Green Energy and Technology

Uwe Ahrens

Airborne Wind Energy

An Overview of the Technological Approaches

Springer

Green Energy and Technology

Climate change, environmental impact and the limited natural resources urge scientific research and novel technical solutions. The monograph series Green Energy and Technology serves as a publishing platform for scientific and technological approaches to “green”—i.e. environmentally friendly and sustainable—technologies. While a focus lies on energy and power supply, it also covers “green” solutions in industrial engineering and engineering design. Green Energy and Technology addresses researchers, advanced students, technical consultants as well as decision makers in industries and politics. Hence, the level of presentation spans from instructional to highly technical.

Indexed in Scopus.

Indexed in Ei Compendex.

Uwe Ahrens

Airborne Wind Energy

An Overview of the Technological Approaches

Foreword by Markus Hecht

Springer

Uwe Ahrens
aap GmbH
Berlin, Germany

ISSN 1865-3529 ISSN 1865-3537 (electronic)
Green Energy and Technology
ISBN 978-3-031-19953-0 ISBN 978-3-031-19954-7 (eBook)
https://doi.org/10.1007/978-3-031-19954-7

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Foreword

Substitution of fossil energy by green energy becomes more and more urgent for many reasons; slowing down climate change and reducing income for inhuman regimes are the main incentives.

The classical green energy sources such as hydroenergy, wind energy by turbines and solar energy are supported by politics but economic and ecological constraints are hindering a sufficiently fast growth of installations and by this fossil energy is still dominating with all the negative consequences. The very promising change is possible through Airborne Wind Energy. The reachable gain of energy is tremendous, in the Megawatt range per installation. The undesired implications are nearly neglectable.

With the huge yield also the use of electric energy for heating or hydrogen generation or synthetic fuel is again a conceivable option.

Regarding the implications, small land consumption, neglectable noise effects and friendliness to birds and other wildlife are evident for Airborne Wind Energy.

Hopefully this book will support that the good expectations will be realized soon. Time is urgent and many details cannot be optimized by theory but by experience only. This experience must be gained by realization. Teething problems are an unavoidable challenge with every novelty. But as many elements as automatic control, power electronics, lightweight materials and even the wheel rail contact made significant progress in knowledge and optimization methods in recent years' time, it is mature now to start the large-scale realization of Airborne Wind Energy.

July 2022

Prof. Dr.-Ing. Markus Hecht
Technische Universität Berlin
Berlin, Germany

Preface

Airborne Wind Energy (AWE) Technologies Harvest Electricity from the Sky!

Ensure 100% power supply in Europe with 1% of its land area.[1] That is the potential of Wind and Airborne Wind technology![2]

> There is enough energy in high-altitude wind to power civilization 100 times over.

And how this can happen in concrete terms is shown in this book. It presents the most important systems for the use of Airborne Wind energy (or Airborne Wind Technology). It does not claim to be complete in every respect and is rather to be understood as an atlas of this still-young technology. The motivation for writing this book is that most countries in the world want to switch to renewable energy sources as part of their climate policy.

Energy is a scarce commodity. It must be available at all times and at prices that are affordable for the individual and, if possible, provide a competitive advantage for the national economy. Today, sustainability, especially freedom from CO_2 emissions, and geopolitical harmlessness are indispensable secondary conditions. The use of wind energy can achieve all of these. Its economic viability is determined by high output and constant availability. Here, Airborne Wind technology has a clear comparative advantage over other systems. Economists should study it intensively.

And, to state it clearly in advance, we need much more affordable renewable energy in all forms as soon as possible. This is also because we are currently painfully aware of how dependent we still are on energy imports and how much this dependence affects us personally, but also economically. This book is only intended to show that

[1] Europe [3].

[2] *Source* Prof. Ken Caldeira—Department of Global Ecology, Carnegie Institution for Science, Stanford University.

the use of high-altitude winds is an additional and important energy source that offers enormous economic and ecological advantages, just as the existing CO_2-free energy sources already do.

In the following, the basic considerations, as well as advantages and disadvantages, partly also in comparison with established methods, of the respective Airborne Wind turbine methods are explained.

It will be shown that Airborne Wind technologies are a true innovation and are about as different from traditional wind power as a fuel cell engine is from a gasoline engine. In principle, they have many competitive advantages over renewable but also fossil energy sources already in large-scale use and established.

Quote from US Department of Energy November 2021, under the title: "Message from the Secretary"[3]:

"Challenges and Opportunities for Airborne Wind Energy in the United States.

Designs for AWE systems to date are diverse and largely experimental. To date, there is little agreement on a preferred technology or approach, and no megawatt-scale AWE systems have been commercially deployed. Several AWE concepts under development show promise." End quote.

Why this statement is no longer correct, they learn in this book. Thus, it underlines the necessity of this book quite particularly.

After reading this book, you can form your own opinion about which AWE concepts are the most promising.

Motive

In 2022, over 80% of the world's energy needs will still be met by fossil fuels.[4,5]

Whether CO_2 emissions are solely responsible for climate change is still a matter of debate.[6]

What is indisputable, however, is the fact that our fossil fuels and our resources are finite.

Therefore, in my opinion, the use of Airborne Wind technology is inevitably scientifically proven and easy to understand.

I have given the respective companies of the individual technologies to revise the contents for the presentation of their respective technology or to enter their current data and information themselves. Therefore, this book is quasi already peer reviewed. In the cases where the companies did not comment, these areas have been researched or estimated and color-coded by me.

---

[3] US Department of Energy, Washington [5].

[4] Statista: Anteil Erneuerbarer Energien am weltweiten Primärenergieverbrauch in den Jahren 1990 bis 2019 [4].

[5] aap GmbH [1].

[6] EIKE "Nicht das Klima ist bedroht, sondern unsere Freiheit" [2].

