Green Energy and Technology

Uwe Ahrens
Moritz Diehl
Roland Schmehl *Editors*

Airborne Wind Energy

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Airborne Wind Energy

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ISSN 1865-3529 ISSN 1865-3537 (electronic)
ISBN 978-3-642-39964-0 ISBN 978-3-642-39965-7 (eBook)
DOI 10.1007/978-3-642-39965-7
Springer Heidelberg New York Dordrecht London

Library of Congress Control Number: 2013947816

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

To Corwin Hardham, 1974-2012
Pioneer of Airborne Wind Energy

Foreword

This book provides an excellent overview of the field of airborne wind energy. For someone starting to explore wind power in the upper atmosphere, the basics are now available in a single source. There are gaps in the knowledge, but those are where opportunities are.

Back in the 1970's, when I was investigating the ideas that eventually led to my paper "Crosswind Kite Power" (Journal of energy 4(3), pp. 106–111, 1980), my knowledge of the field consisted of George Pocock's book describing early 19th century kite-drawn carriages. In searching the literature I found Payne and McCutchen's 1975 patent for power generation using kites. My home computer at the time was a kit-built Sol 20 with 64 kilobytes of memory. At that time, funding for research into large-scale airborne wind energy production was non-existent.

In comparison to those days, the current state of the field is truly inspiring. Seeing the great variety of hardware that is working today is especially rewarding. I am pleased that Makani has chosen to follow the ideas for generating power by using drag power, or adding drag to the kite in the form of wind turbines, much as I discussed in my paper. With many new materials and resources, they have gone far beyond what I suggested.

When I was planning "Crosswind Kite Power", I was torn between using lift power, in which the lift of the kite pulls a load on the ground, or drag power, as the primary example for the paper. Although, at that time I was somewhat biased toward using lift power for small applications that could be more easily implemented and could be scaled to larger sizes, I decided to use an example of drag power because the lift power calculations would have required more computer power than I had available. I am delighted to see that this book provides several examples of each approach to power generation.

We are fortunate to have this compendium of information in one place. I congratulate the editors on their vision and work.

Livermore, California, June 2013 *Miles Loyd*

Preface

Dear readers,

this book is a collection of selected articles on airborne wind energy, a renewable energy technology that uses airborne devices to harness the power of the wind. Motivated by the aim to make the world less dependent on fossil energy sources, this technology is currently under investigation by researchers at start-up companies and universities. These researchers are all driven by the conviction that airborne wind energy systems have the potential to substantially contribute to the generation of cost-competitive renewable energy in the years to come, complementing other renewable energy systems.

The motivation for editing this book was that we felt a strong need for a monograph that combines and presents the many existing and exciting results from the researchers working in the field. Before this book, several authors had already written important scientific publications related to airborne wind energy, but these were scattered in diverse research journals, each with a different scope. A unified presentation of the topic was missing.

We are very happy that the present book contains reviewed articles from most of the many scientists that made important contributions to the field. In this book, they present their newest findings or make previous results more accessible to the public. We are equally happy that we succeeded in convincing nearly all start-up companies in the field to present some of their research results to the public, despite the fact that they need to protect their intellectual property. These authors present their research results in a form that allows the reader to get an understanding of the current industrial state-of-the-art of the technology, and even to draw some comparisons between the realized concepts.

One of the aims of the book is to further deepen the scientific exchange and mutual interactions within the young and vibrant airborne wind energy community. Let us in the following first give a short historical perspective on airborne wind energy, and then describe the organization of the review process and the contents of the book in more detail.

A historical perspective on airborne wind energy

The idea to use airborne devices, in particular kites, for generation of usable power dates back many centuries; most ancient civilizations knew how to fly kites, and occasionally people used them to pull loads on the ground, like carriages or ships. Probably the first dedicated research volume on the topic appears in 1827, when George Pocock publishes the book "The Aeropleustic Art or Navigation in the Air by the use of Kites, or Buoyant Sails" and experiments successfully with carriages driven by kites, which he calls *charvolant*.

