Chapter 1
Airborne Wind Energy: Basic Concepts and Physical Foundations

Moritz Diehl

Abstract Tethered wings that fly fast in a crosswind direction have the ability to highly concentrate the abundant wind power resource in medium and high altitudes, and promise to make this resource available to human needs with low material investment. This chapter introduces the main ideas behind airborne wind energy, attempts a classification of the basic concepts that are currently pursued, and discusses its physical foundations and fundamental limitations.

1.1 Introduction

Airborne wind energy (AWE) regards the generation of usable power by airborne devices. In contrast to towered wind turbines, airborne wind energy systems are either flying freely in the air, or are connected by a tether to the ground, like kites or tethered balloons. It turns out that all airborne wind energy systems with significant power output are mechanically connected to the ground in order to exploit the relative velocity between the airmass and the ground; in fact, to be able to harvest wind power, they need to maintain a strong force against this motion. They can be connected to a stationary ground station, or to another moving, but non-flying object, like a land or sea vehicle. Power is generated in form of a traction force, e.g. to a moving vehicle, or in form of electricity. The three major reasons why people are interested in airborne wind energy for electricity production are the following:

- First, like solar, wind power is one of the few renewable energy resources that is in principle large enough to satisfy all of humanity's energy needs.
- Second, in contrast to ground-based wind turbines, airborne wind energy devices might be able to reach higher altitudes, tapping into a large and so far unused

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wind power resource [1]. The winds in higher altitudes are typically stronger and more consistent than those close to the ground, both on- and off-shore.

- Third, and most important, airborne wind energy systems might need less material investment per unit of usable power than most other renewable energy sources. This high power-to-mass ratio promises to make large scale deployment of the technology possible at comparably low costs.

This chapter has as its aim to introduce the main concepts behind airborne wind energy, and is organized as follows: in Sect. 1.2 we discuss one of the most fundamental concepts of airborne wind energy, crosswind kite power. In Sect. 1.3, we give an overview of different airborne wind energy systems, most of which use the concept of crosswind kite power. In Sect. 1.4 we prove and discuss the fundamental limits for any airborne wind energy device. Finally, in Sect. 1.5, we conclude the chapter with a summary and a list of open questions.

1.2 Crosswind Kite Power

Every hobby kite pilot or kite surfer knows this observation: As soon as a kite is flying fast loops in a crosswind direction the tension in the lines increases significantly. The hobby kite pilots have to compensate the tension strongly with their hands while kite surfers make use of the enormous crosswind power to achieve high speeds and perform spectacular stunts. The reason for this observation is that the aerodynamic lift force F_L of an airfoil increases with the square of the flight velocity, or more exactly, with the apparent airspeed at the wing, which we denote by v_a. More specifically,

$$F_L = \frac{1}{2}\rho A C_L v_a^2, \tag{1.1}$$

where ρ is the density of the air, A the airfoil area, and C_L the lift coefficient which depends on the geometry of the airfoil.

Thus, if we fly a kite in crosswind direction with a velocity v_a that is ten times faster than the wind speed v_w, the tension in the line will increase by a factor of hundred in comparison to a kite that is kept at a static position in the sky. The key observation is now that the high speed of the kite can be maintained by the ambient wind flow, and that either the high speed itself or the tether tension can be made useful for harvesting a part of the enormous amount of power that the moving wing can potentially extract from the wind field.

The idea of power generation with tethered airfoils flying fast in a crosswind direction was already in the 1970's and 1980's investigated in detail by the American engineer Miles Loyd [9]. He was arguably the first to compute the power generation potential of fast flying tethered wings - a principle that he termed *crosswind kite power*. Loyd investigated (and also patented) the following idea: an airplane, or kite, is flying on circular trajectories in the sky while being connected to the ground with a strong tether. He described two different ways to make this highly concentrated form of wind power useful for human needs, that he termed *lift mode* and *drag* *mode*: while the lift mode uses the tension in the line to pull a load on the ground, the drag mode uses the high apparent airspeed to drive a small wind turbine on the wing.

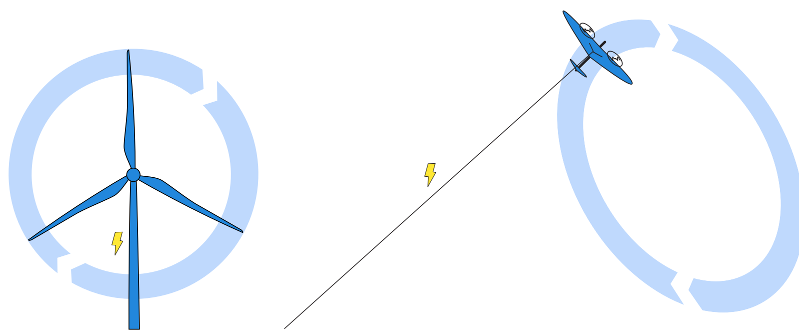

Fig. 1.1 AWE systems replace the tips of a wind turbine (left) with a tethered fast flying wing (right, operating in drag mode). Illustration by R. Paelinck.

It is interesting to compare crosswind kite power systems with a conventional wind turbine, as done in Fig. 1.1, which shows a conventional wind turbine on the left and an airborne wind energy system in drag mode on the right. Seen from this perspective, the idea of AWE is to only build the fastest moving part of a large wind turbine, the tips of the rotor blades, and to replace them by automatically controlled fast flying tethered wings. The motivation for this is the fact that the outer 30% of the blades of a conventional wind turbine provide more than half of the total power, while they are much thinner and lighter than the inner parts of the blades. Roughly speaking, the idea of airborne wind energy systems is to replace the inner parts of the blades, as well as the tower, by a tether.