This symbol is an indication that the marked statements are particularly important.

Quick Note on Gendering

I am the father of two daughters, who are also the real catalyst for my decades of work in the field of Airborne Wind energy.

I have learned a lot from them in recent years, especially with regard to gender-inclusive language. I would like to note here that I am very much in favor of inclusive language and apologize in advance, however, if any exclusionary wording has slipped through my fingers. This is in no way my intention.

And, very important! By the end of this book, you may wonder why we haven't been generating our energy using Airborne Wind technologies for a long time?

You will find some arguments and reasons in the economic aspects section.

Berlin, Germany Uwe Ahrens

References

1. aap GmbH, A. U. (2022). Hochrechnungen und Fakten zu AWE III. *Datensammlungen (2022-02-12 Basisdaten Springerbuch III).* Berlin, Germany: aap GmbH. Abgerufen am April 2022
2. EIKE "Nicht das Klima ist bedroht, sondern unsere Freiheit". (2022). Von It is not the climate that is threatened, but our freedom: https://eike-klima-energie.eu/ abgerufen
3. Europe, A. W. (2020). *Airborne Wind Energy – eine aufstrebende Technologie.*
4. Statista: Anteil Erneuerbarer Energien am weltweiten Primärenergieverbrauch in den Jahren 1990 bis 2019. (2022). Von https://de.statista.com/statistik/daten/studie/153867/umfrage/anteil-erneuerbarer-energien-am-energieverbrauch-weltweit-seit-1990/#:~:text=Die%20Statistik%20bildet%20den%20Anteil,8%20Prozent%20am%20globalen%20Prim%C3%A4renergieverbrauch. abgerufen
5. US Department of Energy, Washington. (2021). Von Message from the Secretary: chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/viewer.html?pdfurl=https%3A%2F%2Fairbornewindeurope.org%2Fwp-content%2Fuploads%2F2021%2F12%2Freport-to-congress-challenges-opportunities-airborne-wind-energy-united-states.pdf&clen=1436333&chunk=trueabgerufen

Contents

Chapter 1
Introduction

Researchers, developers, entrepreneurs and enthusiasts around the world are working on developing the use of the much more energetic high-altitude winds (see Fig. 1.1). The book focuses primarily on presenting the various possibilities for energy harvesting. Some of the approaches presented below are currently no longer being pursued because the companies lacked the funding to implement them. Some of the companies have therefore disappeared from the market, and others are currently struggling to survive with crowdfunding campaigns. I have deliberately refrained from identifying the financing situation of the respective companies, because from my point of view all approaches should be pursued and financed as long as we do not have enough CO_2-free electricity. Because all high altitude wind technological approaches have one thing in common:

They are base-load capable or have very long delivery times.

Since the publication of the Club of Rome's "Limits to Growth"[1] in 1972 at the latest, we have known that we have to treat the earth much more carefully. And humankind has already achieved important things, if we consider the management of the ozone hole in the ozone layer and the fight against forest dieback. In doing so, we have only fought or are fighting two developments that threaten our existence and are caused by humans. But for years now, we have been feeling the experts' forecasts in our own bodies and in most regions of the world through heat waves at

[1] Club of Rome [1].

U. Ahrens, *Airborne Wind Energy*, Green Energy and Technology,
https://doi.org/10.1007/978-3-031-19954-7_1

Fig. 1.1 Mapping of current and previous technology developers (Worldwide player)

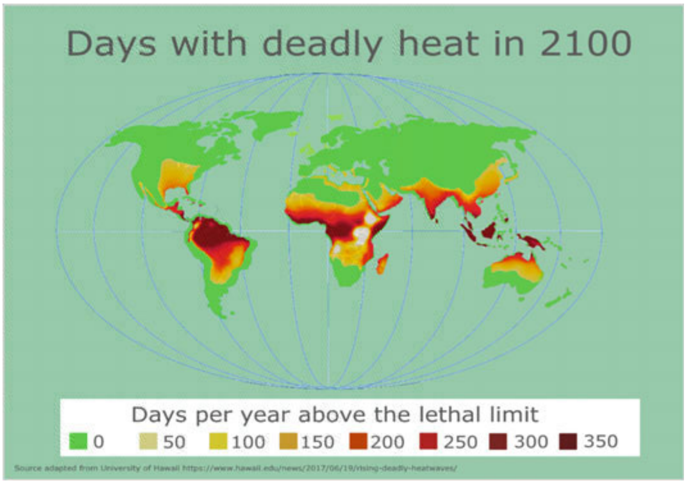


Fig. 1.2 Prognosis for days with deadly heat

ever shorter intervals and ever greater temporal extensions. The European heat wave of 2003 claimed 70,000 lives (7,000 of them in Germany alone).[2]

If you extrapolate this figure to a year, more people died in these few days than the previous Corona pandemic claimed in victims.

A study by the University of Hawaii[3] paints a bleak prognosis (see Fig. 1.2) if we continue to do business as usual.

At the same time, however, they also show that we can prevent the worst from happening if we sharply curb emissions.

---

[2] DW: Immer mehr tödliche Hitzewellen [2].

[3] University of Hawaii [3].

This book will show how high-altitude wind technologies can contribute to this necessary mitigation.

The biggest problem of the energy transition is the insufficient baseload capacity of the main sources of renewable energy.

We are in a situation where we are deploying all possible sources of zero-emission energy as fast as we can. There are many approaches and the high-altitude wind technologies presented in the following can, as well-foundedly proven in this book, make a significant contribution to stopping climate change, or at least effectively slowing it down, mainly due to their high full-load hours, low consumption of resources and their gentle treatment of the environment. And they do so with a very attractive cost structure.

