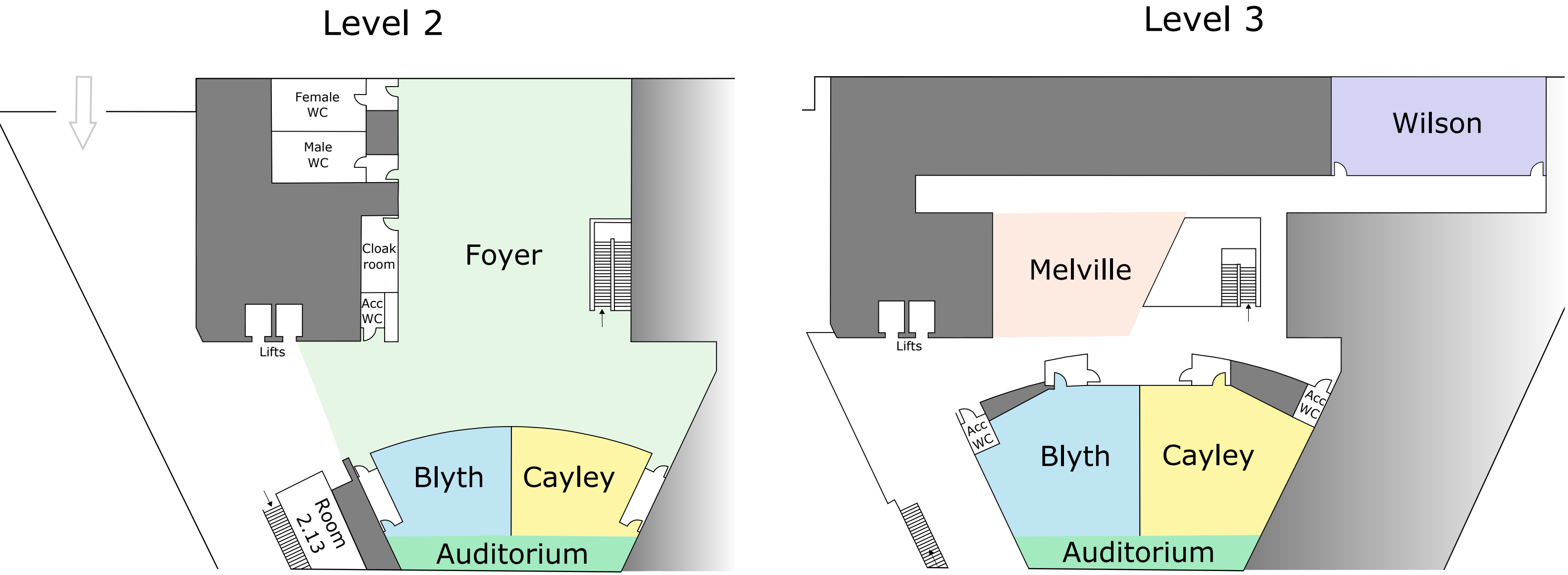
AIRBORNE WIND ENERGY CONFERENCE 2019

15-16 OCTOBER
UNIVERSITY OF
STRATHCLYDE
UNITED KINGDOM
awec2019.com

BOOK OF ABSTRACTS

Map of Conference Building



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Editors
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Program - Tuesday, 15 October 2019*

Time		Page		Page		Page
8:30	Registration				[Foyer]	
9:00	**Conference Opening**		Roland Schmehl, *TU Delft*		[Auditorium]	
			Stefanie Thoms, *Airborne Wind Europe*			
			Bill Leithead, *University of Strathclyde*			
9:20	**Introduction**		Giles Dickson, *WindEurope*			
9:40	**Plenary 1 Talk**		Sören Sieberling, *Ampyx Power*			19
10:10	**Plenary 2 Talk**		Doug McLeod, *Makani*			33
10:40	Coffee				[Foyer]	
	AWES Development [Blyth]		**Control Crosswind** [Wilson]		**R&D Panel** [Cayley]	
11:10	Joep Breuer, *Kitepower*	41	Eva Ahbe, *ETH Zurich*	46	Jochem Weber, *NREL*	57
					Roderick Read, *Windswept*	59
11:30	Lode Carnel, *Kitemill*	42	Hironori A. Fujii, *TMIT*	47	Kristian Petrick, *Airborne Wind Europe*	61
11:50	Michiel Kruijff, *Ampyx Power*	43	Ignacio Oficialdegui, *Acciona Energy*	51	**Panel discussion** moderated by	
12:10	Andy Stough, *Windlift*	45	Manfred Quack, *SkySails Power*	53	Roland Schmehl, *TU Delft*	11
12:30	Lunch				[Foyer]	
13:40	**Plenary 3 Talk**		Cédric Philibert, *International Energy Agency*		[Auditorium]	34
13:50	**OEM 1 Panel**		Johannes Peschel, *Kitepower*			69
14:00			Thomas Hårklau, *Kitemill*			70
14:10			**Panel discussion** moderated by Udo Zillmann, *Airborne Wind Europe*			11
15:10	**Poster 1 Spotlights**		Poster 1 Presenters			
15:30	Coffee				[Foyer]	
16:00	**Poster 1 Session**				[Melville]	
	Eiji Itakura, *Toyota Motor Corporation*	71	Peter Listov, *EPFL*	80	Rachel Leuthold, *Uni Freiburg*	85
	Uwe Fechner, *Aenarete*	73	Mahdi Ebrahimi Salari, *Uni Limerick*	81	Alan Mortimer, *Wood Clean Energy*	86
	Alex Rementeria, *Cranfield University*	75	Jonathan Dumon, *Gipsa-lab*	82	Manuel C.R.M. Fernandes, *Uni Porto*	87
	Solenn Le Pense, *KPS*	76	Tallak Tveide, *Kitemill*	83	Rigo Bosman, *DSM*	91
	Antoine Morvan, *ENSTA-Bretagne*	79	Hiroshi Okubo, *Kanagawa IT*	84	Jochem De Schutter, *Uni Freiburg*	92
	Wind Resource & Energy Prod. [Blyth]		**Performance Modeling** [Wilson]		**Airspace & Regulation Panel** [Cayley]	
16:30	Mark Schelbergen, *TU Delft*	93	Thomas Haas, *KU Leuven*	96	Kristian Petrick, *Airborne Wind Europe*	99
16:50	Philip Bechtle, *Uni Bonn*	94	Tim Brodrick, *KPS*	97	**Panel discussion** moderated by	
17:10	Markus Sommerfeld, *Uni Victoria*	95	Vincent Bonnin, *Ampyx Power*	98	Corey Houle, *Twingtec*	11
17:30	End-of-Day					
18:30	**Busses Depart for Dinner**				[Foyer]	
19:00	**Conference Dinner**				[Tall Ship]	

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

Program - Wednesday, 16 October 2019*

Time		Page		Page		Page
8:30	REGISTRATION				[FOYER]	
9:00	**KEYNOTE**		Lorenzo Fagiano, *Politecnico di Milano*		[AUDITORIUM]	35
9:40	**OEM 2 PANEL**		Alexander Bormann, *Enerkite*			101
9:50			Rolf H. Luchsinger, *Twingtec*			105
14:10			**PANEL DISCUSSION** moderated by Udo Zillmann, *Airborne Wind Europe*			11
10:45	**POSTER 2 SPOTLIGHTS**		Poster 2 Presenters			
10:55	COFFEE				[FOYER]	
11:15	**POSTER 2 SESSION**				[MELVILLE]	
	Michael Perlberger, *Brainwhere*	109	Hiroki T. Endo, *Niihama-Kosen*	111	Taewoo Nam, *Toyota Research Institute*	113
	Daniel Zywietz, *Enerwhere*	110	Espen Oland, *Kitemill*	112	Masafumi Narikawa, *University of Fukui*	115
	SYSTEM OPT. & COST MODELING [BLYTH]		**AWES RESEARCH** [WILSON]		**UTILITY & PROJECT DEV. PANEL** [CAYLEY]	
11:30	Mitchell Cobb, *NC State University*	117	Max Rüger, *Uni Bonn*	132	Kester Gunn, *RWE Renewables*	154
					Ciaran Frost, *BVG Associates*	155
11:50	Elena Malz, *Chalmers*	118	Gonzalo Sánchez-Arriaga, *UC3 Madrid*	133	**PANEL DISCUSSION** moderated by	
12:10	Filippo Trevisi, *DTU*	119	Tarek N. Dief, *Kyushu University*	134	Udo Zillmann, *Airborne Wind Europe*	11
12:30	Mark Aull, *Windlift*	120	Rik Bättig, *ftero, ETH Zurich*	137		
12:50	LUNCH				[FOYER]	
	REGULATION & SAFETY [BLYTH]		**CONTROL LAUNCH & LANDING** [WILSON]		**MODELING & SIMULATION** [CAYLEY]	
13:50	Corey Houle, *Twingtec*	123	Lorenzo Fagiano, *Politecnico Milano*	141	Frédéric Bourgault, *New Leaf Mgmt*	156
14:10	Sebastian Rapp, *TU Delft*	122	Audrey Schanen, *Gipsa-lab*	142	Mikko Folkersma, *TU Delft*	157
14:30	Gillian Vallejo, *Natural Power*	121	Espen Oland, *Kitemill*	143	Oliver Tulloch, *Uni Strathclyde*	159
14:50	Neal Rickner, *Makani*	124	Paul Williams, *Ampyx Power*	145	Mac Gaunaa, *DTU*	160
15:10	COFFEE				[FOYER]	
	AERODYN./STRUCT. MODELING [BLYTH]		**CONCEPT DESIGN** [WILSON]		**AIRBORNE WIND EUROPE** [ROOM 213]	
15:40	Mojtaba Kheiri, *Concordia University*	125	Christof Beaupoil, *someAWE Labs*	147	Members (only) meeting	
16:00	Urban Fasel, *ETH Zurich*	127	Florian Bauer, *TU Munich*	151		
16:20	Ashwin. A. Candade, *Enerkite / TU Delft*	128	Jochem De Schutter, *Uni Freiburg*	152		
16:40	Paul Thedens, *SkySails Power*	131	Paul Williams, *Ampyx Power*	153		
17:00	**CONFERENCE CLOSING PANEL TALK**		Roland Schmehl, *TU Delft*		[AUDITORIUM]	
			Udo Zillmann, *Airborne Wind Europe*			
			and invited guests			
17:40	END-OF-DAY					

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Roland Schmehl
Delft University of Technology

Oliver Tulloch
University of Strathclyde

Welcome and Introduction to the Airborne Wind Energy Conference 2019

Roland Schmehl[1], **Oliver Tulloch**[2]
[1]Faculty of Aerospace Engineering, Delft University of Technology
[2]Wind Energy and Control Centre, University of Strathclyde

Dear conference participants,

Welcome to Glasgow and welcome to the 8th international airborne wind energy conference AWEC 2019! We are excited to present to you an inspiring program in a beautiful location for the two conference days.

The scientific program of AWEC 2019 includes:

- An invited keynote presentation of 40 minutes, by
  - Lorenzo Fagiano, Professor of Controls at the Politecnico di Milano
- An introductory presentation of 20 minutes, by
  - Giles Dickson, Chief Executive Officer at Wind Europe
- Three plenary presentations of 20 minutes, by
  - Sören Sieberling, AP-3 Project Manager at Ampyx Power,
  - Doug McLeod, Technical Program Manager at Makani and
  - Cédric Philibert, Senior Analyst at the International Energy Agency
- Eleven contributed talk sessions in three parallel tracks with altogether 42 presentations
- Two poster sessions, each preceded by plenary spotlight presentations, with altogether 21 poster presentations
- Five panel discussions covering all aspects of airborne wind energy which include a further 10 presentations

All abstracts presented in this book have undergone a peer review process, and we want to thank all authors and all reviewers at this place for having contributed to a high quality scientific program, as we believe.

In order to make orientation easier, we decided to rename the four main conference auditoria after renowned researchers in airborne wind energy:

- “Blyth Auditorium” (Auditorium B) honoring James Blyth (1839–1906), a Scottish electrical engineer and academic at Anderson’s College, now the University of Strathcldye. He built the first known structure by which electiricty was generated from wind power (1887). This turbine powered his holiday cottage in Marykirk;
- “Cayley Auditorium” (Auditorium C) honoring Sir George Cayley (1773–1857), an English engineer, inventor and aviator. He designed the first glider to carry a human aloft and discovered the four aerodynamic forces of flight: weight, lift, drag and thrust;
- “Wilson” (Conference Room 6&7) honoring Alexander Wilson (1714–1786), a Scottish meteorologist, astronomer and academic at Glasgow University. He conducted the first kite-based measurements in the atmosphere (1749); and
- “Melville” (Level 3 Foyer) honoring Thomas Melville (1726–1753), a Scottish natural philosopher. As a student at Glasgow University he conducted the atmospheric measurements with Alexander Wilson. Together they measured air temperature at various levels above the ground simultaneously with a train of kites.

Kitepower B.V. 40 m^2 kite (24 August 2018)

The side program of AWEC 2019 includes:

- a welcome reception on October 14 in the Glasgow City Chambers;
- two lunches and four coffee breaks in the conference premises, free for all conference participants;
- a dinner aboard the Tall Ship ‘Glenlee’ on October 15.

The city of Glasgow is named by National Geographic as one of its “Best of the World” destinations, while voted by Rough Guide readers the world’s friendliest city! Glasgow is a city with a very strong, indeed a globally renowned, knowledge base sector and vibrant wind energy sector. UK’s largest onshore wind farm, Whitelee, is just 20 minutes from the city centre.

Founded in 1796 as the Andersonian Institute to be a “place of useful learning”, the University of Strathclyde received its royal charter in 1964 as the UK’s first technological university. Based right in the very heart of Glasgow, the University of Strathclyde was awarded Scottish University of the Year 2020 by the Times and Sunday Times Good University Guide.

The Wind Energy and Control Centre (WECC), in the Department of Electronic & Electrical Engineering at the University of Strathclyde, is one of the largest wind energy research groups in the world with over 80 research assistants and PhD students. WECC has expertise in turbine and powertrain design; fault diagnosis, failure rate analysis, O&M and asset management; offshore networks, connection-to-shore and grid integration; power production forecasting, turbine and array dynamics, modelling and simulation; turbine and wind farm control.

WECC leads the UK’s pre-eminent doctoral training programme in offshore renewable energy, the EPSRC Centre for Doctoral Training in Wind & Marine Energy Systems & Structures (CDT-WAMSS). The centre was first established in 2009 and over the past decade it has trained more than 100 doctoral students, working with over 40 industrial partners and with graduates providing expertise across all areas of wind and marine energy engineering. As of October 2019, the CDT brings together the leading UK research groups in Wind Energy at Strathclyde, Marine Energy at the University of Edinburgh and Offshore Structures at the University of Oxford.

The conference would not have been possible without the support of its sponsors, who are listed on pages 8–9 and, to which we want to express our sincere gratitude. We are also grateful to the City of Glasgow and the Lord Provost for hosting the Welcome Reception in the Glasgow City Chambers. A special thanks also goes to the Glasgow Convention Bureau and the TIC conference staff for providing exceptional support to this event.

We also want to thank all members of the programme committee and organising committee – listed on page 10 – for their efforts in making the conference a success. And within the organising committee, we want in particular to thank, Stefanie Thoms for her outstanding contributions that have not only made this conference possible but have greatly enhanced the conference experience for all participants.

Last but not least, we are grateful to you, the participants of AWEC 2019, not only for coming to the conference, but also for your various contributions and your hopefully active participation in the discussions during pannel sessions, after talks, at lunches, dinners and coffee breaks. We very much look forward to an inspiring and exciting conference together with you!

Sincerely,

O. Tulloch

Roland Schmehl

Delft University of Technology
Delft, The Netherlands

Oliver Tulloch

University of Strathclyde
Glasgow, United Kingdom

Institutional Sponsors

University of Strathclyde Founded in 1796 as the Andersonian Institute, it is Glasgow’s second-oldest university with over 22’000 students from 100 countries. It was awarded University of the Year 2012 and Entrepreneurial University of the year 2013 by Times Higher Education. In 2019 it is again shortlisted for the University of the Year at the Times Higher Education University Awards. The Wind Energy & Control group is an international leader in wind energy and the control of wind turbines and wind farms.

Airborne Wind Europe As the association of the European airborne wind energy industry, Airborne Wind Europe promotes the generation of energy from winds at higher altitudes by means of airborne wind energy systems. It represents the interests of the airborne wind energy industry as well as academia to decision makers in politics and business, provides reliable and high-quality information and data on airborne wind energy and is coordinating the industry at all levels.

Delft University of Technology The TU Delft is the oldest and largest technical university of the Netherlands. According to the 2019 QS World University Rankings it is among the top 20 universities for engineering and technology. It is the highest ranked university of the country. Founded in 2004 by Wubbo Ockels and continued in 2009 by Roland Schmehl the Airborne Wind Energy Research Group is a pioneer and international leader in this innovative technology.

European Academy of Wind Energy EAWE is an international community that promotes and supports the development of wind energy science to exploit wind energy to its full potential for the benefit of the world. EAWE is a non-profit organization governed by Europe’s leading universities and research institutes on wind energy. A Technical Committee “Airborne Wind Energy” was established in June 2019.

