes (Fig. 4c), or with thinner control-ropes (Fig. 4d).

Ground-Gen HAWECs							
Fixed/Moving	Airborne System	Company	Power Class	Main force	Actuators		N. Ropes
					On ground	Airborne	
Fixed ground station - Pumping System	Leading edge inflatable kite	KiteGen Stem	kW	Lift	x		2
		WindLift	kW	Lift	x		3
		Kitenergy	kW	Lift	x		2
		Swiss Kite Power 2	kW	Lift	x		3
		KitePower	kW	Lift		x	1
		Swiss Kite Power 1	kW	Lift		x	1
	Foil kite	SkySails Power	kW-MW	Lift		x	1
		EnerKite	kW	Lift	x		3
	Delta Kite	EnerKite	kW	Lift	x		3
	Swept Rigid Wing	EnerKite	kW	Lift	x		3
	Glider	Ampyx Power	kW-MW	Lift		x	1
		e-Kite	kW	Lift	x		2
	Glider with rotors	Kitemill	kW	Lift		x	1
		TwingTec	kW	Lift		x	2
	Semi-rigid Wing	KiteGen Stem	MW	Lift	x		2
	Paraschute	GuangdongTech	MW	Drag		x	2
Aerostat	Omnidea	kW	Magnus effect		x	2	
Moving ground station	- Rail	Leading edge inflatable kite	KiteGen Rail Carousel	MW-GW	Lift	x	2
		Kitenergy	MW	Lift	x	2	
		Foil kite	NTS		Lift	x	4
	-Axial	Leading edge inflatable kite	KiteGen Carousel	MW	Lift	x	2

Fig. 7. Groud-Gen AWESs. Summary of GG-AWESs.

There are also two GG concepts that are worth mentioning: one uses parachutes which exploit aerodynamic drag forces [14,15], the other uses rotating aerostats which exploit the Magnus effect [16,17].

The most important aircraft used for GG systems are here listed:

1. *Leading Edge Inflatable* (LEI) kites [18] are single layer kites whose flexural stiffness is enhanced by inflatable structures on the leading edge (Fig. 5a and b). Mainly two kinds of LEI kites are used in AWESs:
 - (a) *Supported Leading Edge* (SLE) kites [19] are LEI kites with at least one bridle which supports the leading edge close to its central part (Fig. 5a). In comparison with C-kites (that are described in the following), the traction force of the central bridles makes the wing flat in its central region and this is claimed to increase the wing aerodynamic efficiency.
 - (b) *C-kites*, which are generally controlled by four main bridles directly attached to extreme lateral points of the kite edges (Fig. 5b). In pumping generators, the C-kite is held with either one, two or three ropes. In generators with one rope, the rope is connected to both the leading edge bridles, while trailing edge bridles are controlled by a 'control pod' (i.e. a flying box with one or more actuators) attached to the rope a few meters below the kite. The micro-winches inside the control pod are used to steer the kite and control the angle of attack. In case of two ropes, left bridles converge in one rope and right bridles converge in the second rope. The angle of incidence is fixed and the kite steers due to the difference in the ropes tension. In case of three ropes, there is one rope for each trailing edge bridle and one rope connected to the leading edge bridles. In this case, kite steering and angle of attack can be controlled from the ground.

The stiffened tube-like structure of LEI kites is especially useful for take-off and landing maneuvers when the wing is not yet supported by wind pressure. The ease of handling is very appreciated also during small-scale prototyping and subsystem testing. However LEI kites have severe scalability issues as the tube diameter needs to be oversized in case of large wings.

2. *Foil kites* (also called *ram-air kites*) are derived from parafoils [20]. These double-layer kites are made of canopy cells which run from the leading edge to the trailing edge (Figs. 5c and 6b). Cells (some or all) are open on the leading edge in a way that the air inflates all cells during the flight and gives the kite the necessary stiffness. Bridles are grouped in different lines, frequently three: one central and two laterals. With respect to LEI kites, foil wings have a better aerodynamic efficiency despite the higher number of bridles and can be one order of magnitude larger in size.
3. *Delta kites* are similar to hang glider wings. They are made by a single layer of fabric material reinforced by a rigid frame. Compared with LEI or foil kites, this kind of aircraft has a better aerodynamic efficiency which in turn results in a higher efficiency of wind power extraction (as discussed in Section 7). On the other hand, their rigid frame has to resist to mechanical bending stresses which, in case of high aerodynamic forces, make it necessary to use thick and strong spars which increase the aircraft weight, cost and minimum take-off wind speed. Durability for fabric wings such as LEI, foil and delta kites, is an issue. Performance is compromised soon and lifetime is usually around several hundred hours [21].
4. *Gliders* (Fig. 5d) can also be used as GG aircraft. Like delta kites, their wings are subject to bending moment during the tethered flight. Gliders, and more generally rigid wings, have excellent

aerodynamic performance, although they are heavier and more expensive. Lifetime with regular maintenance is several decades.

5. *Swept rigid wings* are gliders without fuselage and tail control surfaces (Fig. 5e). Flight stability is most likely achieved thanks to the bridle system and the sweep angle.
6. *Semi-rigid wings* are also under investigation by the Italian company Kitegen Research. They are composed of multiple short rigid modules that are hinged to each other (Fig. 5f). The resulting structure is lighter than straight rigid wings and more aerodynamically efficient and durable than fabric kites.
7. *Special design kites*: Kiteplanes [22] and Tensairity Kites [23] are projects developed by TUDelft (The Netherlands) and EMPA (Research Center for Synergetic Structures, ETH Zurich), that aim at increasing the aerodynamic efficiency of arch kites without using rigid spars.

4.2. Fixed-ground-station systems under development

This subsection provides a list of fixed-ground-station GG AWES which are summarized in Figs. 7 and 10.

