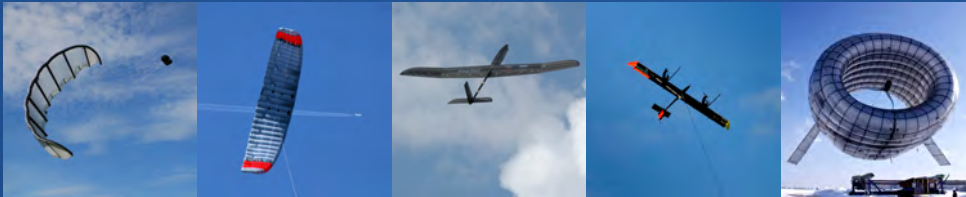


# AIRBORNE WIND ENERGY 2015 CONFERENCE

15-16 JUNE 2015  
DELFT UNIVERSITY  
OF TECHNOLOGY  
THE NETHERLANDS  
[www.awec2015.eu](http://www.awec2015.eu)



## BOOK OF ABSTRACTS



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# AIRBORNE WIND ENERGY 2015 CONFERENCE

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### **Roland Schmehl**

Chair organisation committee  
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## **Welcome to the Airborne Wind Energy Conference 2015**

### **Roland Schmehl**

Faculty of Aerospace Engineering, Delft University of Technology

Dear AWE friends and conference participants,

I would like to welcome you to the Airborne Wind Energy Conference 2015 in Delft on behalf of the organising committee. Much has happened since the AWEC 2013 in Berlin. To name some of the industry highlights: with the acquisition by Google, the team of Makani Power has developed a 600 kW energy kite and is now already performing flight tests with this impressive machine. Having grown to a respectable size of more than 25 employees, Ampyx Power has developed two prototypes of the PowerPlane AP-2 and registered these with the aviation authorities as aircraft. EnerKite and TwingTec have also developed new generations of prototypes for automatic launching and landing. e-Kite on the other hand has built an advanced 50 kW ground station for pumping kite power systems, using a direct drive electrical machine. All these rapidly proceeding activities indicate to me that the investment climate for commercial development of innovative wind energy solutions is getting better. Notable governmental funding of commercial activities has come from ARPA-E and SBIR programmes in the U.S., the SME Instrument in Europe and the ZIM programme in Germany. I am convinced that the increasing maturity level of the technology has a positive effect on the success rate of grant applications and that also the exploration of innovative funding instruments, such as crowd funding, contributes. Ampyx Power and EnerKite are two examples for recently implemented successful campaigns. In the academic sector the highlights are the ERC project Highwind, which moved with Moritz Diehl from the Uni-

versity of Leuven to the University of Freiburg, the A2WE project of a Swiss consortium (ETHZ, EPFL and FHNW) and the Kite Power 2.0 project of TU Delft and the Karlsruhe University of Applied Sciences. Of particular importance will be the AWESCO Initial Training Network, which started this year under the coordination of TU Delft. I will describe AWESCO and the envisioned impact of the network in a dedicated presentation (see p. 89).

Next to the technical development more systematic and coordinated approaches to regulation and certification are being implemented. Because of the possible interference with air traffic, these are important aspects of the technology which require particular attention to reduce the risk of delays during the commercial deployment. One of the central initiatives is the German IG Flugwind (Airborne Wind Energy Interest Group) coordinated by Jens Rauch of the FGW e.V. and Guido Lütsch. Finally, I would like to remark that last year, in May, my former colleague and mentor Prof. Dr. Wubbo Ockels sadly passed away. I would like to dedicate this conference to him, also on behalf of the AWEC committees. You will find a separate memorial note on p. 12.

As the authors among you know we will record the presentations at the conference to make the AWEC 2015 into the first online Airborne Wind Energy Conference. It is my ambition to use this material, with your consent, also for my online course on Airborne Wind Energy. I am wishing you an inspiring conference and a pleasant stay in Delft,

Roland Schmehl



**Gerard van Bussel**

Chair programme committee  
Chair holder Wind Energy  
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## Welcome to the Airborne Wind Energy Conference 2015

**Gerard J. W. van Bussel**

Faculty of Aerospace Engineering, Delft University of Technology

Dear conference participants,

It is a pleasure to welcome you to the Airborne Wind Energy Conference 2015 here at the TU Delft. As chair of the programme committee I was impressed by the number and quality of the abstracts submitted and I am curious to experience the undoubtedly interesting scientific event that takes place the coming two days.

My own background is in “conventional” wind power and I have been working in this field already since 1976. At that time TU Delft was one of the pioneers researching novel concepts in modern wind power technology. And, as you may know, TU Delft is also one of the pioneers in Airborne Wind Energy – most notably connected to the work of my former colleague Wubbo Ockels. The emergence of Airborne Wind Energy or Kite Power, as we called it initially, reminds me on the early days of “conventional” wind power. Various intriguing concepts, novel technologies and new use of materials, advanced control strategies to adapt to the fluctuating wind resource, are similarities. But there are also clear differences such as the ability to fly crosswind on a tether at high altitudes. These properties as well as the further reduction of material use are clear advantages compared to “towered” wind turbines. On the other hand, reliability and robustness are crucial for a safe and economically viable operation of any wind energy conversion system. And particularly these aspects are a serious challenge for flying wind power systems in continuous operation exposed to varying wind conditions. Just as even more advanced intelligent control technologies with a high reliability level.

The Airborne Wind Energy R&D community is systematically addressing these challenges and has progressed substantially over the past years. I am convinced that we will soon see the first test installations operating uninterrupted over longer and longer periods – some of the presentations in this conference will address this.

It is also clear that more investments are needed in the development of existing and novel renewable energy technologies to abate climate change. Of course we should continue developing existing renewable energy technologies, but also invest in novel promising technologies. This obviously comes at a high risk but I am convinced that we are able to make some good and educated choices. And Airborne Wind Energy is such a novel technology – high risk and high potential – that we have adopted here at the TU Delft. In our new DUWIND (Delft University Wind Energy Institute) R&D programme Airborne Wind Energy has become a new line of research.

I will also strongly support and facilitate the process to stimulate and integrate Airborne Wind Energy R&D in existing European organisations, such as the EWEA (European Wind Energy Association) and the EAWE (European Academy of Wind Energy). The European Wind Energy Master (EWEM), a two year master course coordinated by TU Delft, is another effective means to disseminate R&D results by means of MSc education and research in an international context.

I wish you all a fruitful and stimulating conference, as well as a joyful stay in Delft.

Gerard van Bussel



**Hester Bijl**

Dean

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## Welcome to the Faculty of Aerospace Engineering

**Hester Bijl**

Faculty of Aerospace Engineering, Delft University of Technology

Dear conference participants,

I would like to welcome you to the AWEC 2015 on behalf of the Faculty of Aerospace Engineering. As its dean, I am particularly delighted that we have the opportunity to host this event here in Delft because it is the first conference organised within the frame of the Marie Skłodowska-Curie Initial Training Network AWESCO. With participants from all over the world, from industry and academia, the conference will be an excellent opportunity to learn about the current state of technology, to exchange ideas and to network.

The Faculty of Aerospace Engineering is one of the largest of the eight faculties of TU Delft and also one of the largest faculties in northern Europe devoted entirely to aerospace engineering. With our four departments we are covering many different engineering aspects of aircraft, spacecraft and wind energy systems. Key areas with more fundamental research character are aerodynamics, flight control, aerospace structures and materials. More oriented towards the application are the key areas of aircraft and spacecraft systems. Kite power, the theme of this conference, fits perfectly into this blend of multidisciplinary engineering aspects.

For example, much research has already been done at the faculty on aerodynamics and structural dynamics of flexible wings, particularly inflatable wings, as used for some of the kite power systems. The aeroelastic phenom-

ena related to fluid-structure interaction can be rather complex and play an important role for the manoeuvring of the wing. At my former Chair of Aerodynamics we have developed various methods for computational simulations and operate several wind tunnels that are used for experimental validation. Regarding flight dynamics a reliable automatic control which is sufficiently robust against fluctuating wind environment will be one of the key ingredients for a successful commercial development of the technology.

The AWESCO network, which is coordinated by TU Delft, is addressing the important technical challenges of kite power and in this sense continues the line of research of my former colleague Wubbo Ockels. He established the kite power research group in 2004 and was responsible for the implementation of the current 20 kW prototype. Being one of the first operational kite power systems this prototype had its maiden flight in January 2010 and was successfully demonstrated in automatic operation in June 2012. In my view AWESCO will not only be important for generating high quality research results in support of the commercial development activities, but also to provide highly skilled PhDers for the emerging industry.

I am wishing you a successful conference and an interesting and stimulating scientific debate.

Hester Bijl



#### **Organising committee**

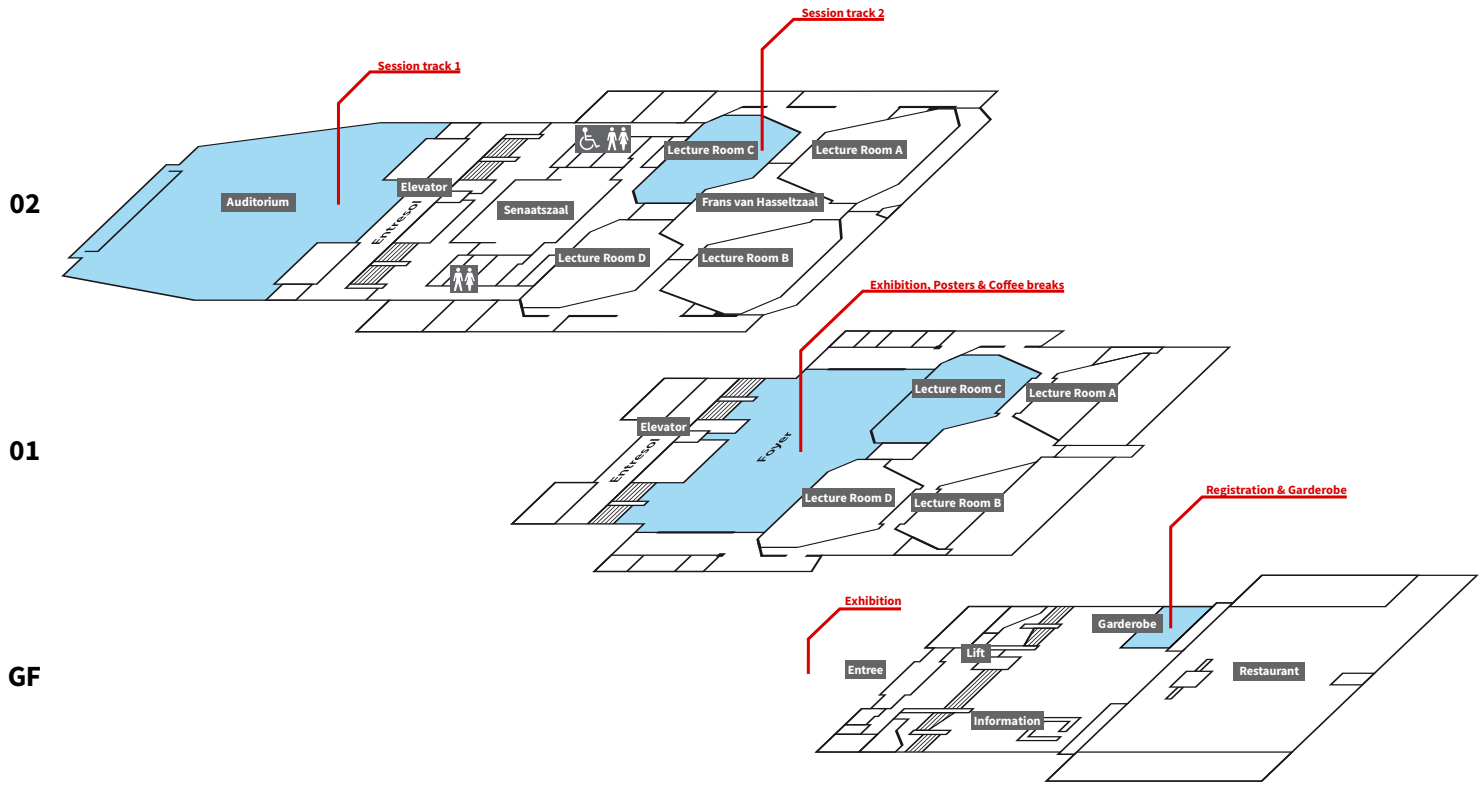
- Roland Schmehl (chair), TU Delft, Netherlands
- Axelle Viré, TU Delft, Netherlands
- Sylvia Willems, TU Delft, Netherlands
- Roger Coenen, TU Delft, Netherlands
- Jan Harms, TU Delft, Netherlands
- Navi Rajan, TU Delft, Netherlands
- Guido Lütsch, BHWE, Germany

#### **Programme committee**

- Gerard van Bussel (chair), TU Delft, Netherlands
- Roland Schmehl, TU Delft, Netherlands
- Axelle Viré, TU Delft, Netherlands
- Moritz Diehl, University of Freiburg, Germany

- Rolf Luchsinger, EMPA/TwingTec, Switzerland
- Sören Sieberling MSc, Ampyx Power, Netherlands
- Colin Jones, EPFL, Switzerland
- Sebastien Gros, Chalmers, Sweden
- Christoph M. Hackl, TU Munich, Germany
- Christopher Vermillion, UNC Charlotte, USA
- Linda Kamp, TU Delft, Netherlands
- Roland Ort, TU Delft, Netherlands
- Ahmad Hably, Grenoble Institute of Technology
- Alexander Bormann, EnerKite, Germany
- Adrian Gambier, Fraunhofer IWES, Germany
- Aldo Zraggen, ETH Zurich, Switzerland
- Johan Meyers, KU Leuven, Belgium

# Aula Congressentrum



## Conference Programme

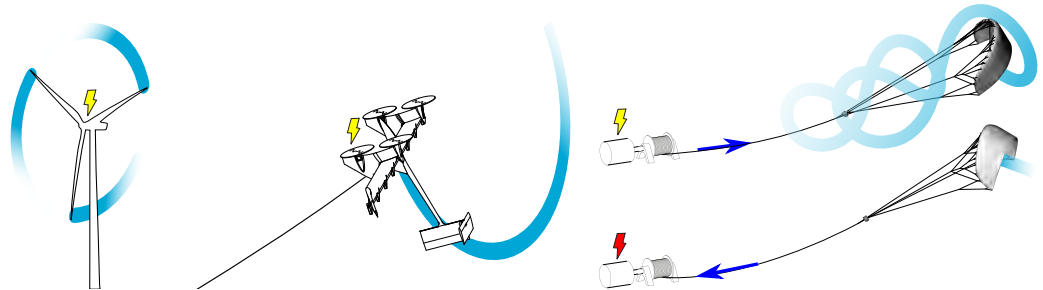
The two conference days are each introduced by a plenary session in the auditorium of the Aula Conference Centre. Following these the programme is split in two parallel presentation tracks. The timing of the presentations is such that switching sessions is easily possible. To summarise the conference will have

- 3 plenary presentations, each of 25 minutes duration,
- 5 plenary presentations, each of 20 minutes duration,
- 46 presentations, each of 20–25 minutes duration, in two parallel tracks,
- 16 poster presentations,
- a kite boarding simulator including virtual environment and force feedback,
- a screening of the Airborne Wind Energy documentary produced by Chase Honaker.

The poster sessions do not only provide a communication platform to the poster presenters, but also create an opportunity for extensive networking. Other possibilities for exchanging ideas with fellow conference attendees will be during the coffee and lunch breaks and at the conference dinner at the Art Centre Delft. For your convenience

we have provided an author index at the end of the book. Using the momentum of the conference we have compiled a short survey about regulation and certification issues. Following a short summary. In total 21 different organisations have completed the survey. 10 different AWE prototypes were reported. 3 of them are rigid wing and 7 of them are flexible wing types. The prototype weights vary between 0.5 – 450 kg. Prototypes are mostly from private companies, only 2 are operated by universities, the remaining 8 are from companies.

Currently, different certification categories exist. 6 of the 10 prototypes are officially registered with the civil certification authority. 2 of them are registered as air traffic obstacle, others are unmanned glider, tethered kite etc. The lack of consensus is striking. For similar concepts, while some aviation authorities require personnel training, some of them do not require this. Similarly, some prototypes need licensed personal to operate. While most of the prototypes are allowed to operate at nights, some of them can operate only during day hours.



## Monday, 15 June 2015\*

Time		Aula Congrescentrum		
08:30	–	09:30	Registration – Registration Desk	
<b>Auditorium</b>				
09:30	–	10:00	<b>Welcome Notes – Conference Opening</b>	
			<b>Dr. Roland Schmehl</b> , Associate Professor, Faculty of Aerospace Engineering, TU Delft	4
			<b>Prof. Dr. Gerard Van Bussel</b> , Chairholder Wind Energy, Faculty of Aerospace Engineering, TU Delft	5
			<b>Prof. Dr. Hester Bijl</b> , Dean, Faculty of Aerospace Engineering, TU Delft	6
			<b>Auditorium</b>	<b>Page</b>
			<b>Lecture Room C</b>	<b>Page</b>
Session: <b>Industry Highlights</b>				
10:00	–	10:25	<b>Damon Vander Lind</b> , Makani Power	17
10:25	–	10:50	<b>Michiel Kruijff</b> , Ampyx Power	21
10:50	–	11:15	<b>Alexander Bormann</b> , EnerKite	23
<b>11:15</b>	–	<b>11:35</b>	<b>Coffee</b>	
Session: <b>Regulation and Wind Environment</b>				
11:35	–	11:55	<b>Richard Ruiterkamp</b> , Ampyx Power	79
11:55	–	12:15	<b>Ben Glass</b> , Altaeros Energies	81
12:15	–	12:35	<b>David Brandt</b> , EWC Weather Consult GmbH	82
12:35	–	12:55	<b>Ilona Bastigkeit</b> , Fraunhofer IWES	83
<b>12:55</b>	–	<b>13:50</b>	<b>Lunch</b>	
Session: <b>Implemented Concepts I</b>				
13:50	–	14:10	<b>Thomas Harklau</b> , Kitemill	25
14:10	–	14:30	<b>Rolf Luchsinger</b> , TwingTec AG	28
14:30	–	14:50	<b>Tiago Pardal</b> , Omnidea	31
14:50	–	15:10	<b>Bjarke Kronborg</b> , eWind Solutions	33
15:10	–	15:30	<b>Lukas Braun</b> , Enevate	37
<b>15:30</b>	–	<b>15:50</b>	<b>Coffee</b>	
Session: <b>Business Development</b>				
15:50	–	16:15	<b>Matthew Doe</b> , TU Delft	65
16:15	–	16:40	<b>Wolbert Allaart</b> , Ampyx Power	67
16:40	–	17:05	<b>Gordon Planes</b> , T'Sou-Ke First Nation	68
17:05	–	17:30	<b>Corey Houle</b> , Twingtec AG	71
<b>17:30</b>	–	<b>19:30</b>	Closing Remarks of the Day and Free Time	
Session: <b>Modelling, Simulation and Control (Rigid Wing)</b>				
			<b>Alain de Solminihac</b> , ENSTA Bretagne	44
			<b>Damian Aregger</b> , FHNW	45
			<b>Moritz Diehl</b> , University of Freiburg	58
			<b>Henrik Hesse</b> , ETH Zürich	59
Session: <b>Control and Optimisation</b>				
			<b>Curran Crawford</b> , University of Victoria	53
			<b>Christoph Hackl</b> , Technische Universität München	60
			<b>Sanket Sanjay Diwale</b> , EPFL	61
			<b>Ramiro Saraiva</b> , Federal University of Santa Catarina	62
			<b>Marcelo De Lellis</b> , Federal University of Santa Catarina	63
Session: <b>Modelling, Simulation and Control – Soft Wing I</b>				
			<b>Roland Schmehl</b> , TU Delft	39
			<b>M Prabu Sai Manoj</b> , IIT Madras	40
			<b>Julius Berens</b> , TU Delft	47
			<b>Jelte Van Til</b> , TU Delft	48
<b>19:30</b>	–	<b>23:00</b>	Dinner at Art Center Delft, with screening of AWE documentary	

\* Schedule reflects the status at the time of printing of this book and may be subject to change.

## Tuesday, 16 June 2015\*

Time	Auditorium	Page	Lecture Room C	Page
Session: <b>Finance and Networking</b>				
09:30 – 09:50	<b>Bryan Roberts</b> (via video link)	85		
09:50 – 10:10	<b>Guido Lütsch</b> , HWN500 Network	86		
10:10 – 10:30	<b>Roland Schmehl</b> , TU Delft	89		
10:30 – 10:50	<b>Udo Zillmann</b> , Daidalos Capital	90		
10:50 – 11:10	<b>Chris Vermillion</b> , UNC Charlotte	91		
<b>11:10 – 11:30</b>				<b>Coffee</b>
Session: <b>Materials and Implemented Concepts II</b>				
11:30 – 11:50	<b>Emre Dikmen</b> , Kontra Engineering	29	Session: <b>Modelling, Simulation and Control – Soft Wing II</b>	
11:50 – 12:10	<b>Alfred Van den Brink</b> , E-Kite	35	<b>Adrian Gambier</b> , Fraunhofer IWES	49
12:10 – 12:30	<b>Tobias Schneiderheinze</b> , TU Chemnitz	72	<b>Michael Erhard</b> , SkySails	55
12:30 – 12:50	<b>Joep Breuer</b> , Airborne Technology Centre	73	<b>Uwe Fechner</b> , TU Delft	57
12:50 – 13:10	<b>Ingo Berbig</b> , TU Chemnitz	74	<b>Reinhart Paelinck</b> , FlySurfer Kiteboarding R&D	77
<b>13:10 – 14:15</b>			<b>Stefan Wilhelm</b> , Hamburg University of Technology	75
<b>Lunch</b>				
<b>Poster Session (Foyer)</b>				
<b>Group Photo</b>				
Session: <b>Concept and Design</b>				
14:15 – 14:35	<b>Florian Bauer</b> , Technische Universität München	93	Session: <b>Modelling, Simulation and Experiments</b>	
14:35 – 14:55	<b>Stephan Schnez</b> , ABB Switzerland Ltd	95	<b>Ahmad Hably</b> , Gipsa-Lab	41
14:55 – 15:15	<b>Moritz Diehl</b> , University of Freiburg	96	<b>Antonello Cherubini</b> , Scuola Superiore Sant'Anna	42
15:15 – 15:35	<b>Gabor Dobos</b> , Chemotronik Kft. (via video link)	97	<b>Nedeleg Bigi</b> , ENSTA Bretagne	43
15:35 – 15:55	<b>Björn Renneisen</b> , TU Berlin	98	<b>Maximilian Ranneberg</b> , EnerKite	51
<b>16:00 – 16:15</b>			<b>Evangelos Ploumakis</b> , TU Delft	52
Closing Remarks				

\* Schedule reflects the status at the time of printing of this book and may be subject to change.

## Wednesday, 17 June 2015

Flight demonstration at Valkenburg airfield, Katwijk, The Netherlands, optional, depending on local weather conditions.





## **AWEC 2015 is dedicated to Wubbo Ockels, 1946–2014, Pioneer of Airborne Wind Energy**

Unconventional thinker, visionary and pioneer for sustainability – these are just some of the terms that describe Wubbo Ockels, our former chair holder and colleague at Delft University of Technology. In 1985, he became the first Dutch astronaut in space flying for the European Space Agency on the Space Shuttle Challenger. In 1992, he started an academic career that would lead him to inspire and shape generations of students in Delft, creating an awareness for sustainability. One of his most prominent visionary initiatives was the Laddermill, the characteristic cable loop reaching far into the sky, with kites attached to tap into the kinetic energy potential of the jet stream. In 1997, Wubbo patented this idea and explored its potential in the years to come. In 2004 he assembled a dedicated research group which by 2010 had advanced to regular tests of the mobile 20 kW kite power system that is still used as research and development platform today. Yet, this was only one of the many strands of his scientific interests.