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- Oliver Tulloch, University of Strathclyde, UK
- Hong Yue, University of Strathclyde, UK

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- David Ainsworth, KPS, UK
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- Roy Smith, ETHZ, Switzerland
- Alexandre Trofino Neto, UF Santa Catarina, Brazil
- Axelle Viré, TU Delft, Netherlands
- Chris Vermillion, NC State University, USA
- Hong Yue, University of Strathclyde, UK
- Udo Zillmann, Airborne Wind Europe, Belgium

R&D Panel

- Jochem Weber, NREL, USA
- Roderick Read, Windswept & Interesting, UK
- Roland Schmehl, TU Delft, The Netherlands
- Stephanie Mann, ORE Catapult, UK
- Dominik von Terzi, TU Delft, The Netherlands
- Kristian Petrick, Airborne Wind Europe, Belgium
- David McMillan, Uni Strathclyde, UK
- Philip Bechtle, Uni Bonn, Germany

OEM 1 Panel

- Johannes Peschel, Kitepower, The Netherlands
- Thomas Hårklau, Kitemill, Norway
- Udo Zillmann, Airborne Wind Europe, Belgium
- Stephan Brabeck, Skysails, Germany
- Richard Ruiterkamp, Ampyx Power, The Netherlands
- Doug McLeod, Makani Power, USA
- Cédric Philibert, IEA, Belgium
- Giles Dickson, WindEurope, Belgium

Airspace & Regulation Panel

- Kristian Petrick, Airborne Wind Europe, Belgium
- Corey Houle, Twingtec, Switzerland
- Dieter Moormann, RWTH Aachen, Germany
- Nathanel Apter, FOCA, Switzerland
- Amanda Boekholt, FOCA, Switzerland
- Martin Lohss, Skysails, Germany
- Neal Rickner, Makani, USA
- Michiel Kruijff, Ampyx Power, The Nettherlands

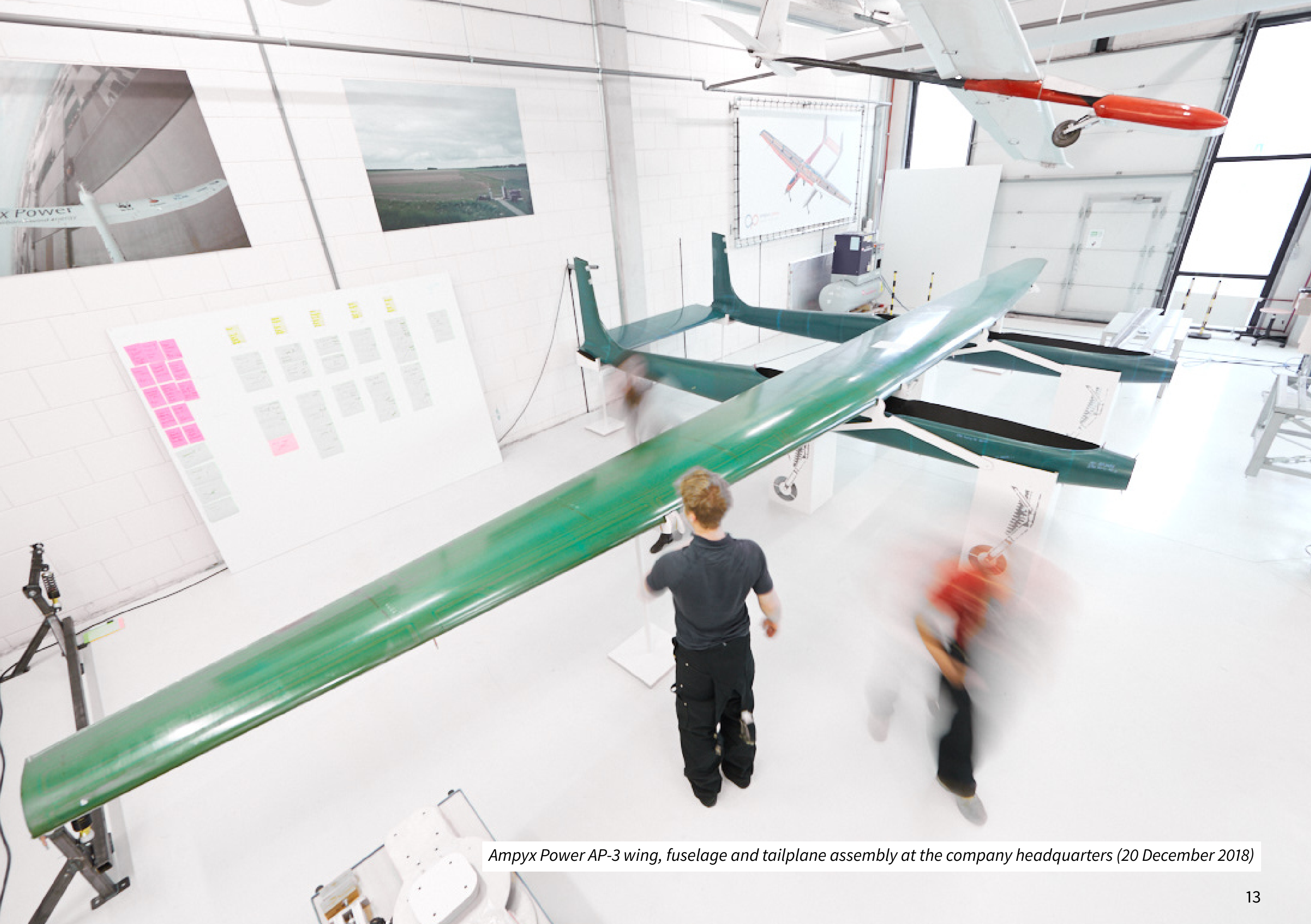
OEM 2 Panel

- Alexander Bormann, Enerkite, Germany
- Rolf H. Luchsinger, Twingtec, Switzerland
- Udo Zillmann, Airborne Wind Europe, Belgium
- David Ainsworth, KPS, UK
- Max Ter Horst, e-kite, The Netherlands
- Reinhart Paelinck, Kiteswarms, UK
- Robert Creighton, Windlift, USA
- Fort Felker, Makani, USA

Utility & Project Developer Panel

- Kester Gunn, RWE Renewables, UK
- Ciaran Frost, BVG Associates, UK
- Udo Zillmann, Airborne Wind Europe, Belgium
- Giles Hundleby, BVG Associates, UK
- Henk Hutting, NuCapital, The Netherlands
- Fabian Wendt, Ramboll, Germany
- Carlos Llopis, Siemens Gamesa, Germany

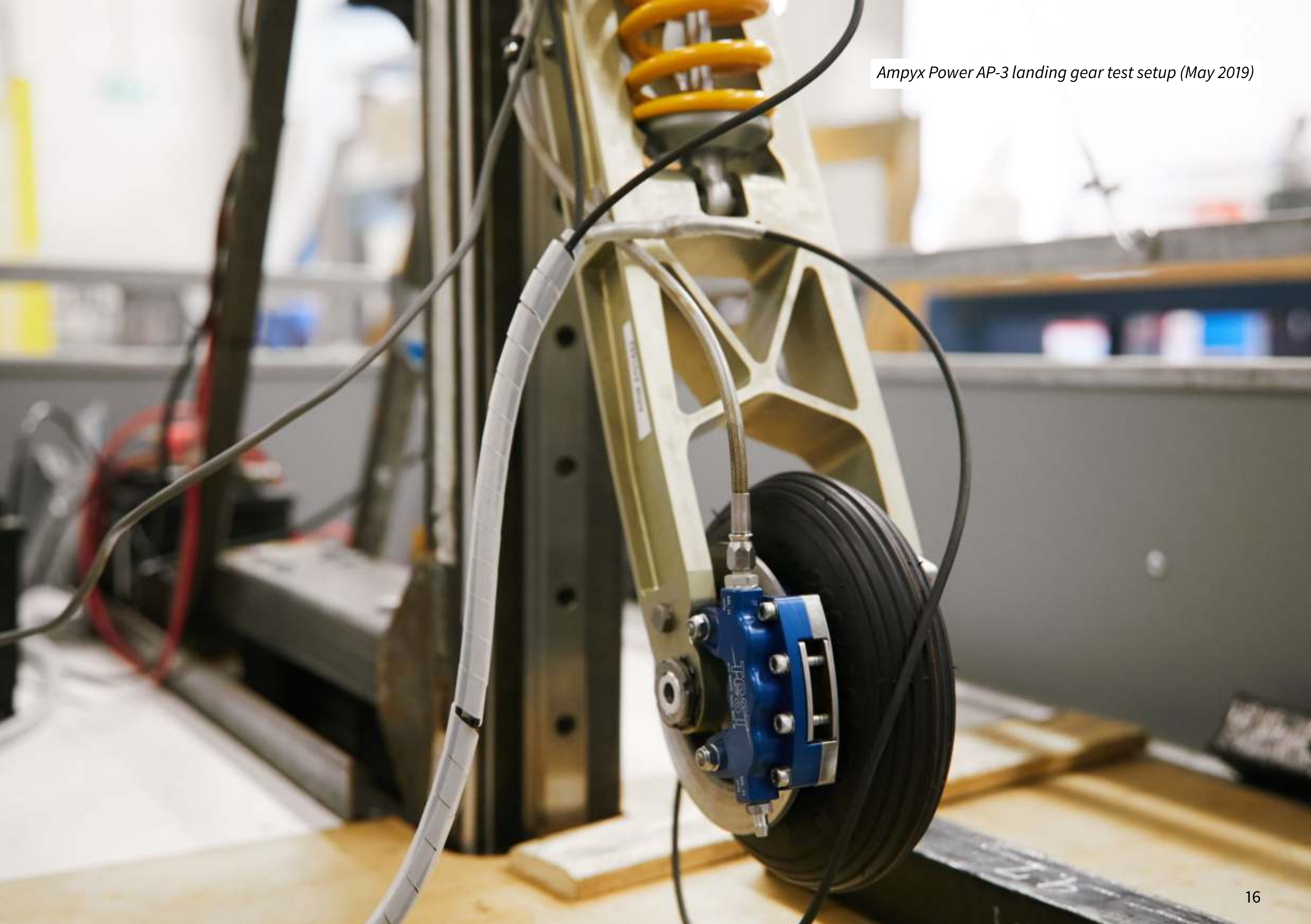
Ampyx Power AP-2 flying maneuvers using the AP-3 control algorithms (18 September 2018)



Ampyx Power AP-3 wing, fuselage and tailplane assembly at the company headquarters (20 December 2018)

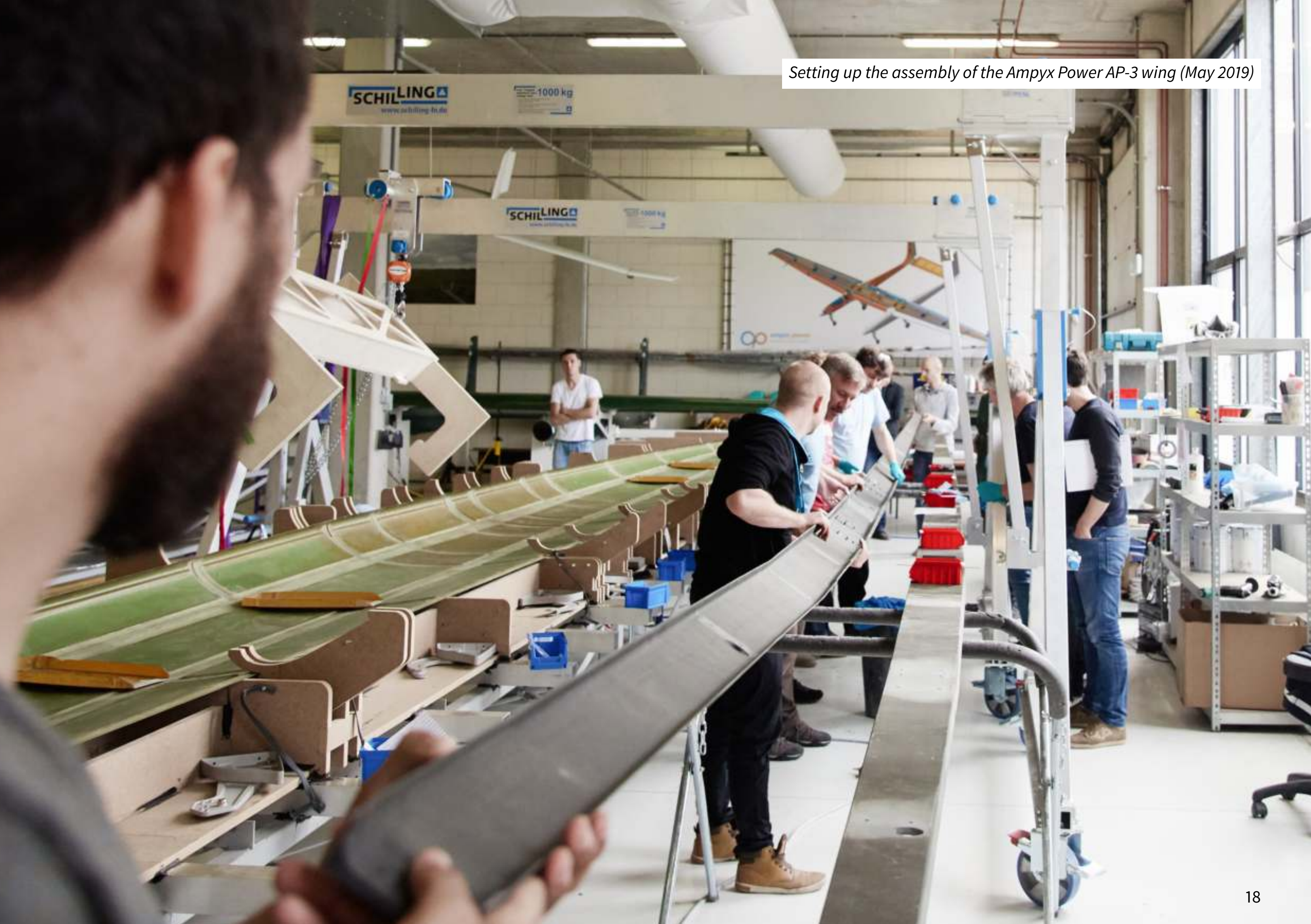
Ampyx Power AP-3 from the bottom: landing gear and tether attachment

Ampyx Power system engineer Fahri Akçomak at work



Ampyx Power AP-3 landing gear test setup (May 2019)

Ampyx Power AP-3 propeller test stand (July 2019)



Setting up the assembly of the Ampyx Power AP-3 wing (May 2019)

Sören Sieberlng

AP-3 Project Manager
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Status Update and Review of the AP-3 Development

Jaap Bosch, Sören Sieberling, Stefan Wilhelm
Ampyx Power B.V.

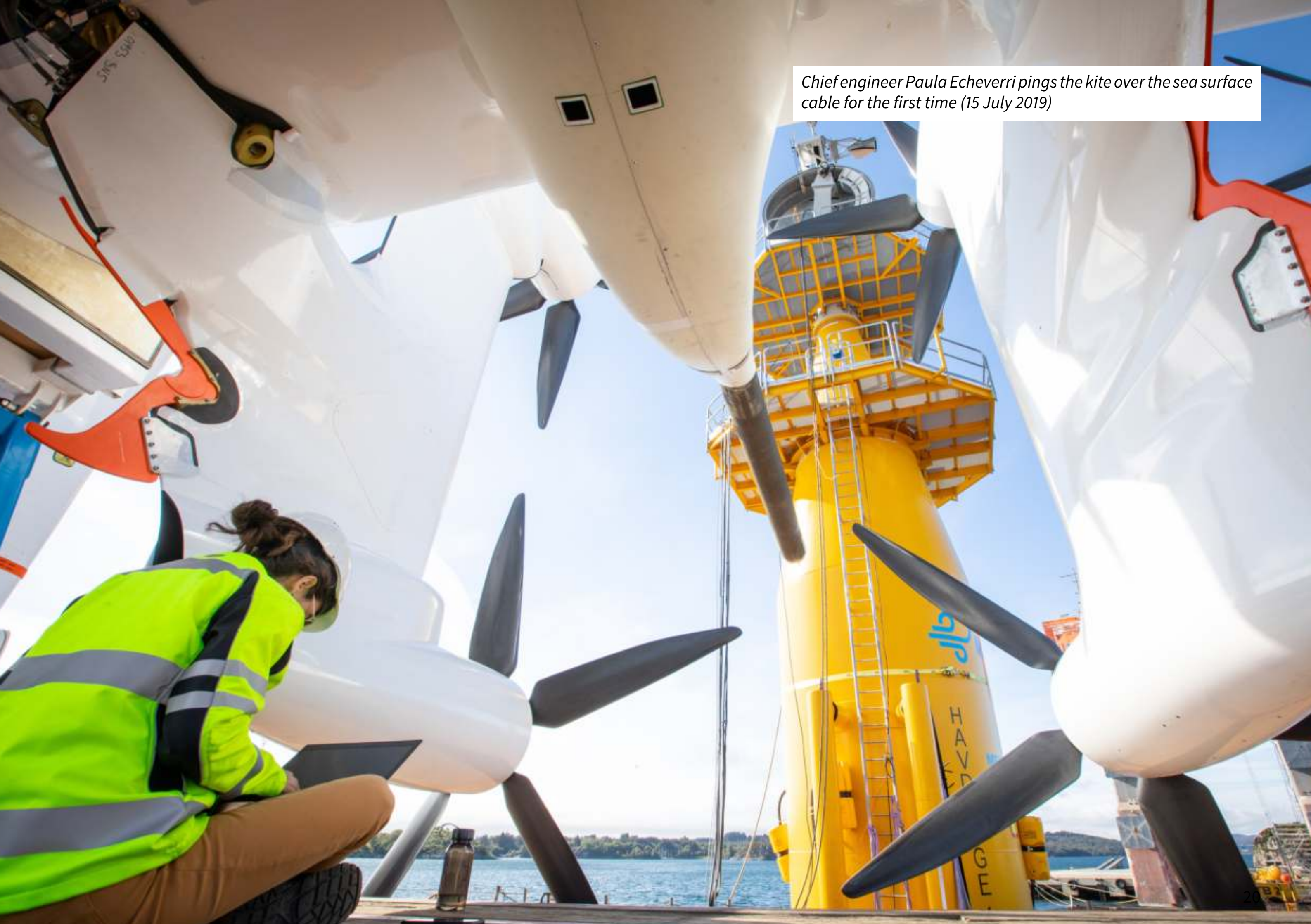
With the development of AP-3, the pre-commercial demonstrator of Ampyx Power, we aimed to advance Ampyx Power on the ladder from start-up to developer of certifiable multi-megawatt scale AWES. This paper discusses what it takes to work towards a certifiable system. It will give an update on where Ampyx Power stands with the development of AP-3.

In order to professionalize, Ampyx Power has made a fundamental change in its work approach compared to the earlier prototypes, AP-1 and AP-2. The design has been built up from scratch, by defining overall program objectives and success criteria in 2014. System engineering processes are applied hierarchically in order to create a safe, consistent and traceable design, resulting in thousands of item and component requirements which will be formally verified before integrating them into systems and finally into the AWES facility.

The AP-3 design includes the avionics, system architecture and safety approach of the commercial certifiable AP-4 product. It is going through EASA approval of flight conditions to support a permit to fly.