However, for much over a century, most energy related innovations are related to coal and petrol; it is only during the energy crisis of the 1970s that a strong interest in non-fossil power sources arises again. This also includes airborne wind energy and, astonishingly, already in 1975 appears a patent by Payne and Mc Cutchen on the "Self-Erecting Windmill" which contains nearly all concepts of airborne wind energy for electric power generation, including on-board wind turbines and even a dual plane system. Four years later, in 1979, the Australian engineer Bryan Roberts performs first experiments towards the exploitation of high altitude wind power by devices that he calls the *flying electric generators*.

A seminal contribution to the field appears in 1980, when the American engineer Miles Loyd publishes his article "Crosswind Kite Power" and with it lays the foundation for a quantitative analysis of airborne wind power systems. Loyd also patents a crosswind system that uses on-board wind turbines which transmit their power via three moving tethers to the ground. In the two decades from 1980 to 2000, airborne wind energy remains nearly stagnant, while the ground-based, conventional wind power technology develops tremendously and establishes a de-facto standard with the three-bladed Danish wind turbine.

However, with the advent of new tether and control technologies, airborne wind energy research starts to accelerate again at the turn of the century, as illustrated in Fig. 1. In 1997, the Dutch astronaut and university professor Wubbo Ockels patents

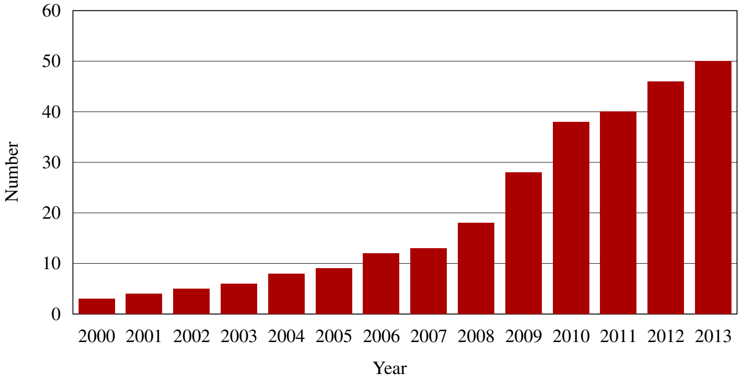

Fig. 1 Number of institutions actively involved in airborne wind energy (data 2000-2011 contributed by Allister Furey)

the concept of the Laddermill, a series of multiple stacked kites driving a generator on the ground, and starts to investigate flexible wing systems in pumping mode with his team at Delft University of Technology. In 2001, the company SkySails is founded in Germany, and develops the first commercial kite system for ship traction. A large-scale variant is experimentally demonstrated and flown automatically a few years later on cargo ships.

In 2005, a high altitude wind power (HAWP) conference was held at AeroVironment in California, while in 2006, the company Makani Power is founded in California, with substantial funds by google. Initially working on flexible pumping kite concepts, the focus is later shifted to rigid wings with on-board generation. Simultaneously, the companies WindLift in the US and NTS in Germany are founded, and the KiteGen project in Italy realizes a pumping kite power system based on a dual line surf kite. In 2007, an international workshop on "modelling and optimization of power generating kites" is held at KU Leuven, Belgium, and a variety of research papers on the control of airborne wind energy systems appear.

In 2008, the start-up company Joby Energy is founded in California, and helps to create the Airborne Wind Energy Consortium (AWEC). The idea to form the AWEC emerges in 2009, when a high-altitude wind power conference is held in Chico, California. In 2010, the first Airborne Wind Energy Conference (AWEC 2010) is held in Stanford. From then on, there is one annual international conference, alternating