We experienced him as a truly inspiring teacher and colleague as well as a relentless activist for a sustainable environment. During lunch breaks at the faculty he would often pose daring engineering questions to staff and stu-

dents to subsequently work out a solution together at the white board. These brainstorming sessions were indeed moments for developing great ideas. Wubbo was also an important facilitator for research and development. He effectively employed his broad network of personal-professional relations and was often central in triggering the interest and support of politicians and industrial decision makers, both on national and on international level. But most remarkable was the passion with which he pursued all these activities.

We would probably not be where we are today if it wouldn't be for his dedication and passion. We were fortunate to have the opportunity to know him and work with him. We are missing him.

The active and alumni members of the kite power research group and supporters: Roland Schmehl, Uwe Fechner, Rolf van der Vlugt, Nana Saaneh, Joris Melkert, Aart de Wachter, Barend Lubbers, Jeroen Breukels, John van den Heuvel, Robin van Kappel, Claudius Jehle, Marien Ruppert, Stefan Haug, Joost Schwooll, Joost Kirkenier, Edwin Terink, Stefan de Groot, Filip H. Saad and Henriette Bier.



*The 20 kW energy kite of Makani Power in front of the San Francisco skyline (27 November 2013).*





*The 600 kW energy kite is being moved out of the Makani headquarters (24 April 2015).*

*The M600 in supported hovering mode (22 May 2014).*





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## Developing a 600 kW Airborne Wind Turbine

**Damon Vander Lind**  
Makani Power

Wind power has been a source of renewable energy for over a century, but only 3% of the world's power comes from the wind. Incremental improvements to existing wind technologies are not enough to make clean energy globally significant.

Makani Power, which has been acquired by Google in 2013, is working to make clean energy accessible for everyone. We are developing energy kites, a new type of wind turbine that can access stronger and steadier winds at higher altitudes to generate more energy with less materials.

In most places around the world, there is a significant increase in wind speed at higher altitudes in the terrestrial boundary layer. Makani's energy kite can reach these more powerful winds without the significant costs of tall towers. In addition, Makani kites are able to capture a low quality resource more effectively by sweeping out a larger volume of air in every unit of time.

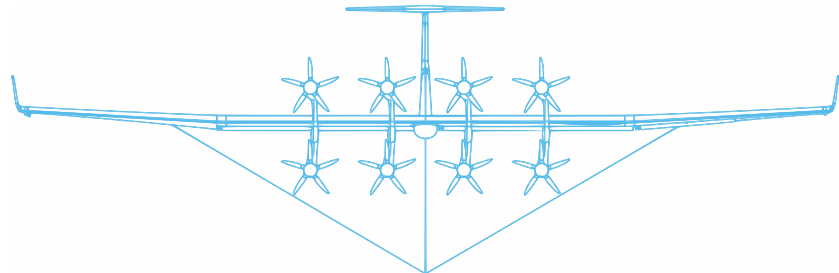
Since the Airborne Wind Energy Conference 2013 in Berlin we have been working hard to design, build, and begin

testing of a 600 kW energy kite, the M600.

Our M600 energy kite comprises a high aspect ratio carbon fibre wing with eight onboard rotors, each of which is used both for generation and for launching and landing. Power is transmitted to and from the ground through a carbon fibre electromechanical tether, and enters the electrical grid through a perch and ground station that the kite rests on when not operating. Because of the robust, predictable nature of this architecture, the M600 is able to operate fully autonomously with a small land footprint.

In this talk I will review the Makani system architecture in general, and will speak about the work involved in the development of the latest Makani 600 kW prototype as a step beyond our previous 20 kW technology demonstrator. Scaling up from small demonstrators to full scale flight vehicle is no small task, and we will share some of the challenges, lessons learned, and unexpected opportunities that we have encountered along the way.

The figure depicts a front view of the M600 energy kite.







*Launch of the Ampyx PowerPlane AP-1B1 (29 September 2012).*



*Ampyx PowerPlane AP-2A1 during flight (photo taken by its tail camera on 12 May 2015).*





PowerPlanes AP-2A1 and AP-2A2 in the workshop of Ampyx Power (9 April 2014).



**Michiel Kruijff**

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## Status and Development Plan of the PowerPlane of Ampyx Power

**Michiel Kruijff, Richard Ruiterkamp**

Ampyx Power B.V.

Ampyx Power develops the PowerPlane<sup>®</sup>, a novel wind energy technology that will eventually allow sustainable production of power at lower costs than fossil-fueled alternatives. It thus has the potential to trigger a paradigm shift in the electricity sector and can accelerate the transition to a renewable energy supply. The technology generates energy by flying a tethered glider-plane attached to a ground-based generator following a cross-wind pattern as the tether unwinds under high tension (plane spirals away from the generator), and rewinds under near-zero tension (plane glides back to generator). Ampyx Power currently operates 2 prototype PowerPlanes (incl. AP-2A1 and AP-2A2, about 20 kW net power production demonstrated) in a test-field in The Netherlands, for which it has obtained type registration and an exemption (license to operate) from the national authorities based on a thorough safety analysis, implementation of a safety system, pilot training and operations manual. The 5.5 m prototypes serve to demonstrate the principle of a fully automatic operation (power generation, → land → launch → power generation), as well as to raise technology readiness level for the certifiable commercial system prototype AP-3 (200 kW) and the to-be certified commercial version AP-4 (2 MW) concept. These systems shall be operational in the coming few years. The AP-3 is the pre-commercial system that is to demonstrate full autonomy, performance and cost predictability, reliability and safety. It also serves as learning platform to meet the

challenges of site development, grid connection, maintainability and 24/7 operations. AP-3 is currently under development following stringent aeronautical design processes, airworthiness and safety standards, which we consider a necessity not only from perspective of certification, but also for commercial viability. The AP-4 shall operate at a Levelised Cost of Energy (LCoE) well below that of conventional wind energy, as predicted by extrapolation of flight data based on validated dynamic simulation over a range of wind speeds for typical sites, coupled to a structural mass model and cost model including capital and operational aspects. Performance efficiency and nominal operation at very high gee load is yet to be demonstrated. This is the topic of current work. Uptime and reliability can be analysed and improved by strict design rigour but have eventually to be demonstrated in the field and will undoubtedly need to improve over time as flight hours and operational experience accumulates. System sizing is done based on end-to-end modelling of design, performance and LCoE. This approach leads not necessarily to a system of optimal power production, but one of lowest energy price. It guides us with trade-offs such as tether diameter selection (air drag losses vs. wear and maintenance cost), tether length (land lease cost vs. cycle efficiency), wing area (total power vs. relative material cost). The presentation will address the current status of Ampyx Power technology, the roadmap forward to a commercial implementation and its rationale.



*Operation of the EnerKite EK02 prototype wing (18 November 2014).*





**Alexander Bormann**

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## Global Economy of Airborne Wind Energy and our Path Towards a Market-Ready Technology

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What are the capital and operational costs, suitable power curves and site-specific wind conditions which define the economic viability of Airborne Wind Energy Systems (AWES) as a competitive source of electricity? And how can developers as small as an SME assess competitive advantages and bring products to the market?

While conventional wind turbines in the MW-range are aiming for larger towers and higher hubs in order to harvest stronger winds, small and mid-size wind turbines struggle to find economic wind conditions.

Ideal typical levelised cost of electricity (LCOE) for EnerKite's EK200 and EK1M systems are assessed using the global wind data from the IRENA wind atlas [1] at 80 m, assuming simplified wind profiles as used for the EEG Reference Yield and based on the design power curve. The results are compared to data available for 100 kW wind turbines including a reference to the economy of today's MW wind turbines.

While size and configuration of an AWES comes along with specific risks and barriers, a roadmap for the market entry is developed based on the specific results. Further, a GIS-based system for the pre-evaluation of potential sites is developed.

Within two years from now the first prototype of an EK200 unit with 100 kW will be brought to pilot operation. For the generation of an adequate basis for permissions EnerKite pushes toward standardisation of the risk assessment and performance estimation. Theoretical models are validated by use of the results of the 30 kW demonstrator platform, which soon will be fitted with the first system for autonomous launch and landing of semi-rigid wings.

The author will illustrate the current status of the developments as well of the joint activities towards system-independent technical guidelines for the design, performance and safe operation of AWES. While certification becomes a minor task for smaller units, permission by aviation authorities is needed to operate an AWES on the 24/365 basis. The development of a standardised risk assessment and risk management includes specific obstruction markings for AWES as a common field of interest and cooperation.

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*Kitemill prototype at Lista airfield (22 April 2015).*





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## Kitemill, a Driver of Second-Generation Wind Energy!

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Kitemill AS

Within the coming years, subsidies for renewable energy solutions (windmills and solar panels) are largely disappearing. The demand for clean energy sources is however increasing and as such cost competitiveness will be a key issue. Airborne wind energy has been identified as a promising second generation technology but there remain technical and commercial challenges for a wide deployment. Kitemill has been running a parallel road by developing its technology as well as preparing the foundation for a commercial deployment. The company is lean organisation with strong industrial backing and governmental support works toward the minimum viable solution for a commercial introduction of the best-suited technology able to change the global energy mix. This paper will discuss the main technical characteristics and the business strategy of the company, as well as regulatory and certification aspects.

The core focus of Kitemill has always been the development of the most effective flying vehicle. It switched early on from soft to rigid materials because of its durability and controllability. Due to an attractive investor model, Kitemill has access to valuable resources from the airspace and defence industry in Norway. This led to an optimal design balancing the aerodynamic and structural requirements of the vehicle. In addition, the control system for the kite turbines was developed for Kitemill. To

realize this technical progress, the communication with civil aviation authorities was a key accelerator rather than a barrier for the development. This parallel track has resulted in Kitemill achieving a fully autonomous 5 kW pilot as well as securing the needed permits and customers for its first commercial plants. The ongoing and future work focuses on the upscaling of all components towards a competitive product in the global energy mix.

Since the beginning, Kitemill have issued a consistent specified need to the Civil Aviation Authorities. This has resulted in a permanent permission to operate to 1 km height in a suitable volume. The process and its conclusion should be useful knowledge to anyone intending to acquire permission to fly kites for the purpose of producing energy day and night in the future.

AWE companies seeking a access to airspace with suitable condition are invited to come to Lista, in Norway, to test the technology. Firstly with access to wind resources and necessary resources, new services from independent suppliers are expected. The approval for operation granted to Kitemill by the Norwegian CAA allows the AWE industry to start with blank sheets developing requirements for the applications, this opportunity should be treated respect by establishing an industry standard. Kitemill invites the industry in a dialog towards in industrial standard for the AWE industry.



*Testing the TwingTec wing in the Alps (23 November 2012).*



*TwingTec's Twing with integrated launching and landing (12 May 2015).*





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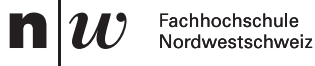
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## Closing the Gap: Pumping Cycle Kite Power with Twings

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Pumping cycle kite power has attracted considerable interest over the last years. Several startups and research teams investigate this technology, particularly in Europe. The basic concept of pumping cycle kite power is well understood and theoretical and experimental investigations have revealed the potential of this technology. However, there are still some key elements of the technology where there is so far no consent among the different teams on how to solve them. In particular, the design of the kite and the launching and landing concept are topics, where very different solutions are followed up. For the kite, several teams operate with flexible tube and foil kites which stem from the surf kite industry. These kites are controlled either by the ground station through a multiline configuration or by means of a control pod below the kite. On the other end of the spectrum, a rigid glider with all the control surfaces of an airplane is used, moving the control authority from the ground station into the wing. As usual all these different approaches have advantages and disadvantages. TwingTec is convinced that the ideal wing for pumping cycle kite power is a synergetic combination of the light weight property of the surf kite with the aerodynamic and structural property of the glider. To this end we have developed over the last three years the twings, an acronym for tethered wing. Recently, we have demonstrated autonomous controlled pumping

cycles with our twing technology.

With respect to launching and landing, passive concepts which rely on the wind over ground as well as active concepts such as a tow launch or a rotating arm concept are studied. We are convinced that only active systems can fulfil the requirements of a commercial kite power system. By investigating a number of different approaches, we came to the conclusion that a system where rotors are integrated into the twing is the best option to fulfil all the necessary requirements. With such a tricopter design, the twing hovers during launching and landing leading to good control possibilities of these critical phases. The transitions into and out of the pumping cycles are done at high elevations enabling ample time and space for these processes. Finally, motor trust during hover can be augmented with the aerodynamic forces of the ambient wind resulting in increased stability of the launching and landing manoeuvre. The talk gives an overview over our TwingPower technology which has been pushed ahead over the last years in the frame work of a joint research project with Empa, FHNW and ETH. We consider TwingPower as the first system where all key elements of pumping cycle kite power including launching, landing and re-launching under various wind conditions in a closed loop process without human interaction can be achieved.



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## Design Considerations and Control Implementation for a Two-Tethered Kite-Based Airborne Wind Energy System

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In order to build a kite-based wind energy prototype, which employs the phenomena of traction power conversion in a pumping cycle, we have applied the system layout and design for a small-scale prototype concept developed in [1]. Several modifications at the mentioned system design have been made to allow us to test the concept according to energy generation via winding the tethers on a winch and to build it in a more cost efficient way via narrowing down the operating conditions and using low cost electronics. The assumed operation conditions are a maximum kite area of 6 m<sup>2</sup> and maximum wind velocity of 6.5 m/s in an altitude range of about 20 m – 40 m. The aim of our work is to provide our design considerations for several disciplines (mechanics, electronics and controls) while building the prototype and to implement several control schemes in the future.

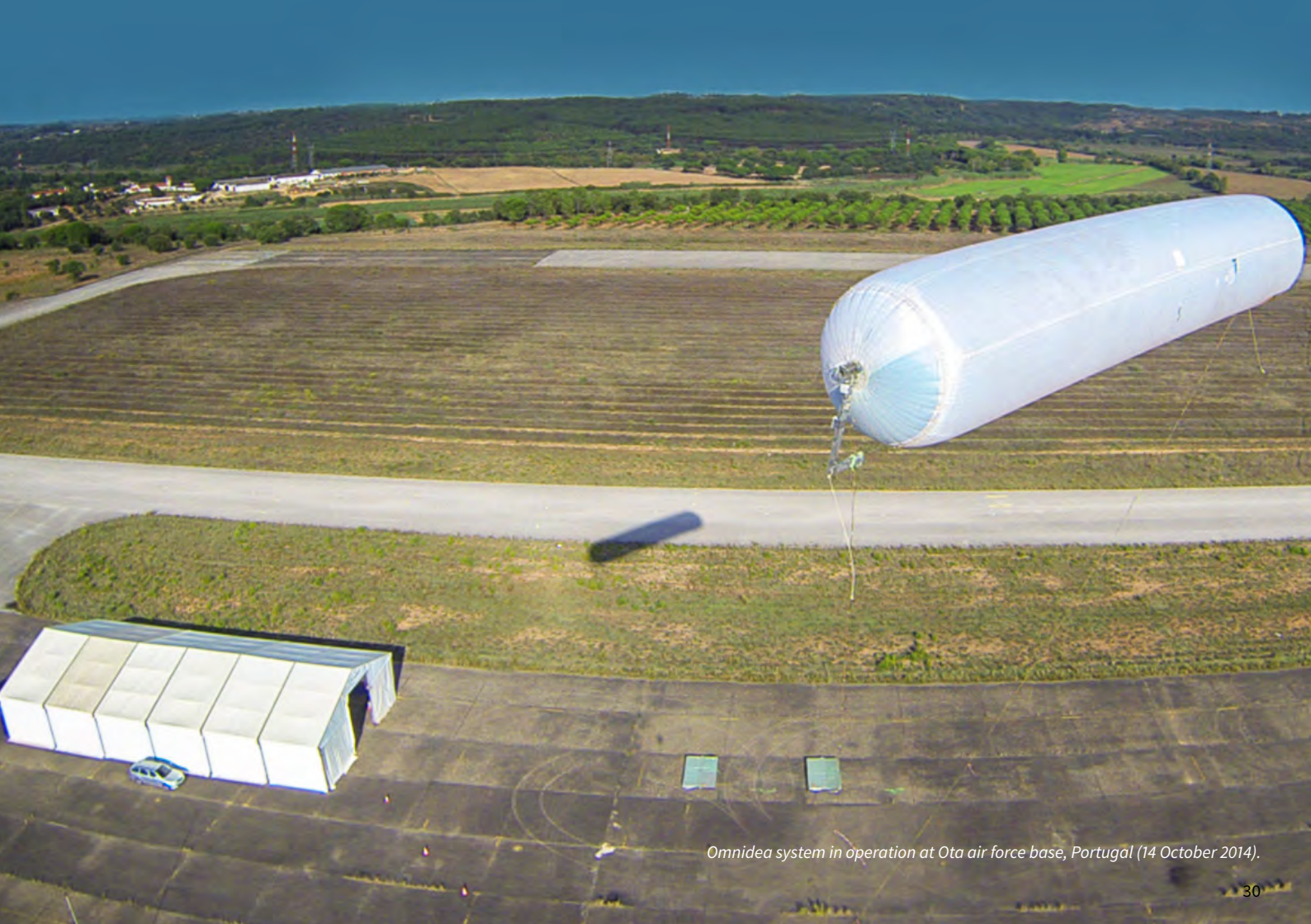
Instead of using a three-tethered leading edge inflatable kite, a two-tethered ram-air inflated kite is being used. In case of using a ram-air inflated kite, both tethers of the kite are responsible for load transmission and steering of the kite. The used steering mechanism, in which the first and second tethers are guided by pulleys, is already known from the literature [1]. The actuation of the steering is carried out via a closed loop synchronous motor and linear motion system combination. In addition to the already-known steering mechanism, both tethers

are wound on a winch for converting the components of traction power (which are linear velocity and force) into components of rotational power (which are torque and angular velocity). While one side of the winch transfers rotational motion to an alternator in only one direction, the other side is driven by an electric motor in only the opposite direction.

An encoder is mounted on the generator shaft and its measurement data will be used to measure the reel out tether length in order to determine the kites position in combination with IMU sensor data. The kite is connected with an on-board IMU which provides measurement data for 3D accelerations and 3 orthogonal angular velocities. The communication is conducted by two wireless devices using “Zig- Bee” protocol. For the beginning, the control strategy developed in [1] in which a closed loop proportional controller which controls the velocity angle of the kite can be implemented on the built mechanism with the additions of reel-in and reel-out phase control strategy and experimental data [2].

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*Omniidea system in operation at Ota air force base, Portugal (14 October 2014).*



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## Analysis of Experimental Data of a Hybrid System Exploiting the Magnus Effect for Energy from High Altitude Wind

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The determination of the operating conditions for a hybrid lighter-than air platform with aerodynamic lift from the Magnus effect for the system being developed by Omnidea was one of the objectives of the test campaign conducted at the Ota air force base, Portugal. Tests were conducted for a period of one year using an airborne module (ABM) in the form of a cylinder 16 m in length and 2.5 m in diameter [1]. This presentation describes results obtained from the analysis of wind data to assess the energy that can be extracted from the wind by the system and evaluates the nominal operating conditions for constant operation under most wind conditions.

The system, comprised of an ABM incorporating a range of sensors for measuring atmospheric parameters as well as the performance of the ABM, was operated to gather data to characterize the behaviour of the ABM under varying condition and wind speeds in the range of 3 to 12 m/s. The results obtained serve to calculate the experimental values of  $C_L$  and  $C_D$  in order to validate the theoretical models used in the initial study [2,3]. Wind data acquired during the period November 2013 to October 2014 with a ZephIR 300 Lidar with an operating range of up to 200 m

are compared with WRF model forecasts for the same period. Analysis of test results and wind data indicate that adequate aerodynamic force for the production of power can be generated over wind speeds ranging from 3 to 20 m/s. Values of the force density over a range of rotation speeds are discussed. The amount of energy that can be generated is demonstrated by considering the variables that can be adjusted to suit prevailing conditions. Finally a new prototype comprised of a cylinder 16 m in length and 3.7 m in diameter with refinements of components is described for tests scheduled for the third quarter of 2015.

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*Manual launch of a Genetrix surf kite equipped with the TU Delft Kite Control Unit (24 October 2011).*





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## eWind Solutions Company Overview and Major Design Choices

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eWind Solutions is a new player in the small airborne wind energy space. We exist to help people reach their goals by providing them with affordable clean energy. This presentation will introduce you to the company and key people from the management team. eWind Solutions is located at the Oregon Technology Business Center—a business incubator in Portland, Oregon, USA. From here we are developing and testing our technology. Our presentation will focus on our major design and business decisions, as well as our expected development trajectory. These decisions include low altitude flight, ground generation, rigid wing, single tether, leasing business model, grant financing, on-shore deployment and grid connection.

Our most noteworthy divergence from the major players is an explicit and direct focus on operating at low altitudes, namely below the FAA guidelines of 500 feet. This means we are developing a smaller unit (10 kW). This choice enables us to more affordably conduct prototyping as well as build a market outside the regular competition. Further, the design choice allows quicker deployment and usability in more adjacent markets. Low altitudes require high manoeuvrability and still high lift. They put additional stress on our requirements for a light kite, which is why we pursue ground generation. This enables us to use more robust components, enabling a cheaper and more reliable ground station optimised for low rotational speed.

A rigid wing provides improved aerodynamic perfor-

mance and a more durable kite. Additionally, it better enables the use of a single tether, as the tether is just for force transmission and not for flight control. With a smaller kite removal of a tether is a significant advantage to reduce weight and drag, thus leading to increased power output.

With a small product for deployment at small residential and commercial properties in rural areas, the owner would typically not have available cash to outright purchase the unit. To make the product easier to buy, we will be providing our customers with an optional leasing model.

Our funding will initially depend on grants; to date we have received 100,000 USD. We have found that the industry as a whole is so new that attracting private investments is very difficult. We hope this will change during 2016.

Our customers are on land and our product will be on land, near the place of consumption. This reduces complexity and installation costs. Further, it enables grid connection and thus our ability to tap into various governmental net metering incentives for wind power. We intend to pursue this, knowing that it will require certification. As such, off-grid applications are likely to be the first usage.

We will include a broader discussion about pros and cons in regards to the ability to operate above and below the FAA limitations.

*e-kite 50 kW ground station (17 April 2014).*





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## Design of the e-50 Ground Station

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e-Kite is a new player in the AWE industry and founded in 2013 by a team with a strong background in the development of direct drive wind turbines. The main focus of development is a commercially viable two-line kite power system with a robust 50 kW ground station and a lightweight wing. A high energy extraction efficiency is achieved by implementing a pumping cycle with energy production phase, efficient reel-in process and using a direct drive generator. Because of its mobile ground station, the kite power system is particularly suitable for companies and farmers in remote locations, army, festivals, etc. Since the kite altitude is not exceeding 100 m the system can be operated in compliance with current airspace regulations. A high safety level is achieved by using two traction cables and implementing a robust steering mechanism at the ground.

At the core of the ground station is an efficient direct drive generator with electrical field excitation and integrated differential steering system. This system is located in the generator rotor and mechanically connected to the two traction cable pulleys. A high reliability is achieved

by using industrial grade components which have proven to work well in the wind industry. A full back-2-back converter controls both generator and grid connection. An industrial controller is used with a robust sensor/actuator network. The complete ground station can rotate and position itself towards the kite by an integrated yaw system. Cable spooling is realized by a robust system with minimal pulley guidance and targeting to reduce tether wear. All systems (i.e. generator control, control system, kite, steering, yaw, cable spooling etc.) are tested against design specification and fully operational.

