Preface

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To Wubbo Ockels, 1946-2014
Pioneer of airborne wind energy

Foreword

We live in a strange world.

On the one hand, we all want to save energy: the average world temperature is rising, with one record year following the other; almost all scientists and politicians agree that greenhouse gases, notably CO_2, are the main cause of this change; they agree that this change will continue to cause significant damage to the livelihoods of hundreds of millions of people, and that the only way to limit climate change is to reduce the world's greenhouse gas emissions; most of the world's governments just committed themselves in Paris to the ambitious aim to limit global warming to less than two degrees Celsius; in summary, nearly everyone agrees that the use of fossil fuels needs to be significantly reduced.

On the other hand, we consume more fossil fuels than ever: the world has the lowest prices for fossil fuels since long; oil costs only 50 dollar per barrel, about 30 cents per liter; and western politicians and most of their electorates are happy about these low prices; the US-led shale gas revolution helps to limit the costs of fossil energy for decades to come; the world oil consumption and the world coal consumption continue to grow; in summary, the greenhouse gas emissions have never been higher than today, and continue to grow year after year.

Most of the authors of this volume, and many other people concerned with the world's climate, including myself, have a dream: we want to live in a world where fossil fuels are mostly replaced by renewable energy sources.

I believe that this dream can become reality. We experience already that solar and wind power installations grow year after year. They start to become competitive at many places, thanks to government support and technological advances. Already today, the yearly electricity output of wind and solar power installations exceeds the output of about one hundred nuclear power plants worldwide, providing the equivalent total energy needs of about 20 million people with European lifestyle. Unfortunately, much more investment in renewable energy sources is needed to replace most of fossil energy production. This investment into renewable energy sources will only happen under two conditions:

- First, renewable energy sources must become available in even larger quantities and at a reasonable price for both the economy and the environment. Here, research on new and even more competitive renewable energy technologies can play an important role, including storage and distribution technologies, and research non new and possibly disruptive new concepts. Airborne wind energy, that could tap into resources not commercially available with conventional wind turbine technology, could become a game changer, if successful. The present book is both, a motivation for airborne wind energy, as well as a testimony of the advancements that have been achieved in this young field in the last years. It is a reason for optimism.
- Second, fossil fuels must become more expensive (or forbidden). This point is often forgotten, probably because it is difficult to achieve and thus a reason for pessimism. But without higher prices for fossil fuels, the transition to a carbon free economy can unfortunately not become reality. The low price for oil, notably for ship diesel, was arguably one of the main reasons why one of the most developed airborne wind energy technologies, traction kites for cargo vessels, did not sell well on the market, forcing the company SkySails GmbH to file for bankruptcy at the start of this year. One might hope that this bankruptcy was an exception and will not become the rule, but as a matter of fact, any new energy technology has to compete with fossil fuels, and is bound to loose on a free market without carbon pricing, as I will argue below.

One might hope that OPEC and the other oil producers might one day decide to reduce oil production, such that the oil price will rise again. This would give another short time boost for renewable energies, as in the 1970's and in the previous decade. But unfortunately, one cannot reasonably hope that the world prices for fossil fuels would ever become high enough to render large amounts of renewable energy sources competitive. The reason is simple: the production costs of oil, gas and coal are extremely low at the best locations, and will stay low for decades to come. For example, the production costs for a barrel of oil in Saudi Arabia, with its vast reserves, are below 10 Euro, that is 6 cents per liter. Combined with the ease of storing, transporting and converting them, fossil fuels are simply too attractive to be driven out of the market without external intervention.

What would happen if the world relies more and more on carbon free technologies? Would fossil fuel producers reduce their production accordingly? Unfortunately not. If significantly fewer people than now would need oil, its price would sink close to its technical lower limit, about 6 cents per liter. It is impossible to imagine that this low cost, together with the ease of use, can be beaten by any other energy source. Thus, exactly if renewable energy sources become successful and start to replace fossil fuels, which we all hope, fossil fuels would become so cheap that new renewable energy installations would no longer be economical. The world would consume more and more of the cheap energy, and some of it would be renewable, but the total greenhouse gas emissions would remain high.