4.2.1. KiteGen Research

The Italian KiteGen Research (KGR) was one of the first companies to test a prototype of Ground-Gen AWES [24]. KGR technology is based on a C-Kite integrating on board electronics with sensor and is controlled by two power-ropes [25] from a control station on the ground [26] (Fig. 4c). The first prototype, named KSU1 (acronym for Kite Steering Unit) [25,27], was successfully demonstrated in 2006. After a few years of tests, the company focused on the development of a new generator, named 'KiteGen Stem', with a nominal power of 3 MW [28]. In this system, the ropes are wound on special winches [29] and are driven by a pulley system through a 20 m flexible rod, called 'stem', to an arch-kite or a semi-rigid wing. The stem is linked to the top of the control station through a pivot joint with horizontal axis. The most important functions of the stem are: (1) supporting and holding the kite and (2) damping peak forces in the rope that arise during wind-gusts. The entire control station can make azimuthal rotations so the stem has two degrees of freedom relative to the ground. The 'Stem' concept was first patented in 2008 [30] and is now used by more and more companies and universities.

At the beginning of the take-off maneuvers, the kite is hanged upside down at the end of the stem. Once the kite has taken off, the production phase starts: the automatic control drives the kite acting on the two ropes, the kite makes a crosswind flight with 'eight shape' paths; at the same time ropes are unwound causing the winches to rotate; the motor-generators transform mechanical power into electric power. The company aims at retracting the cables with minimum energy consumption thanks to a special maneuver called 'side-slip' or 'flagging' [21]. Side-slip is a different flight mode where the kite aerodynamic lift force is cleared by rewinding at first one rope before the other, which makes the kite lose lift and 'stall' and then, once fully stalled, both ropes are rewound at the same speed and the kite precipitates flying sideways. This maneuver can be done with flexible foil kites or semi-rigid wings. In this phase, the power absorbed by motor-generators is given by rope rewind speed multiplied by the resulting aerodynamic drag force of the side-slip flying mode. This power consumption would be a small percentage of the power produced in the production phase. After rewinding a certain length of the ropes (less than the total rope length in order to exploit only the highest winds) another special maneuver

restores the gliding flight and the aerodynamic lift force on the kite. At this point one pumping cycle ends and a new production phase starts.

KGR patented and is developing special aerodynamic ropes [31] in order to increase their endurance and to increase system performances. KGR also plans to use the Kitegen Stem technology to produce an offshore AWES [32] since offshore AWESs are very promising [33].

4.2.2. Kitenergy

Another Italian company, Kitenergy, was founded by a former KiteGen partner and is also developing a similar concept by controlling a foil kite with two ropes [34,35]. The prototype of the company features 60 kW of rated power [36]. Kitenergy submitted also a different GG-AWES patent [37] that consists in a system based on a single motor-generator which controls winding and unwinding of two (or more) cables and another actuator that introduces a differential control action of the employed cables. Another prototype developed by its co-founder, Lorenzo Fagiano, achieved 4 h of consecutive autonomous flight with no power production at University of California at Santa Barbara in 2012 [38].

4.2.3. SkySails Power

The German company SkySails GmbH is developing a wind propulsion system for cargo vessels based on kites [39]. A few years ago a new division of the company 'SkySails Power' has been created to develop Ground-Gen AWES [40] based on the technology used in SkySails vessel propulsion system. Two products are under development: a mobile AWES having a capacity between 250 kW and 1 MW, and an offshore AWES with a capacity from 1 to 3.5 MW. SkySails' AWES is based on a foil kite controlled with one rope and a control pod (Fig. 4b) which controls the lengths of kite bridles for steering the kite and changing its angle of attack [41]. Control pod power and communication with the ground station is provided via electric cables embedded in the rope. SkySails also has a patented launch and recovery system [42] designed for packing the kite in a storage compartment. It is composed by a telescopic mast with a special device on its top that is able to grab, keep and release the central point of the kite leading edge. When the system is off, the mast is compacted in the storage compartment with the kite deflated. At the beginning of the launching operation, the mast extends out vertically bringing the deflated kite some meters above the ground (or the sea level). The kite is then inflated to have appropriate shape and stiffness for the production phase. Kite take-off exploits only the natural wind lift force on the kite: the system at the top of the mast releases the kite leading edge, the pod starts to control the flight and the winch releases the rope letting the kite reach the operating altitude. While the energy production phase is similar to that of the KGR generator, SkySails has a different recovery phase. Specifically, SkySails uses high speed winching during reel-in while the kite is kept at the edge of the wind window. The kite is then winched directly against the wind without changing the kite angle of attack. Though it might seem counter-intuitive at first, this kind of recovery phase has proven to be competitive [43].

4.2.4. TwingTec

The Swiss company Twingtec is developing a 100 kW GG-AWES. After having tried several concepts including soft wings and rigid wings, the team is now tackling the problem of automating take-off and landing with an innovative concept: a glider with embedded rotors having rotational axis perpendicular to the wing plane. The rotors are used during take-off and landing. The company plans to have the generator and power conversion

hardware inside a standard 20-foot shipping container in order to easily target off-grid and remote markets. The AWES will supply continuous and reliable electrical power thanks to the integration with conventional diesel generators [44,45].

4.2.5. TU Delft

At Delft University of Technology, the first research in Airborne Wind Energy was started by the former astronaut, Professor Ockels, in 1996 [46]. A dedicated research group was initiated by Ockels in 2004 with the aim to advance the technology to the prototype stage.

Recently, Delft University of Technology and Karlsruhe University of Applied Sciences have initiated a joint project to continue the development and testing of a mobile 20 kW experimental pumping kite generator [47]. A main objective of this project is to improve the reliability and robustness of the technology and to demonstrate in the next months a continuous operation of 24 h. At present, they use the third version of a special design LEI kite, co-developed with Genetrix/Martial Camblong, of 25 m² wing surface area. Together with an automatic launch setup [48], the wing demonstrated fully automatic operation of their 20 kW system in 2012 [47]. Like SkySails' system, this prototype is based on a single tether and an airborne control pod (Fig. 4b) but they also control the angle of attack for powering and depowering the wing during production and recovery phase, respectively. An automatic launch and retrieval system for 100 m² LEI kites is under development [49].