A fully automated system is foreseen for vertical launching and retrieval of the kite to support autonomous operation. Field testing is ongoing since Q3 2014 at a dedicated test location in Lelystad, The Netherlands. Several milestones are passed so far for first energy production and longer than 1 hour autopilot flight. The next steps in system development include achieving a 24 hour autopilot control, upscale the rigid wing kite capable of producing 50 kW rated power and implement the new vertical launching & landing system.





*Testing the TU Delft 20 kW kite power system at Valkenburg airfield, Leiden, The Netherlands (12 April 2012).*



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## Preparing the Road for 24 Hours Flight Operation of a Pumping Kite Power System

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Based on the unique 20 kW technology demonstrator of the Delft University of Technology, a private-public partnership targets for further improvement of the system.

Therefore, the team of enevate b.v. systematically improves the KPS's reliability and robustness with the aim of demonstrating 24 hours of continuous automatic operation. To achieve this goal, system components are being redesigned, control algorithms are made fault-tolerant and capable of adapting to changing wind conditions.

The kite is steered and de-powered by a Kite Control Unit (KCU), suspended about 10m below the kite and connected to the main tether from the bottom and to power and steering lines from the top. As this main tether does not conduct electricity an airborne power supply is required. It consists of a wind turbine, which is directly mounted on the KCU. Both, maximum power point tracking and power management are implemented within the KCU using a single printed circuit board. The latter manages all power related tasks comprising a highly available power supply, which is guaranteed by a battery back-up. The central on-board control system of the KCU is composed of a three-processor logic, working on three separate layers. To achieve high reliability, these layers can be bypassed regarding the level of criticality, enabling controllability of the system in case of a subsystem failure.

The top-layer runs a Linux operating system, handling the communication and the sensor data collection. In the fu-

ture all flight path computations will run on this layer. The second layer, an ARM micro-controller, manages the positioning of the two drive trains, providing the possibility to feed-in manual steering override commands. The third layer is transforming the position control commands of layer two into motor currents. All layers are designed such that they cannot block each other in the top-down direction, which implies that faulty data can not affect the operation of the layer underneath.

Although this architecture achieves a high level of reliability it cannot ensure that the system does not experience faults or failures during automatic operation. Therefore, the flight control system has to be able to recognise undesired states and to react adequately without human interaction. This ability is realized by employing a Health Supervisor that acts as a guarding loop. It regularly checks the system for certain health symptoms such as irregularities in the KCU, inconsistency in the predicted flight path or other hazardous flight dynamic states. Based on those symptoms the Health Supervisor assigns a certain health status to the system. The supervisor consequently has the authority to overrule the autopilot in order to initiate automatic counteractions. The counteractions thus cover a range of minor changes in the system behaviour and updates in the desired flight path as well as immediate landings or emergency touchdown manoeuvres.





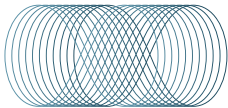


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## Traction Power Generation with Tethered Wings – A Quasi-Steady Model for the Prediction of the Power Output

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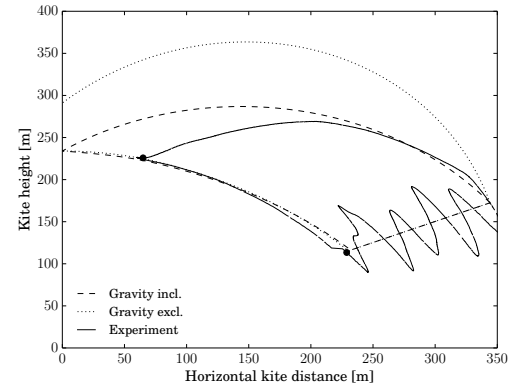
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The traction force of a kite can be used to drive a cyclic motion for extracting wind energy from the atmosphere. We present a novel quasi-steady modelling framework for predicting the power generated over a full pumping cycle. The cycle is partitioned into traction, retraction and transition phases, each described by an individual set of analytic equations [1]. The effect of gravity on the airborne system components is included in the framework. A trade-off is made between modelling accuracy and computation speed such that the model is specifically useful for system optimisation and scaling in economic feasibility studies. Computed results are compared to experimental measurements of a 20 kW kite power system operated up to a cable length of 720 m [2]. Computation and experiment agree reasonably well, both at moderate and at high wind speeds, indicating that the effect of gravity has to be taken into account for a predictive performance simulation.

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*Kite position in side view over a full cycle. The dotted line represents the massless model, the dashed line represents the gravity included model and the solid line the experimental data. Moderate wind velocity case.*

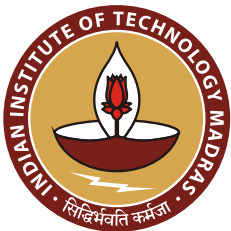


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## Quasi-Steady Fluid Structure Interaction Model of the Surf Kite

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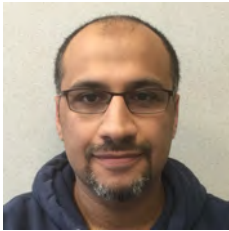
Airborne wind energy is a new and promising class of wind energy systems. The core concept of the traditional wind mills was born ages ago and is still a rigid design compared to this new class of wind energy extraction devices. In the present study, we have used a kite based airborne wind energy system in which kites are employed to extract energy from the air and supply this mechanical energy into ground generator for further use. Our main focus in this study is to develop a reduced computational model to investigate the parametric space in order to maximize the extracted force values.

In this study, Fluid-Structure Interaction (FSI) model of the Kite North Rhino [1] is developed. Airfoil cross sections of the kite with various geometrical factor like camber and thickness as well as for different angle of attacks are solved for aerodynamic coefficients using commercial solver ANSYS-FLUENT. With this results, a fit function is estimated in terms of above variables. A 3D potential flow based solver along with above 2D results is used to calculate the aerodynamic loads [2]. This is implemented in an open source Matlab toolbox called Tornado [3]. Tornado uses an extended version of the potential flow 3D vortex lattice method and has been written by Prof. Tomas Melin from KTH, Sweden. The structural modeling is done using the commercial solver ABAQUS (Solver-FEA) with a finite element analysis (FEA). The CAD model

of the kite is developed in SolidWorks and imported to ABAQUS. For FEA, three dimensional two node beam elements are used to model inflatable leading edges, struts, tips and trailing edges and three node triangular shell elements are used to model canopy structure of the kite. A mesh convergence study of the model has also been performed. A coupled FSI solver is developed integrating these two in a loosely coupled scheme [1]. The aerodynamic loads are updated on the structural nodes in the coupled solver at each time which we call as a quasi-FSI model. For a given wind speed, angle of attack, camber and thickness values, the aerodynamic loads that are calculated from the aerodynamic model are transferred to finite element model and the information of the deformed geometry is obtained from the FEA. This information is fed into MATLAB algorithm for the set of loads to run the next iteration. This process is repeated till convergence. This quasi FSI model is used to investigate the system's parametric space in order to optimize the total force extracted.

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## Éoliennes Volantes: Airborne Wind Energy Activities at the Gipsa-Lab

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Gipsa-Lab, Grenoble Institute of Technology

During the last 4 years, several interesting theoretical and practical actions were carried out by a team of Gipsa-lab at the Institute of Technology in the domain of Airborne Wind Energy. In addition, two Ph.D. theses were defended in 2014 [1].

The first thesis, by Mariam Ahmed, proposes several control schemes to a kite generator system based on model predictive control and virtual constraint control dedicated for periodic systems. In addition, she has focused on grid integration of these systems. The mechanical power generated by the kite's traction force is transformed into an electrical one via a permanent magnet synchronous machine and injected in the grid or used to supply an isolated load after passing a power electronics interface. These control schemes have been developed for grid connected or stand-alone operation and are tested in a hardware-in-the-loop simulator [2].

In the second thesis, Rogelio Lozano Jr. has worked on the modelling and control of a kite system. He proposed an observer-based control for energy production with a rigid wing generator system in a yoyo trajectory. He has also studied flying kites in the absence of wind using the reverse pumping principle. In addition, an indoor wind tunnel has been built in order to validate the different prototypes and control schemes proposed. Some outdoor tests have been performed [3].

In this presentation, an overview of the Gipsa-lab's present and future activities in the domain of Airborne Wind Energy will be given. Recent results obtained for the energy production control of an experimental Mag-

nus cylinder in presence of wind gusts will be presented. A mathematical dynamical model of a Magnus cylinder has been proposed and experimentally identified. An observer-based control strategy, which has been successfully applied for a rigid wing prototype, has been validated successfully in a simulation environment. This control is implemented and validated experimentally in our indoor wind tunnel.



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## Modelling and Design of Off-Shore Floating Platform for High Altitude Wind Energy Converters

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Wind turbines represent one of the cheapest and well-known types of renewable energy generators. Given the huge availability of windy offshore locations, in the last years there has been a growing interest towards offshore wind farms. Existing offshore turbines are usually deployed in shallow waters and are fixed on the seabed, nonetheless a few prototypes of floating wind turbines exist. The high cost is still a limiting factor to the commercial development of floating wind turbines.

High Altitude Wind Energy Converters (HAWECs) represent a promising new technology that aims at providing low cost renewable energy by exploiting high altitude winds. It has been predicted that an HAWEC can be up to two orders of magnitude lighter than a conventional wind turbine featuring the same rated power. However, HAWECs require a large amount of airspace, they present safety issues, and they might also face the so called Not-In-My-BackYard (NIMBY) effect.

The installation of HAWECs in marine offshore locations makes it possible to get around safety and NIMBY issues. Among the possible marine layouts, a particular case of interest is the one that considers a HAWEC system installed on a slack-moored floating platform, which can be installed in deep waters that are the cheapest and the most abundantly available.

Thanks to their lightweight and the favourable loading conditions, floating offshore HAWECs can be potentially much cheaper to deploy than offshore traditional tur-

bines. In particular the dimension of the floating platform that is required to sustain the HAWEC structure can have relatively small mass and encumbrance. In order to properly address the problem of design and verification of a deep water offshore HAWEC installation, we developed a simplified model which couples the hydrodynamics of the floating platform, the aerodynamics of the airborne system and the electromechanics of the power unit.

This paper provides a first insight into the hydrodynamics of a full scale floating HAWEC. Two different kinds of platform are considered. The first is the so called "flat" platform, and the second is the so called "funnel" platform. The flat platform is basically a flat-bottomed barge, while the funnel platform is composed by two parts: a large upper part that holds the HAWEC, and a lower ballasted part aimed at lowering the centre of gravity, improving the overall stability and reducing the pitch and roll wave-induced motions. The funnel layout is specifically designed for HAWEC applications and analysed here for the first time. For both platforms the hydrodynamic coefficients and the time response to incoming waves are provided. The effect of the platform motion on the kite control is also analysed. As a result, a numerical methodology is provided to compare different types of platform. Finally, a roadmap to a full scale offshore HAWEC is proposed, starting from a theoretical analysis, through simulations, small scale wave-tank experiments and full scale prototype.



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beyond the sea®

## A Quasi-Analytical 3D Kite Tether Model

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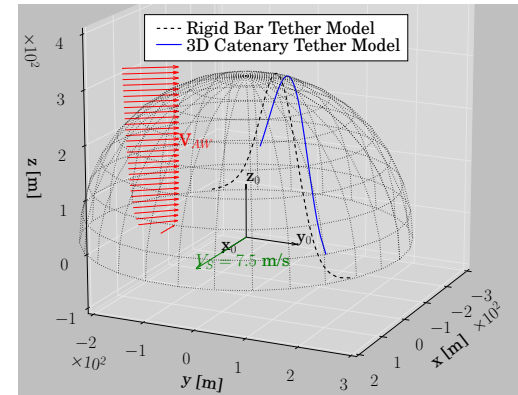
This work is part of the beyond the sea® research program led by the LBMS laboratory of ENSTA Bretagne. The whole project attempts to develop tethered kite systems as an auxiliary propulsion device for merchant ship. One of the main unsolved issue unsolved concerns ship-kite mechanical interactions.

In order to model these interactions, the priority is to characterize the tether behavior. A first step is to develop a method dedicated to solve any static flight equilibrium of the kite and the tether system. Consequently, taking into account the wind gradient effect, a model based on the catenary model is proposed. This model has been developed both in position and force formulations. Aerodynamic load on the tether is assumed to be constant along the tether. Furthermore, the kite is considered in a static flight with a constant lift-to-drag-ratio.

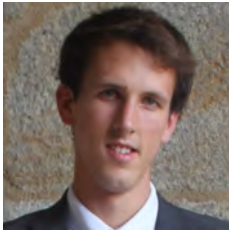
For a given kite position, the position formulation allows to predict the tether shape and all forces within the tether. Coupled with the kite model, this formulation is useful to obtain the whole static flight solution domain. Therefore, the flight window's edge is defined and is compared with the flight window's edge obtained with a single rigid bar tether model (cf. Figure 1). Moreover, tether forces at the kite location and at the attachment point are also compared. Significant differences are shown and demonstrate the relevancy of this model.

By contrast to the position formulation, the force formulation is fully analytical. Providing the tether forces, the

kite location is obtained. Assuming the aerodynamic load on the tether is negligible compared to its weight, the minimum wind velocity at kite location which allows a downwind static flight is expressed with a very simple formula. Coupled with the wind gradient model, the corresponding wind velocity at the measurement altitude (currently 10 m) is obtained. Then, using this methodology, the existence of an optimal tether length to fly with a minimum wind velocity is demonstrated.



Flight window's edge obtained with the 3D catenary tether model (blue line) compared to the flight window's edge obtained with a single rigid bar model (black dashed line).



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## Kite as a Beam – An Analytical 3D Kite Tether Model

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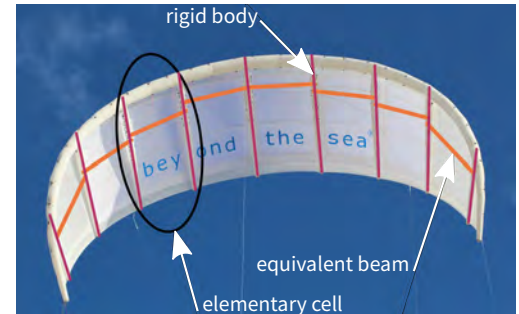
This work is part of the beyond the sea® research programme lead by the LBMS laboratory of ENSTA Bretagne in collaboration with the French skipper Yves Parlier. The project attempts to develop a tethered kite system as an auxiliary device to the propulsion of merchant ships.

To design new large wings, flow structure interaction and non-linear stiffness must be taken into account. Today, fully coupled FEM/CFD simulation of a soft structure is possible but still requires too much computational time for design purposes. Nevertheless, Breukels [1] and Bosch [2] developed different structural models considering rigid bodies, springs and, more recently, membrane elements. In this context, the purpose of this study is to consider the kite structure as being only an assembly of equivalent beams to reduce computational time as much as possible.

A kite can be considered as a succession of several elementary cells distributed along the span. Each one is composed of a segment of the inflatable leading edge, two lateral battens and the corresponding portion of canopy. From a static point of view, this elementary cell is exposed to a pressure distribution and suspended at its four corner points.

A suitable method is used to reduce the stiffness of each elementary cell to the one of an equivalent beam parallel to the leading edge. Several nonlinear FEM analyses (Abaqus™) were carried out for each elementary cell exposed to a homogeneous pressure followed by a set of linear perturbation computations. Consequently, mechanical properties of equivalent beams (axial, bending,

and torsion stiffness, shear transfer coefficients) and their locations were identified. Thus, a whole kite structure model was built as an assembly of beams connected with rigid bodies as illustrated in the figure.



This simplified structural model can be coupled with a fluid model, like the 3D lifting line method of Leloup [3] to provide information about kite behaviour.

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Materials Science & Technology



## Hardware in the Loop Testing for Autonomous Airborne Wind Energy Systems

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In the emerging field of airborne wind energy a crucial part of the system development is the validation of analytical results and simulation data. Often there exists a gap between theory and real life test data because of unsteady wind conditions or hardware constraints for example. At present, classic design and testing strategies for airborne wind energy system development include analytical calculations, modelling, simulation, wind tunnel testing, tow testing or field testing. While the simulator approach allows for full system observability, it often lacks exact modelling of system constraints and dynamics. Typical problems encountered during field testing can be wind availability or limited repeatability of similar test conditions. A possible solution for those problems is the integration of real hardware subsystems into simulation, called hardware in the loop (HIL) testing. In a HIL simulation one splits the system into two parts, one subpart is referred to as the system under test (SUT). This part can be a controller or an actuator that exists in reality. The other subpart is referred to as the plant simulation. This part is a mathematical model of a dynamic system that interact with the SUT.

A ground generation based airborne wind energy system consists in general of three main components: The ground station, the tether and the kite. For the particular

experimental HIL setup a testing method including two ground stations was developed. The two ground stations are directly connected by means of two tethers. Therefore a physical force interaction between the two ground stations is possible. One ground station acts as the SUT whereas the other ground station acts as a kite emulator. Steering inputs to the ground station (SUT) result in certain tether displacements. These tether movements are fed to the simulator, which in turns calculates the resulting tether forces at every simulation time step. The simulator uses the vortex lattice method combined with a tether dynamics model to calculate the virtual line force values [1]. These calculated forces are then translated into physical tether pulling forces by the second ground station. The physical line forces translate into line movements on the ground station (SUT) which closes the hardware loop.

The setup finally results in a weather independent laboratory test environment for extensive system testing. It is used from simple ground station parameter tuning to autonomous pumping cycle flight path strategy improvement.

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*Mutiny/TU Delft V2 Leading Edge Inflatable  
tube kite finite-element model.*





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## Dynamic Nonlinear Aeroelastic Behaviour of Flexible Wings in an Airflow

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In the development of pumping cycle based airborne wind energy systems, the usage of kites has been a popular choice. In order to improve the efficiency and controllability of the kite, its design needs to be optimized for power generation. These days, kite designs originate from kite-surfing or paragliding. Here safety is the driving design criterion. Therefore it is expected that a redesign for energy generation will yield an improved efficiency of the kite power system. In order to perform this redesign, the flight behaviour of the kite needs to be investigated. This research project builds on previously existing work [1,2,3] in an effort to develop a fluid-structure interactions model that is able to simulate the behaviour of the kite in flight. As this is a very complex task, the analysis tool that is developed in this project is focussed on the local deformation behaviour of this wing when it is suspended in an airflow. The tool is able to capture both the dynamic and the static nonlinear aeroelastic behaviour of the wing at reasonable computation speed.

As the nonlinear aeroelastic behaviour is a very complex and time consuming problem to solve, the algorithm used separates this model from the dynamic flight simulation. A linear simulation is used to simulate this in-flight behaviour. At discrete intervals this linear simulation is corrected using a nonlinear aeroelastic model. This leads to a significant reduction in computational requirements as the nonlinear aeroelastic problem is solved for a limited number of iterations, while it leads to an acceptable

level of accuracy for the description of the dynamic behaviour of the kite.

For the structural modelling of the wing, a previously developed finite element solver is used [1]. This solver uses triangular shell elements to describe the wing structure. It allows for application of different aerodynamic load models. For the purpose of this project the wing is modelled using only these elements, while previously a complete LEI structure was modelled [1]. The applied aerodynamic model [2] is a correlation model that relates a minimum set of parameters to come up with an estimate of the aerodynamic load. The validity of this model is limited but the load estimation can be straightforwardly replaced by a different method for modelling the aerodynamics.

In this project the existing work on aeroelastic modelling was extensively verified. It provides with a good backbone for further research into fluid-structure interactions for kites or other flexible membrane wings because of the modular design philosophy.

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## Dynamic Model of a Bridled Kite Including Rotational Deformations

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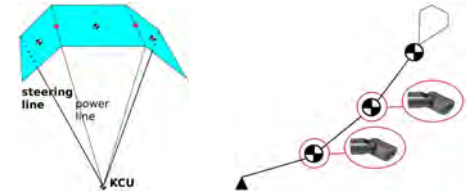
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This study describes a dynamic model of a kite as a main component of an Airborne Wind Energy system for cross-wind operation. The generated power depends largely on the actively controlled flight path of the kite [1] which is why a fast and accurate dynamic model is of vital importance for optimising the governing control algorithms. The model includes basic rotational deformations of the wing (torsion and bending) while being real-time capable for control purposes. It was built in SimMechanics [2] and consists of three rigid plates, interconnected by gimbal joints, which allow for three rotational degrees of freedom (RDoF) per joint (plate intersections physically ignored), as shown in the left figure. To model flexibility, a spring and a damper were associated with each RDoF. A body-fixed coordinate system was defined for each plate to determine local apparent wind velocity and corresponding aerodynamic lift and drag forces. Apparent (centrifugal/coriolis) and gravity forces were implicitly defined in a so-called machine environment. Realistic steering was accomplished through rigid steering lines of variable length, attached to a Kite Control Unit (KCU). The front (power) lines were kept at constant length. The atmospheric wind model (without turbulence) and aerodynamic characteristics were taken from an existing 4-point-mass model [3]. The basic tether model consists of two point masses (2RDoF universal joints between tether segments) and is shown in the right figure. Reeling out or in at constant speed is implemented.

A robust kite model was developed carrying realistic steering, the simulations reproduce the main deformation modes (bending/torsion) and have the potential to run real-time, making the model suitable for control simulation purposes. The kite was steered into eight-figure trajectories, using a planned trajectory and a controller algorithm for the tracking error [1]. Results for angle of attack, traction force and flight velocity were validated by simulation results of a 4-point-mass model (which in turn has been validated against measurement results [3]) carrying the same dimensions, through optimisation of the spring constants in the gimbal joints connecting the kite plates.



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## Recovery Phase Analysis of a Pumping Kite Wind Generator

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The pumping cycle of a kite wind generator distinguishes two phases [2]: the generation phase, in which the tether is reeled out from a drum due to the aerodynamic forced acting on the kite and the recovery phase, where the tether is reeled in back onto the drum. During the first phase, the energy is extracted from the wind and converted to electric energy by a generator, and in the second one, energy is consumed because the generator is used as motor to pull the kite back in.

Because pumping kite power is still an emergent technology, only few experimental setups are operational and therefore, it is difficult to accurately verify the achievable energy extraction. Several theoretical approaches have been proposed to approximate the mean value of the power extraction of a kite in the generation phase [1,4,6,7]. These approaches have been compared in [8] but have still not been verified experimentally.

On the other hand, experimental observations show that the efficiency of the pumping kite systems is strongly dependent on the effectiveness of the recovery phase. A detuned or suboptimal recovery phase leads very fast to a negative net power output. However, only few studies exist on this topic [3,5,7]. In the present work, the recovery phase of the pumping kite wind generator is studied. For the recovery phase, three different approaches can be identified, which are called here fly to zenith (F2Z), pitch and pull (P&P) and free and pull (F&P). In the current work, only the first two techniques, F2Z and P&P, are studied.

The analysis focusses on the calculation of the mean

power that is required to return the kite to the initial position of the pumping cycle. The analysis is approached as a minmax optimisation problem (minimum energy consumption, maximum reel speed). This information is then used to obtain the net power extraction of the whole pumping cycle. It is also expected that the results can be used to support the dimensioning of the electrical machine in order to obtain an optimal pumping cycle with maximum net power extraction.

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*EnerKite team in front of the EK30 ground station (17 July 2014).*



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## Estimation, Optimisation and Validation of Power Curves for Airborne Wind Energy

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Together with the financial aspects such as capital cost and operational cost, the power curve of a wind energy power-plant is the defining characteristic to deduce the economic viability for site specific wind and weather conditions.

Power curves for horizontal axis wind turbines have been studied, validated and optimized for decades.