The power P that can be generated with a tethered airfoil operated either in drag or in lift mode had under idealized assumptions been estimated by Loyd [9] to be approximately given by

$$P = \frac{2}{27}\rho A v_{\mathrm{w}}^3 C_{\mathrm{L}} \left(\frac{C_{\mathrm{L}}}{C_{\mathrm{D}}}\right)^2, \tag{1.2}$$

where A is the area of the wing, C_{L} the lift and C_{D} the drag coefficients, and v_{w} the wind speed. Note that the lift-to-drag ratio $\frac{C_{\mathrm{L}}}{C_{\mathrm{D}}}$ enters the formula quadratically and is thus an important wing property for crosswind AWE systems. For airplanes, this ratio is also referred to as the *gliding number*; it describes how much faster a glider without propulsion can move horizontally compared to its vertical sink rate.

Theoretically, a modern wing with a lift of $C_{\mathrm{L}} = 1$ and an intrinsic drag of $C_{\mathrm{D}} = 0.03$ and a wind of $v_{\mathrm{w}} = 13$ m/s would lead to a power of 217 kW per m^2 wing area. This is not realistic, as it turns out that the tether drag is significant: a more realistic value for the total drag coefficient is e.g. $C_{\mathrm{D}} = 0.07$, leading to a theoretical power output of $P = 40$ kW per m^2 of wing area. This high power density is not yet realized experimentally by any of the competing AWE companies and academic teams, but is confirmed by refined computer simulations and appears realistic. For small scale systems, the tether drag is relatively more important, and so far, a peak power of 6 kW per m^2 is reported in Chapter 26 for a 3 m^2 airplane at 13 m/s wind speed.

It is interesting to compare this power density of 40 kW/m^2 to the maximum power that can be obtained with photovoltaic (PV) cells. The density of solar irradiation on the earth is about 1.3 kW/m^2, and the overall efficiency of standard PV cells is about 20%. Thus, the power generated by one square meter of wing of an AWE system is more than 150 times higher than the power generated by one square meter of solar cells at maximum irradiation. Equipping the wings of an AWE system with solar cells, like a solar airplane – which might sound like a good idea – would add less than 1% to the overall power output. The additional weight and costs largely counterbalance this minor benefit, and therefore none of the existing AWE systems is equipped with solar cells.

Let us look at a larger scale and draw a comparison with wind turbines: the wing of an Airbus 380 has an area of 845 m^2 and weighs about 30 tons, with a wing span of 80 m. If this wing would be the tethered wing of an AWE system, it could in principle lead to a power output of about 34 MW, though the wing would need extra reinforcement to support the load of approximately 9 MN. Assuming a modern fibre with 1 GPa tensile strength, the corresponding tether would need a cross sectional area of 90 cm^2, i.e. a diameter of 11 cm. To reach an altitude of 500 m at an elevation angle of 30 degrees a tether length of 1000 m would be needed, resulting in a tether volume of 9 m^3 with a weight of about 9 tons. In total, with a pumping system, one would need an airborne mass of 39 tons to generate 34 MW. To be on the conservative side, let us reduce this hypothetical power to 30 MW.

The power of 30 MW corresponds to the power output of four of the largest existing conventional wind turbines, the Enercon E-126 of 7.5 MW rated power. Each of these has three rotor blades with a weight of 65 tons, and a rotor diameter of 126 m. Thus, only the 12 blades of these four turbines together weigh about 780 tons, i.e. 20 times more than the corresponding part of the AWE system. If one includes the weight of the rest of the rotors and the towers, the total weight is 12 400 tonnes, or more than 300 times the weight of the airborne part of the AWE system. One can estimate that the electrical generators are similar in size for both systems and that the needed foundations are smaller for the AWE system.

This impressive saving in material comes at a cost, however: while a conventional wind turbine is a stationary construction on the ground, an airborne wind energy system needs to fly to maintain its shape: we have exchanged an intrinsically stable system by an intrinsically unstable one. Just like a car, a conventional wind energy system can be stopped immediately whenever there is a problem, usually without an accident. In contrast to this, an AWE system, just like a plane, once airborne, needs to continue to fly, and whenever one of its parts is not working properly, an accident with total system destruction is looming. For this reason, airborne wind energy systems need sophisticated automatic control [3, 5]. While airborne wind energy seemed more a vision than reality in Loyd's time, it is much easier to realize

AWE systems today, due to the combined progress in tether and wing materials as well as in automatic flight control and navigation technology.

1.3 Classification of Airborne Wind Energy Systems

While we have already discussed the most important concept of airborne wind energy, crosswind flight with its two modes of power generation, lift and drag mode, there is a much wider variety of fascinating concepts in the field of AWE systems. Some generate electrical power on-board the kite, others generate electrical power on the ground, while a third class of systems does not generate electrical power but uses the tether tension for vehicle propulsion. Some AWE systems have flexible wings while others have rigid wings. Most AWE systems are heavier than air and have thus to rely on aerodynamic lift to stay airborne, but a few AWE systems are lighter than air and can thus stay in the air passively. Between all these concepts, many combinations are possible, and many of these combinations are in fact realized. Let us in this section go through all these classifications and discuss the concepts one by one.

On-Board Power Generation

As discussed before, one first and very intuitive way to generate power with a fast flying tethered airplane, or kite, is the following: the plane might carry an on-board turbine to use its high relative airspeed for power generation. Since the electrical generator is part of the flying airplane, we call this principle *on-board generation*, or, according to Loyd, *drag mode*, because the turbine adds extra drag to the airplane. A positive point is that the on-board turbines of crosswind systems can operate at very high rotation speeds, allowing the use of electrical generators without gearbox that can be relatively lightweight for given power, and might be significantly lighter than the slow turning generators of conventional wind turbines or ground-based power generating AWE systems. The idea to generate electrical power on a crosswind kite was first described in the patent [12], and several teams work currently on this promising concept, most prominently the Californian start-up Makani Power. An interesting feature of these systems is the fact that the on-board turbines can be used for vertical take-off and landing, by using the generator in motor mode and using available standard quadrotor control technology.