Ampyx Power has specified and implemented its work processes in a tailored Quality Management System (QMS) including e.g. task specific templates and work orders, as well as guiding procedures, work instructions and trainings. Ampyx Power has recorded all design trade-offs and made design justifications and captured the results in design requirements from facility level to item level. Within the AP-3 program Ampyx Power has built an inventory management system and set up incoming inspections and captured non-conformances and their resolutions. In principle all engineers have peers with whom they have built up shared knowledge and with whom they review each other's work. The full scale of the QMS is exploited and supported by a powerful custom software tool. With its QMS, Ampyx Power is less dependent on specific individuals than before.

The design and modelling suite has been upgraded, through multiple external validations, as well as through extensive CFD analysis and simulation hours. It will be supplemented with flight data to verify the predictability of performance. To ramp up the operational experience, a full-scale test center is under development in County Mayo, Ireland.



Chief engineer Paula Echeverri pings the kite over the sea surface cable for the first time (15 July 2019)

Hardware engineer Crystal Allen applies the Viking compass the team chose to "provide guidance and protection" for the first offshore test of the kite (28 July 2019)

Makani's kite is lifted onto its perch using a commonly available mobile boom crane (28 July 2019)

Makani team in Norway (31 July 2019)

Makani's kite and floating platform were towed offshore by two coastal tugboats (31 July 2019)

Makani's kite and floating platform being towed offshore in Karmøy, Norway (31 July 2019)

Makani’s kite was installed at a depth of 220 m for its first ever flight offshore (1 August 2019)

Makani's kite was installed at a depth of 220 m off the coast of Karmøy Norway (1 August 2019)

For the purpose of this test Makani's command center was installed on a barge and held in position by a tugboat with dynamic positioning capabilities (7 August 2019)

Makani's energy kite launches from a floating platform in the North Sea off the coast of Norway (8 August 2019)

Makani's energy kite is tethered to a floating platform over the North Sea (8 August 2019)

Flight engineers Robbie, Tobin and Simon in the test flight command center on a barge in the North Sea off the coast of Norway (8 August 2019)

Makani's energy kite flies over the North Sea (8 August 2019)

Doug Mcleod

Technical Program Manager
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Lessons Learned from Testing Makani's Energy Kite Offshore

Doug Mcleod, Charlie Nordstrom
Makani

In August 2019 Makani operated it's M600 energy kite prototype from a floating platform in the North Sea. The project advanced from a "Go" decision to a successful offshore flight test campaign in 20 months. This presentation offers an overview of our transition offshore and explores some of the ways we accelerated real-world learning while managing risk.

Makani made the decision to transition offshore to move quickly towards testing our system in the place where energy kites can have the greatest impact. Hundreds of millions of people live within 25 miles of a coastline where winds are strong and steady, but there are currently no options to economically harness this wind resource. Conventional floating offshore wind turbines rely on large platforms anchored to the seabed by multiple lines, and installing them requires specialized equipment, making deployment impractical and expensive. In contrast, to transition Makani's airborne wind power system offshore we utilized a simple floating platform design and leveraged existing supply chains and commonly available infrastructure.

Makani's first offshore flight campaign demonstrated that our simple floating platform design works, and emphasized that Makani is solving the right technical problems by continuing to specialize in creating kites that efficiently harness energy from the wind.

The Makani energy kite rests on its base station atop a floating platform during Makani's first offshore test campaign. August 2019.

Wind Power in the Energy Transition

Cédric Philibert
International Energy Agency

Cédric Philibert

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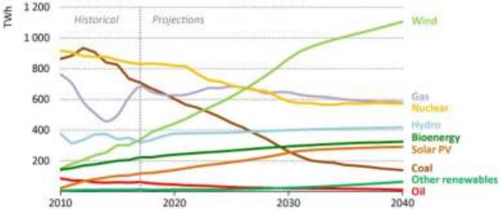
Solar energy and wind energy are the two energy resources that will grow the most in all climate-friendly scenarios. Even in the "New Policy Scenario", that is not stringent enough to achieve the climate goals agreed in Paris (COP 21, 2015), wind power is set to become the first source of electricity in Europe by 2040 or before [1].

In the "Sustainable Development Scenario", wind power even becomes the first source of electricity in the world, though solar energy and hydropower will come in the same ballpark [1]. However, to achieve full decarbonisation of the global economy, more will be needed. Residential heat, industrial heat, fuels and feedstock, and transports fuels, will need to be provided by near-zero carbon energy.

Through direct electrification and the production of hydrogen from electrolysis of water, renewable energies, solar and wind in the first place, may again be at the core of this effort [2, 3].



Electricity generation by source in the European Union, 2010-2040.

Here airborne wind energy, if it "takes off", can play various roles. On shore ("above land"?), it may help overcome the barriers of acceptability and reduce cost. Off shore, and even far off shore, it may provide large additional amounts of cheap electricity to produce on floating platforms various fuels and chemicals, which could then be shipped to customers: hydrogen, ammonia, and, with carbon extracted from the air or waters, methanol and liquid hydrocarbons.

References:

[1] IEA: World Energy Outlook, 2018.

[2] IEA: Renewable Energy for Industry, 2017.

[3] IEA: The Future of Hydrogen, 2019.

Lorenzo Fagiano

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Automation Challenges in Airborne Wind Energy Systems and the Role of Academic Research

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Airborne Wind Energy Systems have undergone major advancements in the last 15 years. Starting from theoretical concepts, more and more sophisticated prototypes have been developed and tested. Today, a thriving community is fostering the industrialization of AWES. Airborne Wind Europe [1] has been founded and is channeling efforts to build industry standards, interact with public institutions, and establish suitable regulations to enable the use of AWES. For most concepts, questions like “Can you really make it work?” and “How much energy can it generate?” have left space to engineering design and optimization processes and extensive test campaigns towards the goal of high reliability and full automation. A recent independent study [2] recognized the huge potential of AWES to contribute to the energy mix and to impact positively our economy and society, as well as the increasing momentum of this sector. The same study also pointed out relevant challenges and a possible road-map to commercialization, which necessarily involves public-private synergies.

Automation has always been and still is a distinctive aspect of AWES, the source of its competitive advantages and of its development risks alike. It is thus not surprising that a large part of the technical challenges that must be resolved pertains to automation in a broader sense. As a matter of fact, AWES are more similar to autonomous vehicles and safety-critical robotic systems than wind turbines. They have to carry out a task by maneuvering in an uncertain environment and taking decisions in autonomy. They have to cope with partially unpredictable wind to remain airborne, and the wrong decision can lead to a catastrophic system failure. In this respect, AWES share the same major challenges that today are at the very center of R&D efforts in many industrial and academic sectors, concerned with fully autonomous systems and artificial intelligence.

This talk will analyze the system automation challenges of AWES, in light of similar ones being addressed in other high-tech fields, and discuss the additional peculiar features of tethered airborne systems. The analysis will lead to reflections on the role of research universities and institutes in this phase of AWES development, as a crucial part of the above-mentioned public-private collaborations.

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[1] Airborne Wind Europe, http://www.airbornewindeurope.org

[2] European Commission, Study on Challenges in the commercialisation of airborne wind energy systems (2018) http://doi.org/10.2777/87591

Kitepower's 40 m^2 Leading Edge Inflatable V3 kite (17 April 2018)

Kitepower's fleet of 25, 40 and 60 m^2 *kites and their control units lined up for a showcase event (29 August 2019)*

Kitepower's 100 m^2 Leading Edge Inflatable kite being deployed (29 August 2019)

Transporting the 100 kW ground station (29 February 2018)

100 kW ground station in operation (26 February 2018)

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REACH: A H2020 FTI Project to Develop a 100 kW AWE System

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At the end of 2015 the REACH[1] proposal was granted by the EU within the H2020 Fast-Track to Innovation (FTI) Pilot. FTI is a fully-bottom-up inno-vation support programme promoting close-to-the-market innovation activi-ties open to industry-driven consortia that can be composed of all types of participants.

Airborne Wind Energy fitted perfectly with the goals of this programme. The REACH consortium consists of an academic partner (TUDelft, the Netherlands), a ground-station supplier (Dromec, the Netherlands), kite supplier (Genetrix, France), a kite control unit supplier (Maxon Motors, Germany) and an integrator (Enevate/Kitepower, the Netherlands). REACH is the second highest grant awarded to Airborne Wind by the EU up to date with a total budget of 3.7 million Euro. FTI might also be useful for other AWE initiatives but has a low grant success rate.

The starting point of the development was the 20 kW system which was developed from the TU Delft system. The final goal was a commercial 100 kW system. This talk will sketch the development of the system during the course of the 4 year project and the contributions of the several partners. Involving key partners in the supply chain from the beginning proved very useful in developing this innovative system.

During the project different challenges overcome, like for example scaling, automation, reliability, safety and system integration. The talk will present the different technology steps the system went through in order to get to the current status of the 100 kW system and indicate how the partners made this H2020 FTI project to a success.

References:

[1] Resource Efficient Automatic Conversion of High-Altitude Wind https://cordis.europa.eu/project/rcn/199241/factsheet/en

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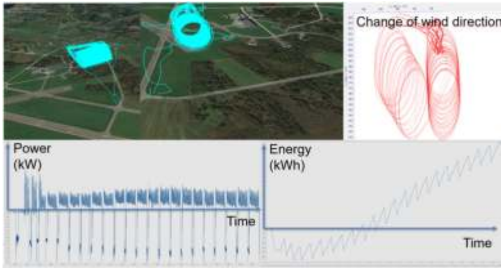
Kitemill: From Minutes to Hours of Autonomous Operation 2017

Lode Carnel, Espen Oland, Sture Smidt, Jo Grini, Christer Svenkerud, Tallak Tveide, Thomas Hårklau
Kitemill

Airborne wind energy holds the premise to be the lowest cost renewable energy technology and has been investigated for almost 15 years. Already in 2015, Kitemill showed autonomous operation in all production phases of our technology. Despite its potential, the technology has not been demonstrated autonomously yet for an extended period which is a requirement to convince large energy companies. Therefore, Kitemill has during the past two years prioritised the robustification of its control system going from proof of principle towards steering its kite turbine over longer periods of time. This presentation will give an overview of our technology choices and show the development during the past years.

The implementation of new sensors, electronics and hardware has increased the continuous autonomous operational time from 15 minutes in January 2018 to more than 2 hours. The pictures below show both the navigational data from the kite (KM0: 0,8 m^2, 6 kg, 5 kW peak electrical power) under several production cycles. Also, the impact of a change in wind direction on the production pattern is shown. The bottom left picture is the produced power data as a function of the testing time showing both the production (positive power) and return cycles (negative power). After a certain amount of time the negative energy from launching the kite is compensated and the kite turbine produces net energy even in only 7-8 m/s of wind (bottom right picture). These results implicate that Kitemill has now a pilot plant that can be demonstrated for visitors if wind conditions are adequate. Future work will focus on scaling our current system (KM0) towards a size (KM1 – KM2) that can compete with other energy technologies but in parallel keep the focus towards demonstrating a 24-hours automatic autonomous flight.



Navigation data (top left) – influence of wind direction on navigation data (top right) – Power production and energy production as a function of time (bottom left and right)

A Roadmap Towards Airborne Wind Energy in the Utility Sector.

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Large-scale commercial implementation of AWES faces a fundamental challenge. Horizontal Axis Wind Turbine (HAWT) manufacturers consistently move towards larger diameters to lower Levelized Cost of Energy (LCoE). Green energy relies less and less on subsidies. AWES' unique selling points will likely be low carbon footprint and access to untapped resources on top of this affordability. Still, AWES must provide competitive LCoE in a very short time, not to be overtaken by a new reality. If they are to take significant share in the energy-mix, multi-megawatt AWES must be developed: large, complex systems, with a capital-intensive development. In going there, commercialization of intermediate sizing can be seen either as a necessary stepping-stone or as a time-consuming distraction. The latter stance favors a development strategy strictly focused on a utility-scale business case. It will drive the architectural choices also for intermediate products in such a way that all invested effort contributes directly to the final goal. For these intermediate products, that are thus not purely optimized for commercialization, more short-term business cases may still be identified. What could those development steps then be? Ampyx Power's AWES uses a rigid-wing aircraft and a ground-based generator [1]. We chose to first make the learning for quality, safety and fully automatic control, through a still relatively small aircraft (AP-3). That eases the expense of manufacturing and risk of early flight testing, leaving only structural upsizing to be tackled next. Our first proposed commercial product AP-4 is sized to be the smallest aircraft that can have competitive LCoE in early business cases (such as repowering), with minimal subsidies. To secure funding for the first series deployment of such a radical innovation, other constraints may apply, e.g. a CAPEX that is already promising. Aiding the AWES case is our finding that a single aircraft design can serve a large range of generators and business cases. This allows for some economy of scale while limiting the overhead in time and money associated to aircraft development.

The result is an AP-4 wing of ~150 m^2 that can be cost-effectively hooked up to any generator between 2 and 3.6 MW. To get significant benefits beyond this combination, the aircraft should be about 50% larger at ~225 m^2 wing area. An aircraft of this size ("AP-5"), combined with a 3-MW generator will annually produce 20% more energy than a 3-MW AP-4, at lower winds and at 10% lower LCoE, and would be altogether more profitable. An AP-5 aircraft with a larger generator, say 5 MW, could unlock the market for floating offshore wind energy with highly competitive LCoE. AP-5 would be the Ampyx Power work horse in the years to come.

In the LCoE-optimal sizing of AP-4 and AP-5, we found that optimal rated power, wing area and cable tension scale virtually proportionally. A key scalability limitation of AWES is that aircraft mass tends to grow faster. Upsizing of utility-scale AWES from generation to generation will be dictated by the rate of innovation enabling the next (near-)proportional scaling step, also for mass. To deliver these innovations is our challenge.

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Andy Stough presenting Windlift's 4.5 m^2 prototype (13 September 2019)

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What is the Right Size for an AWE System?

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The cost-optimal scale for an airborne wind energy system (AWES) is a question that defies simple analysis. Many participants in the AWE industry propose that multi-MW systems are required to compete with traditional wind, while others argue that square-cube scaling renders systems of this size impossible. Windlift will present the results of a study that further explores these questions.

The levelized cost of energy (LCOE) for any energy generation system can be calculated from capital expenditure (including financing, installation, and logistics costs), operations and maintenance costs, system lifetime, and capacity factor. The assumptions involved are many and performing a sensitivity analysis with so many unknown factors risks missing more fundamental drivers of cost. In order to simplify the analysis, Windlift has utilized the specific energy of the flying system as a proxy for system fitness. Specific energy is defined as net system energy output per unit mass (flying). If one assumes that O&M costs are not a strong function of system size and that system weight is a reasonable proxy for capital expenditures, the analysis can inform optimal sizing of a system.

Windlift has utilized a proprietary design tool called Airborne Wind Energy System Optimization (AWESOPT) to conduct the study. AWESOPT is a lumped parameter constrained optimization tool that produces an optimal net power output given a set of inputs. Typically, vehicle design and trajectory parameters are fixed inputs and/or constraints and AWESOPT determines maximal power closed cycles by optimizing flight speeds and drag/thrust at each point in the cycle. Importantly, AWESOPT accurately models the effects of mass on power output, which is both difficult to model and critical to the sizing discussion.

Windlift will present estimates for specific energy as a function of scale, considering sensitivities to mass scaling coefficient, wind shear, and select vehicle design parameters. The presentation will conclude with a brief discussion of the effect of scale on logistics, installation, and O&M costs and a comparison to existing renewable energy technologies.

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Experimental Validation of Path-Tracking Model Predictive Control for Fixed-Wing Power Kites

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Model Predictive Control (MPC) has previously been employed in simulations for the control of flexible as well as rigid wing AWE systems [1]. Successful experimental validation of MPC based controllers have been reported from tow-test experiments with flexible wing kites [2]. Though MPC offers a promising approach to the control of AWE systems through the advantage of incorporating explicit models of the system and maximize for performance, the downsides of MPC such as model mismatch, real-time operational requirements, and solver feasibility dependence are still posing major challenges to the real-world application of MPC in the field of airborne wind energy.

In this talk we present experimental validation of the autonomous flight of a tethered Easy Glider system using a path-tracking nonlinear MPC algorithm. The proof of concept is hereby provided for the system flying in crosswind-like conditions, while a propulsion on the vehicle is used to guarantee a minimum flight velocity. The MPC controller is designed to follow a circle-shaped reference path. This reference path is obtained as a function of the mass, lift coefficient and tether length with the aim of minimizing the aerodynamic losses due to steering. The MPC algorithm takes constraints into account which consist in state (i.e. height and velocity) and input constraints. The model of the system used by the MPC consists of a nonlinear unicycle-like model with an additional state in form of the kite velocity.

Flight experiments of the proposed control scheme were performed with a 1.8 m wingspan, 1.7 kg, foam Easyglider test platform. The glider was installed with a Pixhawk Flight Controller [3] 168 MHz Cortex-M4F microcontroller with 192 kB RAM. Additionally, an on-board companion computer, Intel Up Board (Quad Core, 1.92 GHz CPU, 4 GB RAM), was installed running Robotic Operating System (ROS) for generating MPC solutions in real time and transmitting attitude references to the Pixhawk. The experimental flight test shows the autonomous flight of circular trajectories close to the reference trajectory. The remaining discrepancy between reference and actual path is mainly due to the low tether force due to low wind speed conditions. Additionally, there was a significant model mismatch introduced by the usage of an unmodeled tether of relatively large mass. Future research will focus on improved system identification, including a tether model and further tests under higher wind conditions.

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[2] T. A. Wood, H. Hesse, and R. S. Smith, “Predictive Control of Autonomous Kites in Tow Test Experiments,” IEEE Control Syst. Lett., vol. 1, no. 1, pp. 110–115 (2017)

[3] http://pixhawk.org

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Three-Dimensional Flight Trajectories of Tethered UAV for Optimal Energy Generation

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Three-dimensional trajectories of the tethered Unmanned Aerial Vehicles (TUAV) is studied for periodic motion connected through deployable tether. The motion is not constrained to a spherical surface formed by tether in constant length.Two types of AWE are investigated for the optimal energy generation where 1) UAV affords power through tether (Ampyx type), and 2) UAV contains wind turbine on UAV (Makani type). Performance indices for the optimal trajectories are selected as the time integral of 1) the work done by the traction by tether, and 2) velocity of UAV. The lift power production of the airborne wind energy generation employs commonly many turns of trajectories traced on a gradually growing sphere [1]. The three-dimensional trajectories are sought to utilize the gradient of wind-speed in the 'wind window' distributed different wind strength all over the windows. Results of the analysis is shown in Figs.1 and 2 [2]. Figure 1 shows the optimal power extraction through tether in one cycle of orbit. The tension is seen to reduce to the lowest level at the retrieval as shown. The increase of flight velocity of UAV with wind turbine is shown in Fig.2. The trajectory can be switched between right and left turns to avoid entangling of the tether. The control is simple free from many turns of gradual deployment flight trajectory. These results are necessary to be confirmed by experimental study.