1.1 Historical Overview

Many technologies are based on a long historical development. Airborne Wind technologies are very recent ideas, but in principle an innovative combination of thousands of years of experience.[4] The first kites are reported as early as the 5th century BC. However, recent finds in the Indonesian area leave open the possibility that kites as flying objects could be much older. The use of boards for surfing has been demonstrated as early as 200 AD.[5] It was not until 1970 that the first combinations of surfboards with kites were reported.[6] In this respect, it is hardly surprising that the first attempts to use the gigantic wind potential at higher altitudes were not launched until the beginning of 2000.

References

1. *Club of Rome* (2022). https://de.wikipedia.org/wiki/Club_of_Rome
2. *DW: Immer mehr tödliche Hitzewellen* (2017). https://www.dw.com/de/immer-mehr-t%C3%B6dliche-hitzewellen-weltweit/a-39350778

[4] Wikipedia, Drachen [4].

[5] Wikipedia, History of surfing [5].

[6] Wikipedia, Kitesurfen [6].

3. *University of Hawaii* (2017). https://www.hawaii.edu/news/2017/06/19/rising-deadly-heatwaves/
4. *Wikipedia, Drachen* (2022). https://de.wikipedia.org/wiki/Drachen
5. *Wikipedia, History of surfing* (2022). https://en.wikipedia.org/wiki/History_of_surfing
6. *Wikipedia, Kitesurfen* (2022). https://de.wikipedia.org/wiki/Kitesurfen

Chapter 2
Basic Differences of Wind Utilization Concepts

The first prerequisite for harvesting wind energy is a body of resistance shaped in such a way that it is capable of converting the kinetic energy of the air particles into a force. How this works with today's conventional wind energy is explained in the next chapter. Of course, it is conceivable to build the towers higher and higher in order to be able to harvest energy in the laminar Airborne Wind ranges with conventional wind power as well. However, tower costs increase and the rotor blades enter the bending range due to the ever larger diameters (fiber composite materials are very well suited for tensile loads but not for bending) and must also be disproportionately reinforced. This reduces the economic efficiency.

Therefore, in order to harvest the Airborne Wind energy, flying machines make much more sense.

Here is the basic structure of the conceivable approaches (see Fig. 2.1).

This is only a very rough structure. In fact, aviation has developed a great many options in the meantime. For altitude winch harvesters, this opens up a great many more approaches, since all the aircraft shown in the following diagram (Fig. 2.2) are suitable.

By eliminating the tower and rotor blades and using tethering, there are several ways to convert the enormous Airborne Wind energy into other forms of energy.

U. Ahrens, *Airborne Wind Energy*, Green Energy and Technology,
https://doi.org/10.1007/978-3-031-19954-7_2

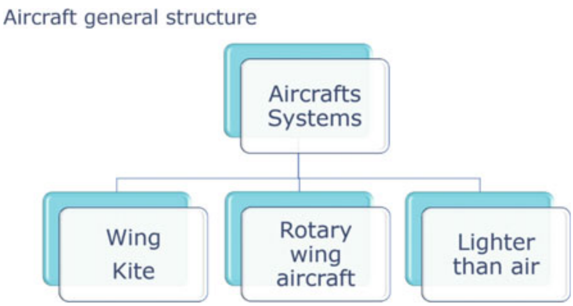


Fig. 2.1 Structure of aircrafts

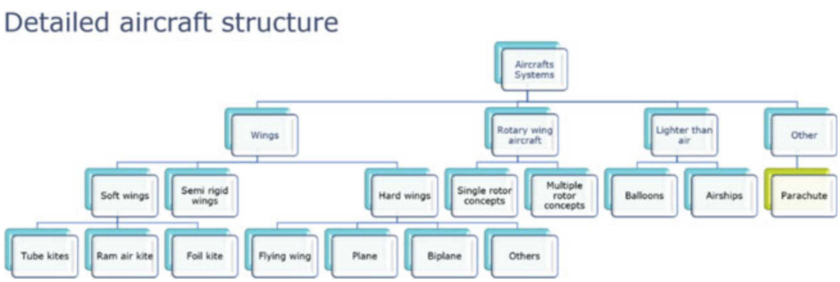


Fig. 2.2 Detailed structure of aircrafts

2.1 Technologies Structure

There are essentially 3 approaches (Fig. 2.3).

Stationary generators

These use the lift force of the flying machines to provide torque for power generation (so-called yo-yo concepts).

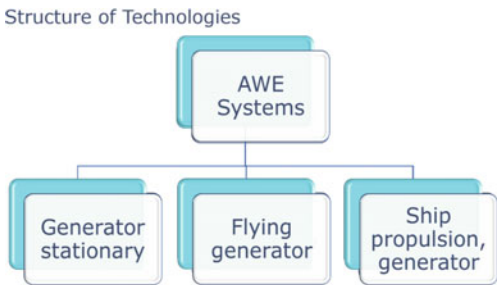


Fig. 2.3 Structure of Airborne Wind energy technologies

Flying generators

In this operation, generators equipped with propellers are mounted on aircraft. These are controlled by Airborne Wind power so that the propellers provide torque to generate electricity.

Flying devices for horizontal force generation

These use the lift force to pull ships or movable generators (e.g. electric locomotives) with the resulting horizontal force.

Let us start with the most commonly used concepts, stationary generators (Fig. 2.4).

In addition to the different forms of converting the Airborne Wind energy, there are also different approaches to generating the lift force. First and foremost is the so-called YoYo approach. With this harvesting technology, the flying machines move either in the form of a lemniscate, in a circular trajectory or along a straight line.

Different flight paths are shown in (Fig. 2.5).

The two main applications of the YoYo concepts are shown in Fig. 2.6 (hard kite or soft kite).

The different harvesting methods of the YoYo concepts are shown in Fig. 2.7.