This study is concerned with the detailed power output of two different airborne wind energy (AWE) systems that are using the YoYo principle.

Until now, no detailed and fully-dynamic model has been used to optimize, validate and publish a complete power curve for a YoYo converter.

Here, a detailed model of the EnerKite EK30 AWE prototype [1] is described and used to validate, obtain and compare power curves for two different wing technologies: Ram-Air Kites need a certain angle of attack to keep their shape. They are stiff with regard to the angle of attack due to their bridle. In comparison semi-rigid wings, which are not in need for a stiff bridle in all conditions, can be directly retracted.

The power curve of currently employed ram-air wings is compared to experimentally obtained power measurements from test flights with the EK30 and a LIDAR wind measurement system. The validated simulation model allows to estimate and optimize both the machine design and operation and the power curve for the EK30 semi-

rigid wings. With appropriate tether forces and torques more than  $4 \text{ kW/m}^2$  wing-surface at wind speeds of  $7.5 \text{ m/s}$  can be achieved.

In the second part, a fast but detailed system model based on a point-mass model described in [2] is presented. The model is used for rapid AWE design and power curve evaluation and compared to the detailed dynamic simulations. The approach is similar to the methods used in [3]. This model is used to gain insight into the effects of realistic altitude-dependent wind conditions, site constraints and different ground station and wing designs.

With regard to future codes for certification, the authors are proposing a standardized altitude depending representation of power curves which allows for the estimation of yield with respect to the time and altitude dependent nature of the winds.

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## Enhanced Kinetic Energy Entrainment in Wind Farm Wakes – LES Study of a Wind Turbine Array with Tethered Kites

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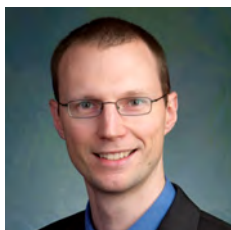
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Wake effects in wind farms are a major source of power production losses and fatigue loads on the rotors. It has been demonstrated that in large wind farms the only source of kinetic energy to balance that extracted by the turbines is the vertical transport of the free-stream flow kinetic energy from above the wind-turbine canopy [1]. In the present study, the possibility to enhance such process by introducing kites in steady flight within the wind-turbine array is studied with numerical simulations. An aligned array of four wind turbines is simulated within the LES framework available in the computational fluid dynamics (CFD) code FLUENT. The turbines are placed in a pre-generated turbulent atmospheric boundary layer (ABL) and modelled as actuator discs with both axial and tangential inductions, to account for the wake rotation [2]. The inter-turbine spacing is six rotor diameters while a kite is suspended three diameters downwind each wind turbine, 0.25 diameters above the top-tip height. The kite is modelled as a body force on the flow, equal in magnitude and opposite in direction to the vector sum of the lift and drag forces acting on the kite. The introduction of the kite system is found to have a significant effect on the power generated by the wind turbine array primarily

due to the enhanced kinetic energy entrainment in the lower part of the ABL. The simulation results, consistent with previous findings [3], clearly suggest that the applied forcing is capable of redirecting the free-stream flow and assist wake recovery. Follow-up research on kites placed in a "fully developed" [4] wind turbine array boundary layer, as well as coupled CFD/RBD (rigid-body dynamics) simulations on kite flight paths (i.e. crosswind) in terms of kinetic energy entrainment in the wake is suggested.

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## To Fly a Kite, Glider or Prop Wing?

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Airborne wind energy is still in its infancy, as evidenced by the variety of technology concepts being pursued by companies and research groups. Many considerations apply when choosing a concept to adopt, including not just operational energy harvesting efficiency and costs, but also take-off/landing operations, noise generation, design elements affecting social acceptance and power output characteristics affecting grid integration. Some concepts place conventional rotors on aerostats (or use the aerostat itself as a rotor) which fundamentally limits power capture as they cannot take advantage of cross-wind operation. Autogiro type concepts use a rotor for both lift and energy capture, so that the rotor must operate at significant yaw angles again reducing efficiency. The remaining concepts can be grouped into either rotor wing or pumping-mode subsets and are the subject of this paper. Rotor wing concepts fly at a constant tether length and use rotors as turbines to extract energy in the generation mode and as propellers for takeoff/landing. Pumping-mode devices use kites or rigid gliders to pull out a tether from a ground-based generator in generation mode, and then use the same electrical machine to reel in the tether during a shorter duration retraction phase.

A dynamic model of these three classes of concepts has been implemented using a Lagrangian dynamics formulation to capture kite and tether inertial effects. Kite attitude dynamics are not included; rather the angle-of-attack and roll angles are used as system control variables, with tether azimuth and zenith angles describing wing/kite position. Aerodynamics models for all three

based on 3D wing theory force the system. The kite is assumed to be rigid, while the rotor forces and power output on the rotor wing are computed using look-up tables from blade element momentum theory pre-computed solutions indexed with tip speed ratio  $\lambda$ . A logarithmic boundary layer profile is used to define ambient wind speeds. Comparing results to previous studies shows the model to have reasonable accuracy for the intended system study.

The dynamic equations governing the systems are implemented in an optimization framework (Matlab package GPOPS) which allows for simultaneous optimization of the flight paths, rotor control variables (flight time of cycle, angle-of-attack rate, roll rate, tether payout acceleration for pumping-mode,  $\lambda$  for rotor wing) and system sizing variables (tether diameter, wingspan, rotor diameter). Average power output is used as the objective function with system mass computed from required tether diameter to sustain the loading. A parametric optimization study is carried out to compare concepts at a nominal rated power of 1 MW. Tether lengths around 1500 m lead to flight altitudes around 500 m in the assumed Class 5 wind speed condition (10 m/s @ 10 m height with 0.1 power law exponent). Multiple initial flight paths are used to demonstrate the presence of local minima. System performance results are used to discuss the relative performance of the concepts and inform future optimization work to include more detailed system mass and cost estimates in a multi-point objective function formulation with multiple flight conditions.

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*MS Theseus with SkySails system.*



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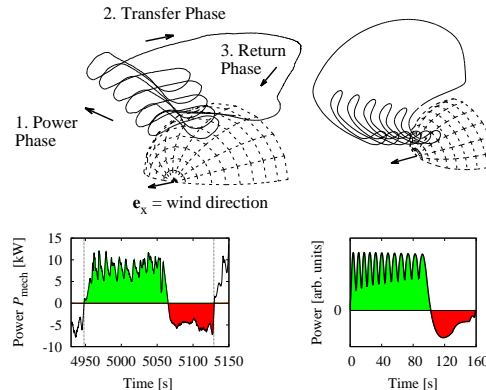
## Automatic Control of Optimal Pumping Cycles in Airborne Wind Energy

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The development of airborne wind energy plants demands for control setups, which allow for fully autonomous power generation cycles. Further, in order to achieve an economic operation, optimisation of the average power output is a crucial design goal. This contribution presents optimisations based on an experimentally verified model. The results aim at being directly implemented to the small-scale prototype in the near future.



Three-dimensional flight trajectories and corresponding time series of mechanical power. Experimental data from autonomous flight operation [1] (left), optimisation result based on this data as initial guess (right).

The first part deals with a simple model for the tethered kite flight dynamics [1], which will be used for both controller design and cycle optimisation. The validity of the model will be discussed by presenting experimental flight results from the SkySails 55 kW small-scale functional prototype [2]. Further, the autonomous operation of pumping cycles based on flight control for pattern eight-down and winch operation algorithms will be briefly summarised. The second part aims at optimisation of the average power output, which is computed by integrating the mechanical energy given as product of tether reeling speed and tether force. The optimisation of complete pumping cycles is implemented as optimal feedforward control problem using the CasADi package [3]. The focus of simulations is clearly put on improvement and further development of operational flight algorithms applicable to the small-scale functional prototype.

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*TU Delft team launching a Genetrix kite on the Maasvlakte2, The Netherlands (22 June 2012).*



# Flight Path Planning in a Turbulent Wind Environment

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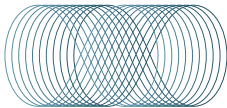
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**KitePower**

**TU Delft**

Converting the traction power of kites into electricity can be a low-cost solution for wind energy. Kite power systems in pumping mode of operation harvest wind energy by reeling out the tether at high force with the kite flying cross-wind manoeuvres and reeling in at low force with depowered kite. Optimising the flight manoeuvres is crucial to achieve a high system efficiency and robust control at varying wind conditions. Sophisticated methods for the optimisation of a closed pumping cycle, combining reel-in and reel-out in a single figure-of-eight, exist [1] but these have not yet been demonstrated for an implemented prototype. Therefore, we developed a flight path planner, that uses a list of attractor points and turn actions for the planning process. The coordinates are calculated using simple, explicit geometric formulas. The path can be adapted to the average wind speed and the vertical wind profile. A small set of parameters is used to modify the flight path and to tune it to achieve optimal results. The planner uses a finite state machine with switch conditions that are highly robust for sensor errors. The performance is verified with a dynamic kite power system model [2]. It is operated in environmental conditions using wind data from the 213 m high KNMI-mast in Cabauw, Netherlands. The turbulence model uses a precalculated 3D wind field according to the Mann model [3]. The performance was evaluated for a maximal heights of 300 and 600 m, which correspond to average heights during reel-out of 98.7 and 197.4 m. The results show, that the decline of the average power output of pumping kite power systems at high wind speeds can be significantly mitigated

using the proposed planning algorithm. In addition it is shown, that reeling out towards zenith after flying figures of eight significantly reduces the reel-in forces and thus increases the total efficiency. Using the potential energy of the kite as a storage for parts of the needed reel-in energy further increases the overall efficiency.

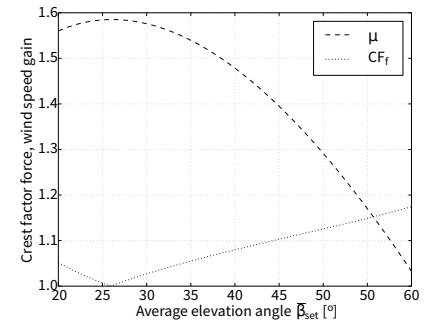


Figure: Nondimensional wind speed gain  $\mu$  and crest factor of the tether force  $CF_t$  as function of the average elevation angle offset. Tether length  $l_t = 300\text{m}$  and  $\alpha = 0.234$  approximated for Cabauw.

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**KU LEUVEN**

## Simulation Results and Software Architecture of a Rotating Launch System for a Tethered Aircraft

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We present our setup to launch an unpropelled tethered sailplane which is being developed within the ERC project HIGHWIND. In particular, we show simulation results for the whole launch execution and present the underlying real-time software architecture. The sailplane is attached by a tether to a rotating arm accelerating the plane. The tether is then reeled out using a winch so that the plane can gain altitude [1].

To compete with regular wind turbines our aim is to develop an Airborne Wind Energy (AWE) system that is compact in terms of ground surface use. In contrast to the regular winch launch of a sailplane, which requires a runway, the rotating setup can be build within an area of a few square meters depending on the size of the sailplane. The dynamical system is composed of the shaft of the tower, the arm, the tether, and the sailplane. Inertial measurement units (IMU) are mounted on the arm and on the sailplane. The plane is additionally fitted with airspeed and angle of attack sensors as well as GPS. The tether direction is measured by a custom-made line angle sensor. Two motors on the tower rotate the shaft and operate the winch. The sailplane is actuated by controlling rudder, elevators, flaps, and ailerons.

As proof of concept for an unpropelled rotation start, we present optimised control trajectories to launch the plane into a power generating orbit. These trajectory are optimised using our inhouse-developed toolbox RAWE-

SOME [2] that contains a model of the tethered plane, uses CasADi [3] for automated differentiation, and IPOPT [4] for optimisation. The focus of this work is to present the software architecture that is needed to control such a dynamical system. Communication protocols were established to gather sensor data and to interface the motors. A hard challenge is to fulfil the real-time requirement in this highly non-linear system. Apart from using efficient algorithms for non-linear model predictive control, we employ the toolchain of the Open Robots Control Software (Orococos) which allows us to write software components that are triggered in real-time. In this paper, we present the integration and interaction of all components in the real-time loop.

The system is ready to use and is able to run advanced nonlinear model predictive control (NMPC) and moving horizon estimation (MHE) algorithms.

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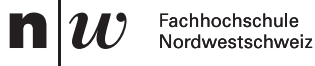
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Materials Science & Technology



## Autonomous Pumping Cycles of Tethered Wings

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The focus of this work is on autonomous pumping operation of rigid tethered wings for ground-based power generation. Twings, an acronym for tethered wings, provide increased aerodynamic performance without significant weight penalties. In this work we focus on control of Twings developed at TwingTec and operated on the two-line, ground-based Airborne Wind Energy (AWE) system developed at Fachhochschule Nordwest-Schweiz (FHNW). In a two-phase pumping operation Twings have the inherent advantage that during the retraction phase they function like a glider and can be stabilised even in the absence of tether forces.

To achieve autonomous pumping operation of Twings we adopt the control strategy in [1] using the velocity vector orientation as feedback variable. To achieve figure-eight trajectories during the traction phase we use a target switching strategy. During retractions the wing is actively depowered using an elevator and guided towards the side of the wind window where the tethers are reeled in under low tension. During this aggressive manoeuvre, however, the Twing can reach high flight velocities. In this talk we therefore outline how the two-phase strategy in [1] has been adapted to achieve reliable pumping operation with rigid Twings on the FHNW platform including a torque-based reeling control strategy.

Tether dynamics during operation at high altitudes have been found in experiments to introduce significant time

delay in the dynamics of the velocity vector orientation. Such system delay causes reduction in control performance during traction and retraction phases. This talk therefore further gives an overview of our parallel development to either incorporate system delay in the control design or reduce estimation delay through sensor fusion. The latter uses an estimator which fuses measurements from range sensing, based on novel ultra-wideband radios, and inertial readings from an inertial measurement unit [2]. The resulting approach improves the estimation during retraction and eliminates lag introduced from tether dynamics. In contrast, we can also model the steering dynamics of the tethered wing as a delayed dynamical system [3]. The parameters of the delayed model, which are identified online from measured data, are then explicitly utilised to account for system delay in the control design. The talk presents experimental results which demonstrate the improved control performance.

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## DC-link Control for Airborne Wind Energy Systems During Pumping Mode

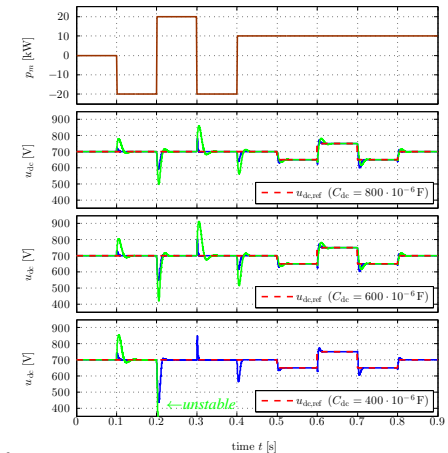
Florian Bauer, Christoph M. Hackl, Korbinian Schechner  
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Airborne wind energy (AWE) systems with electrical machine on the ground are a promising alternative to classical wind turbines. Such systems are operated in pumping mode with the reel-out phase generating electrical power and the reel-in phase dissipating power [1]. We discuss DC-link voltage control of the grid-side voltage source inverter (VSI) which controls active power flow from the machine to the grid. For pumping mode AWE systems, DC-link voltage control is a non-trivial task due to the bidirectional power flow: the underlying DC-link dynamics are nonlinear and non-minimum phase [2,3] during the reel-in phase. Control objective is to design a robust controller which achieves set-point tracking of the DC-link voltage for given set-point(s) under unknown loads.

We compare the classical PI controller design with constant gains with a PI controller design where the gains are adjusted online to the actual operating point and, hence, become state-dependent. Starting with the analysis of the linearised system dynamics, we derive stability bounds on the constant gains of the classical PI controller and illustrate the non-minimum phase behaviour during the reel-in phase. In a second step, we design the "adaptive" PI controller where explicit expressions for the controller gains are derived based on pole placement and the physical boundaries of the system.

Based on realistic models of VSI, pulse width modulation, and filter [2,3], we illustrate the control performance of the classical PI controller and the "adaptive" PI controller under load changes (see interval [0.0–0.5 s]) and set-point changes (see interval [0.5–0.9 s]) for decreasing values of the DC-link capacitance. The "adaptive" PI

controller (blue line) shows a better tracking and disturbance rejection capability than the classical PI controller (green line). For a small DC-link capacitance, the classical PI controller even becomes unstable. The "adaptive" PI controller remains stable and, so, allows to use smaller (cheaper) DC-link capacitors.



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## Predictive Control of an Airborne Wind Energy System using Gaussian Process Models

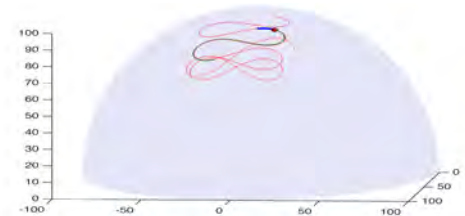
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The performance of an Airborne Wind Energy (AWE) system in crosswind operation depends on the shape and characteristics of the flight path. A control scheme that updates the path online, requires a component responsible for following the requested path despite disturbances and unknown dynamics. We present simulation studies for path following using data-based models.

We demonstrate an online data-based method to identify the dynamics of an AWE kite system using Gaussian processes. A model available from literature [1] is used as a priori information to train a Gaussian process from observed data and to select the state space representing the dynamics. We create a map from the steering input of the kite and states to the future states and their prediction uncertainty. We then formulate a stochastic model predictive control (SMPC) scheme that takes into consideration uncertainty in the learned model. Virtual states and a virtual input are used to define a second order integrator with the states parametrising and selecting the part of the reference path to be followed in the MPC horizon. With this framework we correct model-observation mismatch and perform path following. The virtual input allows the algorithm to choose the speed at which following the path is feasible for the kite. We consider input box constraints and input ramp constraints only, however more general state-input constraints can also be incorporated in the MPC scheme.

To test our method we generate optimal and several sub-optimal feasible trajectories. We then train our model us-

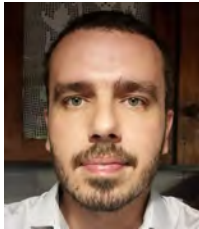
ing an expert that tries to track a path before automatic operation. Once the model is learned with sufficient accuracy we commence the automatic path following. The figure shows an instance of a generated feasible trajectory. The method is tested to track a different part of the path than on which it was trained to ensure that the learning generalises well. The algorithm continues to incorporate information from the new path to better capture the model dynamics while continuously solving the SMPC problem. In general the approach leads to a non-linear programming (NLP) problem and additional work is required to make the NLP suitable for real time implementation, which is a topic under investigation.



Path tracking using GP-MPC on a 500 m radius reference sphere: red line - path to be tracked, red dot - kite position, green line - past 10 s of kite trajectory.

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## Online Parameter Estimation for Flight Control of Tethered Airfoils

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In this paper we propose a model for representing the course angle dynamics, or turning rate, of a power kite. This model is derived from [1] and uses the tether traction force instead of explicit aerodynamic characteristics, such as angle of attack, lift and drag curves. This way the turning rate law becomes more suitable for control purpose in terms of sensing.

An Extended Kalman Filter (EKF) is used to estimate online a parameter that incorporates changes in the kite dynamics due to fluctuations on its mass and/or aerodynamic characteristics. Such variations may, for instance, be caused by weather conditions or wear. Besides allowing the flight controller to self-adapt to parameter variations, the EKF can also be used to filter the noise contained in the measurements of the course angle, thus enabling the control to achieve a good performance even in a noisy scenario.

To generate the flight path and track the course angle reference a control structure with two loops, similar to [2], is employed along with the two EKF outputs: the parameter estimative and the filtered course angle.

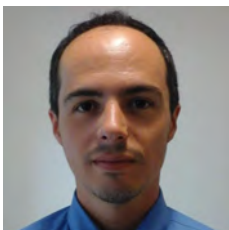
These contributions are validated through computational simulations using two different kite models. In the first model the kite is a mass-point connected by two steering/traction tethers to the ground, where the actuators for manipulating the kite roll angle are located [3].

The second model has four mass-points, three of them for the kite, which is split into one top and two side airfoils. These are connected by two steering and two traction tethers to an airborne control pod, which is able to impose variations on aerodynamic characteristics of the airfoils [4].

We demonstrate that the proposed turning rate law holds for both simulation models, regardless of the different actuation concepts. This is proven by a high correlation coefficient between the course angle obtained by the turning rate model and by simulation. We also show that the parameter estimative keeps tracking its reference value even when variations on the kite mass are imposed or when high levels of white noise are added to the measurement signals.

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## On the Optimisation of Pumping Kites for Wind Power

**Marcelo De Lellis, Ramiro Saraiva, Alexandre Trofino**

Federal University of Santa Catarina, Department of Automation and Systems

This paper deals with optimisation aspects of a Pumping Kite (PK) for electric energy generation. Our numerical results are based on an airfoil with maximum aerodynamic efficiency  $E(\alpha)_{\max} \approx 5$  at an angle of attack  $\alpha \approx 16^\circ$ , projected area  $A = 12\text{m}^2$ , and with two power/steering tethers of diameter  $d_l = 3\text{mm}$ .

Our first contribution is to show the influence of the angle of attack for power maximisation in the traction (reel-out) phase. The PK system behavior in the traction phase has been studied e.g. by [1,3]. However the question of the optimal angle of attack  $\alpha^*$ , for power maximisation, still remains open in the literature, to the authors' best knowledge. Based on an analytical expression for the PK mechanical harvested power  $P$  and the kite tangential velocity  $v_{k,\tau}$  we show how these quantities vary with  $\alpha$ . By increasing the angle of attack, starting at  $\alpha \approx 0^\circ$ , both  $P$  and  $v_{k,\tau}$  increase but peak at different values of  $\alpha$ : the maximum kite tangential speed is achieved at a lower angle of attack than that which yields the maximum mechanical power. If  $\alpha$  continues to increase after the peak values,  $P$  decreases faster than  $v_{k,\tau}$ . In fact, the mechanical power is very sensitive to the angle of attack: by operating the PK system at an angle of attack  $4^\circ$  lower than the optimal value a reduction of about 35% in the harvested power is observed. The numerical results through the analytical expressions are corroborated by a good correspondence with the average values obtained with a 3D point-mass model.

We also show the benefits of torque/force control over reel-out speed control. By controlling the reel-out speed, both  $v_k$  and the tether traction force  $T$  are severely af-

ected by the wind turbulence. At times in our simulations,  $T$  even surpasses the safety level above which structural damage to the PK may occur. Moreover, negative wind turbulence may cause the wing to slow down. As a consequence  $\alpha$  increases, approaching the stall point and hence threatening flight stability. By running a simulation with control of  $T$  and the same perturbation intensity we show how these issues are dealt with, while the reel-out speed is left free to compensate for the wind gusts.

There may exist, for flexible kites, a minimum angle of attack  $\alpha_{\min}$ , or traction force  $T_{\min}$ , under which the airfoil loses its inflated structure (implosion) and collapses. This issue was addressed by [2], who proposed a robustness constraint, based on the apparent wind and  $\alpha$ , to design a passive phase manoeuvre that allows the cycle power to be maximised. To reach the same goal we propose a simpler alternative, assuming a constant base angle of attack ("de-power" setting) and a constant reference of the traction force,  $T_{\text{ref}} > T_{\min}$ , valid for the whole manoeuvre. Again, we show how the force control approach with  $T_{\text{ref}}$  allows the passive phase to be executed while keeping away from the kite implosion condition.