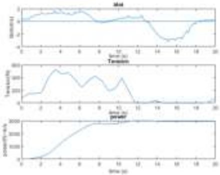

Fig.1 From top to bottom; Time responses of 1) Deployment/retrieval velocity of tether,2.) Tension, and 3) obtained energy.

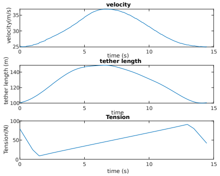

Fig.2 From top to bottom; Time responses of 1) velocity of UAV, 2) Tether length, and 3) Tension.

References:

[1] J. Lago Garcia. Periodic Optimal Control and Model Predictive Control of a Tethered Kite for Airborne Wind Energy. Master's thesis, Delft University of Technology, Kluyverweg 1, 2629 HSDelft, Netherlands, 7 (2016).

[2] Matthew Kelly, An Introduction to Trajectory Optimization, How to Do You Own Direct Collocation,SIAM REVIEW Society for Industrial and Applied Mathematics Vol. 59, No. 4, pp. 849–904.(2017).

WINDSLED 150 m^2 kite flying towards Plateau Station, Eastern Antarctica (28 December 2018)


Maintenance of WINDSLED 150 m^2 kite in Domo Fuji area, Antarctica (14 January 2019)

WINDSLED pulled by a kite in Antarctica Eastern Plateau

WINDSLED: Alternative Model to Conventional Logistics in Polar Regions Based on AWE

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The 21st century started without a logistic solution, economically and environmentally sustainable, for the exploration of the interior of Greenland and the enormous Antarctica Eastern plateau.

In the year 2000, the Spanish polar explorer Ramón Larramendi designed the first prototype of a vehicle that has resolved most of the pending challenges based on the Inuit wisdom and the use of Airborne wind energy, the WINDSLED.

WINDSLED basically consists of a wooden sled, that adapts to the complex surface of the ice, and a NASA type kite (NPW) which is steered manually with a simple pulley system attached to the runners. The kite is positioned up to more than 250m above ground level (in development up to 400 m). It is powered with kites from 5 to 150 m^2 (in development up to 200 m^2). WINDSLED is a modular structure with up to 4 wagons that has already carried 6 persons and more than 2 Tons of weight for thousands of kilometres. It can be carried in a small plane or helicopter. It has performed some of the most relevant exploration expeditions of the 21st century.

This wind powered sled has navigated around 25.000 km in 10 major expeditions with an autonomy of up to 65 days, that covers most of a polar summer season. The whole system has been designed prioritizing reliability and resilience.

The last expedition finished in January 2019, becoming the first Antarctica scientific expedition Zero emission. A circular navigation of one of the highest and coldest regions of the continent that brought scientific data and samples for recognized organizations such as the European Space Agency, Climate Change Institute of Maine, Superior Center for Scientific Research of Spain (CSIC), and some other relevant Polar research Institutions. This expedition saved more than 45.000 liters of fuel just in the polar journey, without taking into account the air shipping, and associated logistics, that had implied heavy conventional machinery.

The main current technical challenge is the fine-tuning of the kite system, in order to improve performance, manoeuvrability and safety, and the automatization of its steering.

WINDSLED is a non-profit collaborative project.

Composite photo of the 20 kN SkySails Power Functional Prototype in crosswind flight

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Extended Periods of Automated Tethered Flight at SkySails

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This contribution is divided into two parts: Most recent data from extended periods of automated tethered flight of a 20kN SkySails Yacht System [1] will be discussed in a first part. Experimental data from the aforementioned system as well as from the SkySails Power small-scale functional prototype [2] will be used for model validation in a second part.

Flight data for the first part has been acquired on the hybrid solar- and kite-propelled yacht "Race For Water" [3] during her circumnavigation. This yacht has been first equipped in 2017 with a SkySails Yacht system, as presented on AWEC 2017 [4]. Updates to the autopilot software in early 2018 included a stepping set point adaptation for the wind window angle for traction force control. Through this increased level of automation the system can be operated for daylong flights with minimal additional burden for the ship crew. The working principles of the set point adaptation will be explained and propulsion performance will be presented.

Acquired experimental data has been used for model validation. Here, a comparison is made between open-loop model validation, where recorded steering inputs are replayed during simulation and closed-loop model validation, where only the set-points are replayed and the steering inputs are a recomputed output of the closed-loop controller. In the case of closed-loop validation, simulated trajectories of a full power-cycle are in good accordance with experimental data. In the case of open-loop validation, resulting trajectories are typically first in good agreement, but then diverge after a few seconds. This divergence is attributed to the fact that recorded steering inputs actually include the closed-loop control response to unmeasured disturbances, such as wind gusts and wind shear. Furthermore, it shows that the flown trajectories require control action to keep the system on a stable trajectory.

In summary, results of this model-validation show that a simple 4-state non-linear state-space model [5] capture the relevant dynamics adequately and can be envisioned for the use in non-linear model predictive control and other model-based control approaches.

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[3] http://odyssey.raceforwater.org

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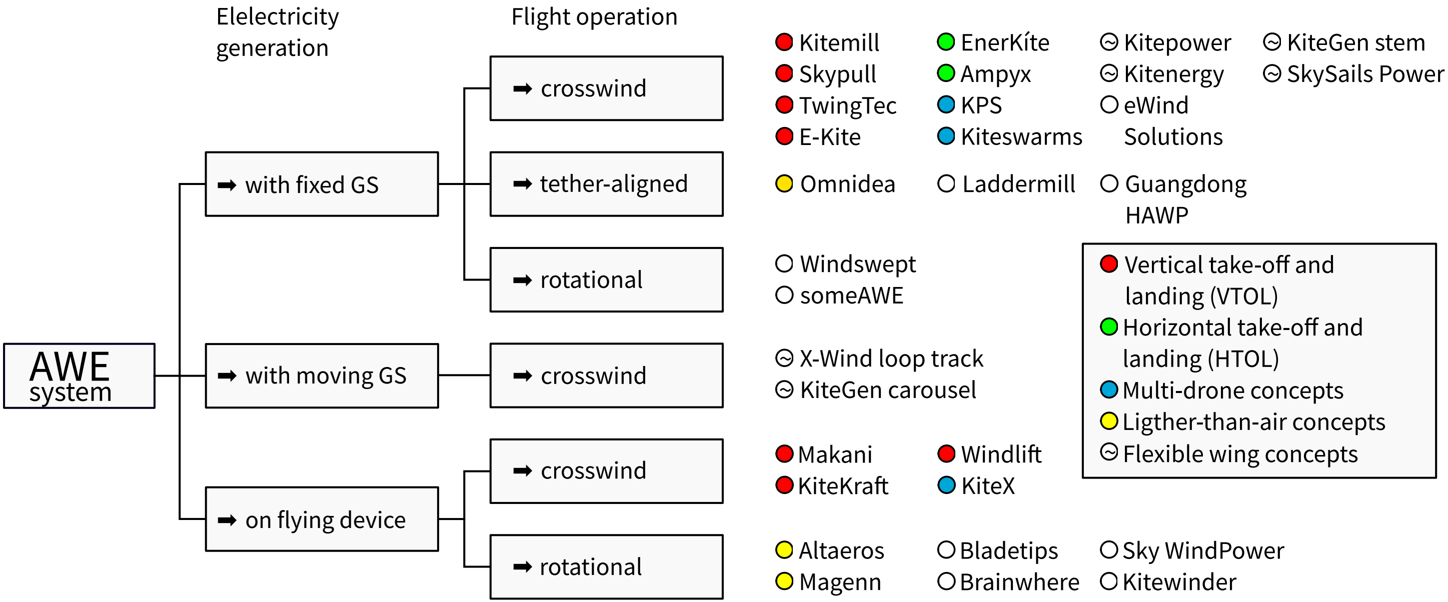
Skysails "Race for Water" Catamaran (25 January 2018)

Proposed classification of AWE systems from http://www.awesco.eu



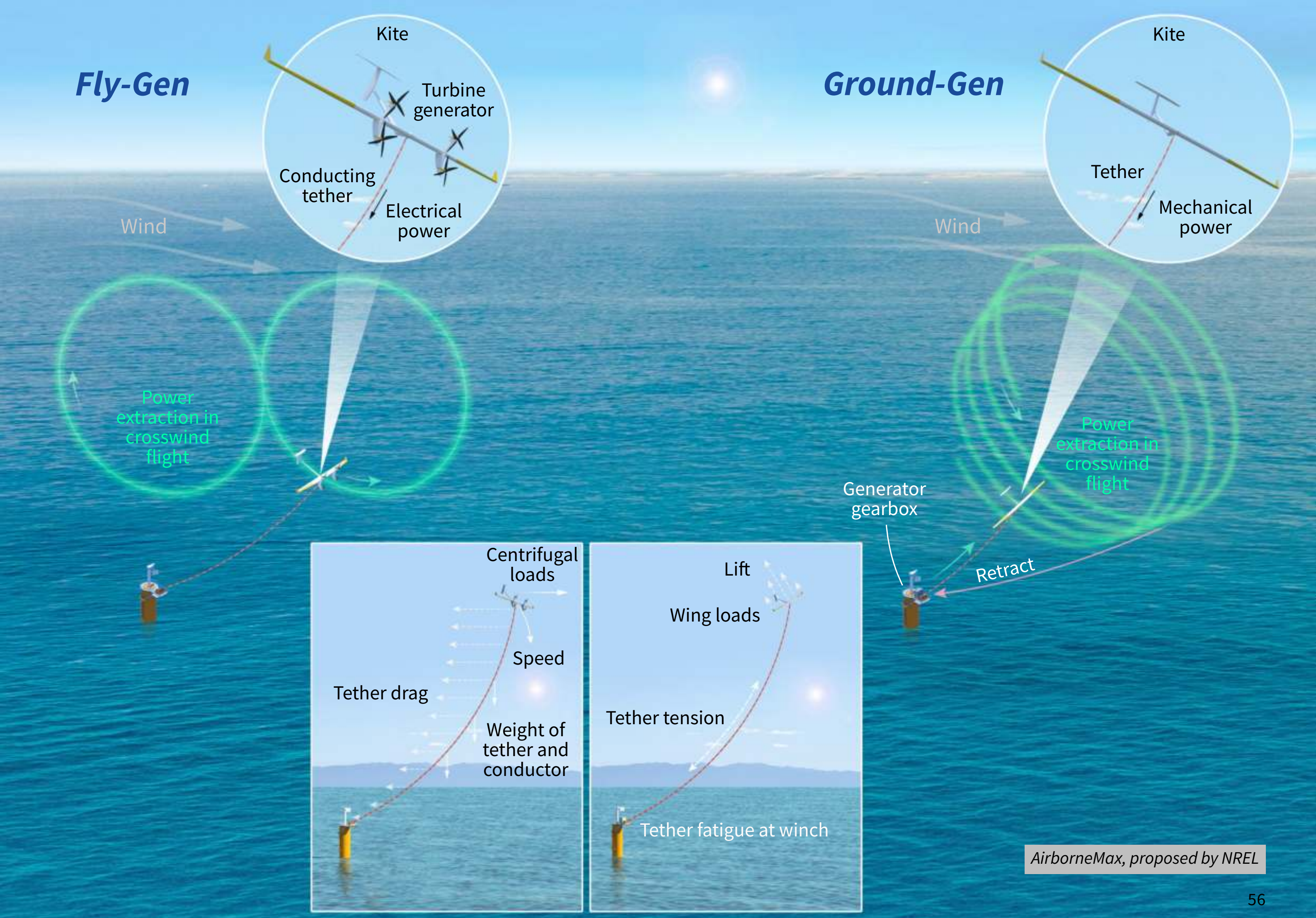
Elelectricity generation

Flight operation

AWE system

- ➡ with fixed GS
  - ➡ crosswind: 🔴 Kitemill, 🔴 Skypull, 🔴 TwingTec, 🔴 E-Kite, 🟢 EnerKíte, 🟢 Ampyx, 🔵 KPS, 🔵 Kiteswarms, ⊝ Kitepower, ⊝ Kitenergy, ○ eWind Solutions, ⊝ KiteGen stem, ⊝ SkySails Power
  - ➡ tether-aligned: 🟡 Omnidea, ○ Laddermill, ○ Guangdong HAWP
  - ➡ rotational: ○ Windswept, ○ someAWE
- ➡ with moving GS
  - ➡ crosswind: ⊝ X-Wind loop track, ⊝ KiteGen carousel
- ➡ on flying device
  - ➡ crosswind: 🔴 Makani, 🔴 KiteKraft, 🔴 Windlift, 🔵 KiteX
  - ➡ rotational: 🟡 Altaeros, 🟡 Magenn, ○ Bladetips, ○ Brainwhere, ○ Sky WindPower, ○ Kitewinder

🔴 Vertical take-off and landing (VTOL)
🟢 Horizontal take-off and landing (HTOL)
🔵 Multi-drone concepts
🟡 Ligther-than-air concepts
⊝ Flexible wing concepts



AirborneMax, proposed by NREL

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AirborneMax – Scaling as the Key Issue for Airborne Wind

Jochem Weber
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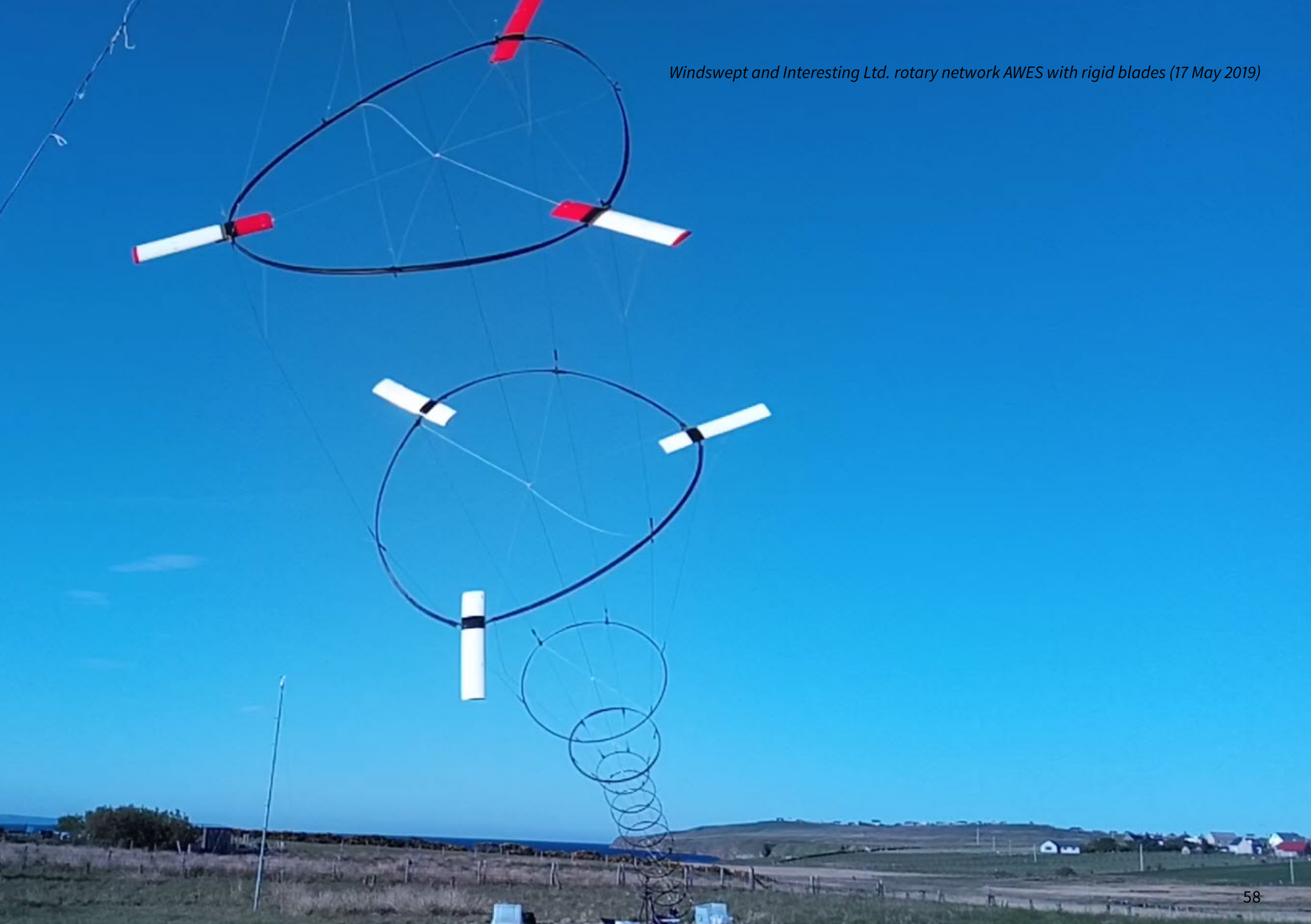
NREL is proposing AirborneMax, a project that will address a core question in the large-scale competitive commercial deployment of airborne wind energy (AWE). With the convergence to lift-driven technologies, the sector has bifurcated into two prevailing technology concept directions: Fly-Gen and Ground-Gen, rigid-wing crosswind kite systems. When targeting utility-scale floating offshore wind farm deployment, a critical and predominant criterion that can define the superior AWE technology concept is the maximal installable capacity in megawatts per unit/device due to the high balance of plant cost. This provides the working hypothesis of AirborneMax. This project will identify and investigate inherent physical phenomena that can cause up-scaling limits specific to each AWE type and assess these phenomena from their basic science to their engineering implementation.