There are several other airborne wind energy concepts that use on-board power generation, but which do not exploit crosswind motion. Though the absence of crosswind motion leads to much smaller power-to-mass ratios, they can be of interest in specific applications. Among these concepts are electrically operated helicopters that work similar to an autogyro, and use the rotors both for power generation as well as the generation of lift. This concept is the basis of the flying electric generators with four rotors currently investigated by the company SkyWindPower

[14]. Early experiments in this line of research were already performed in 1986 at the University of Sydney, as the historical photograph in Fig. 1.2 proves. Other con-

Fig. 1.2 Prototype testing the flying electric generators in Australia in May 1986, showing the powered craft almost in autorotation at a wind speed of 8 m/s. Electricity generation was achieved briefly in another test. The craft, which had a total mass of 29 kg, had two rotating hubs, each radiating a lifting rotor blade and a shorter streamlined blade with a counter-balancing mass at its tip (Photo by Bryan Roberts, provided by PJ Shepard).

cepts use the rotor only to generate power and rely on a balloon filled with Helium to become lighter than air. This is the basis of a concept realized by the start-up Altaeros Energies, whose balloon is torus shaped and surrounds the turbine, and can generate some aerodynamic lift. Other airborne power generation systems also use balloons but generate power with a different rotor concept, e.g. the Savonius-type rotor of Magenn power, which is a large horizontally rotating drum filled with Helium. The power-to-volume ratio of such systems is of course very low.

All on-board power generation systems need a tether that has both to conduct electricity and withstand a strong tension. Given the significant amounts of power that need to be transmitted, a high voltage cable is necessary to keep both tether weight and Ohmic losses small. On the other hand, isolation increases the tether diameter and thus increases tether drag, which is an issue for crosswind systems; also, on-board power converters add extra weight to the airborne system.

Ground-Based Power Generation

An alternative way to generate power from fast flying tethered wings that does not need high voltage electrical power transmission via the tether is the following: one directly uses the strong tether tension to unroll the tether from a drum, and the rotating drum drives an electric generator. As both the drum and generator can be placed on the ground, we call this concept *ground-based generation* or *traction power generation*. For continuous operation, one has to periodically retract the tether. One does so by changing the flight pattern to one that produces much less lifting force. This allows one to reel in the tether with a much lower energy investment than what was gained in the power production phase. The power production phase is also called *reel-out* phase, and the retraction phase *reel-in* phase. When ground-based generation is combined with crosswind motion, Loyd coined the term *lift mode*, because one uses mainly the lifting force of the wing. But due to the periodic reel-in and reel-out motion of the tether, this way of ground-based power generation is often also called *pumping mode*; sometimes even the term *Yo-Yo mode* was used to describe it.

Airborne wind energy systems with ground-based power generation in pumping mode come in many different flavors: many use lightweight flexible wings, often designed and delivered by surf kite manufacturers. Still, there exist notable differences in how they steer the kite and how many lines they use: for example, the Kite Power team at Delft University of Technology uses a single main tether and an airborne *control pod* with electric drives that can control the relative length of the steering lines [7, 16]. Similar pumping concepts were demonstrated by the Swiss Kite Power team, the Greenwing team at TU Munich, as well as by the company SkySails Power. On the other hand, the KiteGen team in northern Italy as well as the companies WindLift and Enerkite have developed pumping systems that use two or even three main tethers to control the kite with the relative length differences of the tethers, see e.g. [3]. An advantage of this configuration is the extremely low weight per square meter of the airborne part of the system. Other systems in pumping mode go the opposite route, and use rigid wings that are similar to those used in high performance sail planes. Like rigid wing systems in drag mode, they have high crosswind speeds and rely heavily on automatic control. The reel-out phase consists of fast loops flown by the tethered airplane, while the reel-in phase sees the airplane flying straight towards the ground station with almost no tether tension. This route is chosen by the company AmpyxPower and by the HIGHWIND team at KU Leuven.

There exist a few ground based power generation systems that use pumping, but not crosswind power, most notably the Helium filled cylinders of the start-up company Omnidea that are connected to the ground on both ends, rotate around a horizontal axis and exploit the Magnus effect to move up and down with different tether tensions. Again, the power-to-mass ratio of systems that do not exploit crosswind motion is expected to be small. On a side note, it is interesting to mention that the Magnus effect is also used for sailing in form of the Flettner rotor.

Other AWE concepts do not use a reel-in and reel-out phase and realize ground based power generation without pumping, such as the gigantic carousel configurations investigated by the start-ups KiteGen in Italy or NTS in Germany, where kites pull a load around a circular track and where ground-based generators are driven by this motion.