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*Kite operation on Valkenburg airfield,  
Leiden, The Netherlands (12 April 2012).*



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## How to Introduce Kite-Based Airborne Wind Energy Systems – The Selection of Niche Strategies to Overcome Barriers to Adoption

**J. Roland Ortt, Linda M. Kamp, Matthew F. A. Doe**

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Commercialising radically new high-tech systems is a risky strategy. Start-ups introducing such systems fail significantly more often than incumbent companies introducing incrementally new systems. In practice, radically new high-tech systems are often introduced in market niches prior to large-scale diffusion in a mainstream market application. A serious gap in the scientific literature is the lack of knowledge regarding specific niche strategies to introduce such systems and the limited understanding of how to assess the market when choosing a specific niche strategy. Also managers and technology developers often lack an overview of the relevant barriers in their field and an insight in which are the most appropriate niche strategies to introduce their radical innovation. Both scientifically and managerially it is highly important to fill this gap. This paper will focus on kite-based airborne wind energy systems (kite-based AWE-systems). In contrast with wind turbines, these systems benefit from higher wind speeds and lower material usage. However, with these benefits come several radical changes which, in turn, hamper direct large-scale diffusion. The goal

of the paper is to indicate how kite-based AWE systems can be introduced. Two research questions will be addressed: (1) What are the barriers preventing direct large-scale diffusion of kite-based AWE systems; (2) What are the niche-strategies to deal with these barriers? The paper is based on literature research and interviews with experts and technology developers in the field of kite-based AWE-systems. A first result from the interviews is a list of the most important barriers. We show how particular combinations of barriers, such as the lack of knowledge of the technology that has an effect on the support and investment opportunities, together block large-scale production and diffusion. A second result is a list of several niche strategies that can be used to tackle the identified barriers in this field. The “geographic niche strategy”, the “demo, experiment and develop niche strategy” and the “educate niche strategy”, for example are identified as good strategies to introduce the kite-based systems. We will discuss the managerial implications of the barriers and the niche-strategies that we found.

Ampyx Power team and PowerPlane AP-2A2 (1 December 2014).







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## Ampyx Power Market Development

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The addressable market for Airborne Wind Energy (AWE) is enormous. The wind turbine market approaches €100 billion annual revenues today, and based on IEA projections, will grow at 8-12% per annum for at least a decade. Moreover even higher growth rates may be achieved, with market acceptance of AWE, as the competitive position of wind power improves compared to alternatives. Ampyx Power considers AWE a 2nd generation wind energy technology. This means that AWE technology will replace current conventional horizontal axis wind turbines altogether over time.

Successful commercialisation of any AWE technology requires

1. a technologically competitive product
2. a clear business model and competitive strategy
3. a credible strategy to develop and finance early stage product deployment projects
4. a pro-active role in shaping the regulatory framework for the respective AWE technology

The presentation will focus on the last three items. The longer-term business model of the company is similar to the existing wind turbine industry: generation of revenues and profit through sales of PowerPlane systems and operations and maintenance services. However, until market acceptance of AWE has been achieved, Ampyx Power actively pursues a competitive strategy of being first mover in certification and deployment.

The wind power market has very significant entry barriers due to the nature of its customer base. This is exactly why the company has started building in-house project de-

velopment capabilities already in 2013, and now actively develops PowerPlane projects in Europe, Australia and North America. Project development partnerships with Staatsbosbeheer (Netherlands) and SeaBreeze (Canada) have been established and are functioning well, and further partnerships are being negotiated. In the course of 2015-2017, Ampyx Power will ensure that a pipeline of projects matching the growth projections for 2018-2020 will be developed.

Risk and expenditure are balanced via a staged project development and funnelling of multiple projects is performed in order to develop only the best performing projects. A deep understanding of the following areas is needed to reach financial close of AWE projects:

1. site selection via multi criteria analyses using GIS software
2. land tenure agreements and options for co-use
3. high altitude wind resource assessment
4. environmental impact assessment (visual, noise, ecology)
5. permitting processes (including aerospace regulation)
6. civil and electrical works (including grid connection processes)
7. market access and Power Purchase Agreements
8. innovative/early stage project financing
9. market partnerships
10. stakeholder management

The above mentioned topics will be addressed and a status update of the projects in our key markets will be given.



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## Harvesting the Wind – A Canadian First Nations Perspective

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From before the time of written history, Canadian First Nations have maintained a tradition of self-sufficiency in food, energy, and culture. That self-sufficiency was a requirement for survival during the time before European and Global technologies began to influence the peoples of Canada. In this new Global era, the need for sustainability has not decreased, but rather become even more important. We all need to respect Mother Earth. Since 2007, the T'Sou-ke First Nation has been one of the leaders among aboriginal peoples in Canada in establishing a sustainable community which draws on renewable natural sources to provide for our energy needs.

Harvesting the energy of the wind by means of Airborne Wind Energy Systems - like kites - is especially important to isolated remote First Nations Communities in Canada. Community power needs are often small enough that kite systems represent an economically viable means of displacing the diesel generation that currently is the only solution available during the Canadian winter.

The T'Sou-ke First Nation is already well experienced in

renewable energy projects, including the use of solar, and storage. This paper explores both the extent of the need within remote Canadian First Nations and Aboriginal Communities, and the potential economic and community benefits of deploying a kite/storage/diesel hybrid system.

Over 100,000 people in Canada depend on Diesel generation as their primary source of electricity. Even without any Feed in Tariff, or other incentive programs, the displacement of diesel generates over \$0.50 per kWh, so that payback periods of less than 2 years are provable. Airborne wind offers almost the only renewable alternative that is useful during the winter in the North of Canada, and the T'Sou-ke First Nations is developing a program for the demonstration of this technology during the winter of 2015/16.

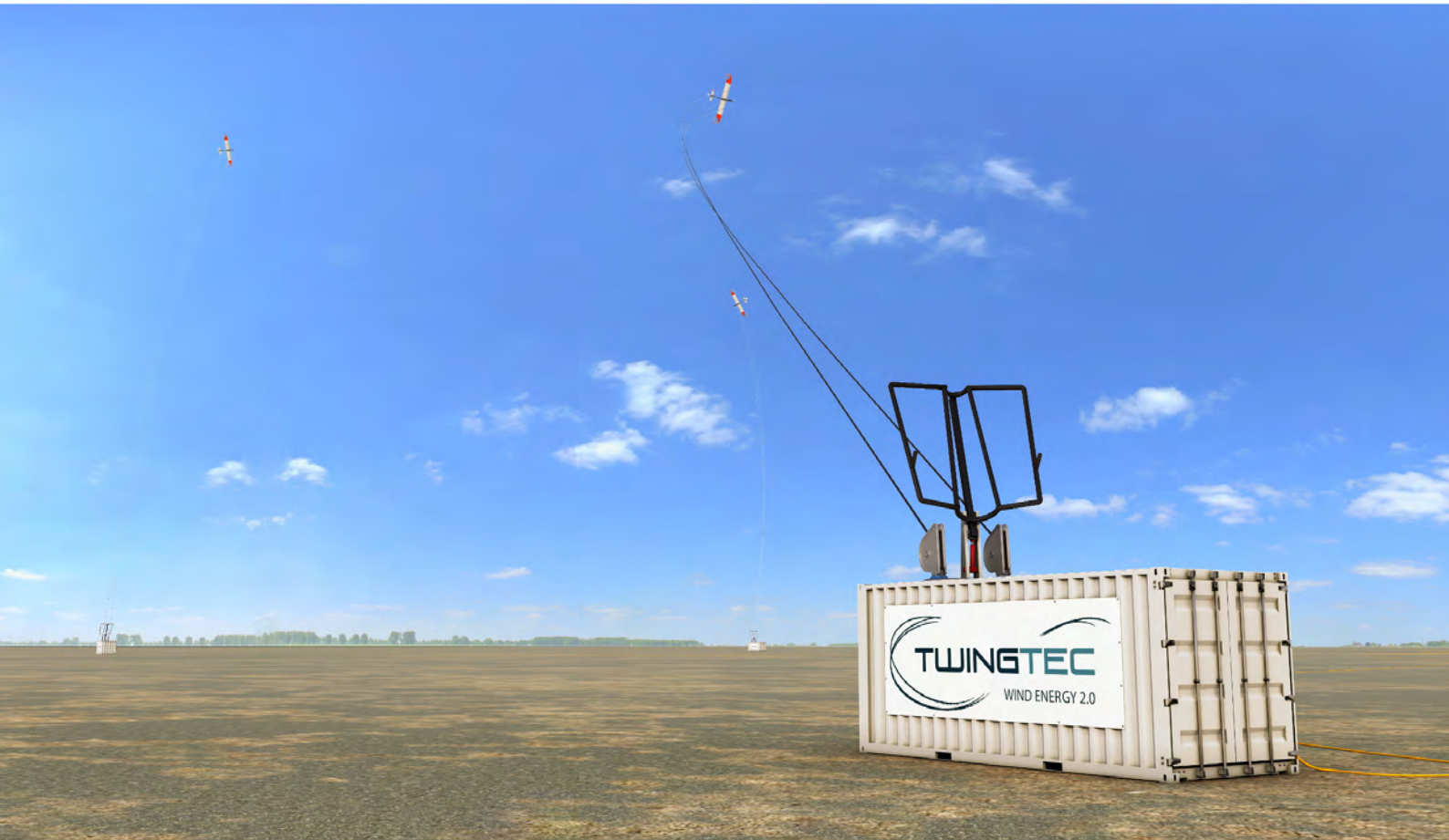
The economic, social, and ecological benefits, and the nature of the Canadian opportunity for airborne wind as the only renewable solution for remote First Nations communities will be fully disclosed.





*Swiss Kite Power project testing  
in the Alps (19 July 2010).*





*TwingTec's vision: TwingFarm (2015).*



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Materials Science & Technology

## Mobile Wind Farms Using Tethered Wings – Technical and Economic Considerations

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The construction of convention wind farms requires large amounts of capital and in order to be economical these costs must be amortized over a long project lifetime, typically 20 years. Airborne wind energy systems, by employing tethered wings coupled to ground based generators, enable a highly mobile power plant concept whereby the entire plant can be quickly transported and installed, even in remote locations. Due to this low cost of installation, a temporary power plant can be realized, a novel concept in the field of renewable energy.

In order to reach power outputs of interest for industrial applications, typically in the MW range, an array of tethered wind energy systems can be utilized. By integrating the ground based generators and all other power conversion hardware into standard shipping containers logistical difficulties and expenses can be minimized. Balance of plant, such as foundations, cables, switchgear, transformers and medium voltage distribution lines can be constructed from standard components, although special considerations are required to maintain flexibility and minimize costs. Grid integration, which can be particularly difficult for isolated grids powered by diesel generators, can be realized using techniques employed by the solar PV industry. Risk mitigation, an important part of every power project, necessitates a wind resource assessment and the implementation of a comprehensive opera-

tional safety scheme, both of which require special attention due to the nature of the technology employed.

An economical project implies that energy can be produced and delivered to the customer at a similar or lower cost than their baseline power supply. For off-grid applications, typically powered by diesel generators the cost of supply is dominated by the fuel costs, including transportation, storage and taxes. For renewable energy projects, the cost structure is dominated by the up-front capital costs, with operation and maintenance making a smaller contribution to the final cost of energy. Airborne wind energy systems have a cost structure somewhere in between conventional renewables and fuel based generators, with lower capital costs due to reductions in material utilization and balance of plant requirements and higher operation and maintenance costs due to periodic replacement of tethers and wings.

Based on discussions with industry experts, energy consumers and independent power providers, a concept for a mobile wind farm using tethered wings has been developed. The technical and economic feasibility of such a project will be presented as well as the practical and financial challenges to realizing such a system. A first look at TwingTec's unique system concept for airborne wind energy allowing for fully autonomous operation, including launching and landing, will be given.



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## **High Performance Ropes and Drums In Airborne Wind Energy Systems**

**Tobias Schneiderheinze, Thorsten Heinze, Markus Michael**  
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The generation of electrical power from wind energy is one of the key aspects of the green energy revolution in Europe. The effectiveness of wind energy systems is directly associated to the height where the energy of the wind is transformed. With increasing altitude, the velocity of the wind and thus the convertible amount of wind energy into electricity is increasing exponentially. Whereas conventional wind turbines reach their technical limits in heights exceeding 200 m, airborne wind energy systems can be used significantly above this height levels. Since almost all the systems are ground-based systems, the strength-mass-ratio of the tension members used as a support, control or pull cord plays an essential role in the flight characteristics and the efficiency of these systems.

Nowadays a variety of polymer ropes and different rope designs is already in use because of the known advantages of fibre ropes, e.g. low weight and high load capacity, good bending flexibility and good corrosion resistance in comparison to steel wire ropes. In addition to these properties, modern textile mechanical components from high-strength, high-modulus polymer fibres

offer even more positive features and set-ups that can raise the capabilities and the potential of airborne wind energy systems to a higher level.

The paper illustrates the different fibre materials and design options of fibre ropes and their optimisation potential by following processing steps e.g. lubricating, waxing, stretching and heat-setting. At the same time it will be shown how ropes can be purposefully adjusted to specific requirements. Some examples are weight optimization and increasing of the lifting capacity, increasing of the resistance to weather conditions as alternating high and low temperatures, humidity, water and ice, salt (and salt crystals) as also UV irradiation.

In addition, the winding properties of the rope are also of outstanding importance. The dynamic tensile load, Hertzian stress and friction occurring on the winch are placing new demands on the fibre ropes, and are influenced by the winch-system to a large extent. It will also be shown, which tests are to be performed for gathering targeted information on the winding performance and thus help to adapt the design of winches for use with fibre ropes.



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## Composites Manufacturing for Airborne Wind Energy

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One of the requirements of the airborne part of an Airborne Wind Energy Plant, the kite, is low weight. On the one hand to keep the mass inertia of the moving system low and on the other hand making it easier to keep the kite airborne in very low wind conditions. Another is of course low costs.

Using High-tech materials like fibre reinforced plastics, commonly known as composites, is a way to reduce weight. As a guideline; composite structures can be about 30% lighter than comparable metallic structures due to their reduced density.

In general there a number of ways to manufacture composite products dependant on the base material. Pre-pregs or pre-impregnated fibres are currently the standard in the aerospace industry to produce high quality parts. But the material is expensive and the technology needs expensive equipment.

Dry fibres are used for infusion techniques. Dry fibres are placed in a single or double sided mould and the fibres are infused with resin using a pressure difference between the in- and outlet. This technique is widely used in the manufacturing of ship hull and wind turbine blades. Infusion gives more flexibility both in material choice as in type of infusion technique depending on the necessary quality of the final product.

The third material is the use of thermoplastics as matrix/resin for the fibres. Thermoplastics can be formed and reformed again through the input of heat. Although not yet widely used for aerospace parts it has great potential due to its impact toughness, and the possibility to weld and recycle.

Most AWE rigid kite and aircraft designs tend towards a carbon fibre/epoxy design. But highly loaded parts are mostly made of metals. Changing to a composite structure will not only result in a weight decrease on part level but also reduce weight/cost in the complete design. A suitable production method of these highly loaded composite parts is closed mould RTM infusion. This process is able to produce composite parts with high tolerances and big differences in wall thickness. In a AWE kite the tether/kite interface could be such part but also the tether/pod interface for soft kites.

The production of composites is very labour intensive, for this reason, automation of the production of composites has become such an important topic. There is a big push from the automotive sector to automate production of composite parts. The aerospace industry is also looking in to automation not only due to production costs but also to ensure a more consistent quality and easier traceability reducing costs in inspection and quality control. In AWE quality will be extra importance due to the expected fatigue effects of the continuous load cycles and safety aspects which will be more stringent than for normal wind turbines.

Several trends in the aerospace composite manufacturing industry seem suitable for Airborne Wind Energy applications to make lightweight and low cost, but high quality, parts in large quantities (compared to aerospace production rates). Automation is the main focus in combination with dedicated infusion techniques and in the future the use of thermoplastic materials.





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## Development of Multi-Functional Narrow Fabric as Tension Member for Winch Operations

**Ingo Berbig, David Holschemacher, Tobias Schneiderheinze, Markus Michael**  
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Today's requirements on modern tension and suspension elements exceed purely mechanical stress. There is a demand for the integration of additional functions, especially for the use in winch operations, which motivates the presented development project regarding a multi-functional narrow fabric. This narrow fabric enables to join several functional elements, e.g. electric conductors, signal transmitters and tension members, in one mechanical component. Developments of the functional elements, of the design of the woven structure and of the purpose-built manufacturing technology have been the main focusses.

The special challenge is to apply particularly light and equally powerful tension and suspension elements. These narrow fabrics not only need to withstand the enormous loads of winding, but also maintain their function. This function divides in the mechanics of winding and the function of energy and signal transmission. Further, the textile tension and suspension elements need to be sufficiently equipped so that they are resistant to external influences such as humidity, insolation, precipitations, aggressive media (mining) etc.

The narrow fabric corresponds to the following structure: Tension members in the form of braided ropes alternate with electrical cables. Due to the larger cross sectional area of the rope, load relief of the electrical cables during potential bending or winding is ensured. The fabric is built in such a way that any additional elements are equally joined in warp direction. The plain weave is used

as the prevailing weave. In so doing, stratification can be avoided. If warp raising or lowering is exchanged for the adjacent elements (rope and cable), the danger of layer formation arises. The adjacent ropes are pulled together to such an extent due to the weft yarn tension so that the ropes might arrange on top of each other. For later use, this case must be eliminated.

The production of a multifunctional narrow fabric requires special technology. In the course of the production, high demands occur particularly on the weaving machine regarding the flexibility of mechanics and control. In the context of the manufacture of a multifunctional narrow fabric, the integration of the functional elements to the weaving process also proves to be particularly critical. While the ropes being a load-bearing element need to be pretensioned before their integration, the cables being a non-load-bearing element can be processed without any pretension. At the same time, it is necessary to realize a preferably symmetrical shedding. This problem has to be solved by the targeted selection of different guide tracks through a stretching unit. In comparison to warp and weft yarns, the functional elements have considerably larger diameters and bending strengths, which also require certain adjustments: Special heddles need to be developed, the process of the deduction is to be adapted to the limited mechanical resilience of the cables integrated in the fabric composite and the provision of the functional elements requires a respective specialized creel.



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## Life Cycle Assessment of Electricity Production from an Airborne Wind Energy System

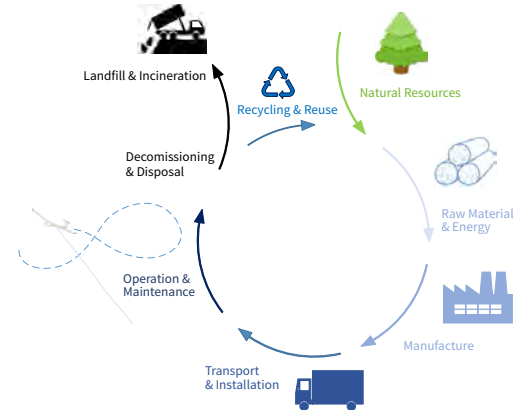
**Stefan Wilhelm**

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In the current literature there is no profound evaluation of the ecological aspects of airborne wind energy systems (AWE). However, it could be very supporting for the AWE pioneers to have a scientific statement about this topic when communicating with stakeholders in the field like financiers, legislative force, local/national/European government, the public and others.

In this study, the environmental impact of 1 kWhel produced from an AWE system is analysed. Subject of the thesis is the implementation of a Life Cycle Assessment (LCA) based on ISO 14040 and ISO 14044. For that purpose, energy and material flows of all life cycle processes from exploitation of raw materials, manufacturing, assembly, transportation, installation, operation and maintenance until decommissioning / disposal / recycling are described. The impact of all life cycle phases on global warming potential (GWP100a) and cumulated energy demand (CED) is assessed using the CML2001 method. In a sensitivity analysis, the relevant factors are determined and their influence on the overall results studied. AWE system developers might consider the driving factors in the early development of their systems.

The study is based on a generalized 1.65 MW rigid wing AWE system with ground based generator in an arrangement of a 300 MW plant. The investigation includes all required components up to connection to the electricity grid at a certain site.





*Operation of the EnerKite ram-air wing (15 August 2012).*



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KITEBOARDING

## High-Performance Soft Kite Technology State of the Art, Limits and Opportunities

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Recent technological developments in the kitesurfing industry may have an impact on how ground-based generation Airborne Wind Energy (AWE) concepts perceive and use soft kites.

As kitesurfing is evolving to a complete sport, users ask for kites that make it possible to go out in nearly any condition. Light wind proves to be the incubator for technological achievements. Hydrofoil and Formula kiteracing have pushed the limits in ram-air soft kite technology, asking for high L/D wings. Performant boards make it possible to go out when the kite can not yet sustain its own weight statically in the air, much like rigid wings. Ram-air kites are therefore not necessarily light. The frustration of dropping a kite in the water in these conditions has led to the development of ultralight depowerable single-skin kites, such as the Flysurfer "Peak" shown in the figure. In this design a minimal number of rib elements are used to bulge the single-skin into a leading edge that induces the characteristic airflow around an airfoil and a lift-generating aerodynamic surface pressure distribution. The lightest weight per projected area of any kite has proven to be key to the ultimate light wind kiting. In practice, these are high performance successors to the classic Nasa Parawing.

System-bound, these single skin and ram-air kites have quite a limited depower range compared to inflatable kites or rigid wings. Therefore, possibilities to build efficient yoyo-AWE systems with double- and single-skin

kites that retain their original shape in the retraction phase are quite limited. An efficient depower range comes in handy when the kitesurfer wants to jump as high as possible, a scenario that is much alike to the yoyo-phase in AWE. Therefore high L/D, high depower inflatable kites have been developed. The aim of this presentation is to show the potential of soft kites in AWE by presenting the state of the art technology in these three soft kite categories. It gives an indication in which AWE system configurations it would make sense to use which kind of soft kite technology.

It discusses the limits of soft kite technology, in practical scenarios, production, lifecycle and scaling.



*FlySurfer "Peak" used for snowboarding (2013).*



*Air traffic and airborne wind energy harvesting at different altitudes at Valkenburg airfield, Leiden, The Netherlands (11 March 2011).*







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## Update on Certification and Regulations of Airborne Wind Energy Systems – The European Case for Rigid Wings

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As an increasing number of Airborne Wind Energy Systems (AWES) is reaching early commercialization operational safety and system reliability become important aspects. This presentation will provide an overview of existing and expected rules and standards for ensuring safe operation of rigid wing AWES. The objective is to systematically determine the relevant authorities and their points of view from the top down to the national levels and provide an overview of relevant system standards independent of the specific AWES concept. This overview will be supplemented by the current specific legislation for rigid wing concepts and the relevant upcoming changes of the European airspace law.

The starting point for identifying the organizations involved in the rule-making processes for the use of airspace in an international context is the ICAO (International Civil Aviation Organization). This UN agency is responsible for providing international Standards and Recommended Practices (SARPs) to ensure safe, efficient and secure use of civil airspace. The EU member states recognise the authority of ICAO and the European Commission (EC) attends suitable ICAO meetings as an observer. The European Aviation Safety Agency (EASA) is responsible for drafting the rules and advising the EC during the process of developing common laws for member states. The Federal Aviation Administration (FAA) is the civil aviation authority in the US and is responsible for the Federal Aviation Regulations (FARs). Accordingly, FAA also references

the ICAO SARPs. Potentially relevant ICAO annexes to all AWE concepts will be discussed and followed down to their implementation in the European legal framework. We will briefly discuss the FAA point of view on AWES based on their UAS roadmap and discuss international actions to align integration of drones into the airspace. Current research activities and technology demonstrations by AWE developers rely on special exemptions for using airspace. These prototypes have a limited mass of airborne components and occupy only a limited airspace volume with human pilots in the loop. They are operating in a selected safe area to mitigate risk to third parties. Nevertheless, the final commercial products are expected to have significantly larger sizes and mass and will occupy larger areas and ultimately have to fully comply with international airspace regulations. On the other hand, AWE technologies have important mitigation factors such as being connected to the tether, operating in a restricted airspace or having speed and range limits. Therefore, a compromise may be reached with authorities on different mitigations depending on the AWE product type, such as being slow, having soft wing, having multiple tether etc. We will finalise the presentation with a comparison of different existing AWES concepts and how they fit in the upcoming European airspace law changes for drones, based on the definitions in EASA NPA 2014-09 and the recently published EASA RPAS concept of operations.