In the past, the research group tested several kinds of wings such as foil kites and kiteplanes. TU Delft also tested an alternative device for controlling the kite: a cart-and-rail system attached to the tips of a ram-air wing and used to shift the attachment point of the two bridle lines. By that system, the wing could be steered and depowered with a minimal investment of energy. Ultimately, the concept was too complex and too sensitive to deviations from nominal operation [50].

4.2.6. Ampyx Power

The first company that developed a pumping glider generator is the Dutch Ampyx Power [51,52]. After several prototypes, they are currently developing and testing two 5.5 m 'PowerPlanes' the AP-2A1 and the AP-2A2 [53]. They are two officially registered aircraft that are automatically controlled with state of the art avionics. They are constructed with a carbon fiber body and a carbon backbone truss which houses onboard electronics with sensors and actuators. Onboard actuators can drive a rudder, an elevator and four flaperons. One rope connects the glider to a single winch in the ground station (Fig. 4a). Ampyx Power is actually one of the few companies which has already developed an AWES [54] that is able to automatically perform the sequence of glider take-off, pumping cycles and landing. Take-off maneuver sees the glider lying on the ground facing the ground station at some meters of distance. As the winch starts exerting traction force on the rope, the glider moves on the ground and, as soon as the lift forces exceed the weight forces, the glider takes off. They also installed a catapult for take-off and they have a propulsion system to climb up. The glider flight is fully autonomous during normal operations even though, for safety reasons, it can be occasionally controlled wirelessly from the ground thanks to a backup autopilot. The pumping cycles are similar to those of a kite. Glider landing is similar to that of an airplane and is being equipped with an arresting line so as to stop the glider in a right position for a new take-off. During a test campaign in November 2012, the system demonstrated an average power production of 6 kW with peaks of over 15 kW (earlier tests showed peak in power production of 30 kW). Ampyx has started the design of its first commercial

product: a 35 m wingspan AP-4 PowerPlane with a 'wind turbine equivalent' power of 2 MW.

4.2.7. EnerKite

The German company EnerKite [55] developed a portable pumping kite generator with rated continuous power of 30 kW. The ground station is installed on a truck through a pivotal joint which allows azimuthal rotations. EnerKite demonstrator uses mainly a foil kite, but a delta kite and a swept rigid wing are also under investigation and testing. The aircraft does not have on-board sensors and is controlled from the ground with three ropes according to the scheme of Fig. 4d. EnerKite is now developing an autonomous launch and landing system for semi-rigid wings [56]. The company plans to produce a 100 kW and a 500 kW system [57].

4.2.8. Windlift

The US Company Windlift [58] has a concept similar to that of Enerkite (Fig. 4d). Their 12 kW prototype uses SLE kites. They aim to sell their product to the military and to off-grid locations.

4.2.9. New companies

The AWE community is constantly growing [24,59] and for every company that goes out of business there are a few that are born. Here are some startup companies that are worth mentioning.

e-Kite was founded in 2013 in the Netherlands and developed a 50 kW GG-AWES (Fig. 4c) based on a direct drive generator. The company is now building a 2-ropes rigid wing that will fly at low altitude [60,61].

Enevatte is a Dutch 4-people startup that is mainly focused on bringing the TU Delft GG-AWES to the next step towards a commercial product [62].

Kitemill, Norway, started the development of a GG-AWES. The company switched early on to a 1-cable rigid wing system with on-board actuators (Fig. 4a) after having faced controllability and durability issues with soft materials [63].

eWind solutions is a US company that is developing an unconventional, low altitude, rigid wing GG-AWES [64].

4.2.10. KU Leuven

KU Leuven has been actively doing research in AWESs since 2006. After significant theoretical contributions, the team developed a test bench to launch a tethered glider with a novel procedure [65]. Before take-off, the glider is held at the end of a rotating arm. When the arm starts rotating, the glider is brought to flying speed and the tether is released allowing the glider to gain altitude. They are currently developing a larger experimental test set-up, 2 m long with a 10 kW winch.

4.2.11. SwissKitePower

SwissKitePower was a collaborative research and development project started in Switzerland in 2009. It involved four laboratories of different Swiss universities: FHNW, EMPA (Swiss Federal Laboratories for Materials Science and Technology), ETH (Federal Polytechnique of Zurich) and EPFL (École Polytechnique Fédérale de Lausanne). The first prototypes, tested between 2009 and 2011, were based on a C-kite controlled by one rope and a control pod. The initial system worked according to the scheme of Fig. 4b, similarly to KitePower and SkySails prototypes. In 2012, SwissKitePower developed a new ground station with three winches that can be used to test kites with 1, 2 or 3 lines [66]. They also tested SLE kites and tensairity kites. The project ended in 2013 and since then FHNW is working in collaboration with the company TwingTec.

4.2.12. NASA Langley

At Langley Research Center, the US space agency NASA conducted a study about wind energy harvesting from airborne platforms after which they developed an AWES demonstrator based on a kite controlled by two ropes and having a vision-based system and sensors located on the ground [67].

4.2.13. Others

In addition to the main prototypes listed above, there are several other systems that have been built.

- Wind tunnel tests of small scale non-crosswind generation, and outdoor crosswind generation tests with a SLE kite [68,69] of GIPSA-lab/CNRS, University of Grenoble.
- Kite control project [70] of CCNR at Sussex University, UK.
- EHAWK (Electricity from High Altitude Wind with Kites) project [71] of Department of Mechanical Engineering of Rowan University.
- Kite powered water pump [72] of Worcester Polytechnic Institute.

4.3. Moving-ground-station systems under development

In addition to pumping systems, a number of AWES concepts with moving-ground-station have been proposed. Their main advantage is the ability to produce energy continuously or nearly continuously. However, only a few companies are working on AWESs with moving-ground-station and there are more patents and studies than prototypes under development. This subsection provides a list of moving-ground-station GG-AWES which are summarized in Figs. 7 and 10.