The presentation of the AirborneMax project at AWEC 2019 will highlight the approach to a profound AWE technology question and bring key players to the table, including technology developers, strategic investors, utilities, energy companies, original equipment manufacturers, academia and research labs to inform, influence, and support the project, and increase its value to the sector and NREL's sector involvement. From an airborne, i.e., bird's-eye perspective, AirborneMax may deliver the first phase in an effort to reveal unknown unknowns to known unknowns and assess their impact; identify potential limitations or showstoppers and address, resolve, and overcome these from the earliest possible stage; and highlight the most promising research and technology development trajectories for AWE to successful market entry at the lowest possible development time, cost, and risk [1].

This project will: 1) define and model design configurations of both Fly-Gen and Ground-Gen systems at single-unit device capacities of 7, 15, and 30 MW, 2) simulate power production operations through methods ranging from first-principle science to in-house software KiteFAST to identify, quantify, and assess all capacity-limiting phenomena and identify the potentially superior max capacity technology. Relevant physics include tether drag, weight, tension, strength, fatigue, conductivity, multi-functionality, wing flow, - loads, flight path, speed, accelerations, structural loading, integrity, flow-induced vibration, oscillation, system dynamics, generator efficiency, power density, conductor losses, heat transfer, and others to be identified during the project, 3) conduct techno-economic analysis using levelized cost of energy (LCOE) and technology performance levels (TPL) [1] of the identified maximal installed capacity-limit configurations, 4) address technological achievability, 5) apply structured inventive techniques such as TRIZ to overcome the identified barriers, 6) develop follow-up researcher, development, and demonstration strategies and high-priority follow-up projects.

References:

[1] Weber J.W.: WEC Technology Readiness and Performance Matrix – finding the best research technology development trajectory. Proc. 4th International Conference of Ocean Energy, Dublin, Ireland (2012)



Windswept and Interesting Ltd. rotary network AWES with rigid blades (17 May 2019)

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Practical Experimentation on Rotary Network AWES

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Simple rigid blades can be sewn together and flown as a networked autogyro kite turbine. Torque from the mechanical drag mode turbine, can be continuously transmitted to a ground-based generator. Torque transmission is limited to within the safe working limits of tensile tethers held apart by a succession of rings. Greater tension, diameter or number of lines allows more torque to be safely transmitted. The simplicity of design and build enables experimentation on modularly scalable system architectures from a small facility. Simulation data (and flying form) shows that torque transmitting kite networks, don't need to rely on rigid ring structure, when the kites are sufficiently banked.

Kite turbine system portability and operation was tested when a scout troupe took an older parafoil kite based turbine to an international jamboree. Analysis by Oliver Tulloch suggested, rigid rotor blades would have a higher power coefficient. Testing proved Oliver correct, the rigid blade rotors, showed even higher efficiency than predicted. The single rigid ring system, (Shown as lower white ring in picture opposite page) with flying weight under 2kg, output over 1.5 kW, flying only 4 m above the ground in 10 m/s wind. When disassembled, the rigid kite ring will still easily fit inside the back of a car.

Stacking the kite rings increases system efficiency by improving kite area to line drag area. Line drag effects can be further mitigated with fairing on the short section network lines, which have near constant inflow. Stacked kite ring turbines tend to be more stable in flight but setting them up to launch is a little harder. The current launch method involves laying the rings out on the ground, attaching them, launching a lifting kite, then hoisting the top of the turbine stack into the air by paying out a back anchor line. Setting the rigging tension correctly by adjusting the height, where the lifting kite line attaches to the top of the turbine stack, still takes practice.

The safety of network architectures was dramatically demonstrated when 7 of 8 tethers were broken yet no part broke away from anchoring. The turbines have continued to work, despite various and multiple line breakages, albeit with deteriorated performance. The line longevity is good as none of the lines abrade on running gear. Significant rotational forces can throw components from a rotor. The two stiffening spar tubes are tied through to stop centrifugal forces causing slippage. We will present advantages of network kites and results from campaigns and simulations. Kite Network turbines work deep in the power zone and have a good propensity for failsafe scaling. We are developing a series of scaled development proposals 5 kW(3x3), 10 kW, 7x5 kW(7x3x3), 50 kW, 7x10 kW & 100 kW. We hope to share some practical lessons and a physical demonstrator model at AWEC 2019 too.

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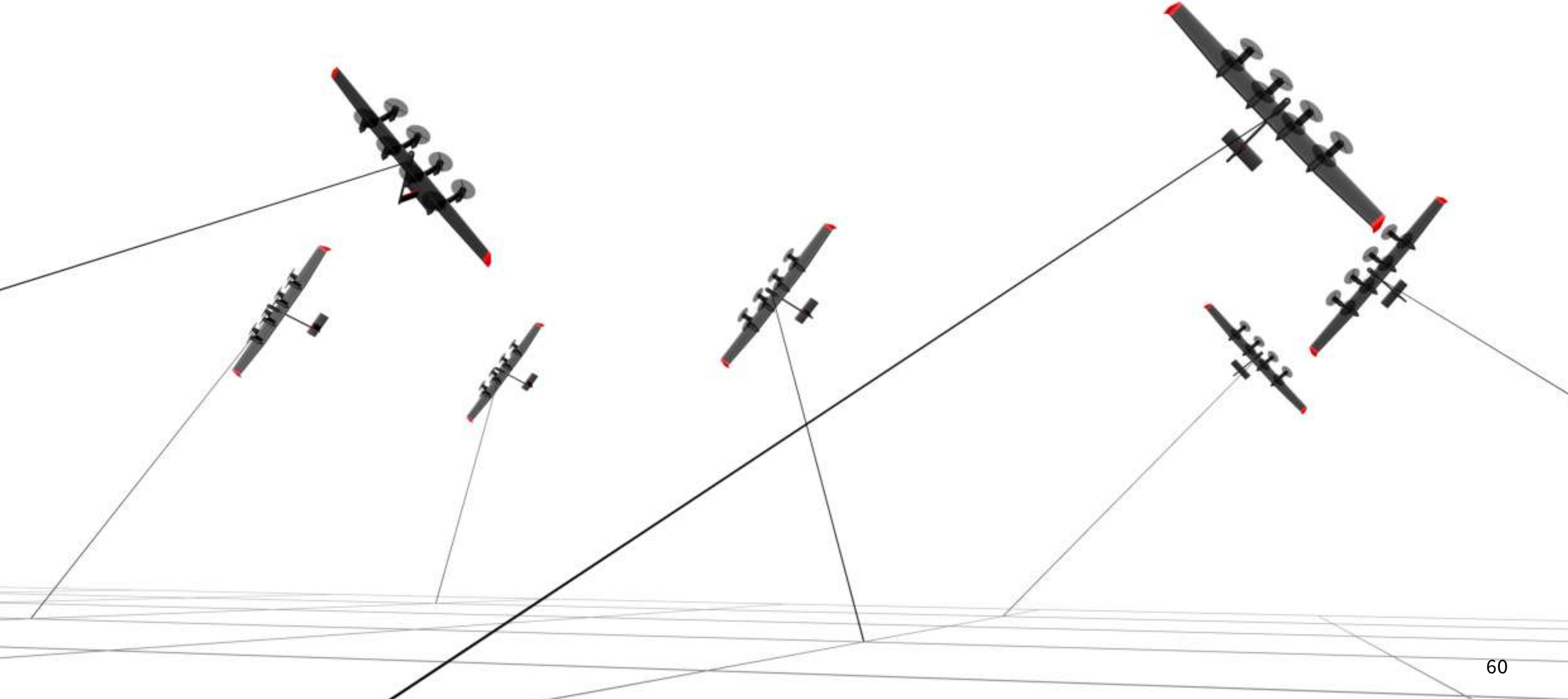
Vision of a kite wind park for MW-scale energy generation



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Airborne Wind Europe

Developing a European Roadmap for Airborne Wind Energy

Kristian Petrick, Udo Zillmann
Airborne Wind Europe

At the Wind Hamburg conference 2019, the members of Airborne Wind Europe agreed to start five Working Groups (WGs) where sector-wide issues would be tackled in a collaborative way. One of the WGs, the “WG Roadmap” was tasked to develop a roadmap for the AWE industry with the objective to describe sector’s potential development and deployment pathways up to 2030. The approach consisted in a bottom-up, Excel-based survey where members were asked to provide their business plans and/or best estimates in terms of pre-commercial and commercial projects:

For each pre-commercial system (pilots, demonstrators, test systems)

- Nominal power of the system
- Investment needs
- Costs per kite and year
- Number of kites built
- Cost per ground-station
- Number of ground-stations required
- Total system costs
- Expected number of employees (direct FTEs)

For each pre-commercial system (pilots, demonstrators, test systems)

- Nominal power of the system
- Price per system and year
- Number of systems sold
- Total sales [€]
- Total capacity installed [MW]
- Expected number of employees (direct FTEs)

Ten companies participated in the exercise, even though some were not providing all data. The provided figures were aggregated and presented as graphs. Data were anonymised to safeguard confidentiality. Preliminary results show:

- One company dominates the sector growth in the “base scenario”
- Cumulated investment needs until 2025 for pre-commercial systems amount to some 250 Mio Euro for nine companies alone
- Most companies plan less than five demonstrators per year, while one company plans more than 20 within two years.
- Six companies start with commercial systems of 100 kW, the others plan between 250 kW and 2000 kW
- First commercial system is planned to be available for in 2020
- Nine out of ten companies plan market launch of commercial systems by 2023.

In addition, potential scenarios for the year 2050 were elaborated based on published scenarios for the wind sector. The WG plans to publish the findings at the AWEC 2019. Unlike other studies on the AWE sector, this exercise intends to provide numbers that come directly from the companies themselves. However, the discussion revealed the high level of uncertainty regarding assumptions and future developments. It is therefore planned to repeat the exercise on an annual or bi-annual basis in order to adapt the figures to latest developments including technological achievements and the policy and regulatory environment.

Kitepower B.V. team in front of their 60 m^2 kite (29 August 2019)

Kitepower co-founders Johannes Peschel (left) and Roland Schmehl (right) explaining a kite control unit (29 August 2019)

German President Frank-Walter Steinmeier and his wife Elke Büdenbender in discussion with Johannes Peschel during their visit of TU Delft (17 May 2018)

Small series of Kite Control Units produced at Kitepower B.V. (26 June 2019)

Harvesting energy at the former naval airbase Valkenburg (29 August 2019)

Flight operation of the kite (24 April 2019)

Light trace of a pumping cycle in the night sky (11 October 2018)

Kitepower and the Journey Towards 24/7 Operation

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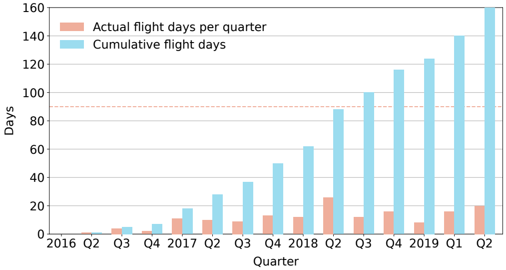
Kitepower is a leading start-up in the field of airborne wind energy, developing innovative and cost-effective alternatives to existing wind turbines by using kites to generate electricity. Kitepower's mission is to develop a commercial airborne wind energy system with a 100kW nominal power output that can supply 450 MWh/year in the Netherlands before scaling up to bigger sizes. This unit shall be integrated into existing (micro) grids, potentially in combination with solar PV and batteries, to reduce diesel consumption and CO2 emissions in remote areas to validate the commercial viability of airborne wind energy.

To reach this goal, Kitepower's approach is to 'go out of the office' as soon as possible and test the system under real life conditions. For that, Kitepower develops and builds the simplest, cheapest and safest system that will reach the goal. Their current system includes a 2nd generation ground station with a 180kW electrical peak power, a 2nd generation kite control unit and a 60 m^2 kite of the 6th generation. The 3rd generation of the ground station has a peak power of 160kW, and the 6th generation kite (100 m^2) is available for testing with the first batch of kite operators already trained.

From the beginning of 2018 until October 2019, Kitepower has performed 92 flights on 65 days at their pilot site in Valkenburg with kites from 25 m^2 to 60 m^2, and with ground windspeeds from 2 m/s to 12 m/s. One aim of these tests was to simplify the system and improve the operational manual such that trained kite operators can operate and maintain the system with ease. Another aim was to establish a remote monitoring platform that can be used by Kitepower staff to supervise the systems anywhere in the world. Last but not least, they aimed to further automate the tuning of new kites by testing them in various operating conditions such as rain, fog as well as low- and high wind speeds.

Currently, Kitepower is focusing on operating the Kitepower system for longer periods (see figure) while increasing the power output and reducing the effort for supervision. After this phase, Kitepower will be able to implement more pilot systems in and outside of the Netherlands.

This talk will provide an update on the milestones that were presented on the AWEC 2017 and a summary of Kitepower's recent test results as well as the planned next steps towards completing the Kitepower mission: a commercial Kitepower system with 100kW average electrical power.



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Kitemill – Past, Present and Future

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Kitemill

Kitemill was established 2008. Backed up by experienced advisors and strong partner, a small team has been running the company by a few suitable strategies. Now, the strength of the team and the importance of the strategies has become clearer. Strategies that have the most influence on Kitemill can be summarized in; priority to testing, connect with the right competence, share risk, build momentum and prioritize the most critical problem.

The lack of rules for operating kites even in low altitudes, led to an early and serous dialog with the national Civil Aviation Authority (CAA). Already in 2015, after a few years with temporary solutions building experience, Kitemill got approval for the first permanent danger area. More recently a second permanent area has been approved and activated, allowing closer coordination with general aviation.

In 2018 Kitemill took the initial steps with a temporary build permit, supporting present and coming operation, involving basic consequence analysis. The permits prove that the method to achieve necessary right to operate is viable.

A central strategy for Kitemill's research & development is to connect with the right competence whenever we face a new challenge. Through several projects we have learned the challenges and benefits with such approach. A critical point is when the R&D projects developed by partners shall be adopted by the company. Several large technology transfer processes have been completed and the small Kitemill team holds comprehensive technology base and corresponding system understanding. This is now proved by several important results from further internal R&D. Further Kitemill sees many new opportunities for cooperation and risk sharing as the technology being industrialized and aims to continue with similar methods.

With a good test site Kitemill have accomplished frequent testing for years. But when the team now being extended it is to operate even more frequent, gradually transiting to continuous operation.

In 2015 Kitemill signed letter of intent for sale of the first kite turbines. In 2017 Kitemill's customer purchased the first plant which since then has been used ad-hoc operation by Kitemill. 2019 Kitemill's customer takes the step from the LoI to a turbine supply agreement for the first kite park. Both Kitemill and the customer now aims for the new contractual milestones.

In a longer perspective Kitemill's strategy is to launch rather small models and aim for utility scale volumes. This will provide a large base of operational hours, necessary to qualify for large scale deployment. Independent of funding, and anchored in history of similar technology introductions, this seem to be the fastest way to become a leading company with the most significant energy technology.

Save from Future Japan Social Crises! ‘Mothership’ Project

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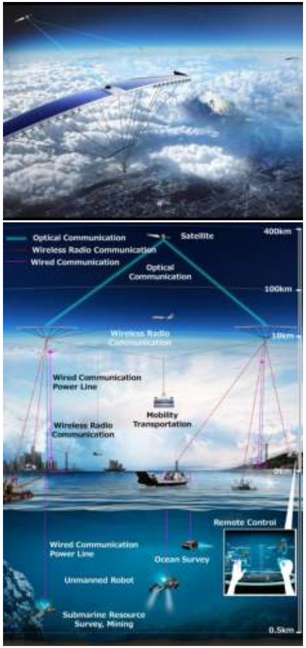
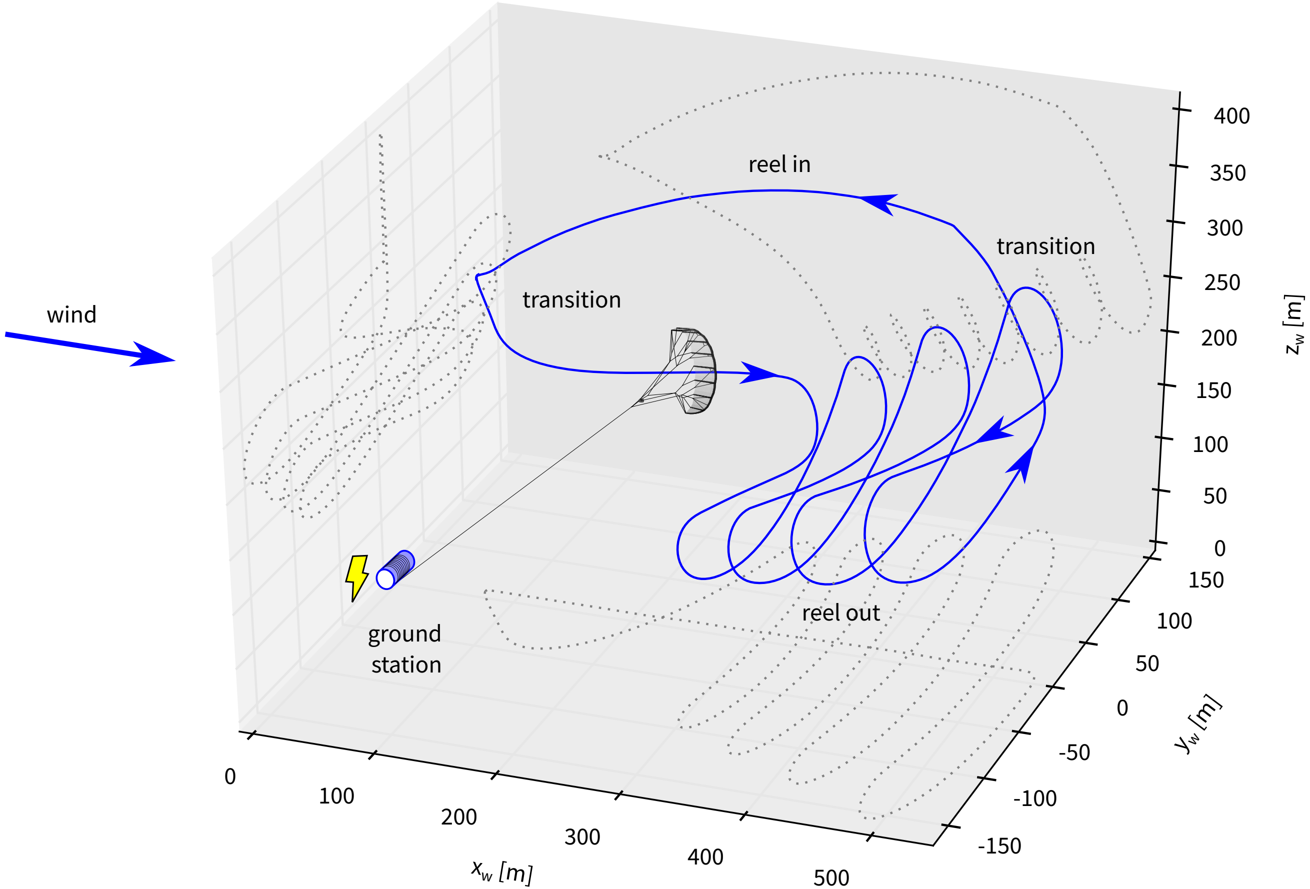
In the near future, many of the developed countries are likely to face energy & environment challenges, accompanied by migration of people from rural areas to the smart cities and increase in the social debt. Japan is likely to be ‘top runner’ in facing them. We are considering a novel solution to address these challenges using the westerly jet stream above Japan. The westerly jet stream is a high- density, seemingly endless renewable energy source, 10km above the ground, generated by the heat transfer from tropical to pole, that induces air convection (physics) with the specific earth shape, size and rotation (occasional lucks for Japan) ‘Mothership’ is a visionary futuristic novel project, in which we are proposing to use a large tethered kite, that utilizes the westerly jet stream to fly at high altitude and offer many social benefits, i.e. ‘harvest energy’, to move heavy payload in remote areas as a ‘sky crane’, to help global optical wireless satellite communication network as a ‘relay station’ even in heavy clouds. We believe that the ‘Mothership’ project shows a large potential to stimulate many industries and ventures by offering innovative solutions and help to save from future social crises.