*Testing the Altaeros prototype (2013).*



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## A Review of Wind Standards as they Apply to Airborne Wind Turbines

**Ben Glass**

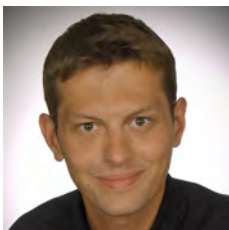
Altaeros Energies Inc.

In order to secure project financing for airborne wind turbines (AWTs) and ensure robust operation in real world conditions, a standard set of wind conditions should be defined which must be considered in the design of AWTs. These standard wind conditions are described for traditional, tower mounted turbines in international standards such as IEC 61400-1 and DNV GL's Guideline for the Certification of Wind Turbines. Certification of standard wind turbines is generally a prerequisite for securing project finance for wind farms, and it should be expected that a similar level of certification rigor will be needed in the airborne wind sector. The nature of AWTs combines elements of wind turbines with aircraft and aerospace systems. As such, IEC 61400-1 is a good starting point but does not adequately describe the wind conditions that AWTs should be designed for. In particular, IEC 61400-1 (and IEC 61400-2 for small wind turbines) does not satisfactorily consider a) the impact of altitude on the direction, magnitude and time content of wind disturbances in the medium and high altitude range in which AWTs operate, and b) discrete vertical wind events—downdrafts and updrafts—which may pose a significant risk for AWT operation. A more complete and applicable set of wind conditions may be found by considering aviation guidelines such as MIL-STD-1797A (for use with fixed-wing aircraft supported primarily by aerodynamic force), USDOT

AC 25.341-1 Dynamic Gust Loads, and USDOT AC 25.415-1 Ground Gust Conditions. These guidelines are based on extensive industry and operational experience, and can provide a complete and credible set of wind conditions for the design of AWTs. In particular, these guidelines contain a detailed description of vertical and lateral wind conditions at ground level (critical for AWT landing operations) as well as low- and medium/high-altitudes. This presentation will provide a review of relevant wind turbine and aviation standards/guidelines and suggest an initial framework for a set of standard wind conditions for the certification of AWTs.

Altaeros Energies is an early-stage company working to bring the first airborne wind turbine to market. The Altaeros Buoyant Airborne Turbine (BAT) holds the potential to deliver cheap renewable energy to rural, island, and offshore sites that face high electricity costs. Founded in 2010 by MIT and Harvard alumni with a background in aerospace, energy, and industrial gases, Altaeros launched its first functional BAT prototype in 2012 and is now working to develop the first commercial scale BAT. Altaeros Energies, located in Somerville, MA, is a founding member of Greentown Labs, the largest cleantech focused incubator in the United States. Altaeros closed a US\$7 Million Series A investment from SoftBank Corporation in November, 2014.





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## Adapting Wind Resource Estimation for Airborne Wind Energy Converters

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Wind resource estimation refers to any technique that assesses the wind potential in order to evaluate whether wind energy is economically viable at the investigated location. Thereby usually the annual energy production (AEP) is calculated based on the wind speed frequency distribution and the power curve. Interruption of operation, as necessary for maintenance and repairs, is usually considered as a capacity factor, e.g. 0.98. Regarding airborne wind energy converters (AWEC) however, one may need to consider additional influences towards the capacity factor, as AWEC may need to land in order to:

- Prevent lightning impact
- Allow de-icing
- Avoid aircraft collision at low visibility

In this work the influence of the before named situations on the AEP is examined for an EnerKite AWEC, for an area covering Germany and parts of the surrounding countries, and for the years from 2012 till 2013. The system operates on altitudes from 50 to 300 m and may also be forced to land if the wind speed falls below the lower operational limit of 2 m/s. After conditions have improved a take-off is required to continue operation. For which it is also necessary that the lower operational wind speed at the lower operational altitude is reached, regardless stronger winds at higher altitudes.

The power production of the EnerKite AWEC depends on altitude and wind speed. Therefore, for every investigated location a wind profile must be used to consider optimal height of operation with respect to power.

The wind speeds are taken from the COSMO-DE dataset

produced by the German weather service DWD. The values are available as timeseries with hourly resolution covering the above mentioned area with a mesh size of 2.8 km. In vertical direction the wind speeds are interpolated to 12 height levels that are uniformly distributed between 25 and 300 m above ground level.

Regarding the prevention of lightning impact, it is first necessary to evaluate the actual likelihood of a lightning striking into the AWEC during the investigated time span. Based on professional lightning records by Nowcast it is assumed that every lightning that has occurred within a certain radius around a potential site would have hit the airborne system. The actual radius depends thereby on the operational height. Furthermore it is presumed, that lightning threat is only given for situations where the line between kite and ground station is wet, as a dry line is supposed to be non-conducting. Finally an indicator for lightning risk is derived from correlating the virtual lightning impacts with radar reflectivity data provided by the DWD which is a sensitive diagnostic for thunderstorms. Based on this indicator it is possible to remove power that would be produced under lightning threat from the AEP. Potential icing of the AWEC can be identified by evaluation of air temperature and humidity which can both be taken from COSMO-DE. These two measures are also used for the spotting of low visibility situations.

As a result, the impact of the individual threats on the capacity factor will be shown as well as a site specific summarized capacity factor. The findings are discussed especially in the context of optimization strategies as well as with respect to operational management of AWECs.



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## **Study on Wind Resources at Mid-Altitude**

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A literature review shows that there are only few studies regarding the properties of mid-altitude winds which are crucial for the assessment of airborne wind energy (AWE) generators [1,2]. Wind data in mid-altitudes is available in low resolution in space and time such that they only can be used for general qualitative analysis.

Three years of research in the field during the execution of the project Onkites [3] have shown that a comprehensive assessment of the potential of AWE systems is extremely difficult. One reason is the limited availability of data on the meteorological conditions in heights above 150 m. Therefore, several measurement campaigns were carried out in the framework of the project. For this aim, a WindCube V2 was used which is a pulsed LIDAR system that can sample up to 12 different heights and up to 250 m altitude. The LIDAR averages values over a range of 20 m during the operation.

Results show that in the case of sunny and warm days, the wind is very turbulent with similar wind speeds at all layers. This phenomenon was observed during all measurement campaigns. It is important to remark that the described effect appears only in the time series with a resolution below minute/hour. In annual time series, where

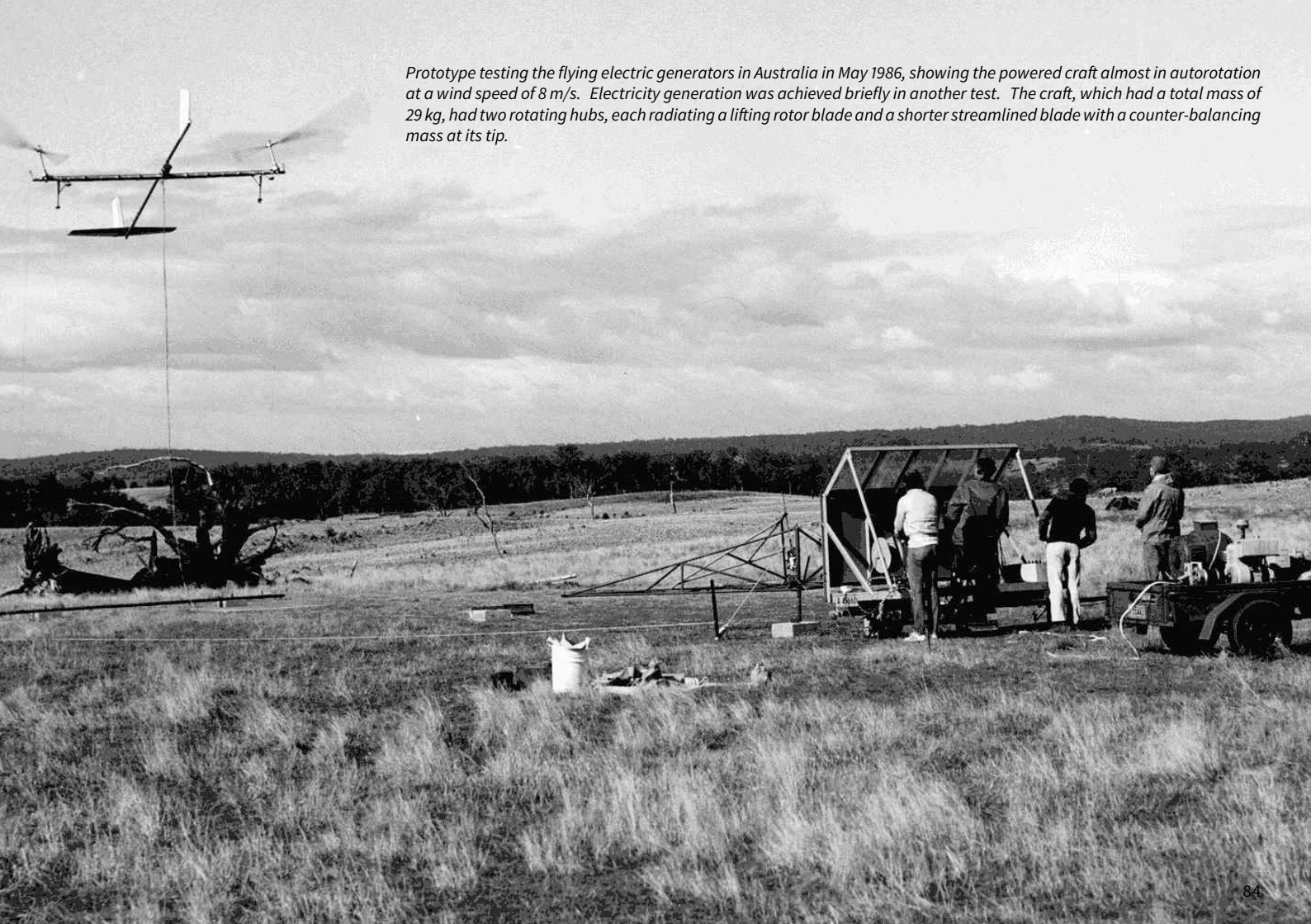
the wind data are daily averaged, the phenomenon remains hidden because of the long-time averaging range. Because AWE systems have to be kept flying all the time, it is very important to know about the wind resources between 200 m and 1000 m at one minute sampling times. However, this information is not available yet and much work has to be done in this direction because many questions are still unsolved.

The currently running follow-up project Onkites II deals with more accurate investigations of specific questions which have remained open in the earlier project. These are especially the wind properties of the upper winds at different thermal stratification and the development of a methodology for yield assessment. During two measurement campaigns, the use of a new scanning LIDAR system is planned, which is able to measure the wind speed up to 1000 m height.

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*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.*



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## Quad-Rotorcraft to Harness High Altitude Wind Energy

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It is well known that powerful and persistent winds exist aloft with annual average power densities as high as 20 kW/m<sup>2</sup>. This figure far exceeds the power density of any other large-scale renewable resource found on Earth. A tethered rotorcraft is proposed to capture this energy. These rotorcraft would develop sufficient lift to keep the system aloft, while simultaneously generating an electrical output for transmission to a ground station [1].

Two jet streams exist in each Earth hemisphere, called the sub-tropical and polar-front jet. The former are relevant as they exist around latitude 30 degrees in bands approximately 1000 km wide over the Mediterranean, Northern India, China, Southern Japan, North America, Africa, Australia, South America and elsewhere. These streams have enormous energy and persistence compared to near surface winds.

Upper wind data statistics for Australia and the USA have been prepared. This data is presented as cumulative probability distributions. The paper will show that due to the persistence of these winds it is possible to achieve near base-load electrical outputs at capacity (or generating) factors of between 70 and 80%.

The paper will detail early Australian work with a towed generating rotor, wind tunnel tests and with atmospheric, low altitude test vehicles. These tests confirm the feasibility of kite-like flight with the rotors simultaneously generating electricity. It is envisaged that a craft having twin or quadruple rotors can generate electricity at altitude when the rotors are inclined at a disk incidence to the on-coming wind. In general, the rotor disks operate

at an adjustable angle up to about 40 degrees. With suitable electrical switching it is possible to fly the system, helicopter- style, using power supplied from the ground through the electro-mechanical tether. This allows easy ascent to altitude through any low-speed, near-ground wind and also to allow descents during short term lulls at altitude.

The paper will next detail, in a manageable manner, the basic mathematics underlying the technology. It will rely on classical helicopter theory to derive the rotor thrusts and the rotors' limits to power generation, through the established technique of retreating blade incidence. The range of useful tip-speed ratios will be presented for the complete range of disk incidences. Power and thrust coefficients will be derived. This mathematics can be used to propose a small quad-rotorcraft for demonstration of the technology at low altitude. It would then be possible to escalate the size to obtain a multi-megawatt output from a single machine.

The final section of the paper will give a dynamic analysis of the system in order to describe a control strategy for the craft's power output, pitch, roll and yaw, using purely blade collective pitch action. Wind axis derivatives will be derived and transformed into tether axes to develop a full set of control equations. Controller gains for stable operation will be demonstrated in a manageable fashion.

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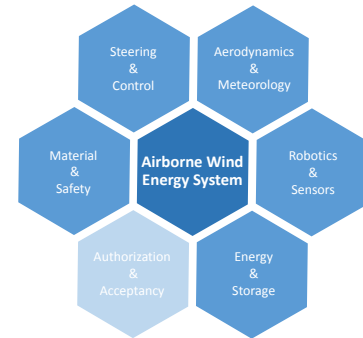


## Airborne Wind Energy Network HWN500 – Shouldering R&D in Co-Operations

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HWN500 Network

HWN500 (“Höhenwindnutzung bis 500 Meter”, or, in English “High Altitude Wind Energy up to 500 Metres”) is a network funded by the German Federal Ministry for Economic Affairs and Energy (BMWi) within the “Zentrales Innovationsprogramm Mittelstand”(ZIM). ZIM is a funding programme for small and medium sized enterprises (SME) with business operations in Germany that want to develop new or significantly improve existing products, processes or technical services. As the cooperation partner of an SME, public and private non-profit research and technology organisations (RTO) are also eligible. Goal of the HWN500 network is to initiate R&D-projects for the development of innovative airborne wind energy systems. High availability, low material consumption and low cost characterize Airborne Wind Energy (AWE) systems. The tethered flying device can flexibly “follow the wind” where it is strongest and therefore uses the persistent wind in altitudes up to 500 m significantly more efficient than conventional (towered) wind power plants. The HWN500 network currently includes 14 industrial and 6 scientific partners, among them 6 developers of AWE systems and is steadily growing. The members profit from project-related cooperations. Goal of the network is to impartially support renewable Airborne Wind Energy (AWE) technologies to mature by identifying and initiating R&D projects that are necessary for commercialization. Therefore, the current state of the art is to be recorded as well as the whole range of AWE-specific re-

quirements to bring AWE systems to market. HWN500 considers the whole range from technological to social, environmental, political, economic and legal aspects. The gap between state of the art and requirements as well as the information about the current situation shall be used for R&D efforts in cooperations of the members of the network and for communication to stakeholders in AWE. To find out the status of development in AWE as well as the most urgent needs within the AWE-industry the network undertook a survey in February 2015. We would like to present at AWEC 2015 the findings and results of the survey as well as the work of the network and its partners.

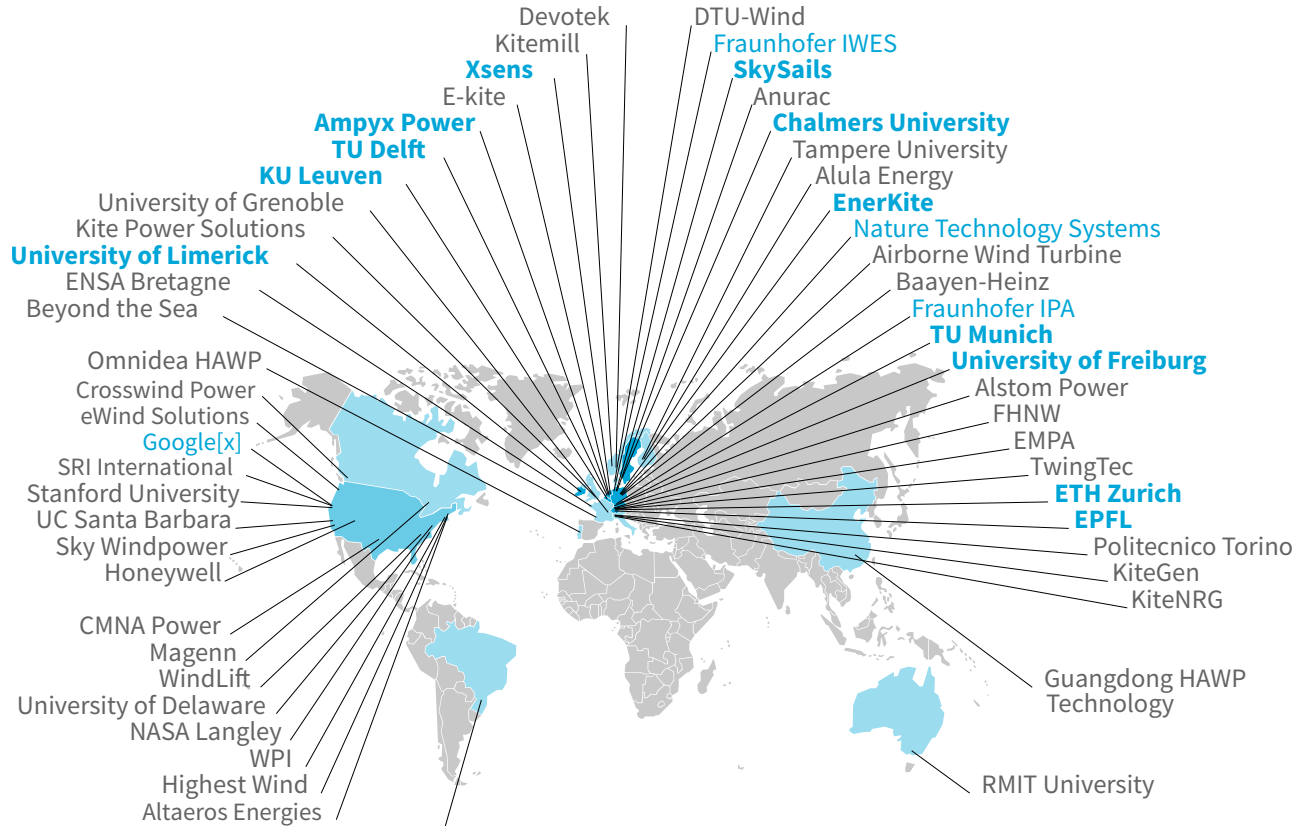


Research areas covered in HWN500



*Leading Edge Inflatable tubular kite and mechatronic  
Kite Control Unit during flight (12 April 2012).*









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## **The AWESCO Initial Training Network – Addressing the Key Engineering Challenges of Airborne Wind Energy**

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AWESCO (“Airborne Wind Energy System Modelling, Control and Optimisation”) is a Marie Skłodowska-Curie Initial Training Network funded by the European Union within the Horizon 2020 Framework Programme and by the Swiss federal government. The network connects twelve European academic and industrial partners who have joined forces to collaboratively train young researchers in the area of airborne wind energy. AWESCO was launched in January 2015 with a duration of 4 years with a total funding volume of 3.4 M€. The research programme addresses the present key challenges of airborne wind energy technologies with the aim of supporting the commercialisation in Europe.

The four research themes in AWESCO are

- Modelling and Simulation,
- System Design and Optimisation,
- Sensors and Estimation
- Control Systems.

Financed network partners are Delft University of Tech-

nology (Netherlands), who is also coordinating the action, Albert-Ludwigs-Universität Freiburg (Germany), Chalmers University of Technology (Sweden), University of Leuven (Belgium), Technische Universität München (Germany), University of Limerick (Ireland), Eidgenössische Technische Hochschule Zürich (Switzerland), École Polytechnique Fédérale de Lausanne (Switzerland) as well as the SMEs Ampyx Power B.V. (Netherlands), Sky-sails GmbH (Germany), Xsens Technologies B.V. (Netherlands) and EnerKite GmbH (Germany). The universities in Delft and Freiburg will employ two PhDers each, while all other network partners employ one PhD.

This presentation will describe the context of the AWESCO network and the four research themes with a special focus on how they are interrelated to address the multidisciplinary character of the AWE technologies. It is further outlined what PhD training events are planned from 2015 until 2018.





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## The Trillion Dollar Drone – A Change of Perspective

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Airborne Wind Energy (AWE) has long been presented as a special form of wind energy and was mostly pitched to corporate investors from the energy industry. The conservative energy industry has met the innovative concept of AWE with limited enthusiasm and a lot of doubts have been raised, especially regarding its technical and legal feasibility. And indeed, AWE has some added technical and legal challenges compared to traditional wind turbines.

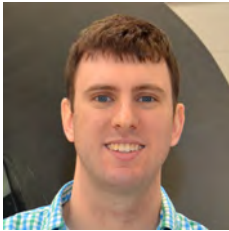
At the same time the potential of the commercial use of autonomous drones has fascinated the business and tech community, the media and the public. Many technology companies have invested in such commercial drones and this has been widely reported. The most popular examples are the proposed delivery drones developed by Amazon and the use of high-flying drones for communication (Facebook and Google). But also hundreds of small drone startups have sprung up. In the perception of the public a large industry of commercial drones is currently in the making. The commercial drone business is “hot”. It receives substantial funding and draws a lot of talent.

If AWE was presented as a drone business it would become easier to demonstrate its technical feasibility. After all, it is just a drone as all the others. As a drone business AWE could also attract additional investors that are not necessarily interested in an energy investment but in the new commercial drone market. The advantages of wind

drones could not only be showed in comparison to wind turbines but could also be compared to other drone businesses. Namely, it could be shown that the economic potential of wind drones is much larger than that of many of the currently hyped uses of drones. Wind drones can rightfully be called the trillion dollar drones. They are also the only drones that can save the world.

Identifying AWE as a special use for drones will bring new players from the aviation and drone industry to AWE. While this will intensify competition amongst AWE companies it will also bring added know-how and funding and will ultimately lead to a faster deployment of wind drones.

The presentation will also discuss the current status and the future of the AWE industry as seen by Daidalos Capital, the only investor specialised solely in AWE and the most successful investor in the industry so far. While the privately funded seed-stage Daidalos Capital AWE Fund I provided valuable resources to AWE in its infant years, the industry has matured and faces somewhat different challenges today and in the future. The Daidalos Capital AWE Fund II has been given a new structure and new investment options to meet these challenges. It will be shown how the Daidalos Capital Fund II can assist AWE companies and the AWE industry in their future development while granting its investors a unique access to a trillion dollar industry in the making.