There is only one way to solve this dilemma: to put a realistic price on greenhouse gas emissions, in order to internalize the costs that they cause. The cap-and-trade scheme that is tried in the European Union should not serve as an example. By construction, such a scheme does not lead to a fixed and predictable extra price on energy usage, which is needed in order to make long-term investments in energy savings and renewable energy sources attractive.

A better way would be via a "climate protection" or "carbon tax", that puts a fixed price on all equivalent greenhouse gas emissions. Ideally, this tax would be raised at the same rate in most countries of the world, and the raised money could be redistributed equally to each country's population (or, in utopia, equally to the world's population). When countries that raise the tax trade goods with countries that do not raise it, tariffs on imported goods can take their carbon footprint into account and thus correct for undesired market distortions. Air and sea traffic needs special attention, but should be included into the tax scheme. Because production of fossil fuels is more centralized than their consumption, the tax would more easily be levied at the production side, acknowledging the fact that all the carbon contained in fossil fuels will ultimately end in the atmosphere.

The desired result would be that the price of fossil fuels, of all carbon intensive technologies, and of all the goods that they produce, would rise in the zone where the climate protection tax is raised. The tax would automatically ensure that the higher the carbon footprint of a good, the higher would be its price. One could start with a tax level that implicitly amounts to e.g. 30 cents per liter of oil. Important is that no exceptions are made for large consumers of coal, oil or gas, and that the tax is guaranteed to remain in place for at least one decade or more, to ensure predictability.

The higher prices of all carbon intensive technologies would have two major effects: first, they would serve as an incentive to reduce fossil energy consumption where it hurts least and can be done most efficiently. Second, and equally important, it would help making the best carbon free energy technologies competitive. Airborne wind energy could become one of these. A climate protection tax would thus be one of the few taxes that distort the market in a desirable way. Large economic zones with significant carbon emissions such as China, the US, India or the European Union would be ideally suited to start, in the hope that other regions would follow.

In summary, we need to work on two sides in order to make renewable energies and in particular airborne wind energy successful: on technology development as well as on carbon pricing. None of the two sides can be successful without the other.

The present book with its 30 interesting and well-written chapters, for which I want to congratulate authors and editor, is not only a pleasure to read; it is also a testimony that technology development of airborne wind energy advances well, and that many smart people work successfully on topics ranging from system modeling and optimization, the many practical issues related to design and real-world implementation, to the socio-economic implications of airborne wind energy. As a veteran in the field, who did his first tether drag and (unsuccessful) crosswind flight control experiments on motorways and football fields in Hamburg in the early 1990s, who experienced the excitement and secrecy that accompanied the new, patentable ideas in the early 2000s, and who witnessed and enjoyed the emergence of a small, but open research community on airborne wind energy in the early 2010s, I am absolutely delighted to see this research community being as large and productive as it is now, in particular the many protoptypes that are now in successful operation. Many of the authors have met at the Airborne Wind Energy Conference AWEC 2015 in Delft, which created, in addition to this book, a highly recommendable video resource (http://www.awec2015.com) of public presentations on many of the topics covered in the book. I am curious about the further developments in the field and look forward to the upcoming meeting of the airborne wind energy community on 5-6 October 2017, in Freiburg (http://www.awec2017.com). I sincerely hope that one or more of the companies which are now active in the field will have created commercial products soon. Most important, I do hope that renewable energy sources such as airborne wind energy will not continue to be suffocated by the low price of fossil fuels – and that scientists do not forget, and politicians start to implement, the one important ingredient that is missing in today's climate policy, without which the transition to a carbon neutral economy will not happen: a carbon tax.

Keeping this in mind, I wish all readers of this volume pleasure while learning about the recent advances of airborne wind energy!

Freiburg, Germany, June 2016 *Moritz Diehl*

Preface

Dear readers,

This book is about the use of kites or, more generally, tethered aerodynamic lift devices for wind energy generation. Not much more than a decade ago this subject was pursued by only a few visionary pioneers, but it has since become a rapidly evolving field of activity of a global community of scientists, researchers, developers and investors. While this development is clearly motivated by the urge to explore innovative and cost-effective technologies to reduce our dependency on fossil fuels and to aid the transition towards renewable energies, it is the conceptual simplicity and potential of airborne wind energy that exerts a certain fascination.