Airborne Wind Energy for Vehicle Propulsion

Some airborne wind energy systems do not generate electrical power, but use the strong tether tension directly to drive a vehicle on the ground, such as a car or a ship. In fact, this class was the one that was described and realized first among all AWE concepts, in the book by Pocock [13] and analyzed in detail in [15]. Also, the first commercial product from the current AWE community falls into the class, the towing kites for sea-going vessels by the company SkySails, which are described in Chapters 20, 8 and 35 in this book. While the AWE community's focus is mostly on electricity generation because of its more generic use, airborne vehicle propulsion could prosper in a significant market - naval transport - and play a crucial part in the overall development of airborne wind energy technology: first, the airborne part of an airborne traction system is nearly identical to a ground-based electrical power generating AWE device in pumping mode, thus many technological developments from traction kites can be taken over by electricity generating ones. Second, the economics of naval traction systems are different: due to the fact that they complement petrol engines their economics depends crucially on the price of ship fuel. Because the engines drive marine propellers with significant power losses, while the towing kites transfer their traction power directly to the ship, their economics is particularly favorable. And third, a ship always has a few people on board that can fix possible technical problems, which might offer advantages in the first development years of the technology. As a matter of fact, ship propulsion is the first AWE market with large scale products on offer, and the company SkySails has reported traction power generation of up to 2 MW with a single kite system.

Flexible vs. Rigid Wings

As mentioned before, an interesting division in the field of AWE systems is between soft, flexible wings that resemble surf kites or parachutes, and rigid wings that resemble airplanes or the tips of wind turbine blades. Flexible wings keep their shape only due to the aerodynamic load distribution generated by the airflow, and can be made extremely lightweight for a given surface area. In case of a crash, they usually do not cause major damage, and are thus much safer to operate in the vicinity of humans. They fly with moderate speeds and can easily be controlled by a human pilot. In contrast to this, rigid wings keep their shape independent of ambient wind conditions and need more mass per square meter wing surface. Due to their higher lift to drag ratio, they can reach very high velocities, which comes with the benefit of significantly higher power output per wing area, but also the danger of considerable damage in case of a crash. Interestingly, only few hybrid systems exist that use a mix of flexible and rigid elements, like hang gliders or toy kites, though it must be said that many flexible wings have some semi-rigid elements such as tubes filled with compressed air (tube kites). An interesting hybrid concept is called *tensairity* and uses compressed air tubes and tension elements to increase the maximum wing loading while maintaining very low weight [2].

It should be stressed that all AWE systems with significant power output – both those with flexible and with rigid wings – have a very strong tether tension, which implies that any AWE device flying close to the ground can cause considerable damage with its tether. For this reason, all AWE systems are tested at some safety distance from humans.

Multiple Wing Systems

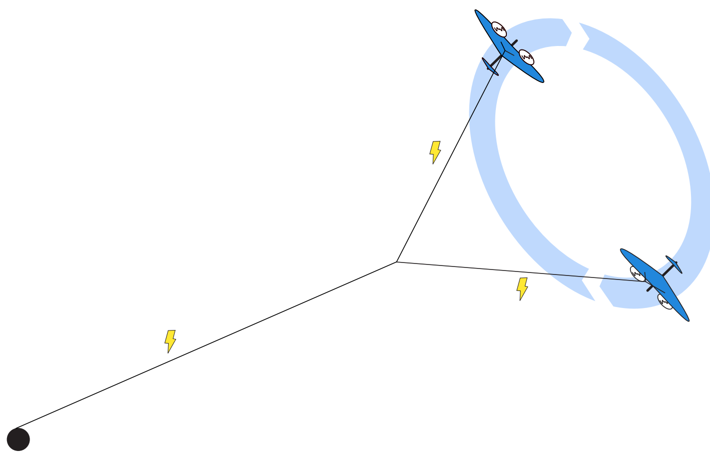

Fig. 1.3 Visualization of a dual airplane system with reduced tether drag. Illustration by R. Paelinck.

Due to the fact that tether drag is a significant obstacle to high gliding numbers it would be beneficial to have short tethers. On the other hand, a long tether is needed to reach high altitudes. For this reason, some concepts use multiple kites and decouple the two roles of the tether by introducing two sorts of tether: first, a *primary tether* that allows the AWE system to reach altitude, and second, two or more *secondary tethers* that are attached to the end of the primary tether, and connect it with the kites, which are attached at their ends. This configuration allows the kites to loop fast around the attachment point between the two tethers, moving only the short secondary tethers, while the primary tether barely moves, as visualized in Fig. 1.3. The first description of such a system, that was not yet built, can be found in the patent [12] with on-board generation. This concept leads indeed to significantly reduced tether drag losses compared to a single wing system, as the detailed investigations in [17] show. The same holds for ground-based generation systems, with dual kites operating in pumping mode, as investigated in [4].

A different concept that uses multiple wings takes several kites and attaches them on the same main tether, one after the other, in order to increase the total wing area. This idea was at the basis of the *laddermill* by W. Ockels, and in principle provides an easy way for creating a large scale system with many medium sized wings stacked one above the other, see the left side of Fig. 1.5. Power could be generated via pumping or in other ways [6]. Care needs to be taken, however, with regard to the spacing between kites, whose airflows influence each other, so that the total power output does not increase linearly with the number of kites. In general, start-up of multiple wing systems is a delicate task, and reliability of the interconnected wings is a critical issue, so that no larger scale AWE system with multiple kites was built yet.

Lighter than Air Systems

While most airborne wind energy systems rely on aerodynamic lift in one form or the other in order to keep the system airborne, a few systems rely on aerostatic lift to stay aloft, i.e. the airborne part of the system is lighter than air. The advantage is that they can stay airborne in the absence of wind indefinitely, and without power consumption. On the other hand, they need a considerable volume to compensate the weight of the rest of the airborne system – this volume is typically filled with Helium. An interesting fact is that power generation comes along with significant tether tension and when the wind blows and power is produced, the tether force, which is partly directed in vertical direction, largely dominates the weight of any airborne wind energy system; thus, the advantages of lighter than air systems become obsolete when they do generate power.

Two of the lighter than air systems that have been realized in recent years, the systems by Magenn power and Altaeros Energies mentioned earlier, both use on-board power generation with the additional weight burden of the electrical generator. To the best of the author's knowledge no crosswind kite power systems exist in this class; their large volume constitutes a fundamental design limitation for achieving high lift-to-drag ratios.