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## Development of a Micro-Scale Closed-Loop Testing Framework for Airborne Wind Energy Systems – A Case Study in University/Industrial Collaboration

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Researchers at the University of North Carolina at Charlotte, University of Michigan, and Altaeros Energies have collaborated over three years to create the first 1/100-scale platform for closed-loop flight characterisation of airborne wind energy systems. This platform, which utilises a water channel and 3D printed AWE lifting body models to replicate full-scale flight dynamics at 1/100-scale, has evolved from a manually-adjustable, passive system (described in [1], [2]) to a closed-loop system where positions and orientations are computed through real-time image processing and tether lengths are controlled via micro DC motors (first illustrated in [3]). The original platform was successfully used in the design of Altaeros' 2013 prototype, which exhibited stable flight at 10-15 m/s sustained wind speeds and gusts up to 21.2 m/s (see [2]). The current platform is being used to perform rapid experimental iteration between different lifting body and control system designs. This iterative process is being utilised by Altaeros Energies and is being explored at a more fundamentally mathematical level at UNC-Charlotte, where researchers are investigating optimal techniques by which experiments can be fused with numerical design optimisation.

This presentation will review the capabilities of the existing water channel platform at UNC-Charlotte, as well as the scaling analysis that provides guidance for designing the 1/100-scale models and control parameters to replicate full-scale flight properties. The presentation will demonstrate, through test data and videos, the use of the

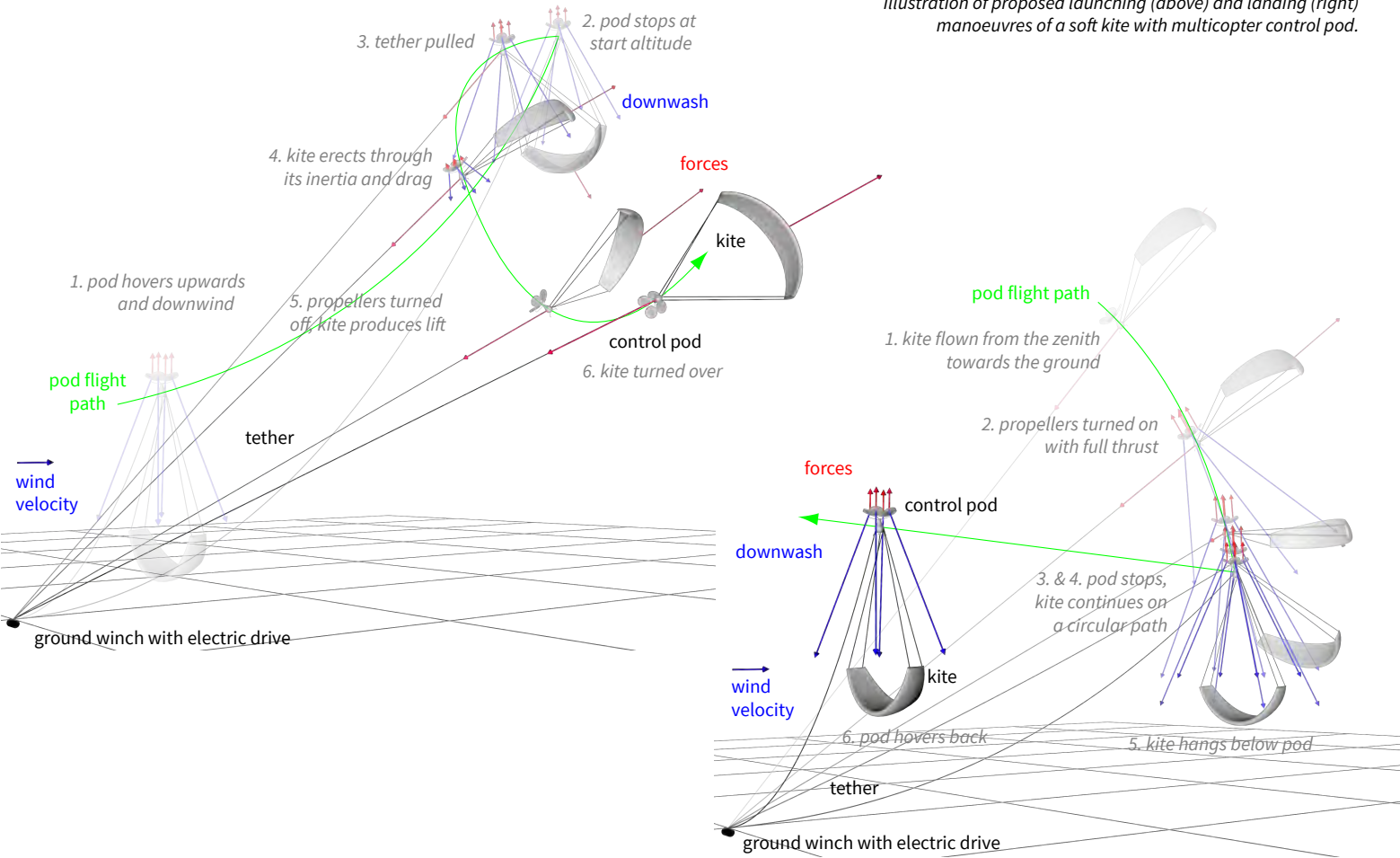
water channel to perform iterative design. The presentation will also describe a mathematical framework for optimally fusing these experiments with numerical modelling.

In addition to serving as a valuable iterative design tool, the 1/100-scale platform serves as a case study in collaboration between multiple universities and an early-stage company, which operate on different timelines and have different intellectual property (IP) interests. In addition to providing a technical description of the experimental platform, this presentation will illustrate how the entities involved have worked together to (1) identify technical objectives that were related to both short-term first-to-market interests and long-term research interests and (2) identify confidentiality boundaries that satisfied the company's need for secrecy and university's need to publish.

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Illustration of proposed launching (above) and landing (right) manoeuvres of a soft kite with multicopter control pod.





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## On Multicopter-Based Launch and Retrieval Concepts for Lift Mode Operated Power Generating Kites

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“Lift mode” operated kites [1] are a promising alternative to conventional wind turbines and “drag mode” operated kites [1], as the generator is located on ground. A key challenge of this technology is the fully automated, and safe launch and retrieval. Several ideas exist, e.g. [2, 3, 4, 5], and are pursued by major players, but most concepts rely on a material intensive and complex ground station and/or on strong and constant winds nearby the ground. With the goal to overcome those disadvantages, in this talk we explore multicopter-based concepts for lift mode kites.

The two sequences depicted on p. 92 illustrate the idea of the launching (top left) and landing (bottom right) of a soft kite with a multicopter control pod: powered by on-board batteries, the pod hovers downwind and upwards while the kite hangs below and the tether is slack. Hereby the leading edge of the kite faces towards the wind vector and thus the kite has similar controllability as if it would be in the zenith. Then, the tether is pulled by the ground winch to erect the kite. Finally, the propellers are turned off, the kite is turned over and power generation is started. During crosswind flight the propellers are used as turbines to power onboard electronics and to recharge onboard batteries. For the retrieval the kite is flown from the zenith towards the ground with reduced speed by depowering. Then, the propellers are turned on

with high thrust, while the tether length is kept constant or the tether is slack. The pod starts to hover in constant altitude and the kite swings below. Finally, the pod hovers back to a landing site. This concept has following advantages: (i) a simple ground station, (ii) no need for wind nearby the ground, and (iii) applicability to attach several kites to a split tether. However, several challenges must be faced like complex flight manoeuvres or the increased mass due to the batteries. In this talk, those concerns are addressed and solutions are explored. Promising dynamic simulations suggest the feasibility of the flight manoeuvres. Furthermore, extensions and applicability of multicopter-based concepts for lift mode rigid kites are discussed.

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*Experimental launch setup of Delft University of Technology (23 August 2012).*



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## The Take-Off of an Airborne Wind Energy System Based on Rigid Wings

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The term airborne wind energy (AWE) refers to wind power generators that use tethered aircraft to convert wind energy into electricity [1–3]. Lower construction and maintenance costs and the possibility to reach higher altitudes, where faster and steadier winds blow, are two main advantages compared to conventional wind power. AWE systems with aerodynamic lift can be classified by the placement of the electrical generators: on-board of the aircraft or on the ground. For systems with ground-based generators, a further distinction can be made between concepts employing rigid-wing aircraft and concepts with flexible wings like kites. Small-scale prototypes (10–50 kW of rated power) of all concepts have successfully demonstrated power generation.

Autonomous take-off from a compact ground area has been achieved with AWE systems with on-board generation [4] and kite-based systems with ground generation [5]. The same functionality for systems with rigid wings and ground-level generators is still lacking. Indeed, autonomous take-off of this class of generators was demonstrated by using a rather conventional winch launch that requires a large ground area [6]. However, if a large area is required for the deployment of an AWE system, this will compromise some of the advantages of AWE mentioned above. The only study in the literature concerned with the launch phase of ground-based AWE systems with rigid wings studies a rotational start-up [7]. There, the focus is on the control and optimisation aspects instead of economic viability and the comparison with other possible methods.

Here, we will present an analysis of several conceivable

launching schemes for a rigid-wing AWE system. More specifically, we will compare a vertical lift approach with vertical-axis propellers, a linear launch technique combined with on-board propellers, and a rotational start-up like the one considered in [7]. The comparison will be based on performance criteria which we will introduce. A deeper study of the concept that is deemed to be the most viable one, i.e. the linear launch manoeuvre combined with small on-board propellers, will be performed. In particular, we derive a dynamical model of the system that includes realistic aerodynamic coefficients, as well as friction and inertia. We use the model to refine the initial analysis in terms of power and land usage required for take-off. Finally, we will present first steps towards the experimental verification of our approach.

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## Multiple Wing Systems – an Alternative to Upscaling?

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All airborne wind energy systems based on crosswind flight suffer from tether drag. Fortunately, tether drag becomes less significant for larger sized systems, because the necessary tether diameter grows only with the square root of the aerodynamic forces acting on the wing. This is the major reason why tether drag becomes insignificant for large kite systems as the 300 square metre Sky-Sails traction kites, while it is significant for small high efficiency wings such as the prototypes successfully built and operated by companies such as Ampyx Power or Makani/GoogleX. The route taken by most actors in the field of airborne wind is thus to upscale the small scale prototypes as fast as possible, in order to create a competitive product. Simulation studies suggest that a power output of 40 kW per square metre wing surface is possible with large scale high efficiency wings [2], while only a fraction of this value has been achieved with the existing small scale rigid wing prototypes so far.

An alternative to upscaling, that can reach a power density of 40 kW per square metre independent of system size, would be to take two or more of the existing small scale prototypes and let them fly circles around each other, as first presented in a patent from 1976 [1]. Because only the short "secondary tethers" move fast in a crosswind direction, this configuration allows one to have the desired effect of a long main tether - reaching high alti-

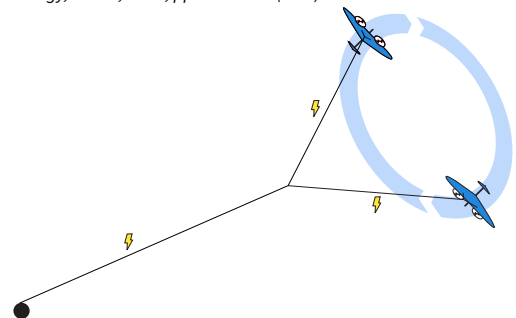
tudes - without the corresponding tether drag. In fact, detailed studies show that optimally sized systems nearly have a constant ratio between wing span and secondary tether length and reach the highest possible power density independent of system size [2].

This presentation reviews the history, current status and remaining challenges of multiple wing systems for airborne wind energy.

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## Identified Flying Object – IFO: an Untethered Airborne Wind Energy System

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The characteristic feature of our AWE-system concept is the use of un-tethered flying devices [1]. Today, the "flagships" of this emerging industry choose to use tethered ones. This fact may have several causes, among others the doubts regarding the technical feasibility as well as the theoretical background of this technology [2].

The presentation begins with the theoretical principles of IFO-gliders and their demonstration with a simple time-domain simulation as well as some existing "proofs of concept". The most critical problem of the idea is that harvested energy has to be stored temporarily on-board the IFO. The presentation discusses some of the possibilities. IFOs apply a special technique of flight called Dynamic Soaring. This way the flying device can capitalise on the energy of wind shears by increasing its own airspeed to several times that of the gradient. Since winds do not stay in place, the flying devices need to follow them. Tethered devices obviously cannot do so. Their untethered competitors (e.g.: IFOs, guided by their LIDAR) are free to rise into and travel with winds that would maximise the continuous yield from an energy extraction aircraft.

Most tethered devices work today near the upper end of the planetary boundary layer, that is: at about 500 m altitude. Summarising wind power data that are characteris-

tic for the particular device and altitude (see figure), one can state that the tethered and conventional types have insurmountable handicaps compared to the IFO.

*Characteristic wind power data of wind power plants [3]*

Type	Height (m)	Wind Speed (m/s)	Wind Power Density (W/m <sup>2</sup> )
Conventional	100	4	38
Tethered	735	7.3	224
Un-tethered IFO	10000	140*	411000

\*Airspeed of the IFO

These first results show that un-tethered flying energy harvesting devices deserve more attention in the future than they had until now.

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## **On Image Interpretation for Position Detection of Kites**

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A method of contactless measuring the position and orientation of a kite is presented. The market for sports and energy kites is growing steadily and it raises the problem of parametrisation and measurement of these kites. Within the framework of a test bench development, a comparison between different measurement methods is done. Subsequently a method is developed with which it is possible to exactly determine the position and orientation of the kite in the wind window. The system has no moving components and transmits the position and orientation information almost in real time.

The simulation of highly flexible airfoils, like a kite or a paraglider, needs a precise interaction of numeric FEM and CFD models. Due to the high flexibility, an accurate simulation with the fluid-structure interaction cannot be carried out with the available CAD/CAE tools. Currently the development of flexible wings is mostly being made with trial- and error, using a large number of prototypes. However, with a rising stage of maturation the recognition of improvements, without objective measurements and a high investment in time and costs is not possible. Due to the size of the airfoil, including the line-system, it is not possible to test the whole system inside of a wind-tunnel. The downscaling of this flexible airfoil is with respect to the Reynolds number infeasible.

For this reason a test bench is developed which allows to test and parametrise different types of kites. The whole test bench is moving at a specific velocity to simulate different wind speeds.

Due to the evaluation as well as the automatic steering, it

is indispensable to know the exact position of the object in the wind window. In this manner it is possible to connect the picture, the calculated position and other measurement data like the line force in the post processing. In addition, a precise automatic control of the kite is only possible if the main system has reliable positioning information in real-time.







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## Challenges in Modelling of Membrane Structures

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Membrane structures, often supported by additional stiff structure, have been used for lifting surfaces since the first kites and aeroplanes (sometimes derided as “string and wire contraptions” by their contemporaries). Since then, technology obviously has come a long way, but, using modern materials like wovens or laminates, membrane structures, often supported solely by pressure differential or inflated tubes, still offer great opportunities for constructing large lightweight lifting surfaces.

While the actual structures often appear to be quite simple, the engineering process is determined by the strong non-linearity of their behaviour and the impact of flow forces on their actual shape. Thus, the accurate prediction of flow and structural behaviour and its interaction is required.

For these fluid-structure-interaction (FSI) simulations the process is usually split in two with separate structural and flow simulation coupled by exchange of flow forces and geometry deformations.

In the poster, initially the simulation of structural behaviour constant-stress-triangle (CST) elements [1], extended by anisotropic material, is discussed.

This is extended by a description of wrinkling modelling, as particular property of materials used for membrane structures (films, wovens or laminates) is their small bending stiffness. While the folds arising from uniax-

ial tension can be captured e.g. by buckling analysis when using higher order shell elements [2], the basic CST-element does not provide for the correct capturing of these effects. To the contrary, artificial folds with frequency and amplitude determined by element size tend to appear, stiffening the structure in direction of these folds. To correct this shortcoming, a wrinkling model has to be employed. The wrinkling model [3] is based on the idea of a fictitious non-wrinkled membrane, subject only to the uniaxial principal stress, in place of the wrinkled membrane. By this approach, the wrinkles are assumed to be of sub-grid scale.

Lastly, the coupling of flow and structural simulations is discussed. The required coupling approach strongly depends on the importance of time-accuracy of the solution. If time-dependency is expected to affect the result, strong or implicit coupling is required, else, weak or explicit coupling may suffice.

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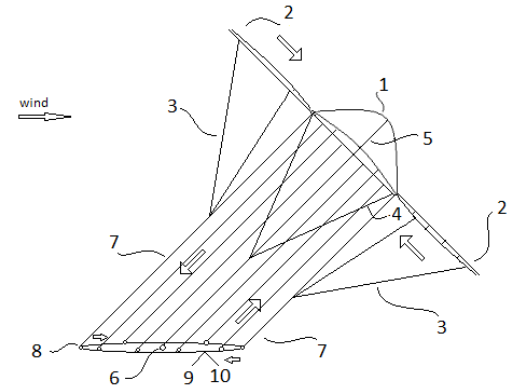
## Rotating Reeling

**Pierre Benhaïem**

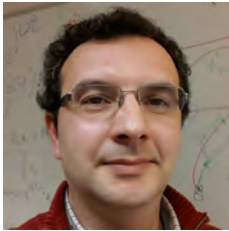
"Rotating Reeling" is a new conversion system working with a rotating kite denoted as "Parotor" and comprising a parachute as hub and soft, for scalability towards kilometre-range, or semi-rigid wings or blades. It is a sort of synthesis of the yoyo and carousel concepts, but where the kite span is roughly the same as the length of the lines. So, Rotating Reeling and Parotor allow a maximisation of land and space used, avoiding difficult management of a farm of kite systems where mobile and relatively long tethers prevent such a maximisation. The rotational speeds of both, conversion system and Parotor, are very low, with the number of revolutions per minute below 1. Linear speeds of both hub and ring are roughly of the same value as the wind speed. A cyclical piloting of wings allows to remove lifter kite. Launching and landing is realised by using mobile stations as anchors.



Next steps are the development of an automated 30 m span wing in the energy production range of 100 kW.



There is one rotating kite (1 and 2) in the air and one ring (9) of mobile stations (8) on a circular track (10) on the ground. The two systems are connected by peripheral lines (7) from the opening of parachute (1) towards mobile stations (8). The angle of attack of the rotating kite (1 and 2) is assured by its hangers (4) tied in the central rope (5) joining the central station (6). Since the kite is tilted while the conversion system is horizontal there are cyclical variations of length of peripheral lines (7). So generators can be settled within mobile stations (8), reeling-out being for the half of the ring turning upwind. Alternately a generator can be settled between the ring (9) and the circular track (10), the conversion being roughly for the half of the ring turning downwind, reeling being used to smooth the cyclical variations of lines lengths.



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## Mesh-Refinement Strategies for Fast Optimal Control and Model Predictive Control of Kite Power Systems

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We consider continuous-time optimal control and model predictive control problems for kite power systems. We solve these problems in a time-mesh that is adaptively refined to achieve a desired level of accuracy.

The proposed mesh-refinement strategy considers, in the optimal control problems (OCP) context, several refinement criteria in a multi-level scheme. A major feature of our strategy is to consider the local error of the dual variables as a refinement criterion. This error can be computed efficiently by comparing the solution of a linear differential equation system – the adjoint equation of the maximum principle – with the numerically obtained multipliers.

Details of this technique and its use in other nonlinear systems are reported in [1,2]. The refinement strategy resulted in higher accuracy levels and yet with lower overall computational time, when compared with the use of traditional meshes having equidistant-spacing in continuous-time OCP, and with a priori discretised versions of the OCP. In particular, the time to obtain a solution with a similar level of accuracy was 4% to 30% of the time needed using traditional equidistant meshes. The

benefits of using an adaptive time-mesh are particularly more evident in highly nonlinear systems, as is the case of the controlled kite and other non-holonomic systems. The technique led to the use of finer meshes in time intervals where sharp turns of the kite occur.

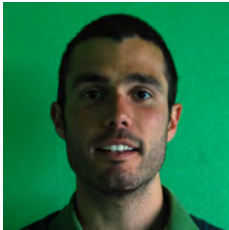
The refinement algorithm is extended to solve a sequence of optimal control problems in a Model Predictive Control (MPC) scheme. In this extension, we consider a time-dependent stopping criterion for the mesh refinement algorithm with different levels. In particular, we impose a higher accuracy requirement in the initial parts of each horizon, which are more relevant in MPC. The use of adaptive refinement in real-time optimization schemes, such as MPC, enables the possibility of obtaining a solution even when the optimization has to be interrupted at an early stage.

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*Genetrix/TU Delft V3 Leading Edge Inflatable kite and TU Delft Kite Control Unit (8 November 2014).*



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## Pumping Kites Wind Farm

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Harvesting wind energy with kites and converting it into electricity is technically feasible, as demonstrated by several existing prototype installations. One of the dominant concepts, at least in terms of numbers of prototype systems, is the conversion of the traction power of kites within pumping cycles, which is also the topic of the present study. For demonstration of economic viability the prototype systems need to achieve prolonged operational times and may need to be scaled-up to the size and numbers applicable in the target market.

At this stage of development of the technology, the following questions need to be answered

- Spacing requirements of individual units in a wind farm?
- Achievable power output per square metre ground surface area?
- Continuous average power output possible by operating multiple units?
- Achievable levelised cost of energy (LCOE)?

The current study addresses these questions. The work is divided in two phases: first, the analysis of the individual pumping kite system, then, the study of the entire kite wind farm.

The analysis of a single pumping kite system starts from an arbitrary choice of kite size. An analytical quasi-steady model is used to describe the traction power of the wing along the pumping cycle. This model has been validated by experimental results and comparison with a more accurate dynamic system model. The strong influence of operational parameters on the energy production re-

quires an optimisation process. A genetic algorithm is used to optimise the traction and the retraction force, the elevation angle and the maximum and minimum tether lengths for different wind speeds. By choosing sets of operational parameters within given ranges, the algorithm is able to optimise the power production, resembling the natural Darwinian selection process.

The optimised system is used to simulate a farm of several identical units. Some thoughts have been put in the spatial distribution and the operation of such farm and interesting results are derived. The LCOE is finally used as an optimisation criterion for the kite size.

The optimal unit for the given prescribed wind conditions, appears to be powered by a 250 m<sup>2</sup> soft-kite, achieving a net power output over the cycle of 90 kW. It is interesting to understand the effects on the cumulative power production of the number of kites and the wind speed. The more units are installed in the farm the more constant is the power produced. Considering the three-dimensional spatial distribution of the kites in the farm, units could be placed much closer than wind turbines leading to a very high installed power per land occupied of 87 W/m<sup>2</sup>. The LCOE of the farm is computed to be in the range of 95 to 105 €/MWh, depending on the number of kites in the farm and the assumptions made on costs of various system components.

The outcome of this study shows a very promising technical and economical potential of the technology. It will hopefully serve as reference to justify the great expectations of the various research groups in the field.





*The K2 boat of Kite Boat Project at the San Francisco Bay (5 June 2014).*



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## Structural optimisation of a kite for ship propulsion

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Currently, flexible traction kites are almost exclusively used for recreational activities like kite surfing. The current designs are the result of collective experience gathered by a large number of designers throughout the years, fuelled by a low cost for prototyping and relatively open IP culture.

With the advent of using flexible kites for extracting wind energy and propelling ships, kite design is moving out of the "comfort zone" and certain design rules of thumb do not apply any more. Add to this the higher cost of prototyping and more of an engineering approach seems justified.

One of the big challenges is to predict the fabric stress and overall deformation of a large kitesurf kite. From tests it has become clear that the kites start to deform significantly when the total line load exceeds 5000 N. This especially affects the L/D of the kite and therefore the upwind capability of the kiteboat.

The approach here described uses a combination of real-time simulation, finite element analysis (FEA) and measurement data. These components interact to both validate the design process and come to improved kite designs.