For conventional wind turbines the tower and foundation transfer the bending moment of the resultant aerodynamic load to the ground. Airborne wind energy systems, on the other hand, are designed as tensile structures and thus require far less material to transfer forces of similar magnitude. As consequence, the system costs can be lower and the environmental footprint can be reduced substantially. Furthermore, the operational altitude can be selected by design and with far less impact on the costs or technical feasibility. This makes it possible to not only adjust the operation dynamically to the available wind resource, but also to access an unexploited large source of energy: wind at higher altitudes.

Clearly, the use of tethered flying devices also entails a number of technical challenges and this has lead to controversial discussions about the economic viability of the technology at large. Because the motion of the devices is only constrained by one or more flexible tethers and, in general, is also inherently unstable, a reliable and robust control is crucial for the commercial use of the technology. It has also become clear that automatic launching and landing will be an enabling technology component, as will be durable and lightweight flexible materials that can sustain a large number of load cycles.

The current research and development activities address these challenges in different ways. Since the publication of the first textbook on Airborne Wind Energy in October 2013, the key industry players have advanced rapidly with building next-generation prototypes. Following the acquisition by Google in 2013, the team of

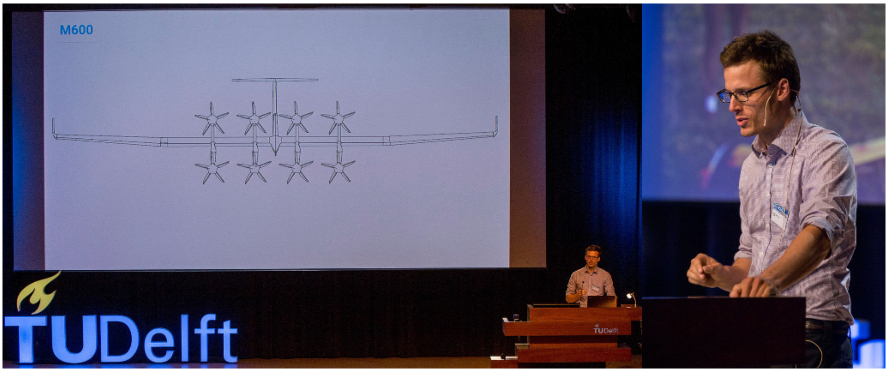

Fig. 1 Damon Vander Lind presenting the M600 energy kite at the AWEC 2015 (http://www.awec2015.com/presentations)

Makani Power has developed a 600 kW energy kite (see Fig. 1) and is testing this flying machine with an impressive 30 m wingspan and eight onboard wind turbines in the vicinity of San Francisco. Having grown to 40 employees, Ampyx Power has developed two rigid wing aircraft prototypes and registered these with the aviation authorities as aircraft. EnerKíte, TwingTec and Kitemill are testing rigid wing prototypes, Kitepower a soft wing prototype with automatic launching and landing capability while Kite Power Systems is testing an implementation which uses two separate soft kites that operate on the same generator. The "IG Flugwind" was founded in Germany as an airborne wind energy interest group and now includes most European system developers. The group has started to systematically approach the regulation and certification of airborne wind energy systems, with the aim to define safety standards for the operation of the system and the interaction with other users of the air space or ground surface.

These activities indicate that the investment climate for the commercial development of innovative wind energy solutions is improving steadily. Notable recent governmental funding of commercial activities has come from the ARPA-E (Makani Power) and SBIR (eWind Solutions, WindLift and Altaeros Energies) programs of the US government, in Europe from the SME Instrument (Ampyx Power) and the Fast Track to Innovation pilot (industrial/academic consortium with Kitepower as central partner) and from several national governments. In Germany, for example, the funding program ZIM for small and medium-sized enterprises (High Altitude Wind Network HWN500) and the projects OnKites I and II (Fraunhofer Institute). In my opinion, the increasing maturity level of the technology has a distinctly positive effect on the success rate of grant applications. The resulting global map of academic and industrial contributors is shown in Fig. 2.