4.3.1. KiteGen Research

The first moving-ground-station architecture which is based on a vertical axis generator has been proposed back in 2004 by Sequoia Automation and acquired by KGR [73]. This AWES concept is based on the architecture described in Fig. 3a. During operations, lift forces are transmitted to a rotating frame inducing a torque around the main vertical axis. Torque and rotation are converted into electricity by the electric generator. This system can be seen as a vertical axis wind turbine driven by forces which come from tethered aircraft. There is no prototype under development, but the concept has been studied in a simulation [13] showing that 100 kites with 500 m² area could generate 1000 MW of average power in a wind with speed of 12 m/s. The considered generator would have a 1500 m radius, occupying a territory about 50 times smaller and costing about 30 times less than a farm of wind turbines with the same nominal power.

4.3.2. NTS Energie

An alternative system based on ground stations that moves on closed track circuits is proposed by KGR [74] and by the German company NTS Energie und Transportsysteme [75,76]. Starting from September 2011, NTS tested a prototype where 4-rope kites are controlled by a vehicle which moves on a 400 m flat-bed straight railway track. They are able to produce up to 1 kW per m² of wing area and they tested kites up to 40 m² [77]. The final product should have a closed loop railway where more vehicles run independently.

4.3.3. Kitenergy

Another rail concept is proposed by Kitenergy [78] and it is based on ideas published in 2004 in Drachen Foundation journal [79]. The concept is based on a straight linear rail fixed on the

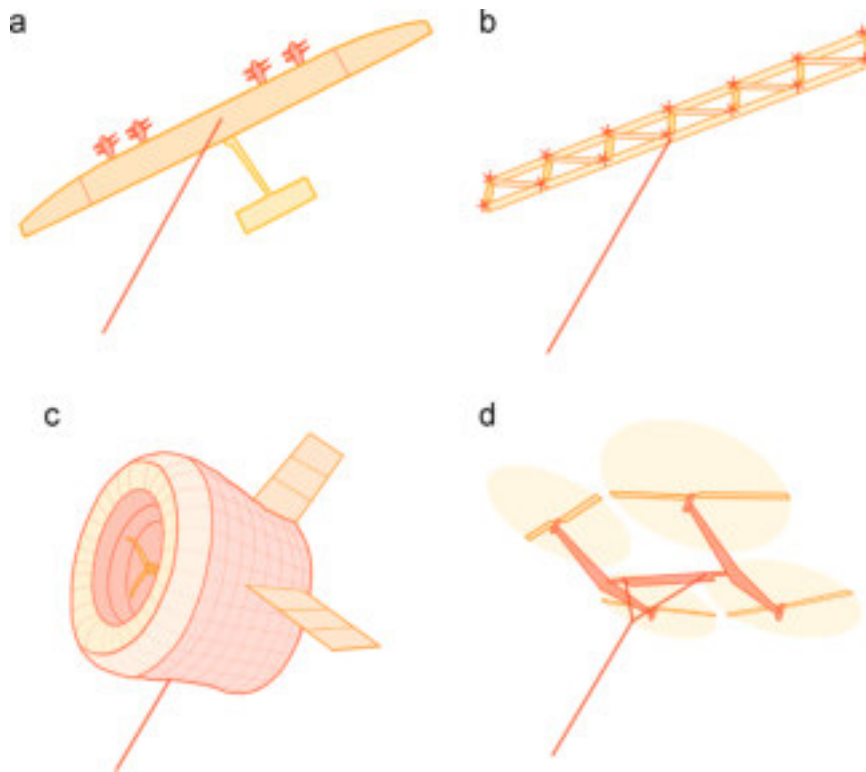


Fig. 8. Different types of aircraft in Fly-Gen systems. (a) Plane with four turbines, design by Makani Power. (b) Aircraft composed by a frame of wings and turbines, design by Joby Energy. (c) Toroidal lifting aerostat with a wind turbine in the center, design by Altaeros Energies. (d) Static suspension quadrotor in autorotation, design by Sky WindPower.

Fly-Gen HAWECs				
General system description	Company	Flying principle	Type	Energy generation system
Turbines on a tethered aircraft	Makani Power	Wings lift	Crosswind	6/8 turbines
	Joby Energy	Wings lift	Crosswind	Several turbines
Tethered quadcopter	Sky Windpower	Rotors thrust	Non-crosswind	4 turbines
Turbine on a lighter than the air balloon	Altaeros Energies	Buoyancy	Non-crosswind	1 turbine
Magnus Effect turbine	Omnidea	Buoyancy	Non-crosswind	Buoyant wind turbine

Fig. 9. Fly-Gen AWESs. Summary of FG-AWESs.

ground with a pivotal joint. The rail direction is then adjusted perpendicular to the main direction of the wind. The ground station of the system is mounted on a wheeled vehicle which moves along the straight rail, under the kite traction forces, back and forth from one side to the other. The power is extracted from electromagnetic rotational generators on the wheels of the vehicle or from linear electromagnetic generators on the rail. The power production is not fully continuous because during the inversion of vehicle direction the power production will not only decrease to zero, but it could also be slightly negative. Nevertheless the kite inversion maneuver could be theoretically performed without the need of power consumption.

4.3.4. Laddermill

Although it cannot be considered a moving-ground-station device, it is important to mention that the first concept of continuous energy production AWES was the Laddermill concept envisaged by the former astronaut, Professor Ockels in 1996 [46].