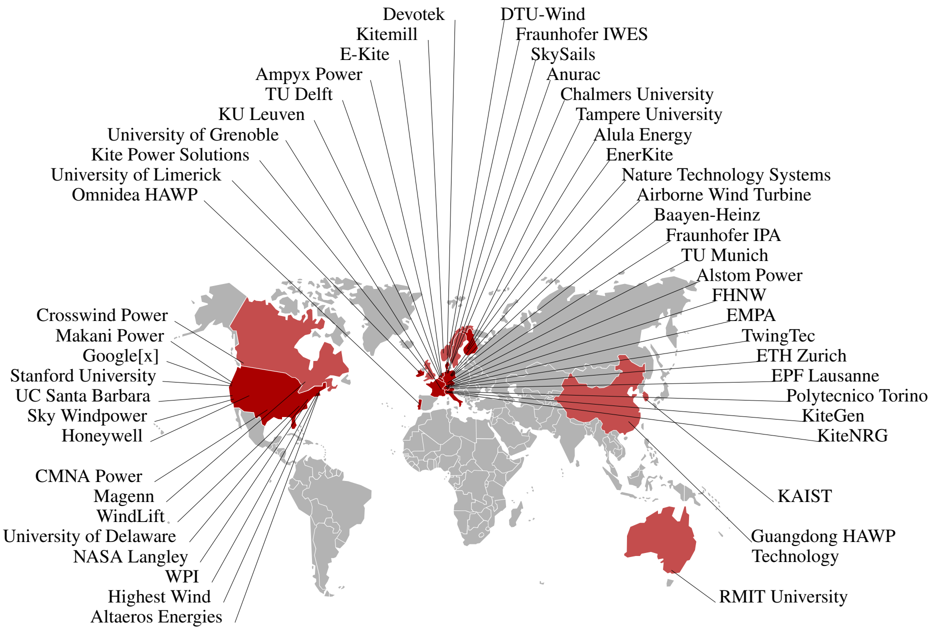

Fig. 2 Airborne wind energy research and development activities by country and by team. Countries with academic or commercial activities in 2013 are colored in red, while dark red indicates that one or more authors from this country contributed to this book.

between the US and Europe. The second conference in this series takes place 2011 in Leuven (AWEC 2011) and the companies Makani Power and SkySails demonstrate fully automatic flight including start and landing.

In 2012, the third conference takes place in Virginia (AWEC 2012). In the same year, Corwin Hardham, CEO of Makani, dies unexpectedly, to the regret of the whole AWE community. In spring 2013, Makani Power is acquired by Google[X], the secretive division of Google dedicated to futuristic long-shot projects, and in autumn 2013 the fourth conference is held in Berlin (AWEC 2013). Also in 2013, the first monograph on "Airborne Wind Energy" is published by Springer Verlag in form of the present book.

Fig. 2 maps the worldwide commercial and academic research and development activities on Airborne Wind Energy in 2013, and also shows the many teams that have contributed to this volume.

About this book

The present book consists of 35 independently written chapters and is the work of many people. Each of the submitted articles underwent a rigorous review process with at least two and up to four reviews per submitted article, and with two consecutive review rounds for the majority of the articles. Altogether, 44 articles were submitted, and 62 reviewers helped to ensure and improve their quality. The names of the reviewers are listed in the following section and we express our thanks for their fast, competent and constructive reviews. To keep the review process as anonymous and impartial as possible, the three editors distributed the submitted articles among each other, each organizing the review process for one subset of articles independently. We did not disclose the names of each article's reviewers to each other, and articles in which one of the editors was directly or indirectly involved were handled by another editor.

We have ordered the chapters into five parts. Part I on "Fundamentals" contains seven general articles explaining the principles of airborne wind energy and its different variants, of meteorology, the history of kites, and financing strategies. Part II on "System Modeling, Optimization and Control" contains eight articles that develop and use detailed dynamic models for simulation, optimization, and control of airborne wind energy systems, while Part III on "Analysis of Flexible Kite Dynamics" collects four articles that focus on the particularly challenging simulation problems related to flexible kites. Part IV "Implemented Concepts" contains eleven articles each of which presents developed prototypes together with real-world experimental results obtained with the different concepts. Finally, in Part V on "Component Design", five articles are collected that address in detail the technical challenges for some of the components of airborne wind energy.

We hope that the present book will serve as a reference to academic and industrial practitioners of airborne wind energy and will allow the interested public to assess the current state-of-the-art of the different implemented concepts. Most important, we do hope that reading the book will be as entertaining and interesting for the general reader as it was for us in the role of editors.