1.4 Fundamental Physical Limits of Airborne Wind Energy

Let us in this section look in more detail at the physical foundations of airborne wind energy. We will derive a refined variant of Loyd's formula defined by Eq. (1.2) and prove that it is in fact an upper limit of the power that any flying wing can extract from the atmosphere. Let us start with a simple, but very fundamental observation that holds for any wind power extracting device. For this aim we do not look at the generated power, but instead at the power that the wind power system extracts from the atmosphere, i.e. the power that is removed from the wind field due to the presence of the device.

Lemma 1.1 (Power Extraction Formula). *Regard a constant wind with speed v_{w}. The total power P_{wind} that a flying wing extracts from this wind field is given by the* *product of v_w with the total aerodynamic force F_a that the wing experiences and the cosine of the angle γ between the direction of this force and the wind:*

$$P_{\text{wind}} = v_w F_a \cos\gamma. \tag{1.3}$$

An intuitive proof of this simple fact can be based on a thought experiment, as visualized in Fig. 1.4: we imagine that the airmass is at rest while the ground anchor point of the airborne wind energy device is mounted on a tractor that moves with a constant speed v_w against this airmass. The resistance of the airborne system causes a total aerodynamic force F_a that has a horizontal force component parallel to the tractor motion of size $F_a \cos\gamma$. This force is directed against the motion of the tractor, and the mechanical power that the tractor needs to maintain its speed is given by $v_w F_a \cos\gamma$. Extending the thought experiment such that not only the tractor, but the whole ground is moving against the air mass and pushed by a magic force, it is clear that the same power formula still holds for the work done by this magic force. The validity of the same formula for a fixed ground and a moving airmass is due to the equivalence of inertial frames; in reality, the magic force moves the airmass relatively to the ground, and is caused by the presence of high and low air pressure regions. □

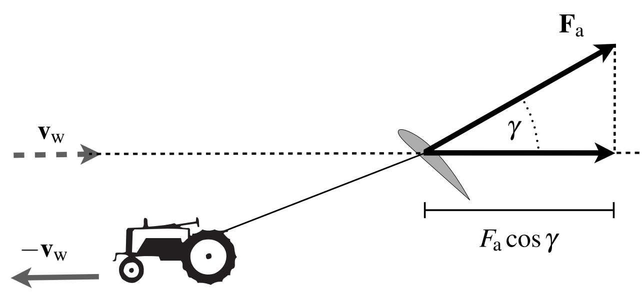

Fig. 1.4 Thought experiment from the proof of Lemma 1.1. A tractor moving at speed v_w and pulling a wing through air at rest performs a mechanical power of $v_w F_a \cos\gamma$. Conversely, if the air moves and the tractor is at rest, the same amount of power is extracted from the relative motion of the air with respect to the ground. It constitutes the power P_{wind} lost by the wind field due to the presence of the wing.

A simple conclusion from the lemma, that gives an upper bound on the usable power, is that no device can extract power from a constant wind field if it does not exert a horizontal force component against this wind. Most AWE devices have some losses, and most exert a force on the ground anchor point that is not parallel to the wind direction. In analogy to a similar expression in solar power, we might call the loss that is due to the fact that the total aerodynamic force is not perfectly in line with the wind direction the *cosine loss*.

In fact, all tethered systems need some elevation angle that the tether forms with the horizontal in order to reach some altitude. Fortunately, for moderate angles, the cosine is still close to one, for example the cosine loss is less than 30% even if the tether goes upwards with an angle of 45 degrees. Optimized AWE systems typically fly at even lower elevation angles, and for e.g. 20 degrees we have nearly negligible cosine losses, of only 6%.

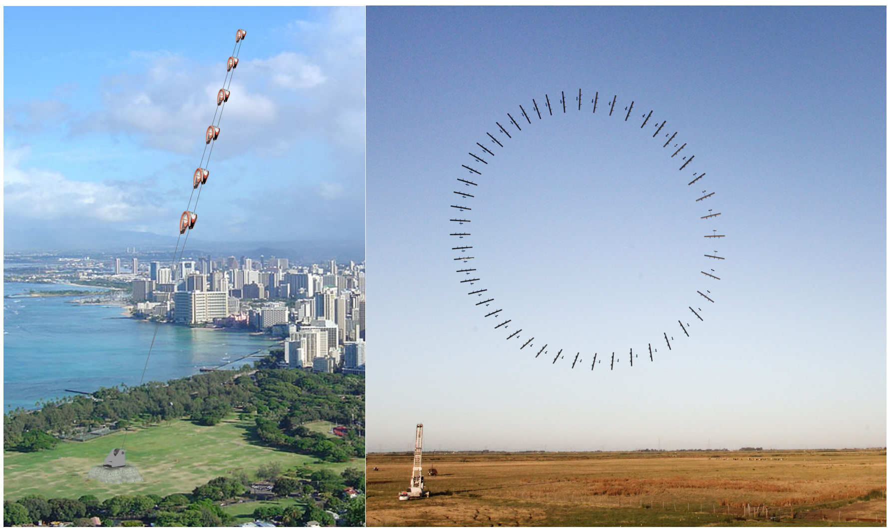

Fig. 1.5 An artistic vision of an AWE system with nearly vertical line (left [8], courtesy Delft University of Technology) and an implemented prototype, with a lower elevation angle (right [11], photo composite courtesy Makani Power).

The lemma forms a strong obstacle for all airborne wind energy concepts whose tether rises almost vertically into the air, cf. the artistic vision at the left of Fig. 1.5. Such systems use a large portion of the aerodynamic force to just pull the tether upwards, without extracting the corresponding amount of power from the wind field: they have very large cosine losses.