5. Fly-Gen Airborne Wind Energy Systems

In Fly-Gen AWESs, electric energy is produced onboard of the aircraft during its flight and it is transmitted to the ground through one special rope which integrates electric cables. Electrical energy

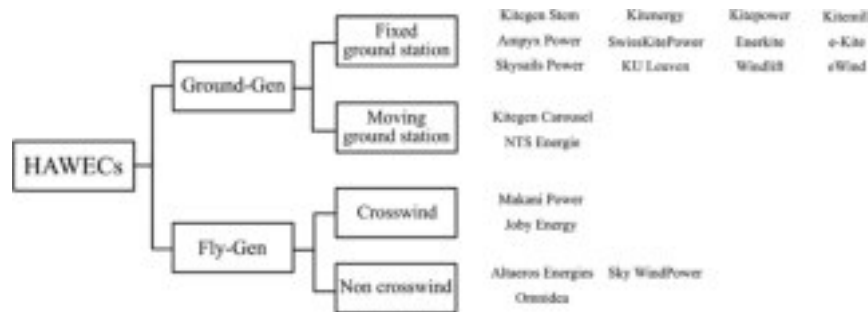


Fig. 10. Classification of AWESs. The different AWESs concepts are listed here as explained in Section 3.

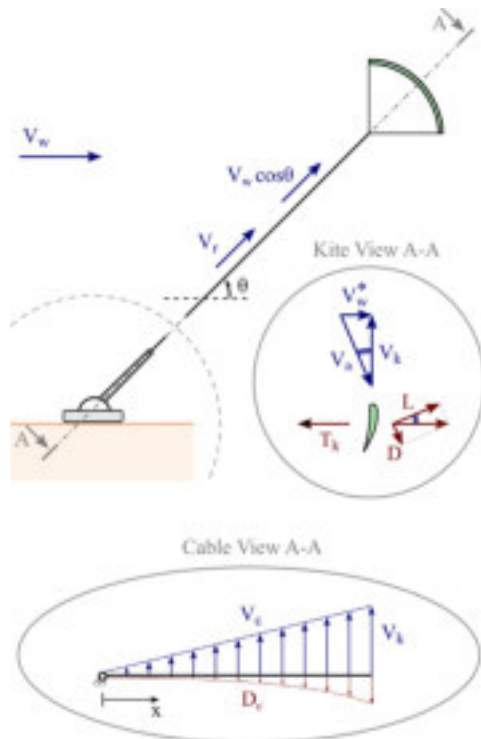


Fig. 11. Basic crosswind model. A simple and well known model for assessing the power output of a crosswind Ground-Gen AWES [6,106,107].

conversion in FG-AWESs is achieved using one or more specially designed wind turbines.

A general classification of these systems is provided in this section.

5.1. Aircraft in Fly-Gen systems

Besides the general classification between crosswind and non-crosswind mode proposed in Fig. 10, FG-AWESs can also be distinguished basing on their flying principles that are:

- **Wings lift:** Achieved with a tethered flight of special gliders (Fig. 8a) or frames with multiple wings (Fig. 8b).
- **Buoyancy and static lift:** Achieved with aerodynamically shaped aerostats filled with lighter-than-air gas (Fig. 8c).
- **Rotor thrust:** Achieved with the same turbines used for electrical power generation (Fig. 8d).

Aircraft in Fig. 8a and 8b fly crosswind and harvest the relative wind, while those in Fig. 8c and 8d fly non-crosswind and harvest the absolute wind.

There is also one FG concept that aims at exploiting high altitude wind energy not by using aerodynamic lift. It uses instead a rotating aerostat which exploits the Magnus effect [80,81].

5.2. Fly-Gen systems under development

This subsection provides a list of FG AWES which are summarized in Figs. 9 and 10.

5.2.1. Loyd's first mechanical concept

One of the most famous and old idea of exploiting wind energy using turbines on a kite belongs to Loyd [6] who calculated that wind turbines installed on a crosswind flying kite could be able to generate up to 5 times the power produced by equivalent turbines installed on the ground. He also patented his idea in 1978 [82]. Loyd's concept foresees a reciprocating wind driven apparatus, similar to a multi propeller plane, with a plurality of ropes linking the aircraft to a ground station.

5.2.2. Makani Power

After about twenty-five years from Loyd's work, Makani Power Inc. [83] has started the development of its Airborne Wind Turbine (AWT) prototypes (as in Fig. 8a). In nine years, Makani tested several AWESs concepts including Ground-Gen, single rope, multiple rope, movable ground station on rails, soft wings and rigid wings [84]. During these years, the company filed several patents where an electric and modern version of Loyd's idea has been enriched with a tether tension sensor [85], an aerodynamic cable [86], and with a new idea of a bimodal flight [87] that has been invented to solve take-off and landing issues. In the bimodal flight the AWT takes off with the wing plane in a vertical position, driven by propellers thrust. This flight mode is similar to a quadcopter flight and rotors on AWT are used as engines. Once all the rope length has been unwound, the AWT changes flight mode becoming a tethered flight airplane. In this second flight mode a circular flight path is powered by the wind itself and rotors on AWT are used as generators [88] to convert power from the wind. During this phase the cable length is fixed. In order to land, a new change of flight mode is performed, and the AWT lands as a quadcopter. Makani has developed and tested its 8 m, 20 kW demonstrator, called 'Wing 7' that showed the capability of fully automatic operations and power production. After these results, in early 2013 Makani was acquired by Google. Makani is currently developing a 600 kW prototype, 'the M600'. The M600 AWT has eight turbines, each with five propeller blades, and has a wingspan of 28 m. The prototype is now undergoing testing [89]. After M600, Makani plans to produce an offshore commercial version of AWT with a nominal power of 5 MW featuring 6 turbines and a wingspan of 65 m.

5.2.3. Joby Energy

Founded in 2008, Joby Energy Inc. [90] is another US company which is developing a FG-AWES. The main difference between Joby and Makani is that the tethered airborne vehicle is a multi-frame structure with embedded airfoils. Turbines are installed in the joints of the frame (as in Fig. 8b). In Joby's concept, the system could be adapted to be assembled with modular components, constructed from multiple similar frames with turbines. The power generation method and the take-off and landing maneuvers are similar to those of Makani concept [91,92]. Joby also patented an aerodynamic rope for its system [93]. In 2009 and 2010, Joby tested different small scale prototypes.