Berlin, *Uwe Ahrens*
Leuven, *Moritz Diehl*
Delft, *Roland Schmehl*
June 2013

Acknowledgements

The present book would not have been possible without the support and careful work of reviewers selected from the international scientific community. The quality of any peer-reviewed scientific book is largely due to the will of reviewers to share their expertise and knowledge with colleagues from all over the world. As a minor token of the editors' appreciation for their diligence and work, the names of all reviewers for this book are listed hereafter:

Hammad Ahmad, University of Limerick, Ireland
Mazen Alamir, Grenoble Institute of Technology, France
William Anderson, Advance AG, Switzerland
Ivan Argatov, University of Oulu, Finland
Jorn Baayen, Baayen & Heinz GmbH, Germany
Tommi Berg, Alula Energy Oy, Finland
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Uwe Fechner, Delft University of Technology, Netherlands
Falko Fritz, SkySails GmbH, Germany
Allister Furey, Kite Power Solutions Ltd, Great Britain
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Sebastien Gros, Chalmers University of Technology, Sweden
Ahmad Hably, Grenoble Institute of Technology, France

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Michiel Kruijff, European Space Agency, Netherlands
Patrick Lauffs, Technical University Munich, Germany
Damon Vander Lind, Makani Power, U.S.A.
Rolf Luchsinger, Empa - Center for Synergetic Structures, Switzerland
Guido Lütsch, BHWE Bundesverband Höhenwindenergie e.V., Germany
Jochen Maass, Hamburg University of Applied Sciences, Germany
Johan Meyers, University of Leuven, Belgium
Mario Milanese, KitEnergy S.r.l., Italy
David Olinger, Worcester Polytechnic Institute, U.S.A.
Reinhart Paelinck, Flysurfer Skywalk GmbH & Co. KG, Germany
Xaver Paulig, SkySails GmbH, Germany
Alexander Podgaets, Novomet, Russia
Chris Purvis, NorthLight Power, U.S.A.
PJ Shepard, Airborne Wind Energy Consortium, U.S.A.
Soeren Sieberling, Ampyx Power, Netherlands
Bernd Specht, SkySails GmbH, Germany
Hans Strauch, Astrium Space Transportation, Germany
Matthias Stripf, Karlsruhe University of Applied Sciences, Germany
Franz Stuber, Münster University of Applied Sciences, Germany
Paolo Tiso, Delft University of Technolgy, Netherlands
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Rolf van der Vlugt, Delft University of Technology, Netherlands
Milan Vukov, University of Leuven, Belgium
Andrew Wagner, University of Leuven, Belgium
Mario Zanon, University of Leuven, Belgium
Aldo Zgraggen, Swiss Federal Institute of Technology Zurich, Switzerland
Udo Zillmann, Daidalos Capital GmbH, Germany

Also appreciated is the contribution of the editorial assistants, Filip Saad and Frerik Andriessen, both from Delft University of Technology. Financial support by the European Research Council (ERC) via the Project HIGHWIND is gratefully acknowledged.

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Nomenclature

a	acceleration [m/s^2]
A	surface area [m^2]
AR	aspect ratio
c_a	availability factor
c_f	capacity factor
B	magnetic field [mGauss]
C_D	aerodynamic drag coefficient
C_L	aerodynamic lift coefficient
C_M	aerodynamic moment coefficient
CF	crest factor
d	diameter [m]
D	duty cycle
D or F_D	aerodynamic drag force [N]
E	energy [J]
E	elastic modulus [N/m^2]
f	frequency [1/s]
f	reeling factor
$\mathbf{F}_a$	resultant aerodynamic force [N]
F_D or D	aerodynamic drag force [N]
F_L or L	aerodynamic lift force [N]
$\mathbf{g}$	gravitational acceleration [m/s^2]
h	altitude above ground [m]
I	electrical current [A]
I	moment of inertia [kg m^2]
L	power losses [W]
L or F_L	aerodynamic lift force [N]
l	length [m]
$\mathbf{M}_a$	aerodynamic moment [Nm]
m	mass [kg]
$\mathbf{n}$	normal vector
p	static pressure [N/m^2]