Cosine Losses due to Gravity

A second source of cosine losses is the weight of the airborne system, which causes that the direction of the aerodynamic force needs to form an even larger angle γ with the wind direction than the tether elevation alone. In most systems, this part of the cosine losses is small, but it can become relevant at low wind speeds and for systems with considerable effective weight per power, i.e. airborne power generation systems that use neither aerostatic lift nor crosswind motion.

In this context, it is interesting to make a short calculation that shows that for crosswind devices the gravitational force turns out to be of minor importance relative to the enormous tension force in the cable: if one assumes that the wing flies with an airspeed of about v_a =70 m/s, and the lift coefficient is $C_L = 1$, the tether tension F_L is according to the lift formula (1.1) approximately 3000 N. If one assumes that one square meter fixed wing surface weighs about 25 kg, it is subject to a gravitational force of below 250 N, i.e. 12 times smaller than the tether tension, resulting in cosine losses due to gravity that are below 0.5 %. A more detailed analysis should also include the weight of the tether, which turns out to be below 3 kg per square meter wing for a length of 1000 m, and the cosine losses remain below 0.5%.

More physically speaking, gravity can be compensated by a very small change of the orientation of the wing, of less than 6 degrees, which results in a downwind tether force reduction of below 0.5 %. Even if the total weight of the system would be much higher, e.g. corresponding to one third of the aerodynamic force, the necessary wing orientation change would be 20 degrees, resulting in cosine losses due to gravity of only about 6 %. This is the reason why gravity can often be neglected in power estimates for airborne wind energy systems.

The Power Limit of Airborne Wind Energy

Using the above Lemma 1.1 and four very straightforward observations, we can derive a limit on the usable power that any wing can extract from a wind field. For better orientation, the relevant speeds and forces of the following considerations are sketched in Fig. 1.6. Let us state the four observations:

1. For the upper limit, we will only need to consider the case that there are no cosine losses, i.e. we will from now on set the angle γ to zero.
2. The usable power P is given by the difference of the total power P_{wind} extracted from the wind field minus the power losses P_{loss}, i.e. $P = P_{\text{wind}} - P_{\text{loss}}$.
3. A lower bound for the power losses is given by the product of the apparent velocity v_a, i.e. the relative air speed of the wing, and the aerodynamic drag of the wing, given by $F_D = \frac{1}{2}\rho A C_D v_a^2$ if C_D is the combined drag coefficient of wing and tether. Thus, we have the bound
$$P_{\text{loss}} \geq v_a F_D. \tag{1.4}$$
4. The total aerodynamic force F_a that the wing experiences is given by
$$F_a = \frac{1}{2}\rho A v_a^2 \underbrace{\sqrt{{C_L}^2 + (C_D + C_{D,\text{power}})^2}}_{=:C_R} \tag{1.5}$$

if the wing flies with the relative air speed v_a, and if in addition to the airplane's lift and drag coefficients C_L and C_D there is an extra drag force with coefficient $C_{D,\text{power}}$ applied, e.g. by an on-board turbine, that might be used for usable power generation. We abbreviate the resultant total aerodynamic force coefficient by C_R.

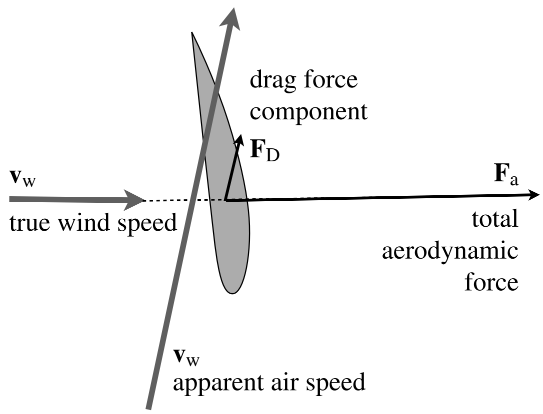

Fig. 1.6 Sketch of the relevant speeds and forces around a wing for wind power generation.

Taking the above four observations together, and treating the relative airspeed v_a as an unknown that we can still choose, we get the following bound on the usable power:

$$P = P_{\text{wind}} - P_{\text{loss}} \leq v_w F_a - v_a F_D = \frac{1}{2}\rho A v_a^2 (v_w C_R - v_a C_D). \qquad (1.6)$$

We can simplify this expression by introducing the *wing speed ratio* $\lambda = \frac{v_a}{v_w}$, that might be seen as a generalization of the *tip speed ratio* of conventional wind turbines. Replacing v_a by λv_w in the above formula gives the fundamental relation

$$P \leq \frac{1}{2}\rho A v_w^3 (\lambda^2 C_R - \lambda^3 C_D). \qquad (1.7)$$

Note that the expression on the right hand side becomes zero for $\lambda = \frac{C_R}{C_D}$, giving a limit on the maximum speed that the wing could fly when driven by the wind, but neither gaining nor loosing power. To get the upper bound on the available power, we can maximize formula (1.7) over the wing speed ratio λ. To do this, let us differentiate the right hand side term w.r.t. λ:

$$\frac{\partial}{\partial \lambda}(\lambda^2 C_R - \lambda^3 C_D) = \lambda(2C_R - 3C_D\lambda)$$

which is made zero by the maximizer, $\lambda_* = \frac{2C_R}{3C_D}$. Thus, we have

$$\max_{\lambda\geq 0}(\lambda^2 C_R - \lambda^3 C_D) = (\lambda_*^2 C_R - \lambda_*^3 C_D) = \frac{4}{27} C_R \left(\frac{C_R}{C_D}\right)^2,$$

which inserted into Eq. (1.7) results in the following limit for the available power, that we directly state in form of a theorem.