5.2.4. Altaeros Energies

Another project based on flying wind turbines in a stationary position has been developed by Altaeros Energies, a Massachusetts-based business led by MIT and Harvard alumni [94–96]. In this case, instead of using wings lift to fly, they use a ring shaped aerostat with a wind turbine installed in its interior (as in Fig. 8c). The whole generator is lighter than the air, so the take-off and landing maneuvers are simplified, and the only remaining issue is the stabilization of the generator in the right position relative to the wind [97]. The aerostat is aerodynamically shaped so that the absolute wind generates lift that helps keeping a high angle of altitude together with the buoyancy force. After their energy production tests in 2012, Altaeros is additionally working on multiple rotor generators with different lighter-than-air craft configurations.

5.2.5. Sky Windpower

Sky Windpower Inc. [98] proposed a different kind of tethered craft called 'Flying Electric Generator' (FEG) (as in Fig. 8d) which is similar to a large quadrotor with at least three identical rotors mounted on an airframe that is linked to a ground station with a rope having inner electrical cables [99–102]. Their concept was the first AWES to be tested in 1986 at University of Sidney [11,103]. Take-off and landing maneuvers are similar to those of Makani's and Joby's generators, but FEG operation as generator is different. Once it reaches the operational altitude, the frame is inclined at an adjustable controllable angle relative to the wind (up to 50 deg) and the rotors switch the functioning mode from motor to generator. At this inclined position, the rotors receive from their lower side a projection of the natural wind parallel to their axes. This projection of wind allows autorotation, thus generating both electricity and thrust. Electricity flows to and from the FEG

through the cable. Sky Windpower tested two FEG prototypes. They claimed that a typical minimum wind speed for autorotation and energy generation is around 10 m/s at an operational altitude of 4600 m [104]. Unfortunately the company went recently out of business.

6. Crosswind flight: the key to large scale deployment

One of the most important reasons why AWESs are so attractive is their theoretical capability of achieving the megawatt scale with a single plant. For example in [11] a 34 MW plant is envisaged with a tethered Airbus A380, and many other publications present theoretical analyses with MW scale AWES [6,33,105]. This scalability feature is rare in renewable energies and is the key to successful commercial development.

With reference to the extraction principles explained in Sections 4 and 5, this section gives an introduction to the modelling of crosswind flight, the most used flight mode in AWE. Modelling the principle of crosswind flight is the first necessary step towards the understanding of AWESs and their potential. A well known basic model is explained for the case of Ground-Gen and Fly-Gen crosswind AWESs.

Only crosswind generation is analyzed because it was demonstrated that it can provide a power one or two orders of magnitude higher than non-crosswind generation [6]. AWESs concepts that exploit crosswind power have therefore a strong competitive advantage over non-crosswind concepts in terms of available power and, therefore, in the economics of the whole system.

6.1. Crosswind GG-AWESs

This section explains how to compute the power output of a fixed-ground-station crosswind GG-AWES (Fig. 1a) during the reel-out phase (Fig. 2a). As already introduced in Section 4, in GG-AWESs, the recovery phase (Fig. 2b) represents an important factor in the computation of the average power output but, for simplicity, it is not considered in the following model.

The expression of the maximum power, P , for crosswind Ground-Gen AWES can be derived following the analytical optimization on the reel-out speed from [6] with the integrations from [106] and [107]. The hypotheses are: high equivalent aerodynamic efficiency, steady-state crosswind flight at zero azimuth angle from the wind direction, negligible inertia and gravity loads with respect to the aerodynamic forces.

With reference to Fig. 11, the velocities are sketched in blue and the forces are sketched in red. The velocity triangle at the kite is composed by the three components V_k , V_a and V_w^* : the aircraft speed, the apparent wind speed at the aircraft and the wind speed felt by the aircraft, respectively. V_r is the reel-out velocity (i.e. the velocity of the cable in the direction of its own axis) and V_w is the actual wind speed. V_w^* is defined as $V_w^* = V_w \cos \theta - V_r$ where θ is the angle between tether and wind direction (that corresponds to the angle of altitude in case of horizontal wind speed and aircraft at zero azimuth). T_k is the tether tension, L is the wing lifting force, D is the drag force (i.e. the drag force of the aircraft D_w plus the equivalent cable drag force D_{ce}). Notice that the velocity triangle and the force triangle are similar because of the force equilibrium at the aircraft, and therefore $V_k = V_w^* G$, where G is the equivalent aerodynamic efficiency [106], $G = L/D$ that is further explained in Eq. (2). Assuming $V_a \cong V_k$ (valid thanks to the hypothesis of high aerodynamic efficiency) and imposing the equilibrium at the aircraft, the tether tension is $T_k = \frac{1}{2} \rho V_w^{*2} 2G^2 C_L A$, where ρ is the air density. The power output can then be computed as $P_k = T_k V_r = \frac{1}{2} \rho (V_w \cos \theta - V_r)^2 V_r G^2 C_L A$. This expression can be optimized [6] in order to choose the reel-out speed that maximizes the

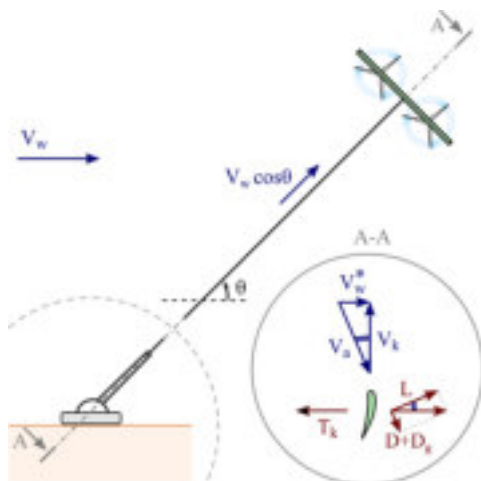


Fig. 12. Basic crosswind model. A simple and well known model for assessing the power output of a crosswind Fly-Gen AWES [6,106,107].