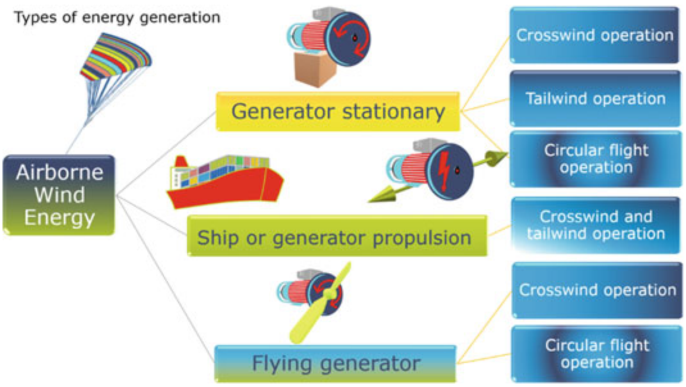
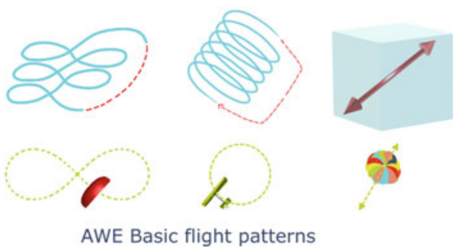


Fig. 2.4 Types of energy generation

Fig. 2.5 AWE basic fligt patterns



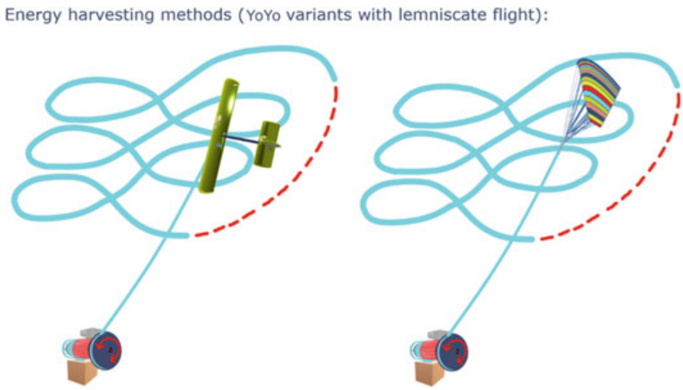


Fig. 2.6 YoYo flight concept with lemniscate path

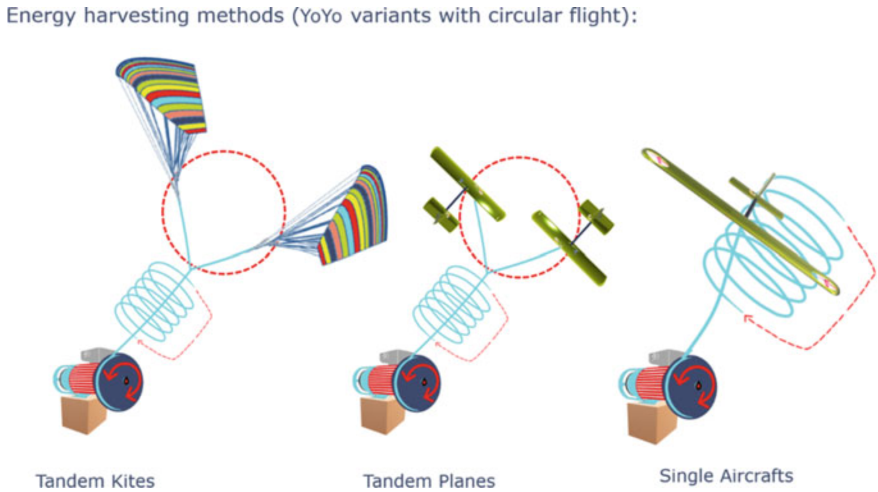


Fig. 2.7 YoYo flight concept with circular path

In the previous two pictures, the dynamic forms of use are shown. In the following picture, the Chinese approach along a straight trajectory is explained.

This idea uses parachutes, rather than flying bodies, to function as drag bodies in the wind. When the top dead center is reached, the parachutes are made to collapse so that they can then be wound up with low air resistance. At bottom dead center, the chutes are allowed to unfold again. And the process starts all over again.

When using the other flight paths, a rope is gradually unwound from a drum. The resulting torque is used to drive a generator. Once the rope is completely unwound (top dead center), the aircraft is controlled to return to the starting point of the yo-yo phase. In this process, the rope is wound up with much less effort. After that, the power generation process starts all over again (Fig. 2.8).

The second main group is the flying generators.

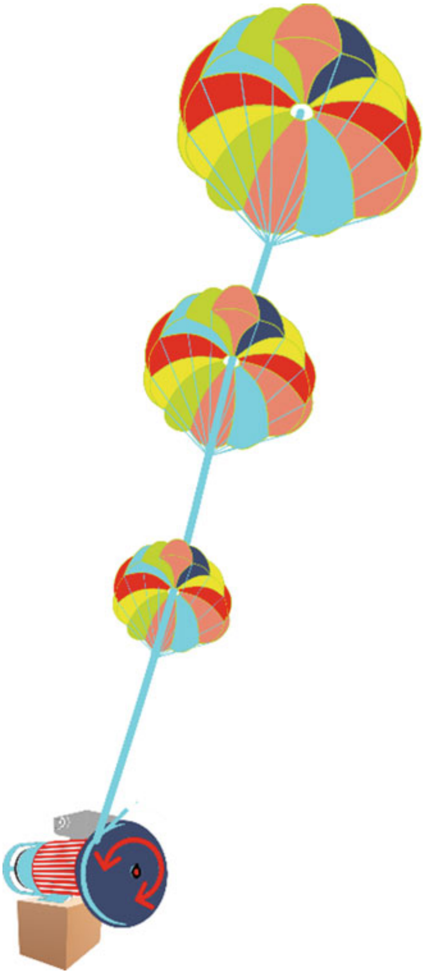


Fig. 2.8 Static use AWE with linear flight track

This primarily means that the generators are taken aloft and the electricity produced is transmitted to the ground via cables in the tethers.