P	power [W]
r	radius [m]
$\mathbf{r}$	position [m]
S	surface area [m^2]
S	safety factor
t	time [s]
T	temperature [K]
T or F_t	tether force [N]
$\mathbf{u}$	control vector
U	electrical voltage [V]
$\mathbf{u}$	control vector
v	velocity [m/s]
v_a	apparent wind velocity [m/s]
v_w	wind velocity [m/s]
v_∞	freestream or upstream velocity [m/s]
$\mathbf{x}$	state vector
α	angle of attack [rad]
β	elevation angle [rad]
γ	flight path angle [rad]
ζ	power factor
η	efficiency
κ	camber
λ	crosswind factor
μ	coefficient of viscous friction [Nms]
μ	dynamic viscosity [Ns/m^2]
ν	kinematic viscosity [m^2/s]
ρ	air density [kg/m^3]
τ	torque [Nm]
τ_μ	friction torque [Nm]
ω	angular velocity [rad/s]

Subscripts

a	apparent
c	cycle
e	electrical
f	force
g	ground
i	reel-in
k	kite
m	mechanical
p	pumping
o	reel-out

r	radial
t	tether
v	velocity
w	wind
τ	tangential

Coordinates and rotation sets

P, Q, R	roll, pitch, yaw angular velocities [1/s]
r, θ, ϕ	radial distance, polar/elevation angle, and azimuthal angle [rad]
x, y, z	Cartesian coordinates [m]
ϕ, θ, ψ	roll, pitch, yaw angles [rad]

Part I
Fundamentals

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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U. Ahrens et al. (eds.), *Airborne Wind Energy,* Green Energy and Technology,
DOI: 10.1007/978-3-642-39965-7_1, © Springer-Verlag Berlin Heidelberg 2013

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.

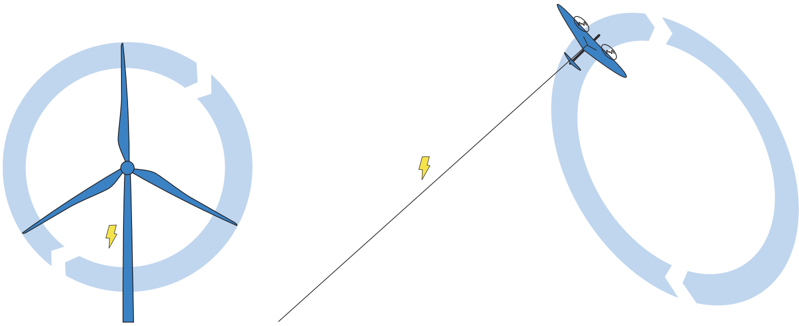

Fig. 1.1 AWE systems replace the tips of a wind turbine (left) with a tethered fast flying wing (right, operating in drag mode). Illustration by R. Paelinck.

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

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

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

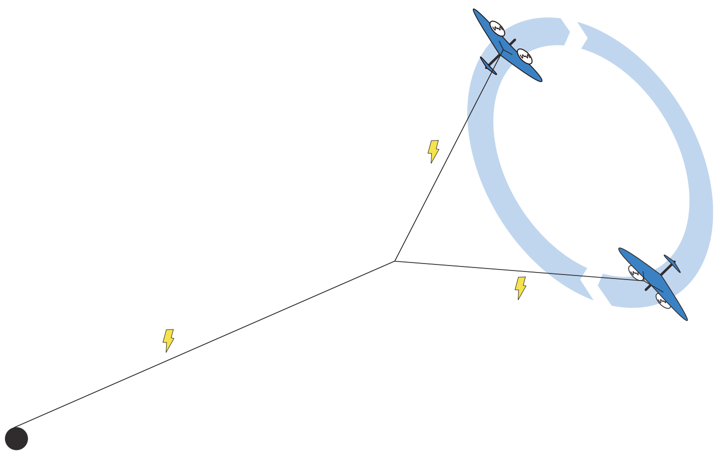

Fig. 1.3 Visualization of a dual airplane system with reduced tether drag. Illustration by R. Paelinck.

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 pro-