power output, by setting $dP_k/dV_r = 0$. This simple optimization leads to the choice of optimal reel-out speed $V_{r0} = 1/3V_w \cos \theta$, and to the optimal power output, P

$$P = \frac{1}{2} \rho (V_w \cos \theta)^3 \frac{4}{27} G^2 C_L A \quad (1)$$

where A is the area of the kite and G is the equivalent aerodynamic efficiency, that is

$$G = \frac{L}{D} = \frac{C_L}{C_{D_w} + C_{D_{ce}}} \quad (2)$$

where C_L and C_{D_w} are the wing lift and drag coefficients, respectively and $C_{D_{ce}}$ is equivalent cable drag coefficient. The expression of $C_{D_{ce}}$ can be computed by equating the energy dissipated by the distributed cable drag force to the energy that would be dissipated by a concentrated equivalent drag force located at the top end of the cable. This leads to $\int_0^r n D_c(x) V_c(x) dx = D_{ce} V_k$ where n is the number of cables, r is the length of each cable, $V_c(x)$ is the velocity in every point of the cable, $V_c = V_k x/r$, and D_c is the distributed cable drag, $D_c = \frac{1}{2} \rho V_c^2 d C_{\perp}$ where d is the cable diameter and C_{\perp} is the perpendicular cable drag coefficient. The expression for the equivalent cable drag coefficient is therefore given as follows:

$$C_{D_{ce}} = \frac{\frac{1}{2} \rho V_k^2 \frac{1}{4} C_{\perp} n r d}{\frac{1}{2} \rho V_k^2 A} = \frac{C_{\perp} n r d}{4A} \quad (3)$$

6.2. Crosswind FG-AWESs

This section explains how to compute the power output of a crosswind FG-AWES (Fig. 1b) during the generation phase. As already introduced in Section 5, unlike crosswind GG-AWESs, crosswind FG-AWESs have the advantage of being able to produce power without the need of a duty cycle for the recovery phase.

Similarly to what already done in Section 6.1, the expression of the available crosswind power, P , for Fly-Gen AWES can be derived following the analytical optimization on the flying generator drag from [6] with the integrations from [106] and [107].

With reference to Fig. 12, using the assumptions and the symbols defined in Section 6.1, it is possible to compute the maximum power, P , for crosswind Fly-Gen AWES by combining three expressions: the drag force from the flying generators $D_g = \frac{1}{2} \rho V_a^2 C_{D_g} A$, the apparent wind velocity $V_a = (V_w \cos \theta) C_L / (C_D + C_{D_g})$ where $C_D = C_{D_w} + C_{D_{ce}}$, and the generators power $P_g = D_g V_a$. Therefore $P_g = \frac{1}{2} \rho V_w^3 A (C_L^3 C_{D_g}) / (C_D + C_{D_g})^3$. A simple optimization $dP_g/dC_{D_g} = 0$ leads to the maximum value of power:

$$P = \frac{1}{2} \rho (V_w \cos \theta)^3 \frac{4}{27} G^2 C_L A \quad (4)$$

that is the same as the Ground-Gen case and occurs when the drag of the flying generators is chosen to be $C_{D_g} = C_D/2$. It is worth noticing that the maximum power expressed in Eq. (4) does not take into account the conservation of momentum and a more rigorous procedure would yield a slightly lower value of P [108]. However, Eq. (4) correctly defines the upper bound for the maximum power and is useful for first assessments.

7. Discussion

In this section, we provide a brief discussion on some techno-economic issues and topics that are considered to be relevant with respect to the current development, trends, and future roadmap of AWESs.

7.1. Effect of flying mass

In all AWESs, increasing the flying mass decreases the tension of the cables. Since Ground-Gen systems rely on cables tension to generate electricity, a higher mass of the aircraft and/or cables decreases the energy production [107] and should not be neglected when modelling [109]. On the contrary, increasing the flying mass in Fly-Gen systems does not affect the energy production even though it still reduces the tension of the cable. Indeed, as a first approximation, the basic equations of Fly-Gen power production do not change if the aircraft/cable mass is included and this is also supported by experimental data [108].

7.2. Rigid vs soft wings

A question faced by many companies and research groups is whether rigid wings are better or worse than soft wings. On the plus side for soft wings there are: crash-free tests and lower weight (therefore higher power) because of the inherent tensile structure. Conversely, rigid wings have better aerodynamic efficiency (therefore higher power) and they do not share the durability issues of soft wings mentioned in Section 4. It is unclear whether one of the two solutions will prove to be better than the other, but a trend is clearly visible in the AWE community: even though a lot of academic research is being carried out on soft wings, more and more companies are switching from soft to rigid wings [110].

7.3. Take-off and landing challenge

Starting and stopping energy production require special take-off and landing maneuvers as explained in Sections 4 and 5. These are the most difficult to automate and are requiring a lot of research in private companies and academic laboratories [49,55,65].

7.4. Optimal altitude

Another interesting question is how much is the optimal flight altitude, i.e. how much are the optimal cable length and elevation angle that maximize the power output. Increasing the altitude allows to reach more powerful winds, but, at the same time, increasing the cable length or the elevation angle reduces the power output according to Eqs. (1)–(4). Considering a standard wind shear profile, the optimal flight altitude is found to be the minimum that is practically achievable [108,111]. However, results greatly change depending on the hypotheses and, for example, a reduction in cables drag might lead to optimal flight altitudes around 1000 meters [111]. More detailed and location-specific analyses could be therefore useful to define an optimal flight altitude. Nowadays, many AWE companies are aiming at exploiting low altitude winds with the minimum flight altitude set by safety concerns. Only few companies and academic institutions are still trying to reach high altitudes.

7.5. Angle of attack control

As shown in Eq. (1), the aerodynamics of the system is very important to the power production. A first aerodynamic design should maximize the value $G^2 C_L$.

A bridle system might be used to fix an incidence angle so that $G^2 C_L$ is fixed at an optimal angle of attack. But it is easy to show that an active control of the angle of attack is essential during the production phase of Ground-Gen or Fly-Gen devices.