The most common approach uses airfoils on which generators with propellers are mounted. In production mode, the propellers are in push or pull mode (when mounted on the back).

The designs are different and are shown graphically in the following pictures.

The cable connection means that the generators can also be used as engines, allowing fully automatic take-offs and landings.

Makani, one of the first companies in the development of AWE harvesters,[i] is based on a carbon fiber composite aircraft with 8 generators (Fig. 2.9).

Kitekraft uses a twin hull missile which is also equipped with 8 generators and uses the lemniscate as a flight path (Fig. 2.10).

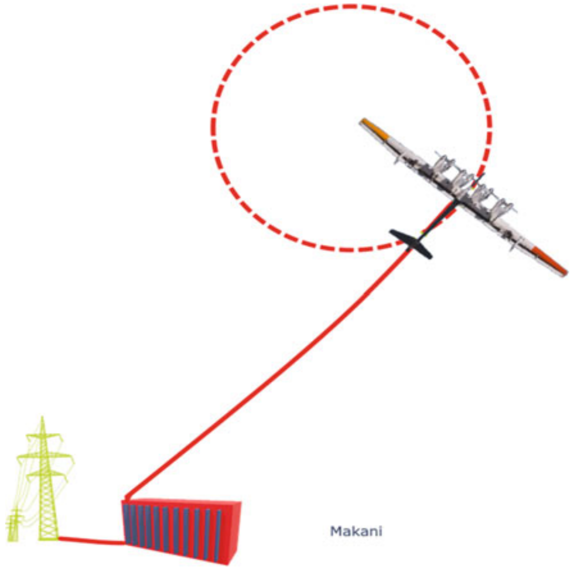


Fig. 2.9 Makani and Windlift concept with pressure propellers in production mode

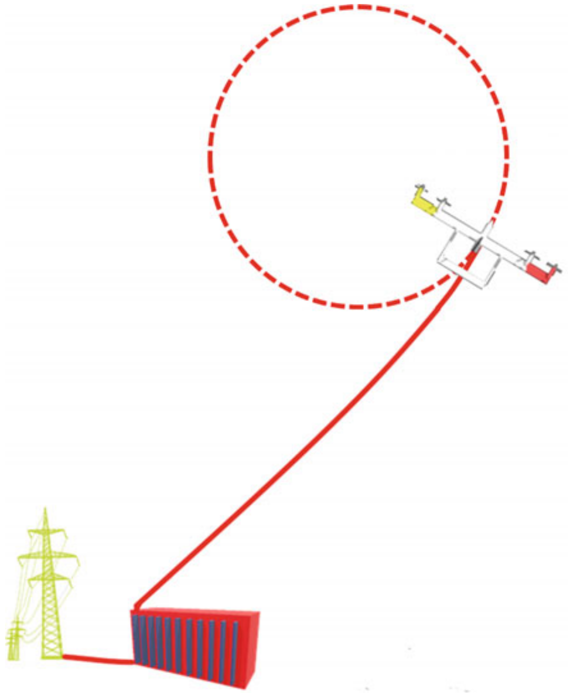


Fig. 2.10 Kitekraft concept with pressure propellers in production mode

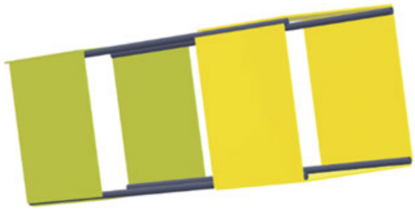


Fig. 2.11 Kids toys box kite

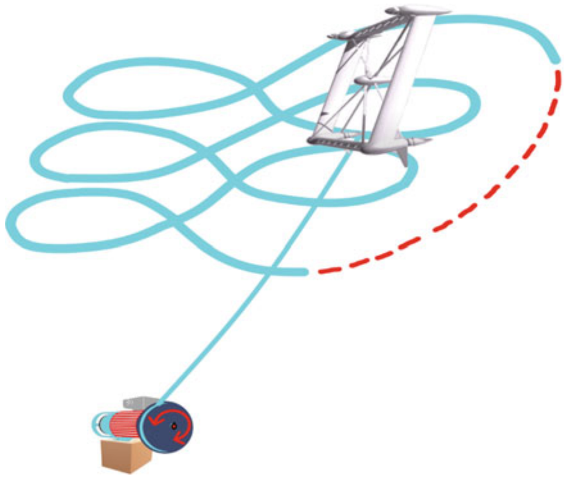


Fig. 2.12 Skypull concept based on the box kite principle

The application of the company Skypull has chosen a completely different missile concept.

The principle of Skypull is similar to an old children's toy cut in half (Fig. 2.11), the so-called box kite. 4 wing segments are arranged in a square and the generators with the propellers are mounted at the corners (Fig. 2.12).

This technology also allows fully automatic takeoff and landing. The generated current is also conducted to the ground via a cable in the tether.

Another technology uses the autorotation effect of rotor blades. When rotor blades are held in the air, they start to rotate (analogous to a conventional wind turbine). The rotation can be used to convert the resulting lift force into electricity by means of the yo-yo effect (Fig. 2.13).

Propellers with motors mounted on the rotor blades allow fully automatic starting. This technology allows a further development: If the motor/generator/propeller combination is designed to rotate on the rotor blade, this technology can also generate electricity through the resulting upward flow of the propellers.

The resulting current is then conducted to the ground via the tether.

The approach of Brainwhere is also interesting. The basic idea is a flying Savonius rotor (Fig. 2.14) with adjustable rotor blades. Sigurd Savonius had the idea to move 2 half-tubes against each other in order to generate a torque by the incoming wind. One advantage of this technology is that it can be used both horizontally and vertically.