This project vision has been approved as a challenging venture and is considered as one of the most important innovative projects in Toyota. Our global team consists of members from Japan, United States and Europe, who are working on actual engineering development. We will share our vision, the current progress and remaining challenges.



Final Goal Image Sketches of ‘Mothership’

Flight path of the TU Delft pumping kite power system computed with a dynamic system model (kite not to scale), from Fechner, U.: A Methodology for the Design of Kite-Power Control Systems. PhD thesis, Delft University of Technology (2016). http://doi.org/10.4233/uuid:85efaf4c-9dce-4111-bc91-7171b9da4b77



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Open Data Project: Flight Data Analysis of Kitepower Systems

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Due to support from the Data Refinement Fund from “4TU.ResearchData” we are able to publish a large data set with logged flight data from 42 flights in the years 2011 to 2015 [1]. These flights were executed by the Kitepower research group of Delft University of Technology.

In total 81 different physical values and control signals where logged during the flights, though in most cases not all values were logged at each flight.

The logged data is provided as .hdf5 file. From this file for each flight the data can be exported as CSV file (comma separated values), a format compatible with nearly any programming environment. Alternatively the archives with the CSV files can be downloaded directly.

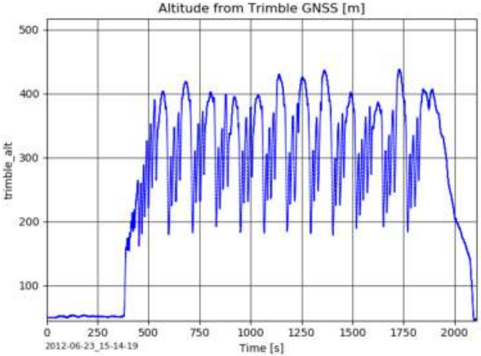
Furthermore Python scripts are provided for extracting meta data, filtering the data and also for plotting. Basic examples how to use the data are also provided in the programming languages Julia and Matlab.

While some of the data was already published before [2] for the first time the complete data of 42 flights is provided.

We present an overview of the metadata such as the test location, kites, sensors and the data fields. Then, an overview and some explanations about the flight data are given. Finally, the use of the Python scripts and the use of the data with other programming languages is explained.

As a highlight the performance of different types of autopilots are shown.

This data set can serve as source for further analysis of kite power systems based on flexible wings for MSc students and PhD researchers.



Plot of the height of the kite during a test flight on 23 June 2012. The max altitude was 438m and the peak mechanical power 20.5 kW at an avarage wind velocity of 9.5 m/s at 6 m height.

References:

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Ram air kite tethered to an adjustable handle bar in the wind tunnel of Cranfield University

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Wind Tunnel Parametric Study of Kite Performance for Power Generation

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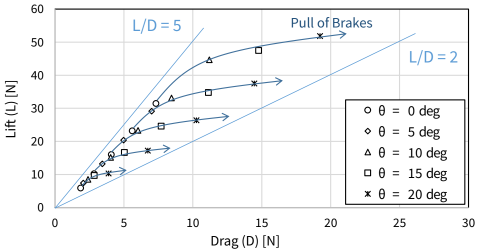
High deformability, high anhedral and low aspect ratio are some of the features that make ram-air kites differ from conventional wings. With the emergence of Airborne Wind Energy technology, it is considered necessary to increase the volume of available data on kite aerodynamics as they are key to a proper technology optimisation. Wind tunnel tests of all-flexible kites are rare because of the practical difficulties in data extrapolation to full-scale, atmospheric flight. However, they are still useful for parametric studies in a more controlled environment.

As a result, wind tunnel tests of a scaled, four-line ram-air kite have been undertaken at Cranfield University. The kite was tethered upside down to a manually adjustable handle bar, which was used to introduce the two main input parameters: handle spanwise spacing and handle pitch angle. The first affects wing anhedral, and the latter is proportional to the amount of pull of brakes and kite attitude.

Tests were carried out over a range of wind speeds for every configuration of wing anhedral and handle pitch angle. A limitation of the tests has been the lateral/directional stability of the kite. The problem was overcome by applying a minimum pull of brakes at every test, which in turn had an impact on the fidelity of experiments.

As for the parametric study, wing anhedral leads to a decrease of both C_L and C_D. The effect of increasing the pull of brakes is that of reducing L/D, a sign of the effectiveness of the device. C_L and C_D have been seen to be Reynolds number dependent, both converging with dynamic pressure. Maximum L/D values above 4 have been obtained with the highest wing anhedral and the smallest pull of brakes.



Lift vs Drag polar; θ = handle pitch angle $\propto$ pull of brakes.

The project is considered valuable as a preliminary study of the impact of wind speed, wing anhedral and pull of breaks on kite performance. Further work will focus on kite stability and an advanced imaging setup, as well as alternative experimental approaches.

References:

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Effect of Wind Variations on Tether Load Transfer from Kite to Winch

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Key to the development of optimized Airborne Wind Energy systems are the use of simulators, providing a development and test platform for subsystems design and control systems. Most of the existing simulators idealize the tether as a rigid or elastic link in between kite and winch [1], as a chain of rigid rods [2], or as a chain of elastic elements neglecting dynamic effects. Studies that do use a more complex tether model tend to focus on control systems and do not look in details at subsystems-induced loads and the performance of the full system [3-4].

Some energy is dissipated along the tether due to damping and drag effects. Given the length of the tether and the temporal and spatial wind variations, it is expected that the tether tension signal originating at the kite will be modified while travelling down the tether, and the line tension signal seen at the winch will be different. This can have significant implications on the loads that have to be considered to design the system components, in order to optimize power production, limit excessive loads on components, and consider components lifecycle.

The KPS simulator consists of a modular Simulink environment that can be adapted to look at specific problems. In this study, we use a model comprising a dynamic winch connected to a lumped mass tether model placed in a 3D turbulent wind field. The tether model is made of point masses connected by spring-damper elements, includes drag forces on point masses, and models reel-in and reel-out by adding and substracting mass points. The kite trajectory is fully specified as a history of kite coordinates.

This study will give some insight into the effect of tether dynamics and energy dissipation on winch loading for specified kite trajectories, which will help assessing the importance of considering those effects. This will ultimately feed into tether and winch design requirements in a view to optimize Airborne Wind Energy systems performance and durability.

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Beyond the Sea project team (from left to right): Christian Jochum, Nedeleg Bigi, Morgan Behrel, Guy Leblanc, Damien Grelon, Yves Parlier and Richard Leloup, at ENSTA Bretagne (15 December 2017)

Beyond the Sea®
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A Fast Simulation Tool for Ships Towed by Kites: Assessment of Propulsion Efficiency

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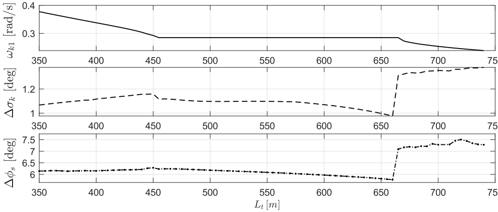
IRDL ENSTA-Bretagne CNRS FRE 3744

Over the past decades, more and more research programs are developing innovative and green propulsion systems for maritime transportation. This is also the application background of the present work, which aims at reducing the consumption of container ships by an alternative propulsion technique. In his pioneering work, Duckworth [1] proposed kite propulsion. Podeur et al. [2] confirmed the potential of this technique to achieve significant fuel savings. However, the assessment of the possible risk entailed in the towing of a ship by a kite has not been studied consistently. Existing literature references consider static equilibrium [3]. The dynamic interaction between a ship and a kite has been studied by Bigi [4]. The main objective of the present work is to precise the dynamic effects on the ship and the kite operability for a realistic sea and wind environment. To achieve this, a unified seakeeping/manoeuvring numerical code is used by updating the equation of motions with the forces generated by the kite [5]. A zero mass model is used for the kite, assuming that the tethers are straight and inelastic. The aerodynamic lift coefficient and the lift-to-drag ratio are functions of the yaw turning rate of the kite. Two types of simulation are considered: firstly, the ship in calm water and, secondly, the ship subjected to regular Airy wave for varying parameters such as wave amplitude, wind force, tether length and ship heading. The results show that the kite is more affected by the dynamic motion than the ship (see figure). Indeed, a lock-in phenomenon between the wave frequency of encounter and the first harmonic of the kite is clearly demonstrated. A dimensional analysis is provided in order to identify this phenomenon prior to simulation.



ω_{k1} kite first harmonic frequency, $\Delta\sigma_k$ kite wind load amplitude, $\Delta\phi_s$ heel amplitude, L_t tether length for a kite area A_w=500 m^2, true wind speed U_{tw}=12.5 m/s, wind direction β_{tw}=45°, a wave encounter frequency ω_e=0.285 rad/s.

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PolyMPC: An Efficient Tool for Embedded Model Predictive Control for Fast Mechatronic Systems

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Nonlinear optimal control and trajectory optimization methods for Airborne Wind Energy (AWE) systems have been extensively explored in recent years. Very promising results have been shown in generating and subsequent tracking of power optimal flight trajectories in simulation studies. Deployment of these algorithms to research and commercial prototypes poses a new challenge, since the computational power of onboard computers is usually very limited. Here we present a new tool that implements the direct collocation of optimal control problems and a nonlinear optimization solver that is optimized for these challenging embedded applications.

Efficient solvers for real-time optimal control are required to run on embedded hardware with highly constrained computational and memory resources. Most existing solvers are based on second-order methods which are prohibitively expensive for many faster applications. The method presented in this paper overcomes many of these challenges.

A nonlinear solver has been developed that applies a Sequential Quadratic Programming (SQP) strategy using an Alternating Direction Method of Multipliers (ADMM) based Quadratic Program (QP) solver. SQP iteratively solves a series of quadratic sub-problems, which are constructed using forward mode automatic differentiation for linearization and a damped BFGS variant for Hessian estimation. The descent steps are taken using the line search method on a merit function. Optimization techniques such as factorization caching and warm-starting result in efficient iterations.

The solver is implemented as a generic nonlinear solver in the form of a header-only module, which integrates into PolyMPC, an open-source C++ library for real-time Nonlinear Model Predictive Control (available for free at https://github.com/LA-EPFL/polympc). A Chebyshev pseudospectral collocation-based approximation method is used to efficiently discretize the OCP.

We leverage the flexibility of templated C++ with the Eigen linear algebra library to construct a problem specific solver which uses only static memory allocation. The implementation is suitable to solve small sized problems on an ARM Cortex-M7 microcontroller with Floating Point Unit (FPU), which was tested on a simulated path following problem of a two-line soft-wing kite as described in [1]. The computation times on three different platforms is shown in the table below. With 63 optimization variables and 45 nonlinear equality constraints the controller object uses 83280 bytes of memory when using single precision floating point types.

Platform	Solve time [ms]	Factor
Intel Core i7 2.8 GHz	5.83	1.0
ARM Cortex-A15	19.21	3.3
ARM Cortex-M7	349.00	59.9

References:

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A Study on Power Transmission Techniques for Marine Airborne Wind Energy Farms

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The slender structure of airborne wind energy (AWE) systems has made them ideal for floating offshore applications although the limited maximum distance of current marine high voltage AC (HVAC) technology (<50 km) can be a barrier for their development [1]. This research work is a literature review to study advanced marine power transmission technologies including high voltage DC (HVDC), low-frequency AC (LFAC) and direct interconnection technique (DIT), and their compatibility with AWE technologies. The absence of reactive power in HVDC has led to fewer power losses and higher transmission distance compared to marine HVAC. However, high cost and failure rate of power electronic converters (PEC) negatively affects the economy and reliability of HVDC [2]. Marine LFAC has higher loadability and distance compared to subsea HVAC [3]. The low operating frequency of LFAC (16.7 Hz) is compatible with the generated frequency of AWE devices; therefore, there is no need for PECs and their associated equipment in the offshore substation. However, LFAC requires shunt reactors and larger power transformers [3]. DIT relocates marine-based PECs to the onshore site to relieve the negative effects of offshore PECs on the cost and reliability [4]. Considering the cost of PECs between €111/kVA and €150/kVA [5], DIT can save €22.2M-€30M in capital cost of a 200 MW offshore AWE farm. The development of DIT for AWE systems needs more investigation as challenges like mechanical torque regulation, reactive power exchange, and flight control complexity are reported [6]. Less power losses and better economy of LFAC compared to HVDC [7] and its frequency compatibility with AWE devices show a significant potential for LFAC to be used as a marine power transmission for future floating offshore AWE systems. However, more investigation is necessary to examine this technology for AWE devices.

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Power Curve Analysis Of Airborne Wind Energy Systems

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Power curves are used as a tool to analyze the economic feasibility of wind turbines. Over the years, these power curves have been validated and improved by incorporating on-field data from the already installed wind turbines. Currently, there are very few working prototypes of AWE systems and none of them is a fully functioning commercial unit. Thus, the power curves for AWE systems are still an open topic of discussion in the research community.

In [1], a study is presented discussing a family of power curves of the Enerkite AWE prototype EK30 for different altitudes derived with a focus on motor and structural constraints. In [2], a simplified model is analyzed to estimate the maximum feasible drag power for an on-board production system. In [3], an optimal control problem is discussed which is then used to obtain power curves for a rotary kite AWE system. Limits in power and allowable torque/force have been discussed in [4] for a kite power system in pumping mode.

In the authors’ previous work [5], a 6-DOF model for a Magnus-based AWE system validated in simulation environment. In addition, a static model of the production cycle has been presented. Based on this model, we will present a high-level algorithm that gives reel-in speed, reel-out speed, working altitude, and elevation angle, taking into account system saturation. Different ground station structures, including electrical and hydraulic solutions, have been considered.

The resulting power curves consist of different phases where each phase corresponds to different configuration of control variables. They illustrate the high flexibility of on-ground airborne wind energy systems and their potential over conventional wind turbines. On the other hand, this approach can be also used to study the effects of design parameters on the performance.

As authors are working specifically on Magnus-based on-ground AWE systems, numerical application for this type of systems is done to draw comparisons with conventional horizontal axis wind turbines. More details can be found in [6].

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The Second, Most Important, Law of Tether Scaling

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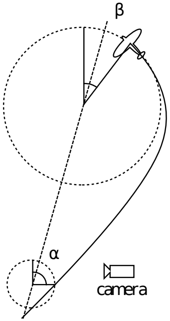
We will present a differential equation describing the tether as a curve in 3D space along the length of the tether. Compared to simpler models, it gives more fidelity. Compared to piecewise stiff tether simulations it is easier to reason about and is calculated quickly.

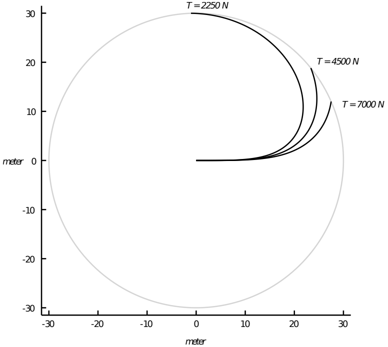
By using this equation, we arrive at 'the second law of tether scaling'. The tether length is not only limited by tether drag but also tether mass. The law states that a minimum tension is given by:

$$T > \mu \left(\frac{vl}{R}\right)^2$$

where T is tether tension, l is the length, μ is the weight per meter, v and R is the flying speed and looping radius of the kite.



We have done experiments using an in-situ method of estimating the tether drag coefficient by measuring the phase difference of the tether at the winch and the kite looping. This showed preliminary results close to the expected value $C_{(D,t)} \approx 1.1$ [1].



Numeric solutions of tether shape for a looping kite looking from the winch along the centerline. The curves show different tether tensions, for tether length 400 m, diameter 4 mm, looping radius 30 m and kite speed 40 m/s. Note 4500 N is approximately according to 'the second law'.

References:

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Airborne Wind Power Generation Employing Straight Bladed Wind Turbines

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A ground-generator-type airborne wind power generation (AWPG) system is proposed for utilizing high and steady wind power over the canopy of a ground wind boundary layer The proposed system employs vertical-axis wind turbines carried by a kite or aircraft and a tether driving mechanism to convey the high sky wind energy generated by the windmill down to the ground generator. Research and development are currently in the stage of a Phase 1.5 prototype that includes two 0.65 m (span) x 0.6 m (diameter) straight bladed wind turbines The system is expected to produce wind energy power of 6 kW with an eight figured periodic flight, which represents approximately 30 times greater wind energy generation than the usual on ground operation of 0.2 kW.