A variation of the angle of attack can be induced by a change in the tether sag or in the velocity triangle. As for the tether sag, it is

possible to compute the variation of the nominal angle of attack thanks to the model provided in [112]. Depending on the value of the design parameters, the model would give a numerical value between 7 deg and 11 deg for a large scale AWES. As regards the velocity triangle, assuming controlled constant tether force (a common constraint in a real power curve [108,50]) and computing the effect of a different absolute wind speed on the angle of attack with a simple velocity triangle, a variation of about 3.5 deg or 4 deg can be reasonably obtained.

Such variations of the angle of attack can decrease substantially the power output or even make the flight impossible. For example, using the values of the aerodynamic coefficients for an airfoil specifically optimized for AWESs [113], a steady state variation in the angle of attack of just ± 2 deg can lead to a decrease in power output between 5% and 42% with respect to the optimal angle of attack. Real time control of the angle of attack in current AWES prototypes from Ampyx and Makani [52,108] limits the angle of attack variation to ± 2 deg in a real flight time history.

7.6. Cables

Cables for AWESs are usually made of Ultra-High-Molecular-Weight Polyethylene (UHMWPE), a relatively low-cost material with excellent mechanical properties [114] even though many different materials are being used and studied [115]. The cables can be 1, 2 or 3 and in some concepts they carry electricity for power generation or just for on-board actuation. Each of these choices has advantages and disadvantages, and, at the present time, any prediction about the best tethering system would be highly speculative. The tethers also represent a known issue in the AWE community [116] because of wear, maintenance and aerodynamic drag.

7.6.1. Polynomial curvature

It is worth noticing that Section 6 describes a steady state flight with straight cables under known tension, but for very long cables this model is not accurate. For example, removing the straight cable hypothesis gives a fourth order polynomial shape function [112] for cables in steady state flight. The curvature is acceptable for short round cables ($C_{\perp} = 1$ and r up to 1 km), while it is highly undesirable with extremely long round cables (e.g. $r=10$ km). Reducing the cable aerodynamic drag to 0.2 allows reasonable curvatures with lengths of several kilometers (e.g. $r=5$ km).

7.6.2. Unsteady analysis

Very long cables should be studied removing also the steady state hypothesis in order to consider the fact that, in unsteady flight, the lower part of the cables could reasonably move less than in steady state flight, thus dissipating less energy.

7.6.3. Tethers electrostatic behavior

Some concerns have been raised regarding the behavior of tethers in atmospheric environment [117]. An analysis performed on dry and wet polyethylene ropes without inner conductors [14] shows that non-conductive tethers will not trigger a flashover in typical static electric fields of thunder clouds, however non-conductive tethers are very likely to trigger a flashover when subjected to impulsive electric fields produced by lightnings. It is reasonable to say that AWESs will not work during thunderstorms and that lightnings should not be an issue. However, an analysis regarding the electrical atmospheric behavior of tethers with inner conductors could be useful to understand the worst atmospheric conditions to which conductive tethers might be exposed.

7.6.4. Aerodynamic drag opportunities

A reduction in the cable drag coefficient would likely lead to an increase in power output by two or three times thanks to better aerodynamic efficiency, increased flight speed and higher operational altitude [111]. Several patents have been filed to address this issue [86,93,118] even though the reduction of cable drag by means of e.g. fairing or streamlined cross-sections has not been experimentally demonstrated yet. Because of the potential advantages, funding opportunities might be available for concepts in aerodynamic drag reduction [119].

7.6.5. Nearly zero cable drag

As regards the aerodynamic cable drag, two patented concepts might provide an important improvement in the long term by setting to zero the aerodynamic drag for the majority of the length. They are worth being mentioned even though no prototype already exists for both of them. The first appeared in the very first patent about high altitude wind energy in 1976 [120] and described the so-called 'dancing planes' concepts. Two Fly-Gen turbines are held by a single cable, the top part of which splits into two. Each turbine is tethered to one of these ends and follows a circular trajectory so that only the two top parts of the cable fly crosswind through the air and the main single cable stands still under balanced tensions. Several studies already exist for this promising concept [121,122]. The second [123] describes a 'multi-tether' AWES where three cables are deployed from three different ground stations and are eventually connected to each other in their top end. A single tether connects the top end of the three cables to one kite that is then geometrically free to fly crosswind within a certain solid angle without moving the three lower cables but only changing their inner tension. The further the ground stations are spaced apart, the larger is the allowable solid angle. For both of these concepts the result is the same: high altitude crosswind flight is achieved with the longest part of the cables completely fixed in space, thus allowing to reach winds at very high altitude with a relatively short dissipative cable length.

7.7. Business opportunities

To date, several tens of millions dollars have been spent for the development of AWESs, which is a relatively low amount of money, especially if one considers the scale of the potential market and the physical fundamentals of AWE technology. The major financial contributions came, so far, by big companies usually involved in the energy market [119]. The community is growing both in terms of patents and in terms of scientific research [59]. But still, there is no product to sell and the majority of the companies that are trying to find a market fit are now focusing on off-grid markets and remote locations where satisfying a market need can be easier at first [110].

8. Conclusions

High altitude wind energy is currently a very promising resource for the sustainable production of electrical energy. The amount of power and the large availability of winds that blow between 300 and 10000 meters from the ground suggest that Airborne Wind Energy Systems (AWESs) represent an important emerging renewable energy technology. In the last decade, several companies entered in the business of AWESs, patenting diverse principles and technical solutions for their implementation. In this extremely various scenario, this paper attempts to give a picture of the current status of the developed technologies in terms of different concepts, systems and trends. In particular, all existing AWESs have been briefly presented and classified. The basic

generation principles have been explained, together with very basic theoretical estimations of power production that could provide the reader with a perception on which and how crucial parameters influence the performance of an AWES.

In the next years, a rapid acceleration of research and development is expected in the airborne wind energy sector. Several prototypes that are currently under investigation will be completed and tested.

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