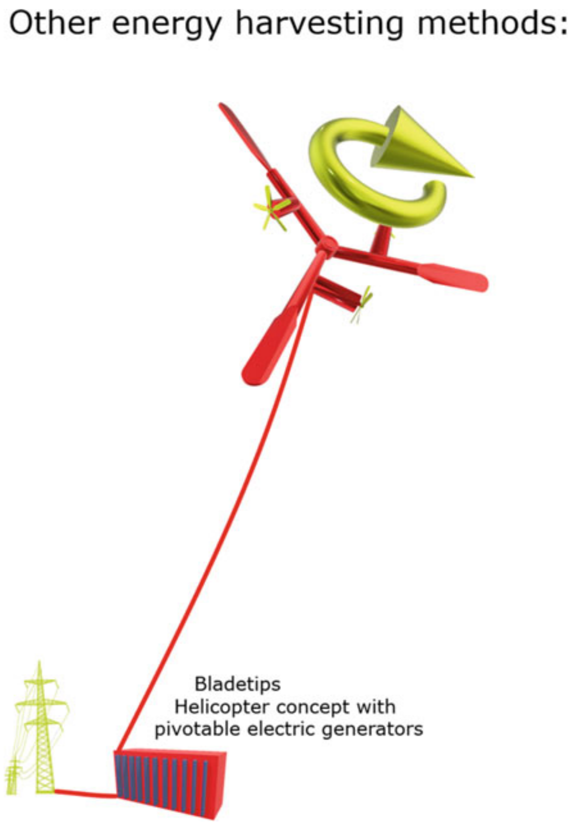


Fig. 2.13 Further AWE harvesting methods

Brainwhere has further developed this approach into an Airborne Wind harvester that can also be launched and landed fully automatically.

In principle, several flying wings are arranged horizontally in a circle and attached to a ring. The angle of attack of the individual wings on this ring can be varied as a function of the rotational and inflow speed. This makes it possible to make optimum use of horizontal winds. The generator, driven by the rotating ring, conducts the current downward through the tether (Fig. 2.15).

Mixed approaches to Airborne Wind energy harvesting are found in lighter-than-air technologies.

The first two implementations in the diagram above (Fig. 2.16) fall into the group of flying generators. The third approach uses the Magnus effect to drive the resulting lift a generator using the yo-yo effect.

The first solution is virtually a conventional wind turbine encased in a hollow lighter-than-air lifting body. By means of a suitable aerodynamic shape, the missile aligns itself automatically.

The second idea is also based on the Savonius rotor concept. Simply explained, it is an inflatable Savonius rotor with multiple blades (rotor blades). Generators are

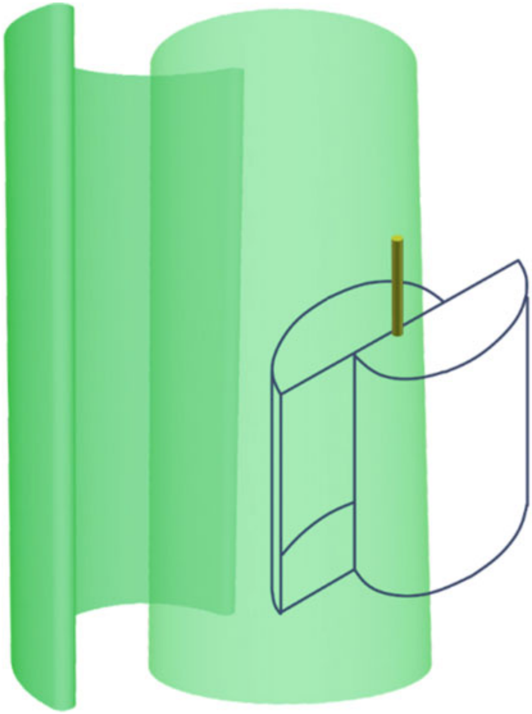


Fig. 2.14 Savonius-rotor concept

installed at the ends of the axis of rotation in this concept. When the buoyancy body is filled with a gas that is lighter than air, the resulting static buoyancy force allows it to be positioned on 2 ropes at a height that makes it spin optimally.

The ropes prevent the generators from rotating together with the buoyancy body. Therefore, the torque of the rotor generates electricity, which is conducted downwards via corresponding cables integrated into the ropes.

The third lighter-than-air concept is based on the Magnus effect (Fig. 2.17). Heinrich Gustav Magnus was the first to describe this phenomenon in fluid mechanics. A cylinder rotating in the flow generates a force. You can easily prove this force yourself experimentally. If you wind paper with threads at the ends and then allow it to unwind itself, you can see that the roll unwinding due to gravity deviates forward or backward from the direction of fall, depending on the winding direction.[ii]

This effect is already being used as a propulsion in shipping. Anton Flettner came up with the idea of patenting this force for driving ships (Fig. 2.18). He built a rotatable and motor-driven vertical tube on a ship. By changing the direction of rotation, it was possible to control the direction in which the ambient wind was used to propel the ship (Figs. 2.19 and 2.20).

This brings me to the operation of the third approach to harvesting Airborne Wind energy with lighter-than-air bodies.