Performance and power generation tests of the Phase 1.5 windmill model were conducted in October 2018 at the wind tunnel facility of Maeda Corporation. The wind tunnel test showed that the power factor was 21% and the maximum power generation was approximately 20 W. We developed a field test model equipped with two Phase 1.5 wind turbines (a single pair), and conducted a power generation demonstration test of the floating wind turbine system by running a carry vehicle at Menuma Air Field on January 24-27, 2019. An outline of this test is provided in Figures 1-3. A generator was installed on the bed of the towing truck, and the number of revolutions of the generator and the generated power were measured. The time history of the generated power and rotational speed of the generator are indicated in Figure 4. A maximum of approximately 30 W of power generation was recorded.

Fig. 1 Overview of experimental setup

Fig. 2 AWPG field test

Fig.3 Generator (SKY-HR125) on vehicle bed

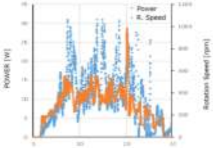

Fig. 4 Output power and rotational speed

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Comparison of Engineering Induction Models in a Multi-Kite Optimal Control Problem

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Due to straightforward system scalability and low tether drag, the multi-kite airborne wind energy system (MAWES) appears [1] to be a promising concept. The low-order design space exploration of such a system is an ongoing challenge because design decisions and flight trajectories are highly interdependent. This challenge has been approached (as, for example, in [2] [3] and [4]) from an optimal control perspective, in order to include the influence of physical and control constraints. From [5] and [6], we know that the inclusion of an induction model will change the outcome of a MAWES optimal control problem. However, as there are many low-order ("engineering") induction models available, it is not yet certain how best to select a model for this MAWES optimal control task.

In this work, we formulate a trajectory-optimization problem for a three-kite, lift-mode MAWES using various engineering induction models – including a steady actuator disk model and the classic unsteady rotor model of [7]. We solve these problems in the awebox open-source toolbox [8]. The goal is to compare the similarity between the resulting optimization solutions, and consider any computational trade-offs. Based on this comparison, we draw conclusions about the sensitivity of the solution to the induction model and make recommendations for future model selection.

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Complex Wind Profiles Measured Offshore and Their Relevance to Airborne Systems

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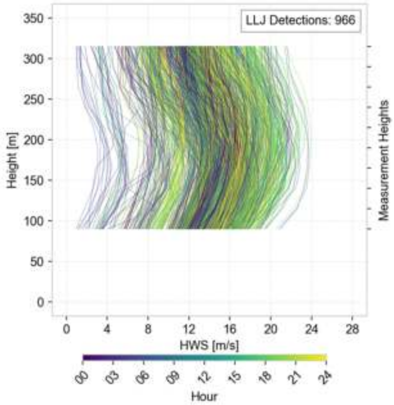
Airborne wind energy systems have the obvious advantage of being able to exploit the stronger and steadier wind speeds typically found at higher altitudes than those experienced by ground-based wind turbines. However, the relationship between wind speed and height above the sea (called wind shear) is often complex, as has been shown by long term measurements using scanning lidar systems.

Wood Clean Energy has years of experience of measuring wind conditions at offshore locations and has built up a good understanding of complex sheer characteristics and their prevalence, along with other important parameters including veer, diurnal effects and seasonal variations. This understanding is considered essential for optimal design of airborne wind energy systems and may in fact present a further opportunity where lidar measurements can be integrated with system controls in real time, thereby hunting the strongest and steadiest winds at whichever altitude they are occurring at that point in time.

Wood Clean Energy will share its findings from several offshore lidar measurement campaigns in the context of airborne wind system requirements and will invite engagement with the sector on further work to support the commercialisation of this exciting technology. Approximately nine years of lidar measurements, acquired since 2011 at four North Sea locations, were used to assess wind conditions between 40 and 300 m above sea level. Focus was placed on the identification of complex shear events (inclusive of low level jets (LLJs)). Diurnal, directional and seasonal variation of complex shear events will be discussed and their implications for operations.

Discussion will also include future lidar applications of value for the Airborne sector including the potential for active control, and wake characterisation.



Lidar measured wind shear profiles.

Heading Angle Control for Path–following Guidance with Large Domain of Attraction of a Pumping Kite Generator

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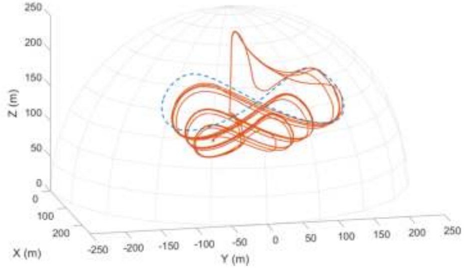
We address the problem of controlling the heading angle of a power kite to follow a prescribed geometric path.

In a first stage, we solve an optimal control problem to determine a kite trajectory that maximizes the energy generated during the traction phase of a Pumping Kite Generator. (This problem has been widely studied in the literature; see e.g. [1] and references therein.) The obtained trajectory is then used to define a time–independent geometrical path, parameterized in the azimuth and elevation angle, in spherical coordinates, as well as a target speed under which the path should be followed.

In a second stage, such path is used as the reference in a path–following guidance method, based on a modified nonlinear guidance logic, given by an explicit expression.

Such controller has been shown to be asymptotically stable and has demonstrated a superior performance in following straight and curved paths when compared with other common navigational guidance laws. In the modified controller, the domain of attraction is significantly enlarged, which represents our main contribution (see [2]). Robustness of the method under fast changing wind conditions, such as wind gusts, is analyzed in simulation.



Reference path (dashed-blue line) closely followed by the kite trajectory (solid red) during production phase.

References:

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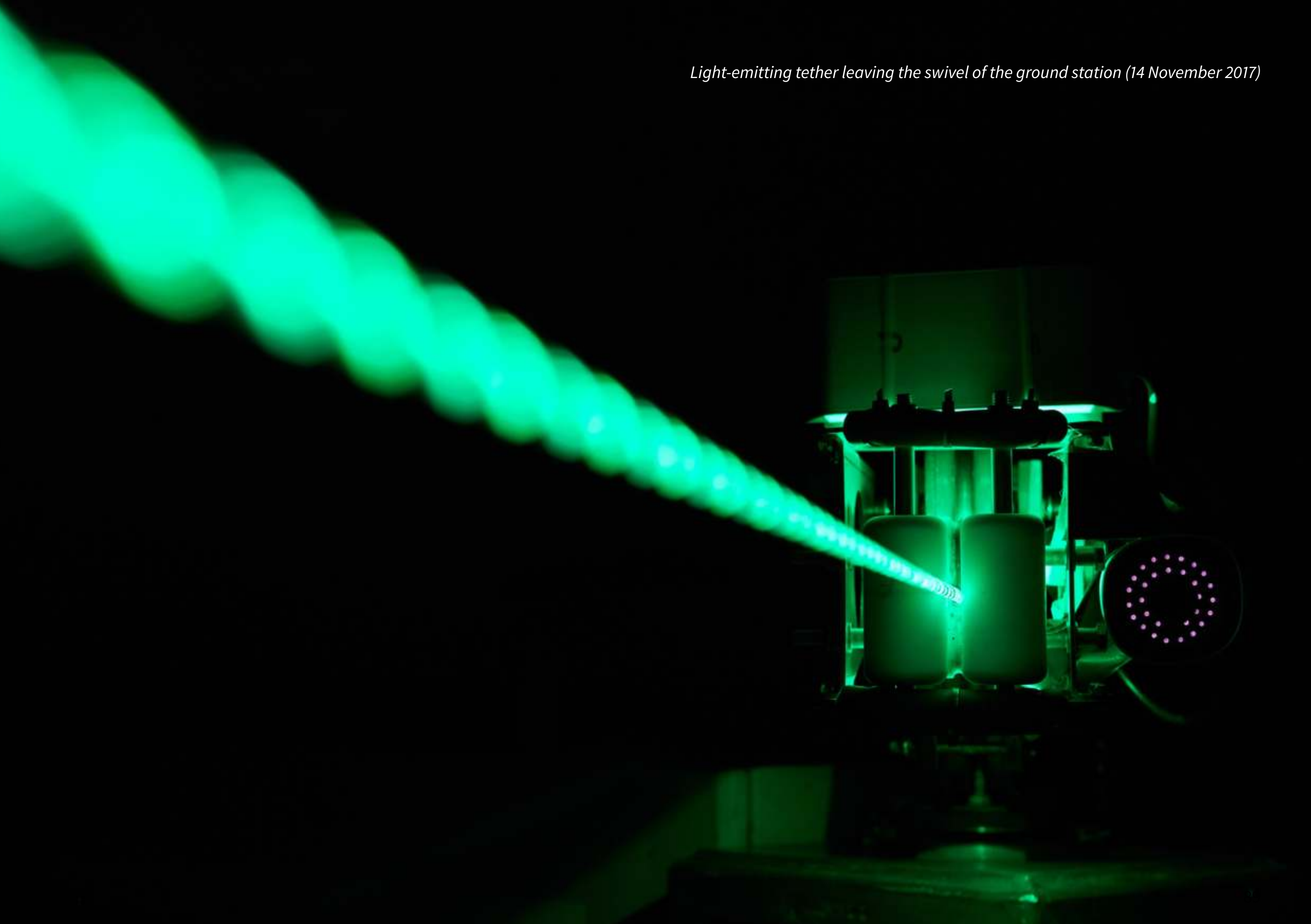
20 kW ground station of Kitepower B.V. at the Afsluidijk in operation during the Windvogel project of Daan Roosegaarde (14 November 2017)



Light-emitting tether leaving the swivel of the ground station (14 November 2017)

Kites with light-emitting tethers during the Windvogel project of Daan Roosegaarde (15 November 2017)

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Engineering with a Bending-Optimized HMPE AWE Tether

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The Airborne Wind Energy industry is moving from small scale hand-controlled prototype drones and kites to full scale autonomous controlled commercial systems. Power systems of 100 kW up to 2 MW are already commercial or being developed. In the current commercial scale prototypes, the tether has a critical role since the tether is a single point of failure and at the same time a costly component. Engineering the tether in the sense of extended safe and reliable operations is a balance between low tensions (large rope size), reduction of drag and CAPEX costs. DSM Dyneema has extended the tether CBOS testing [1] towards 21mm and has engineering data available to design medium size tethers. In the graph data are presented where the lifetime engineering data are translated into a maximum amount of power that can be transferred per kg of fiber in the rope. The results are based on 26 x 16 mm bending optimized flat rope (250 g/m, image) and extrapolated towards larger and smaller rope sizes. A larger rope size will result in a lower tension and in an increased bending cycle lifetime. The power transferred per kg Dyneema® fiber is showing an optimum. The amount of power (kW for one year) that can be transferred by 1kg of Dyneema® fiber per meter of tether is depicted. The pulling force of the drone is set at 10 tons. As function of the size of the rope, represented by its weight (kg/m), an optimum can be noticed.

As an example, the optimum of 7 kW/kg/m can be used for estimating the desired pulling force at a given tether size for an AWE system. If the running (yo-yo) length is 200m and the system has 2 sheaves and a 0.25 kg/m flat rope, the optimum pulling force is 7 tons. The rope will transport 176 kW for one year. These results are based on cycles to break. After one year the rope will fail. It is advised to calculate with a well-defined margin on life time.

Power transferred in kW/kg/m for one year by a bending optimized flat tether with Dyneema® DM20XBO fiber at different rope weights running over one sheave with D/d = 30 and a drone pulling force of 10 tons.

Bending optimized flat rope construction results in increased power transfer.

References:

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OpenOCL - The Open Optimal Control Library

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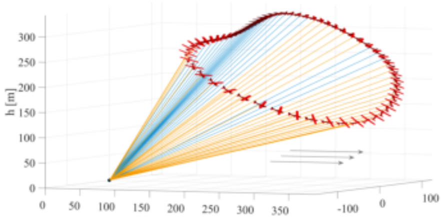
With *OpenOCL*, we aim to develop an optimal control modeling framework that allows to define optimal control problems in a user friendly way. Domain specific models for *airborne wind energy* can be implemented in Matlab or using the *optimal control modeling language* (.ocml). A library of power optimization models for the *Ampyx Power AP2* system is available at the *OpenAWE* project [1]. Results are shown in the figure on the right.

The two main applications of optimal control are **trajectory optimization** and **model predictive control**. *OpenOCL* is designed to be used for both. While *trajectory optimization* can be used to study, analyze, and simulate the behavior of the system, *model predictive control* can be used to control the actual physical system in a real-time loop.

For trajectory optimization, *OpenOCL* implements a *direct collocation* method that transcribes the continuous time optimal control problem into a *non-linear program*. The non-linear program is then solved using **ipopt** [2]. For real-time model predictive control there is an interface to **acados** that allows to generate efficient code that can run on embedded systems [3]. Derivatives for the models are automatically generated using *CasADi* [4].

OpenOCL is available online as a Matlab package at https://openocl.org/



An optimal flight path for an airborne wind energy system to generate maximal power calculated by OpenOCL using CasADi and Ipopt, flight models from OpenAWE. The system generates power when the winch releases tether (indicated by the orange lines).

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Clustering Wind Profile Shapes to Estimate Airborne Wind Energy Production

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Airborne Wind Energy (AWE) systems use tethered flying devices to access higher altitudes, typically up to 500 meter, where wind is generally stronger and more persistent. To estimate the Annual Energy Production (AEP) of AWE systems, the wind speed statistics close to the ground are typically extrapolated to higher altitudes, introducing substantial uncertainties. A methodology is developed for characterising a site's wind resource using a set of wind profile shapes. It is demonstrated how this wind resource representation is used together with a performance model to do fast AEP calculations for flexible-kite pumping AWE systems.

The wind profile shapes and corresponding statistics are obtained from the Dutch Offshore Wind Atlas (DOWA) wind dataset. The wind profile shapes do not only describe the change in wind speed with height (wind shear), but also the change in wind direction (wind veer). The Quasi-Steady Model (QSM) of a pumping flexible-kite AWE system as proposed by Van der Vlugt et al. [1] assumes no change in wind direction with height. It is assumed that the kite is continuously steered to correct for the changes in wind direction without penalizing its performance. The QSM is used to specify the mean cycle power output of an AWE system for relevant combinations of wind profile shapes and reference wind speeds at 100 meter height, yielding a power curve for each wind profile shape. The power output is obtained by optimising the mean cycle power over a small set of operational settings [2]. The wind profile shape statistics together with the corresponding power curves are used for estimating the system's AEP.

It is investigated how many wind profile shapes are needed to characterise the wind resource in the fast AEP calculation for the AEP to converge to a steady value. The convergence is studied using a wind resource representation that is obtained specifically for the evaluated location and one that represents a larger area. For the single location representation, the AEP fluctuations are moderate starting from eight wind profile shapes. The multi-location representation is used to evaluate the spatial variability of the AEP over the Netherlands and North Sea.

As a first step in validating the fast AEP calculation, results of the adapted QSM are compared to flight test data of an endurance test campaign of Kitepower's technology demonstrator. This data set allows assessing the modelling accuracy for roughly 1000 pumping cycles and a larger spectrum of wind conditions compared to earlier validation studies [1].

References:

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Airborne Wind Energy Resource Analysis: From Wind Potential to Power Output

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Airborne Wind Energy Systems (AWES) have different power generation characteristics than conventional wind turbines, which can not be accurately captured in the traditional power curve. One important aspect is that it can harvest wind energy in a much wider range of altitudes than conventional wind turbines. Theoretically also High Altitude Winds (HAW) can be harnessed and the systems can be placed at a larger variety of sites.

Project developers lack technical knowledge for assessing the potential of AWES. It is up to the AWE community to fill this gap. A first step towards this goal is taken by performing a new wind resource study for AWE using the ERA5 re-analysis data, a world-wide, historical wind data set. In the "Airborne Wind Energy Resource Analysis" [1] we study the wind resource in Europe from 2010 to 2017, using a fine spatial and temporal grid, and for maximal operating altitudes of AWES between 300m and 1500m. For most of Europe we find that the wind power density which is available for 95 % of the time increases by a factor of two when continuously adjusting the harvesting height compared to a fixed harvesting height at 100m. The data and source code used for this analysis is available from [2] Following-up on the wind resource study, the ERA5 data is also compared to LiDAR data to assess the uncertainty of the AWE resource analysis.

An important future step for the AWE community would be reaching a consensus on how to characterize the power output of an AWES. These characterizations could be used together with the ERA5 wind data to make projections of the energy production of AWES farms. This requires that the power output is specified for each AWES concept and for a large spectrum of wind conditions. An example for a simplified version of such an interface will be discussed. We then interface the power output with time-dependent current exchange energy prices, in order to allow project developers to compare the economic performance of different AWES designs at different sites and energy markets of interest.

Additionally, a new possibility on characterizing AWES power output is explored as part of this project. An ERA5 data driven methodology of characterizing the wind resources is developed, covering a wider range of altitudes relevant for AWES. The wind resource is represented by a set of wind profile shapes and their probability distributions. An AWES power output specification as a function of the wind profile shape and wind speed at 100m, together with the wind profile shapes and probability distributions, is used for performing AEP estimations.

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[2] P. Bechtle et al., https://github.com/rschmehl/awe-era5

Parametric AWES Sizing Study Using Mesoscale Wind Profiles

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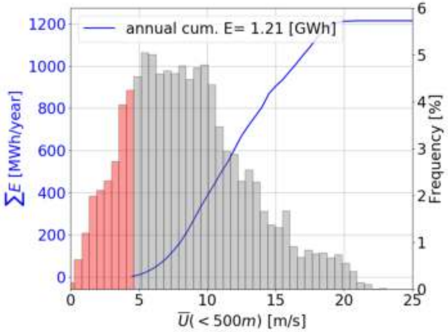
Airborne wind energy systems (AWES) aim to operate at altitudes above conventional wind turbines where wind speeds are generally higher and assumed to be more predictable. However, these devices will still operate within the atmospheric boundary layer, the part of the atmosphere which is directly influenced by the contact with earth's surface. Therefore, a wide range of atmospheric stability conditions develop as a result of synoptic and diurnal weather patterns. These lead to significant variations in wind speeds and wind speed profile shapes [1].