Theorem 1.1 (Power Limit of Airborne Wind Energy). *Let us regard a wing with area A and aerodynamic coefficients C_L and C_D that is moved in a wind field of constant wind speed v_w with air density ρ. When the wing's motion through this wind field is not only influenced by its intrinsic lift and drag, but also by additional drag forces, such as an on-board turbine with corresponding drag coefficient $C_{D,power}$ and by non-aerodynamic forces, such as a tether, then the total usable power P that can be harvested from the wind using these extra forces is limited by*

$$P \leq \frac{2}{27}\rho A v_w^3 C_R \left(\frac{C_R}{C_D}\right)^2 \quad \text{with} \quad C_R = C_L \sqrt{1 + \left(\frac{C_D + C_{D,power}}{C_L}\right)^2}. \tag{1.8}$$

This limit can be achieved if the total aerodynamic force is in line with the wind direction, if the wing drag is the only loss, and if the airspeed of the wing is made equal to

$$v_a = \frac{2C_R}{3C_D} v_w. \tag{1.9}$$

The formula in the theorem is a similar expression as the one derived by Loyd. The formula above gives, however, an upper limit that is true for any wing that is flying in any given wind field in any direction, and on which any other possible non-aerodynamic forces may act. It is thus a fundamental limit of how much useful power any flying body can extract from the wind field.

Remarks on the Airborne Wind Power Limit

A few remarks are in order to fully illuminate the conclusions from the above physical considerations:

- One astonishing observation is that at the optimal operational speed, two thirds of the wind power are dissipated in form of drag losses, and only one third harvested as usable power. This is due to the fact that we optimized not with respect to efficiency, but with respect to the maximum power that a given wing area could generate. Thus, an optimally operated AWE system does remove three times more power from the wind field than it harvests as usable power, i.e. $P_{wind} = 3P$.
- For high glide ratio $\frac{C_L}{C_D}$ and small extra drag, we have $C_R \approx C_L$, which is usually a good assumption for crosswind systems.
- In the optimal case, the airplane or kite is flying at a much higher velocity than the real wind, $v_a = \frac{2C_R}{3C_D} v_w$. This velocity is 2/3 of the maximal velocity that could be obtained by the tethered wing without energy extraction, which is given by $\frac{C_R}{C_D} v_w$. Drag and lift mode are different ways to achieve this speed reduction.

- Because the intrinsic gliding number $\frac{C_L}{C_D}$ enters the limit quadratically, it is an important quantity, and it is beneficial to have low drag coefficients C_D. Unfortunately, the tether drag can usually not be neglected, and forms part of the intrinsic drag. For very efficient airfoils, the tether drag can become the dominant drag contribution.
- The above limit is also valid for negative drag, i.e. for propellers that actually propel the airplane. Flying much faster – and thus presumably harvesting a larger area – will not allow us to harvest more wind power with a given wing area than the limit allows.

The Power Harvesting Factor ζ

It is interesting to compare the useful power P that a given wing with area A harvests from the wind field with the wind power P_{area} that flows through a cross sectional area of the same size, and which is given by

$$P_{\text{area}} = \frac{1}{2}\rho A v_{\text{w}}^3.$$

Let us define the ratio between the two as the *Power Harvesting Factor* ζ:

$$\zeta = \frac{P}{P_{\text{area}}} = \frac{P}{\frac{1}{2}\rho A v_{\text{w}}^3}. \tag{1.10}$$

For a given AWE system with wing area A, one can measure both the wind speed v_{w} as well as the generated electrical power P in order to determine the harvesting factor ζ. Due to the power limit of Theorem 1.1, we know, however, already an upper limit for ζ:

$$\zeta \leq \zeta_{\text{max}} = \frac{4}{27} C_R \left(\frac{C_R}{C_D}\right)^2. \tag{1.11}$$

For a tethered wing with $C_L = 1$ and $C_D = 0.07$ and no additional drag we have $C_R \approx C_L$ and $\zeta_{\text{max}} \approx 30$. This factor is not yet realized experimentally, but there is a race to achieve the highest possible zeta factors among the rigid wing AWE teams. The best experimentally realized harvesting factor so far is $\zeta = 8$ as reported by Makani Power in Chapter 28 of this book. Modern wind turbines have a zeta factor of approximately 5.5.

For flexible wings, the gliding number $\frac{C_L}{C_D}$ is typically much lower, and the power harvesting factors will typically be much lower. For example $C_L = 1$ and $C_D = 0.2$ result in a maximum possible harvesting factor of $\zeta_{\text{max}} \approx 4$. Of course, flexible wings might compensate their low zeta factors with lower costs per square meter of wing surface.

It is interesting to compare the power harvesting factor with the Betz limit, which limits the power that can be extracted from a given cross sectional area of the wind field. The Betz limit is given by $\frac{16}{27}$, and is nearly reached by existing wind turbines.

Thus, the number $\frac{27}{16}\zeta$ can be interpreted as the factor of how much more power a wing of area A can harvest compared to a wind turbine of swept area A.

For example, a power harvesting factor of $\zeta = 30$ for a high efficiency wing means that the wing with area A can extract as much power from the wind field as a wind turbine with a disc area of $\frac{27}{16}\zeta A \approx 51A$. Thus, if such a wing shall achieve the same power output as the largest existing wind turbine, the E-126 with 126 m rotor diameter and 12468 m^2 swept area, it needs a wing area of about $A = 250\text{m}^2$ e.g. a rigid wing of size 5 m times 50 m.