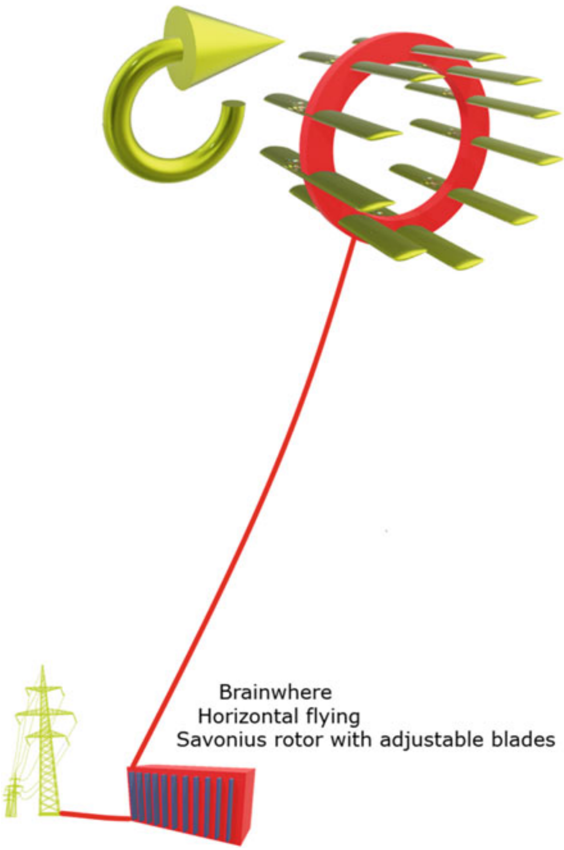


Fig. 2.15 Horizontal flying Savonius rotor

Omnidea is building a lighter-than-air missile as a platform for:

- Validation and calibration of satellite data
- Satellite communication via laser links
- Payload testing prior to spacecraft launch
  - Forest fire monitoring
  - Maritime surveillance
  - Atmosphere/climate change
  - Emergency management
  - Advertising and aerial photography
  - Video recording and monitoring
  - Telecommunications.

and last but not least

- Use of wind energy.

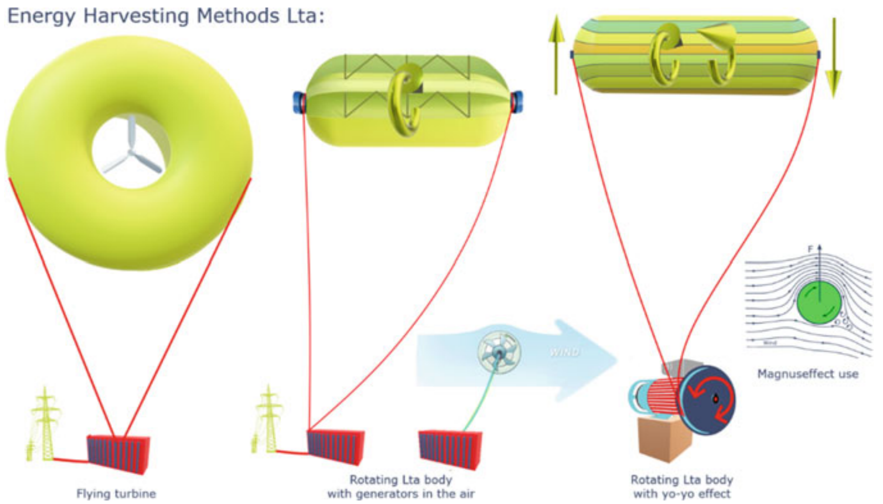
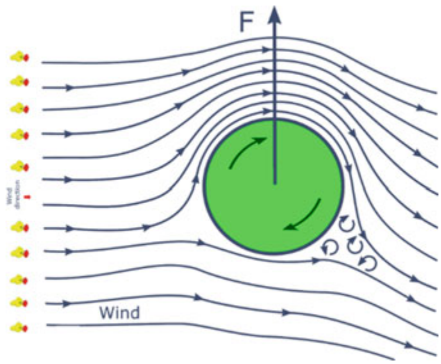


Fig. 2.16 Lighter than air concepts

Fig. 2.17 Principle of Magnus effect



The basic idea behind this idea is primarily the creation of a stable, mobile, flying platform to perform various tasks and not the use of Airborne Wind energy to produce electricity. Therefore, a description of this approach belongs rather in a book about lighter than air technologies.

However, since this technology can also be used to generate electricity via the YoYo approach, this should be mentioned here for the sake of completeness.

Motors at the ends of the lighter-than-air body can cause it to rotate. Through the action of the Magnus (Fig. 2.21) effect, a lift or down force can be generated. With the YoYo concept, generators positioned on the ground can produce electricity.

Now we come to the third main group of altitude wind harvesting approaches. A dynamically operated flying object (flying wing, kite etc.) generates a force vector. This vector can always be decomposed into three directions of action. Depending on the height winch system, the respective X-, Y- or Z-portions or the vector direction itself are the basis for the conversion (Fig. 2.22).

Fig. 2.18 Boat with Flettner rotor engine

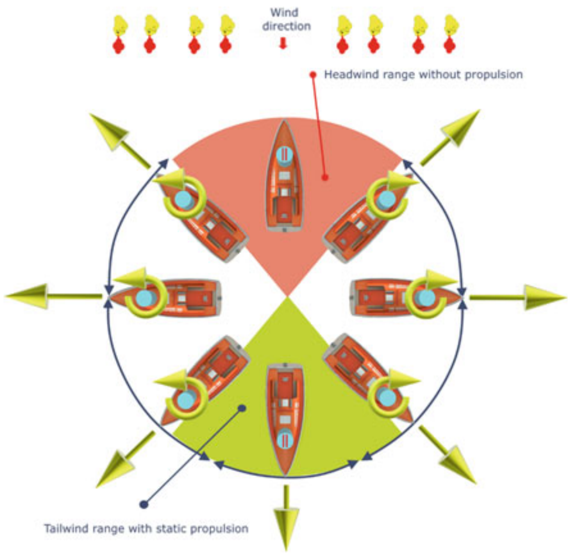


Fig. 2.19 Direction of movement Flettner rotor drive

The third main application group for Airborne Wind energy utilization uses kites for horizontal power generation. The first implementation is the ship propulsion of the company Skysails.

This application has already been in use for over 15 years[1,iii] in international shipping and demonstrates the robustness and industrial suitability of the use of Airborne Wind energy in daily operations (Fig. 2.23).