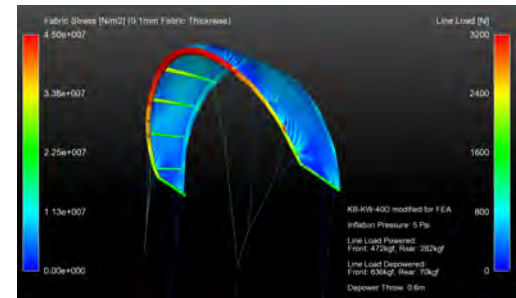
During boat tests a large number of sensors are measuring data like boat speed and course, (apparent) wind speed, line load and angle, etc. Also a number of cameras are registering kite deformation and movement.

The Kite Modelling Software functions mainly as a

parametrised kite design tool but also delivers complete input files for both the real time simulator and the FEA software. A closed canopy and tube mesh, lumped mass bridle, aero forces, inflation pressure and boundary conditions are automatically regenerated after each design change.

A real-time simulation is built with a freely available physics toolkit and solver within the Rhino3D CAD software environment. The kite model is fully flexible and is built along the lines of the ADAMS model of Jeroen Breukels[1].

FEA analysis is done with an open source FEA package, using a dynamic explicit solving method.



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*Flexible strip with pressure sensors applied to a rigid wing in the TU Delft wind tunnel.*





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## A Tool for Aerodynamic Analysis of Flexible Kites

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Studies have shown that the power harvesting efficiency of a pumping kite system is determined mainly by two performance characteristics of the kite. For a given size of the wing the cycle power output increases on the one hand with the lift-to-drag ratio [1] and on the other hand with the available de-power range [2]. In search of an improved kite design, this study aims at identifying shortcomings of current design procedures, with a special focus on the aerodynamics. These procedures are mostly derived from the kitesurf industry where thorough aerodynamic analysis is generally not integrated systematically in the iterative development cycles. As a result, little is known of the kite while in-flight, such as shape, angle of attack, and pressure distribution. Knowledge of these parameters is essential for the quantification and identification of design improvements. These values are furthermore crucial for the validation of numerical models. In order to provide a solution for the lack of experimental data of in-flight kites, a system for in-situ measurement of the surface pressure distribution was developed and validated.

The developed system is based on Micro-Electro-Mechanical-System (MEMS) barometric pressure sensors, the LPS25H by STMicroelectronics [3]. A set of sensors are mounted on a flexible circuit board printed on PEN (Polyethylene naphthalate) which is completed with a single board computer to control and store measure-

ments. The barometric nature of the LPS25H sensors in addition to the necessity of the dynamic pressure in the computation of the pressure coefficient led to the development and integration of a pitot-static unit. All components were individually tested to evaluate their reliability and accuracy.

The validation of the system was performed in an open jet low-speed wind tunnel mounted on a rigid wing section featuring integrated pressure tabs. With the addition of improvements to reduce the system roughness, the results showed a minimum pressure coefficient overestimate of 5% compared to the pressure tabs at 0.4 chord. The sensors between 0.15 and 0.65 chord showed similar response with errors varying between -5% and +10%, while at the leading edge and trailing edge of the profile larger errors were observed. The latter is explained by the larger relative thickness of the pressure strip compared to the airfoil thickness in those regions. The system still requires further research before it can be fully deployed, but the initial results are promising.

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## Design of a Lightweight and Durable Kite for Cost-Effective Traction Power Generation in a Pumping Kite Power System

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This presentation focuses on a design exercise for a pumping kite system. In recent years most research has been dedicated to inflatable kites for a pumping kite power generation system. As the technology matures, these inflatable kites now show their limitations in terms of durability, scalability, aerodynamic performance and therefore overall power generating performance.

The challenge was to design a lightweight yet strong, stable yet agile and high performance yet low cost kite. The system was designed for a continuous traction phase power of 40 kW (between 200 to 700 m of tether length) at a ground-based (6 m) wind speed of 5 m/s up to 12 m/s and to remain operable up to 25 m/s. The trade-off criteria were primarily costs, stall speed, retraction phase power and design risk.

The kite was sized for the 40 kW traction power requirement at low wind speeds. This resulted in a kite with a 12.7 m<sup>2</sup> main wing and a (limited) span of 10 m. The kite is fully built from carbon-fiber-reinforced polymer (CFRP). The structure was designed for a maximum traction load of 20 kN with a safety factor of two. The main wing is partly designed as a sandwich structured wing box to counter buckling. The traction tether is split into a two-line bridle attached to the wing in such a way that the bottom skin is only loaded in tension. This eliminated the need for sandwich structure in the bottom wing box panel. It has an inverted T-tail connected to the wing with an up-

ward swept tail boom to reduce drag at high angles of attack. This resulted in a kite of only 40 kg. The kite has ailerons, a rudder and an elevator and is therefore fully stable and controllable, even when the tether is disconnected. The bridle split has a pulley for free roll movability. On-board power is generated using a small turbine. The flight computer is situated in the ground station and is linked to the kite by a wireless communications link system. For the aerodynamic analysis, XFLR5 was used and for the structure, thin-walled beam stress analysis in combination with von Mises-stress analysis and curved-plate buckling analysis were used.

The power production performance was analysed using a Weibull wind speed distribution and optimised cycle output for every wind speed. It was then compared to a conventional 40 kW rated power wind turbine. With a yearly average of 22.6 kW the kite proved to produce 8% more energy per annum, at a fraction of the material usage. The main structural components of the kite are expected to have a lifetime of 5 years. The tether would need replacement two times per year. With a levelised cost of energy (LCOE) of 0.113 €/kWh (75% of PV solar) a return on investment of 9.8% would be achieved. Upscaling of the kite to a minimum of 100 kW average power output, would drive the required LCOE down. Design choices and trade-off will be elaborated more on in the poster.





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## Multiple-Wake Vortex Lattice Method for Airborne Wind Energy Membrane-Wing Kites

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A suitable wing design for pumping kite power generation is the leading edge inflated (LEI) tube kite because the bridling and leading edge design allow the wing to be depowered while retaining good steerability. Current LEI kite design is typically empirical. Fluid-Structure Interaction (FSI) modelling is necessary to decrease design time and gain insight into the physical processes driving kite performance.

Unfortunately, the current kite aerodynamic models do not meet the requirements for LEI tube kite FSI modelling: they are either fast but insufficiently accurate, or accurate but computationally expensive. In particular, the current fast aerodynamic models are not able to represent the effects of the multiple flow separation regions – such as behind the LEI tube and above the canopy's trailing edge – inherent to an LEI tube kite flying at a large range of angles of attack.

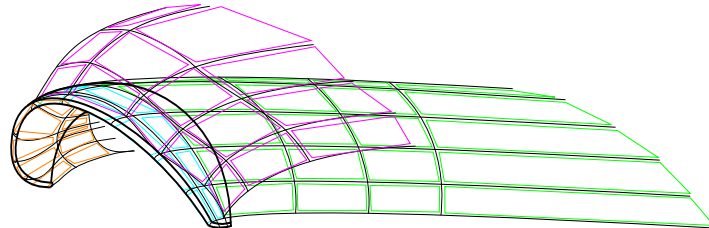
It is well established that 2D multiple wake vortex models can model multiple separation regions over membranes. Consequently, it is probable that a multiple-wake vortex lattice method (VLM<sub>MW</sub>) could model the multi-

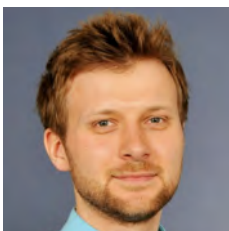
ple separation regions expected on a 3D membrane-wing surf-kite. To the author's present knowledge, no such VLM<sub>MW</sub> aerodynamic model has yet been constructed for 3D membrane-flow problems.

This ongoing M.Sc. thesis is intended to evaluate the hypothesis that a quasi-steady multiple-wake vortex lattice method can quickly and accurately model surf-kite aerodynamics to generate aerodynamic surface load distributions.

This VLM<sub>MW</sub> models the vorticity generation in the flow with multiple vortex lattices shed from the separation locations, as well as the standard bound vortex lattice. The separation locations are fixed at known locations. The impermeability boundary conditions allow for membrane deformation such that the model can be used for FSI functions. The figure shows the multiple-wake layout of the flow model.

The lift and drag polars generated for arc-shaped wings with a single-wake model have been validated for a Clark-Y airfoil arc-shaped paraglider, as well as the Mutiny "V2" kite of TU Delft.





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## Visual Motion Tracking for Estimation of Kite Dynamics

Max Polzin, Henrik Hesse, Tony A. Wood, and Roy S. Smith

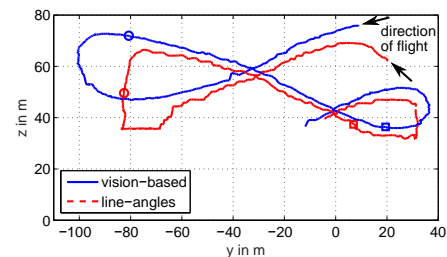
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This work presents a novel estimation approach for an autonomous tethered kite system. We propose an estimator which relies on visual motion tracking of the kite position from ground-based video recording. The proposed visual tracking approach is used to assess the quality of existing estimators and is eventually applied for real-time estimation of the kite dynamics in closed-loop operation of the AWE system developed at Fachhochschule Nordwestschweiz (FHNW). The focus in this work is on the development of a fast and reliable visual tracking algorithm that can be used for real-time estimation in experiments of autonomous tethered kites.

The developed visual tracking algorithm combines a fast tracking algorithm with a reliable object detector to exploit advantages of both methods. The implemented tracker is a dual correlation filter (DCF), first proposed in [1]. It is not suitable for long-term robust motion tracking since erroneous tracking occurs occasionally. These inevitable tracking failures can be tackled by resetting the tracking algorithm with assistance of a detector [2]. The latter is much more discriminating but comes with a significant computational cost. A reliability measure was therefore added to the DCF tracking algorithm in this work to provide a threshold when the detector is triggered. This improves computational efficiency of the combined visual tracking algorithm and allows reliable real-time estimation of the kite dynamics.

To demonstrate the proposed estimator, we have implemented the visual tracking algorithm in Matlab which is able to track objects (40x40 pixel) in over 100 frames

(1280x960 pixel) per second. For three videos of representative kite power test scenarios (sunny, cloudy and a small kite on long lines) with 23300 frames each, we achieve accurate estimates of the kite state. The figure below highlights the effect of line dynamics in state estimation from experimental data of the two-line system at FHNW. The markers clearly demonstrate the lag introduced in line-angle-based estimates which is especially evident in (up-loop) curves where line tension is low.



Kite path based on filtered line angle measurements against visual motion tracking. Markers illustrate the instantaneous tracked positions at two different time instances.

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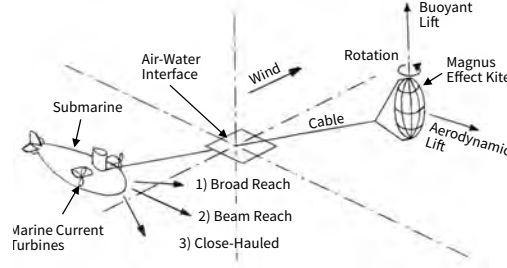
## Wind Fisher: Autonomous Kite Towed Submarine for Airborne Wind Energy Capture and Storage

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Wind Fisher is a new startup project, based in France, designing and developing an autonomous maritime platform, consisting of a Magnus effect, lighter-than-air kite, pulling a submarine with marine current turbines for electrical generation and with a chemical synthesis plant for energy conversion and storage. The figure shows a functional schematic of the Wind Fisher System.



Functional schematic of the Wind Fisher System

Wind Fisher submarines are designed to operate in the Southern Ocean around Antarctica, isolated from other human activities, to chase the persistent winds in this region. In this manner, the Wind Fisher system resolves two commonly voiced problems for the AWE industry: 1) Airspace conflict with aviation due to the flying kites and tethers; and 2) Safety of the general public in case of loss of flight control and subsequent crash.

The authors intend to present their theoretical work regarding:

- The system design features and trades to be made to insure: an autonomous functioning of the system in different conditions (up wind, down wind, and no wind), as well as, an overall positive generated power.
- The Magnus effect kite control approach, including the balloon rotation velocity control and the navigation of the kite.
- As well as, the development status for a Magnus effect kite prototype to be built for the concept validation step.



*Visualising the wing tip vortex of a ram-air kite suspended in a wind tunnel (TU Delft experiments at the University of Stuttgart, 2008).*



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## Fluid-Structure Interaction of an Inflatable Kite Wing

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Kite power is one of the promising concepts in Airborne Wind Energy. The complex flight patterns, the unpredictable nature of cross-winds, and the highly flexible and inflatable design of the kite wing make the dynamics and control of the wing highly complex. Existing methods make use of approximated structural and fluid-dynamics models to predict this behaviour [1]. Also, most of the approximate solutions can only be used to simulate the wing under ideal conditions. Reliable simulation models that can provide high fidelity results are imperative for further development of kite power systems.

A novel fluid-structure interaction (FSI) simulation technique is being developed at the Kite Power group of TU Delft. The proposed method brings in Finite Element (FE) computing techniques for the precise structural and aerodynamic analysis of the airborne kite. The objective is to develop a non-linear dynamic FE structural solver coupled with a CFD tool that can allow for the complex dynamics of the highly flexible, inflated kite under a variety of flight conditions.

The outputs of the FSI simulator will provide better insight into the kite dynamics. The framework can be utilized in the optimization of flight paths and in enhancing kite performance. An FSI simulator can analyse the kite's behaviour under extreme and non-ideal conditions.

It can be used to guarantee the kite's stability during launching, reeling, steering, low-wind and under other adverse conditions where there are high chances for the kite to collapse. The system can be used to optimize existing control algorithms which makes automation feasible. The project is at its inception and the methods are at the formulation stage. In the initial phase, a minimal structural solver with the capacity to resolve nonlinear structural dynamics on 2D membrane elements will be coupled with an existing CFD code. Fluidity is an open-source CFD code that is being developed at the Applied Modelling and Computation Group (AMCG), Imperial College, London [2]. In-built routines for modern CFD techniques like mesh-adaptivity and immersed boundary methods, and hybrid parallelisation using OpenMP and MPI makes Fluidity an ideal choice for the problem at hand. The poster will list the objectives and delineate an initial outline of the project. This research is supported by the European Commission under grant agreement PCIG13-GA-2013-618159.

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## Hello World: someAWE.org

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Over the past decade the Airborne Wind Energy (AWE) scientific, industrial and hobby communities have grown considerably. Scientific and industrial communities have started to build networks and platforms to improve communication and collaboration. However to this day there is no inviting, active AWE online community to support these activities.

Current and past attempts to create an active AWE online community struggle to attract most of the active minds in the space due to the following reasons:

- Lack of focus leading to high noise to information ratio
- Lack of moderation leading to lack of civility and focus
- Relying on "if you build it, they will come", leading to lack of active members

On 15 June 2015 the online platform someAWE.org will go live and try to close this gap by becoming an active, welcoming and open AWE community. The platform will be dedicated to make AWE happen by creating a place to discuss about the technology and related aspects in a friendly but strictly on topic manner. The platform has sound funding and human resources to avoid the three

symptoms that made past attempts struggle/fail. The platform will be completely independent from any commercial interests. It will be open for commercial and open projects. The platform will be actively moderated based on the following criteria:

1. Civility is paramount – Treat others with respect, kindness and generosity.
2. Strictly on topic – No discussion of anything other than *airborne* wind energy.
3. Respect the laws of physics – No discussion of anything that would require the laws of physics to be changed or that requires technology that is not likely to be available in our lifetime.
4. Share – Although someAWE.org is not limited to open source projects: open communication and publishing under an Open license is encouraged.

We would like to use the opportunity to build the critical mass of users to get the community going by presenting the platform to the illustrious circle of AWEC 2015 attendees.





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## A Sociotechnical Approach and a Future Vision Proposal for AWE in the U.S.

**Diana Palacios, Nicole Van Den Berg, Elizabeth Migoni Alejandre, Diana Ita, Milan Veselinov**

The beginning of the 21st century brought with it the exploration of Airborne Wind Energy (AWE). This innovative technology has caught the attention of several research institutes and visionary entrepreneurs who are currently developing different prototypes to harness these winds. An analysis of the current sociotechnical situation and future scalability of AWE technologies in the U.S. is carried out through a multilevel perspective. The application of the Functions of Innovation System (FIS) methodology is used to show the current drivers and barriers of AWE systems and a Backcasting approach (BC) is used to create a desired future vision for AWE and to define the institutional framework and the socio-economical context required to steer current actions.

The most relevant drivers for AWE systems in the U.S. are the high expectations supported by the potential of wind power at higher altitudes, the evolution and increase of entrepreneurial activities, the diversity in knowledge development and thus in number of future users, the annual networking events that have promoted technological development and attracted public funding and stronger private investors, and lower environmental impact in terms of wildlife, noise and visual pollution. In contrast, the lack of a constant financial support has made small teams split between R&D and funding tasks and has created a gap between well-funded and promoted companies and the ones that are not. The uncertainty associated with the take-off stage, prior to market development, sets a competitive atmosphere that conditions knowledge diffusion and decrease the effectiveness of lobbying for an advantageous legislation; this indirectly results in less resource mobility and knowledge development.

In our desired future vision, wind energy systems will become well established in the U.S. energy market and AWE systems will coexist with the ground-based technology to increase their share, reducing the influence of fossil fuels prices on the development of this technology. The different energy demands and environmental conditions will help maintain the diversity of designs, however there will be a leading AWE design. The other designs will also be commercialized but not at the same rate, granting this technology a wide diversity of applications and customers. AWE technology will provide electricity to off-grid areas and other services such as weather monitoring, communication, and will also act as a backup system after natural disasters.

A series of trend events and demands are proposed in order to steer current situation towards the desired future vision; these are: governmental support must be constant and immune to shift in political parties. Policies such as increased carbon taxes and creating incentives for renewable energy (RE) development must be consistent and applied nationwide. NGOs must continue exerting pressure for a shift into a RE based economy. The research, development and implementation of wind energy systems with higher capacity, performance and durability must be supported by a stable public and private economic investment. A clear policy framework that regulates the testing of AWE prototypes is required. Central actors of the AWE network would have to become more efficient at communicating the expectations and needs of all stakeholders and therefore be more effective in their lobbying efforts. Finally, the social resistance to this and other RE must be counteracted by an active user and societal involvement on RE projects at initial stages.



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## Structural Modeling of Thin Membranes for Wind Energy Systems

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Membrane structures have a rich history of use across many disciplines and are widely used in aerospace and structural engineering applications. More recently, thin membranes are often applied in lighter-than-air wind energy systems, such as in [1]. These membranes are especially attractive to airborne wind energy systems for their low mass to surface ratio and their ability to take complex shapes. Although membranes can carry tensile loads very well, they tend to wrinkle under the slightest compressive load. These wrinkles affect the load carrying capabilities of the membrane, and thus the structural performance of the entire airborne system. It is therefore important to accurately model the stress distribution in the membrane to assess its load carrying capabilities. To model the structural behaviour of wrinkles in a membrane, the mesh size in e.g. a finite element model needs to be at least as small as the wrinkles to detect them. Considering the small scale of the wrinkles with respect to the wind energy system as a whole, this requirement often results in unacceptably high computational costs.

In this work, we approached this problem by modelling the membrane wrinkles as a continuous in-plane contraction of the membrane, using an interior-point implementation [3]. This approach allows us to use a mesh size that is much greater than the size of individual wrinkles. The efficiency and robustness of the proposed method was proven mathematically and verified numerically. We validated our method by modelling an inflated, pressurized beam under applied bending loading and comparing the force-displacement curve with experimental data.

This validation, together with the efficiency, robustness, and cost reduction of our method, show its great potential for the structural modelling of large membrane structures such as airborne wind energy systems.

*References:*

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## Development of Airborne Wind Energy Systems in a Competitive Energy Market

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The SkyWindTurbine project was started in the autumn of 2013 with the goal to develop an innovative wind system that can be economically feasible in low wind speed inland regions. A small consortium was founded by QConcepts with the HAN University of Applied Sciences and the German firm Von der Linden as main partners.

After the proof of principle stage the Dutch region Gelderland awarded the development with funds for a prototype project with a fixed wing structure out of bio-fibres. Sustainable production using "flexing" flax fibres and the need for smaller more horizon friendly systems were the key arguments in this decision.

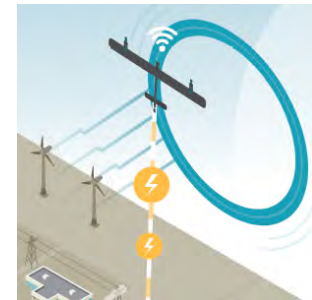
A third generation prototype will be launched in June 2015 for further tests and refinements. The focus in this stage is on:

- Light weight structures and automated production, QConcepts main field of expertise
- Control systems
- Operation at low altitudes and in zones with low wind speeds

The project structure: Collaboration and synergy between fields of expertise and partners are the key ingre-

dients in this development. A student-hub was formed around this and other sustainable energy projects to create a unique R&D environment. The mix of industry professionals, students and researchers create an atmosphere wherein developments and results follow each other rapidly.

Local municipals, universities and SMEs are brought together in this project with as goal to push the boundaries of technology and to create a more sustainable world.





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## Opportunities and Progress in Open AWE Hardware

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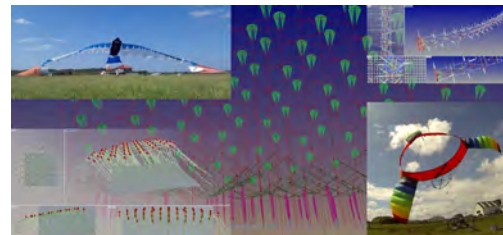
Windswept and Interesting Ltd

Open hardware AWE, is AWE done right. Try our designs and find out why. We have evolved scalable systems within regulatory, economic, safety and material efficiency perspectives. Started by “hobbyist” engineers on shoestring budgets, Open AWE is now, open for business. We provide valuable international cooperation on research, manufacturing and operating standards [1]. Open hardware products by Dan Tracey and Kpower have successfully marketed using traditional manufacturing partnerships and open market funding. Further products with the highest TRL in AWE are on the factory floor. Our open designs are based on commercial off the-shelf (COTS) standards.

New methods, designs and test results are still published daily [2]. Designs scale from personal communication devices to viable gigawatt AWE. Testing has shown that our rope loadpath network structures are scalable and controllable. Our fast load transfer methods are the most efficient AWE forms. Open design products have a reliable test history. They are more reasoned and applicable to manufacture. Increasing collaboration with traditional markets, manufacture and academia is set to continue. The cooperative group has amassed a wide IP pool. Open AWE has no blocking IP. Key concepts in the open AWE IP pool include: soft material scalability, aggregate passive lift stability [3], tensioned transfer efficiency [4], using Earth as a control bar for Mothra arch yaw stability, isometric dome lifting structures, isometric mesh lift fields, individual and grouped kixel steering functions addressable from single locations, phased output from looping parafoils, continuous driving ring foils, torque transfer

over tensioned lift lines by ring and ladder, embedded structural intelligence [5].

Our evolved parametric design standards give system developers and manufacturers instant answers to custom demands. Our open feedback forums are the fertile ground next generation AWE needs. Developers working with open AWE avoid having to learn exacting design skills. Standardised construction rules and guidelines improve FAA compliance and insurability. You can expect more from Open AWE.



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# FUTURE

Airborne Wind Energy.



Demonstration of automatic operation of the 20 kW kite power system of TU Delft at the Maasvlakte 2 of Rotterdam Harbour (23 June 2012). Because of wind speeds up to 15 m/s a small kite of 14 m<sup>2</sup> surface area was used. Pumping cycles ranged up to 700 m altitude.

# PAST

E.ON 550 MW Coal Power Plant.

# PRESENT

Nuon & Eneco 1.5 MW Wind Turbines.





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