Recent academic key contributions are the ERC project Highwind (Moritz Diehl) and the Swiss network project A2WE, both focusing on the control aspects of airborne wind energy, as well as the European Training Network AWESCO. The latter combines 14 PhD projects at eight universities and four industry partners into a truly multidisciplinary approach which covers four central themes: (1) Modeling

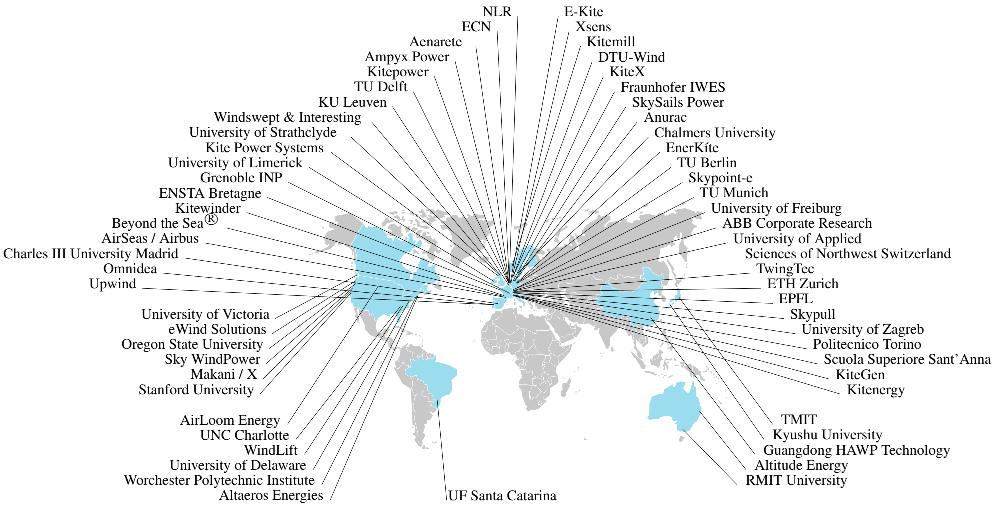

Fig. 2 Airborne wind energy research and development activities in 2017

and Simulation, (2) System Design and Optimization, (3) Sensors and Estimation and (4) Control Systems. Airborne wind energy is also an increasingly present topic at conferences and wind energy conventions. To name some examples: the major international control conferences regularly feature invited tracks on control aspects of the new technology and, on the other hand, the key industry players provide now frequent updates on their development status at the conferences of the European Wind Energy Association (EWEA) and corresponding national events. The increasing recognition of the new technology is also reflected in the fact that the TU Delft Wind Energy Institute (DUWIND) includes airborne wind energy in the R&D program 2015-2020 as one of its five research lines on conversion system level. This is, in my opinion, a notable achievement because airborne wind energy has so far been developed quite independently of conventional wind energy.

But lastly, it is the annual Airborne Wind Energy Conference (AWEC) which connects the global community of scientists, researchers, developers and investors and which makes the field of activity a very special one. This conference and exhibit was held in 2009 for the first time and in June 2015 I had the honor and opportunity to organize a very successful event with more than 200 international participants in Delft (see Fig. 3). The resulting 54 oral presentations, 17 poster presentations, the screening of a unique documentary movie and the many discussions were not only inspiring and motivating but also an indicator for a systematic advancement of the technology development. It was this particular event and the success of the first textbook (almost 50,000 chapter downloads in two years) which triggered the idea

Fig. 3 Group photo at the AWEC 2015 in Delft (16 June 2015)

to produce the present, second textbook on airborne wind energy. Following the call for chapter contributions in August 2015, 33 manuscripts were received in total, of which 28 were based on conference presentations and 5 were new contributions. Because of this dominant proportion of conference material the present book can factually be regarded as scientifically expanded conference proceedings, however of a selected subset of the presented material. Each manuscript was peer-reviewed by at least two and up to five anonymous reviewers and improved within two to three consecutive review iterations. The names of the 96 reviewers are listed on the following pages xv–xvii and I would like to express my appreciation for their fast, competent and constructive feedback. Based on the recommendations I accepted 30 chapters for publication which are divided into five parts.