[1] Höltkemeier [1].

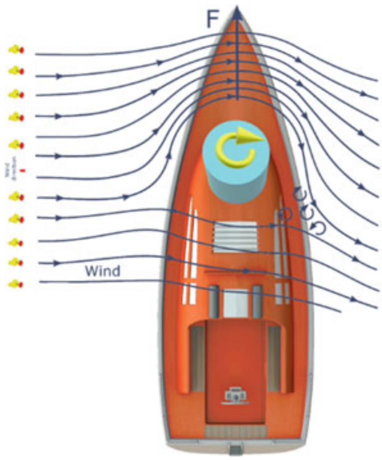


Fig. 2.20 Boat with Flettner rotor top view

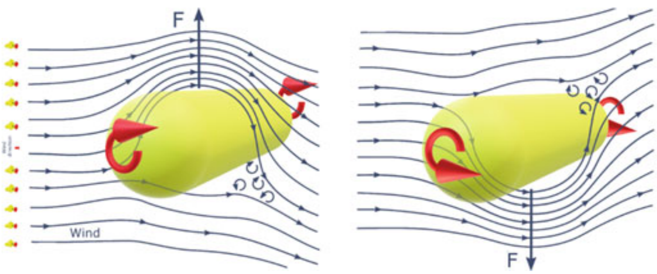


Fig. 2.21 Flettner rotor with Magnus effect

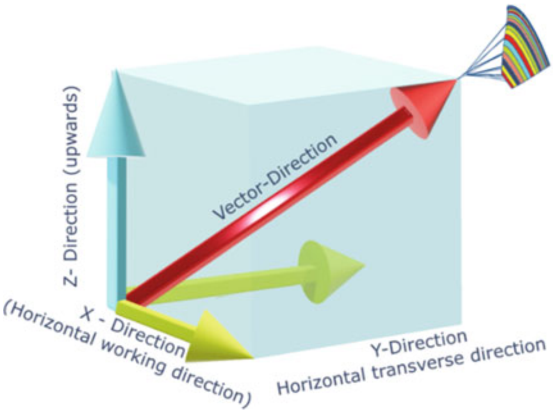


Fig. 2.22 Vector coordinate system

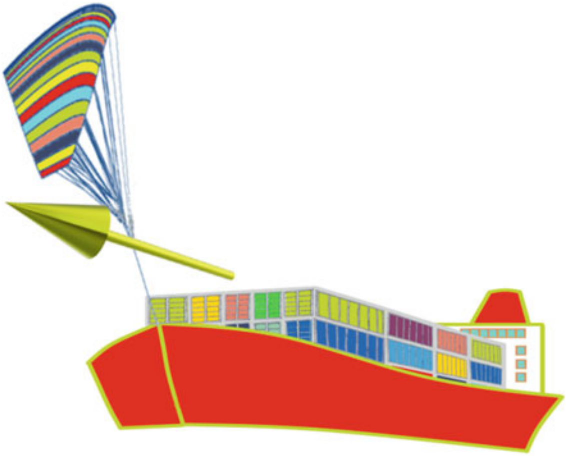


Fig. 2.23 AWE application to support marine propulsion

Fig. 2.24 X-Wind concept

At about the same time, another application was patented. It describes the use of Airborne Wind power to drive generators on the ground by pulling them. One possible application of this patent is to pull rail-mounted electric locomotives in recuperation mode.

Nowadays, modern electric locomotives have the option of being operated in recuperation mode (as in hybrid automobiles). This means that to decelerate the train, the braking energy (mass inertia and lift force) is used to operate the drive as a generator. The resulting electricity is fed back into the grid via a laterally conductor rail (Fig. 2.24).

2.2 Wind Window of the Airborne Wind Technologies

As we have seen and know from our own experience, the wind comes from different directions. A wind window can be thought of as the range in which a kite or flying machine can be moved by the Airborne wind (Fig. 2.25).

Therefore, the wind window of the YoYo or flying generators is the curved part of a quarter sphere shell.

Airborne Wind technologies for horizontal force generation are an exception (Fig. 2.26). Due to the non-stationary control system, the wind window results in a half pipe. The end of the half tube also forms a quarter-sphere.

The radius of the half tube or quarter sphere is determined by the line length.

At the edge of the respective wind windows, in the area of large angles, the lift forces logically decrease. The more a kite or a flying object approaches the zenith or the ground or to the left and right to the edge, the lower the achievable forces become (Fig. 2.27).

Therefore, the wind windows for Airborne Wind turbines are as follows.

While the use of the wind window is quite simple for the stationary height wind turbine systems, the use for horizontal force generation is somewhat more complicated (Fig. 2.28). As we have seen in the illustration of the direction of travel with

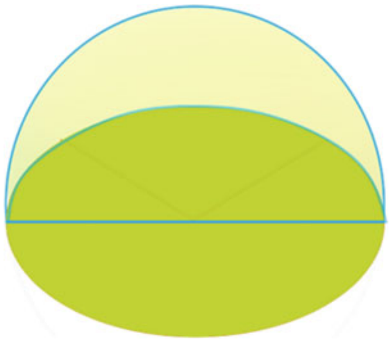


Fig. 2.25 Wind windows YoYo- and flying generator concept

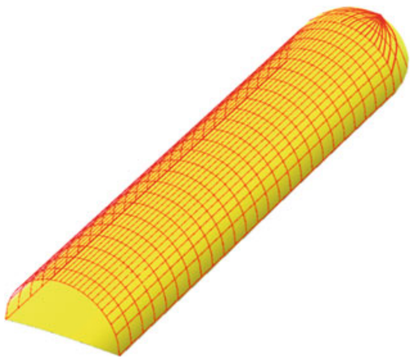


Fig. 2.26 Wind window moving steering unit