A Close Look at Different Ways to Generate Power

As discussed before, there are many different ways to generate power with wind driven, fast flying wings. All ways have in common, however, that they would optimally let the aircraft fly with a speed which is two thirds of the maximally possible speed, $\frac{C_R}{C_D}v_w$. One could reverse the logic and sloppily state that the main aim of power extraction is to bring the kite speed down to this value. Let us discuss in this light again the two standard ways, drag and lift mode, as well as possible combinations of them.

On-Board Generation, or Drag Mode First, one can keep the tether length constant and generate power by an on-board turbine. Because the optimal speed of the kite is $v_a = \frac{2C_R}{3C_D}v_w$, and because the ratios $\frac{v_a}{v_w}$ and $\frac{C_R}{(C_D+C_{D,\text{power}})}$ must be equal to ensure that the total aerodynamic force points exactly downwind, the optimally applied extra drag is easily found to be

$$C_{D,\text{power}} = \frac{1}{2}C_D.$$

This means that we use the on-board turbine to exactly increase the intrinsic system drag by 50%. It is interesting to note that, again, the power dissipated by drag is exactly two times the size of the harvested useful power.

Ground-Based Traction Power Generation, or Lift Mode Second, one can reel out the tether so that the airfoil is driven by relatively less wind. The optimal speed to reel out the tether is given by one third of the wind speed. The tethered aircraft then flies with its maximum speed relative to the remaining two thirds of the wind speed. As discussed before, the lift mode can be used for propulsion of ground vehicles or seagoing vessels, or for electricity generation. For ground based generation in pumping mode, it will easily be possible to operate the winch such that the reel-out speed is one third of the wind speed. For vehicle propulsion or for carousel based concepts, however, the reel-out speed is not a free parameter, and it could in principle be beneficial to combine lift and drag mode, in order to make optimal use of the wing.

Mixed Lift and Drag Mode for Vehicle Propulsion In particular when vehicles are propelled with airborne wind energy, there might be some interest in combining the two standards modes, i.e. to use both, a propeller on the airplane, and the traction effect of the cable. This might be useful when a vehicle is going downwind, but not at the optimal speed given by $\frac{1}{3}v_\mathrm{w}$. If the vehicle goes slower than this, an on-board turbine might be used to add the necessary extra drag to the airfoil, to obtain the optimal airspeed of $v_\mathrm{a} = \frac{2C_\mathrm{R}}{3C_\mathrm{D}}v_\mathrm{w}$, and to make the generated electrical energy useful in other ways. Conversely, if the vehicle goes faster than the optimal speed downwind, a propeller might be used to propel the wing, in order to optimally harvest the wind power. Though this leads to extra power consumption, it is the way that harvests the maximum amount of wind power with the given wing surface, and in theory, the on-board propulsion power could come from regenerative braking of the vehicle. It is interesting to note that this way – traction mode with on-board propulsion – even allows one to go faster than the wind, driven by wind power alone.

Conversely, when a vehicle shall drive against the wind, as for example done in *wind turbine races*, this can in theory also be achieved with airborne wind energy in either lift or drag mode or with a mix of both. Here, the harvested wind energy needs to be invested into vehicle propulsion, e.g. by means of a wheel drive or a marine propeller. If power losses within this extra propulsion system can be neglected, which might be the case on land but certainly not on water, the optimal solution will again be to ensure that the wing moves with its optimal speed, by suitable adaptation of either reel-out speed of the tether, or extra drag by an on-board turbine, or a suitable mix of both. In all cases, flying the wing with a speed of $v_\mathrm{a} = \frac{2C_\mathrm{R}}{3C_\mathrm{D}}v_\mathrm{w}$ will result in the maximum amount of power extracted from the wind field by the given wing.

1.5 Conclusions and Open Questions

This chapter has introduced the main concepts of airborne wind energy. In particular, the idea of *crosswind kite power* – i.e. when tethered wings fly fast in a crosswind direction – makes it possible to obtain very high power densities of theoretically up to 40 kW per m^2 wing area. This power can be harvested in many ways, most importantly by periodically pulling a ground based generator in *pumping mode*, or by using *on-board generation*, i.e. a small airborne wind turbine that is driven by the apparent wind at the wing. We derived a variant of Loyd's formula that forms a fundamental limit on the wind power that any given wing can generate in a wind field. The power maximum is reached when the wing drag dissipates twice as much power as is generated, and when the aerodynamic force of the wing is parallel to the wind direction. The latter is usually not possible because some tether elevation is needed to reach high altitudes; the resulting *cosine losses* are fortunately very small for elevation angles below 30 degrees.

Technological challenges for airborne wind energy that are currently addressed by a multitude of research teams are (i) automated and cost efficient ways for start and landing, (ii) automatic control of the flying system in all wind and weather conditions, (iii) wings that are light, durable, and not too expensive, and (iv) tethers that survive many duty cycles of varying load, for ground-based systems, or tethers and on-board power electronics that allow to transmit high voltage electrical power, for on-board generation. Also, it is still an open question which single AWE system sizes would be most economical: any size between 40 kW and 40 MW seems possible, where the 40 MW system would need a wing with a span of about 100 m but would suffer relatively little from tether drag. A limiting factor for large airborne systems will be the square-cube law, namely the fact that the wing area scales quadratically with the length scale, while the mass scales cubically. An important other question that has not yet been fully answered is the amount of wind power that can be generated on a given ground surface area in case of large scale wind farms, which was estimated by MacKay[10] to be only 2 MW per km^2 for conventional wind turbine parks. This number might be larger for airborne wind energy systems, due to the fact that they can reach higher altitudes with stronger and more consistent winds, and because they might be flown at more than one altitude in order to maximize the power output on a given - but finite - land or sea area.

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