Following an introductory chapter on "Emergence and Economic Dimension of Airborne Wind Energy" is Part I on "Fundamentals, Modeling & Simulation" which contains 7 contributions that describe fundamental aspects of the technology, quasi-steady as well as dynamic models and simulations of airborne wind energy systems or individual components. Part II on "Control, Optimization & Flight State Measurement" combines 5 chapters on control of kite and ground station, 3 chapters on system optimization and 1 chapter on flight state measurement. Part III on "Concept Design & Analysis" comprises 5 chapters presenting and analyzing novel launching and landing concepts as well as novel energy harvesting concepts. Part IV on "Implemented Concepts" contains 4 chapters about established system concepts. The final Part V on "Technology Deployment" comprises 4 chapters on various aspects that are relevant for the commercial deployment of the technology.

I hope that the present book can contribute to the discussion by providing scientific evidence for the technical feasibility of the innovative technology and its economic potential.

Delft, Netherlands, July 2017 *Roland Schmehl*

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This book would not have been possible without the support and engagement of reviewers selected from the international scientific community. The quality of any peer-reviewed scientific book largely depends on the willingness of the 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:

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Editor Biography

Roland Schmehl is Associate Professor in the Section of Wind Energy at the Faculty of Aerospace Engineering of Delft University of Technology. He is head of the Kitepower Research Group and co-founder of the startup company Kitepower. He is coordinator of the Marie Skłodowska-Curie Initial Training Network AWESCO (Airborne Wind Energy System Modelling, Control and Optimisation) which addresses key challenges of airborne wind energy technologies. The multidisciplinary training network includes 14 PhD researchers at 12 European consortium partners and is funded by the European Union's Horizon 2020 Framework Programme and the Swiss federal government. He further coordinates the Horizon 2020 "Fast Track to Innovation" project REACH (Resource Efficient Automatic Conversion of High-Altitude Wind) which aims at commercially developing a 100 kW mobile kite power system based on softwing technology.

He teaches the MSc course "Airborne Wind Energy" and has supervised more than 50 MSc graduation projects on this topic. He has been co-promotor, defense committee member or external assessor of 7 completed PhD dissertations. He regularly tutors student teams in a Design Synthesis Exercise which is the final highlight of the Aerospace Engineering BSc curriculum. He is author of more than 80 scientific publications in various fields of science and engineering. He co-edited the pioneering book "Airborne Wind Energy", published in 2013 with Springer, comprising 36 contributed peer-reviewed chapters. He was speaker at the TEDxDelft in 2012, organiser of the 6th International Airborne Wind Energy Conference (AWEC) 2015 in Delft and a co-organizer of the AWEC 2017 in Freiburg, Germany. The two conferences attracted each more than 200 international participants from industry and academia. Video recordings of the presentations, the posters and the illustrated books of abstracts are available online through open access.

He graduated in 1994 with an MSc degree in Mechanical Engineering from Karlsruhe Institute of Technology, where he also completed his research on the computational modeling of liquid droplet dynamics and liquid fuel preparation for jet engines with a PhD degree cum laude. In 2002 he was awarded a post-doctoral research fellowship at the European Space Research and Technology Centre (ESTEC) in the Netherlands. In this function and later also as consultant, he was involved in the accident analysis of the Ariane 5 upper stage propulsion system (AESTUS), the reentry analysis of the Automated Transfer Vehicle (ATV) and in other studies on propulsion and life support systems. In 2005 he started as Software Architect at TNO Automotive Safety Solutions in Delft, developing a Computational Fluid Dynamics module for the simulation of airbag deployment. He returned to academia in 2009, combining his multidisciplinary industry experience with applied research and education to develop and commercialize a challenging innovative wind energy technology.

Nomenclature

a	acceleration [m/s^2]
A	surface area [m^2]
$\mathcal{R}$	aspect ratio
b	wing span [m]
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
C_p	power 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]
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]
β_s	sideslip angle [rad]
χ	course angle [rad]
γ	flight path angle [rad]
ζ	power factor
η	efficiency
κ	camber
λ	tangential velocity factor, crosswind factor, tip speed ratio
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
n	normal
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, azimuthal angle [rad]
x, y, z	Cartesian coordinates [m]
ϕ, θ, ψ	roll, pitch, yaw angles [rad]