This study presents results from a parametric sizing study of ground-generation AWES. Several representative kite and tether sizes are defined to explore the AWES design space. We estimate average power, annual energy production and dynamic tether loads based on 10-minute modeled wind speed profiles for an onshore location in Northern Germany [2]. Wind speed profiles from the mesoscale Weather Research and Forecasting Model (WRF) [3] are implemented in the open-source Airborne Wind Energy trajectory optimization toolbox (AWEbox) [4]. To reduce computational costs, the one-year wind speed profile data set is divided up into 20 clusters using a *k*-means clustering algorithm and representative profiles are chosen from within each cluster. Results are compared to reference logarithmic and uniform wind inflows. The optimization problem is defined to maximize average power over one pumping cycle, subject to tether speed, length and tension constraints.



Estimated annual energy production of a 12 m^2 wing area ground-generation AWES (blue) over mean wind speeds up to 500 m. Wind inflow is based on 10-min onshore WRF model. The background shows the WRF-simulated annual probability distribution of average wind speeds up to 500 m.

References:

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[2] Sommerfeld,M. et al: LiDAR-based characterization of mid-altitude wind conditions for airborne wind energy system. Wind Energy (2019)

[3] Skamarock,C. et al.: A Description of the Advanced Research WRF Version 3.(2008)

[4] De Schutter,J. et al.: Python toolbox for modelling and optimal control of multiple-kite systems for Airborne Wind Energy. https://github.com/awebox/awebox

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Investigation of Airborne Wind Energy Farm Performance for Different Operation Modes Using Large Eddy Simulation

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In their efforts to compete with conventional wind turbines, leading airborne wind energy companies announced their intentions to develop utility-scale systems with multi-megawatt power yields [1] and therefore, manufacturers of both ground-based and on-board power generation systems engaged in the scale-up process. At these large scales, significant velocity deficits and increased turbulence levels are observed in the airborne system's wake. When operating in a farm, these wakes are expected to have a high impact on the operation of downstream systems, characterized by a decreased performance. We propose a simulation framework combining optimal control [2] and large eddy simulations to investigate the interaction between airborne wind energy systems and the atmospheric boundary layer. In this study, we consider large-scale systems operating both in pumping-mode, i.e. flying crosswind maneuvers in alternating reeling-out and reeling-in phases as well as in drag-mode, i.e. wings with on-board generators operating at a fixed tether length. The wing-tether system is modeled as a three degrees of freedom mass-point and we derive the equations of motions using a Lagrangian-based modeling procedure. The optimal flight trajectory is computed offline by solving an optimal control problem which maximizes the power generated by the system while subject to a set a constraints. A model predictive controller is used to track the optimal trajectory when the system is subject to changes in local wind conditions due to turbulence and upstream systems. The wind environment is modeled as pressure-driven boundary layer and its dynamics are computed by means of large-eddy simulations using the inhouse code SPWind developed at KU Leuven. The effects of the kite system are added onto the flow using an actuator sector method that deals with the difference of length- and timescales between flow and system dynamics. The objective of the work presented here is to investigate each generation mode in terms of wake characteristics and assess their effects on system performance for different layouts of airborne wind energy farms.

References:

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[2] awebox. Modelling and optimal control of multiple-kite systems for airborne wind energy (2019). https://github.com/awebox/awebox

Effect of Mass on Airborne Wind Energy Performance

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This study explores the impact of airborne device mass on system performance and yield in an airborne wind energy system. This is studied using a quasi-steady-state time-stepped model. The baseline system is a utility scale, yo-yo, system flying circular trajectories and operating at constant line tension during generation.

The effect of the airborne device mass on the system power output depends on the wind speed (Figure 1). At nominal rated wind speed there is a small impact (doubling the airborne mass reduces the power output by 12%). During lighter wind conditions the airborne device mass has a larger effect on the system power output (at 75% of rated wind speed doubling the airborne mass reduces the power by 26%).

Varying the airborne device mass significantly impacts the winch requirements. Changes in gravitational potential energy during the generation phase produce a sine-like wave in the power output (Figure 2), and hence also in line speed. A heavier airborne device gives a larger amplitude of variation. This is a tougher requirement for the winch and therefore will have cost implications.

The effect of the airborne mass upon the system's annual yield was also analysed. It was found that doubling the mass reduces the yield by 15%, and halving the mass increases the yield by 6%.

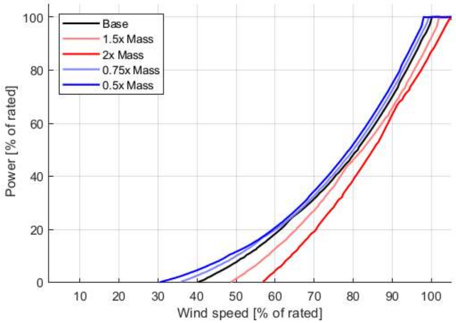

Figure 1: Power curves for a kite system at 5 different airborne masses normalised by the baseline system.

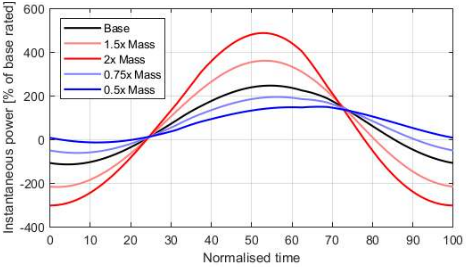

Figure 2: Variation in instantaneous power during a single circular flight trajectory for 5 different airborne masses at the nominal rated wind speed.

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An Analytical Performance Model for AP-4 Conceptual Design Phase

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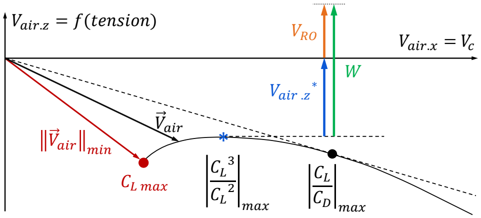
The conceptual design phase of a utility-scaled Airborne Wind Energy System (AWES) spans over the sizing of the tethered-aircraft, the power generator and the tether. The design is further complicated by the fact that these systems cannot be optimized separately given their interdependencies. Numerical approaches of high simulation fidelity have been developed at Ampyx Power, to anticipate on techno-economic performance levels. Yet in a conceptual design scope, these models may be already too detailed, or computationally too expensive to search the design space efficiently. Besides, numerical approaches may lead to obscure results, where the effects of various design choices are combined and their isolated contribution to the overall trend cannot be easily distinguished. If the system behaviour can be approximated by integral equations, then our understanding of the mechanisms at play and of their corresponding governing variables can be made fully explicit.

We present here a physics-based approach to performance modelling that emphasizes a key metric of gliding performance: the 'sink rate' of the tethered-aircraft against the incident wind. The resulting analytical model, which relies on the steady-state aircraft dynamics, approximates sufficiently well the overall behaviour of the system to account for the main trade-offs at play. This approach provides a different point of view than the existing literature, even though it leads to well-established results. It is easily understandable and applicable to various steady-state variations of the well-known straight-line case [1]. Besides, it provides additional levels of insight about the power curve, specially at the operational limits.

This model enables to investigate key trade-offs between high-level design variables, which will be illustrated. We will detail how this analytical approach helped to formulate an airfoil optimization function and more generally, how it can help to reduce the design space and orientate the grid search. Finally, we will present an overview of the various numerical tools used at Ampyx Power and how they integrate into an overall input-output toolchain. We will describe how this quantitative approach is associated to the analytical model described above to converge towards candidate designs for AP4.



Remarkable points along a glide polar: stall, minimum sink rate and maximum glide ratio along with remarkable speed vectors.

References:

[1] Loyd, M. L.: Crosswind Kite Power. Journal of Energy ***4****(3), 106-111 (1980)*

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Developing Airborne Wind Energy Safety and Technical Guidelines

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The aim of the "WG Safety and Technical Guidelines" of Airborne Wind Europe is to draft a guideline applying best practices and complying with official requirements for all safety related issues. The goal is to prevent any damages through AWE systems, to enhance confidence in the compliance with safety and other requirements and to provide guidance to any competent authority and other stakeholders that deal with AWE projects, e.g. regarding granting permits, loan financing, etc. AWE systems will have to comply with two main frameworks:

- IEC Standards which cover electro-technical aspects.
- EASA guidelines and standards which cover all airspace and aviation related aspects.

As AWE technology is a novel application, the two frameworks will be applied in overlap, especially when it comes to safety issues. It was agreed to elaborate a technical guideline structured according to IEC 61400 for wind energy systems and to link or reference crucial requirements and suitable components from the EASA framework. It was agreed that in the beginning, the guideline should be rather on high level, defining clear principles that are acceptable to all companies. However, as the aim is to give also third parties and competent authorities a good understanding whether a company is applying the guidelines (or future standards), it should also include specific information in annexes or additional documents.

The Technical AWE Guideline is meant to become an umbrella document defining all relevant AWE aspects to be presented towards administrations and other stakeholders and where all companies would find the parts relevant for them. The following approach has been taken:

- Working on the draft guideline to present at a starting point to non-AWE stakeholders
- Inviting partners to the process, e.g. universities, suppliers, certification companies, authorities, project developers and planners etc.
- Elaboration of the guidelines with stakeholders: Based on the draft, the guideline will be further developed in subgroups or committees where non-AWE companies will be involved.

The German FGW e.V. (Fördergesellschaft Windenergie) will support the elaboration process. After a prioritisation exercise, six Working Sub-Groups were set up which elaborate the first drafts of the most relevant chapters:

- Tether – durability
- Tether – safe operations
- Ground station
- Airborne structure
- Wind conditions and power performance
- Operation risk assessment

Meanwhile, the first drafts have been shared and commented on. Most advanced is the elaboration of the guidelines for the operational risk assessments which is based on the Specific Operations Risk Assessment (SORA) V2.0 Guidelines recently published by the Joint Authority on Rulemaking for Unmanned Systems (JARUS) on specific operations. It also considers the recent experience of the AWEurope member in applying this process to seek an Operational Approval (OA) for an AWE operation in the specific category.

AWEurope plans to present the approach taken by the Working Group as well as initial findings at AWEC 2019 to seek feedback and further input from stakeholders and experts.

Rotational launch mechanism of Enerkite (25 September 2018)

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EnerKíte - Latest Achievements Towards Next Generation Renewables

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The EnerKíte team has been successful in automation of kite systems for more than a decade. Our first autonomous kite flights with figure of eight patterns took place in May 2008. Since then the technology of the ground-station, the wing and tether and the landing and launching system has been systematically developed, implemented and improved – driven by cost, performance and safety targets derived and approved by customers.

By use of ultra-lightweight wings with high lift configurations, the specific designs by EnerKíte allow for extraordinary capacity factors.

Based on a techno-economical comparison of different launching and landing techniques[1], EnerKíte has chosen a rotating arm. In favour of good scalability, low weight and low complexity of the bridled wings all control forces are introduced solely through actuators from the ground.

On the way to reach higher tether length and altitudes out of the rotation, lots of lessons have been learned, models have been enhanced and validated. Together with the comprehensive software developments and testing and validation programs - including full scale and component, indoor and outdoor testing - we focus now on the further development of the wing structure itself. This is covered by a comprehensive R&D cooperation with leading research institutes and other industry players.

This presentation will give a brief overview on the status of EnerKíte and the currently running R&D programs and cooperation's such as a 2.3 EURm SME phase 2 grant and the EnerWing Project, which is funded by the German federal ministry of economy.

The authors will illustrate major lessons learned and achievements in the field of autonomous landing and launching and lightweight structures.

References:

[1] B. Rieck, M. Ranneberg, A. Candade, A. Bormann, and S. Skutnik, "Comparison of Launching & Landing Approaches," Airborne Wind Energy Conf. 2017, vol. 137, p. 2018, 2017.

EnerKíte

Rotational launch mechanism of Enerkite (9 October 2018)

TwingTec's pilot system next to a wind turbine of comparable power (28 August 2019)

TwingTec's mobile pilot system ready for launching (28 August 2019)

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TwingTec's Roadmap From Full Proof of Concept to the First Commercial Product

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TwingTec

TwingTec is an AWE leader with its ground based generation - rigid wing - VTOL technology. Our main design drivers have been economics, fully automated operation and safety. Key enablers for our product are the emerging civil drone industry and e-aviation. Last year we have reached full proof of concept with a small scale prototype, where launching from a platform on a ground station, power production and landing on the same platform at the specified level of automation was demonstrated.

Extensive testing of the prototype has allowed us to validate the performance of the prototype and our simulation tools. These simulation tools enabled us to determine the power curves of our products ranging from 100 kW to 3 MW and to estimate the annual energy production at different sites. The detailed analysis shows, that the LCOE strongly depends on the size of the system. As a result, products in the range of 100 kW to 500 kW are highly competitive with diesel generators which typically produce electricity for 20-30 Cents/kWh. Integrated in standard shipping containers, these products are easy to transport and deploy which is a major advantage in the off-grid market, where power consumers such as island, communities and mines are often in remote locations which makes the installation of conventional wind turbines prohibitively expensive.

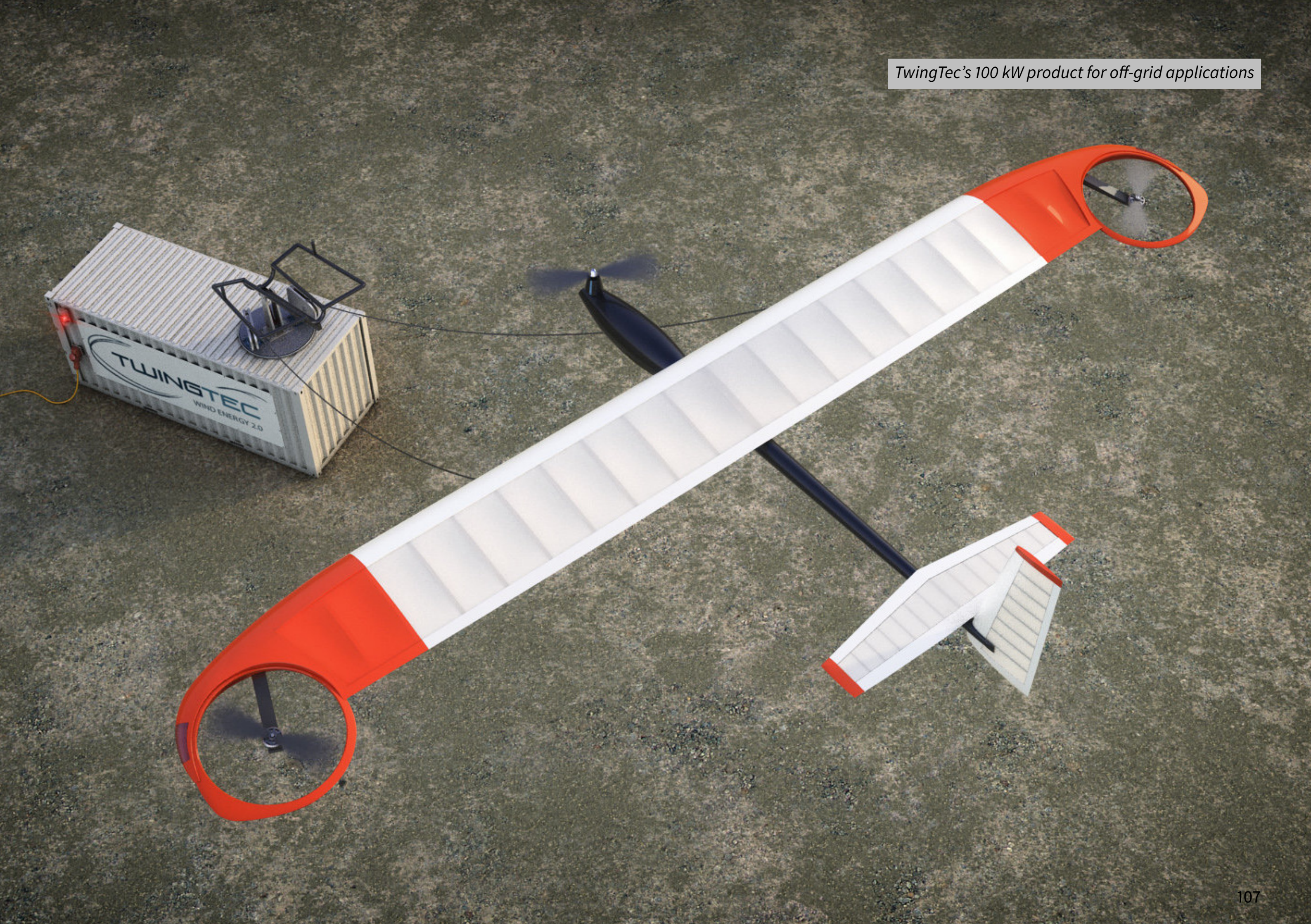
Larger products from 500 kW onwards are interesting for on-grid applications. Our LCOE analysis shows, that the multi-megawatt units have the potential to significantly lower the LCOE of conventional wind turbines, taking favour of the dramatically reduced need for materials and the higher energy production due to their operation at higher altitudes. Installed on floating platforms, airborne wind energy farms with megawatt units will unlock deep off-shore wind, a huge market opportunity where the production potential in Europe alone has been estimated to be 4 TW [1].

With the learnings from the proof-of-concept prototype we started to build a scaled pilot system together with industrial partners this year. The pilot will be tested and operated in Switzerland and abroad. The key focus is on long-term testing and customer demonstrations. In parallel, we will design and build our first commercial 100 kW product for the off-grid market. We are convinced that off-grid is a very interesting starting market for airborne wind energy. Off-grid enables a fast market entry with a relatively small product without the need for subsidies.

References:

[1] Wind Europe, Floating Off-shore Wind Vision Statement (2017). https://windeurope.org/about-wind/reports/floating-vision-statement/

TwingTec's pilot system in hovering mode (21 July 2019)



TwingTec's 100 kW product for off-grid applications

Brainwhere’s airborne wind turbine system

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Brainwhere's AWE System for Harvesting High Altitude Wind Energy

Michael Perlberger
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The Brainwhere airborne wind power solution aims at harvesting high altitude wind energy. Our IP protected airborne wind turbine system operates in a quasi-singular point in space and can be configured as a system-of-systems. We envision to ladder up to jet stream altitude.

The Brainwhere static airborne platform has a hybrid use. While it converts mechanical energy into clean electricity it can also hosts sensing, observation or communication systems.

We have conducted a feasibility study and wind tunnel tests and we are now in the design stage of a flying prototype. From a commercial perspective we have signed a Letter of Intent with a launching customer and we have interest from telecommunication providers.

The key technical challenge we face is cable weight. From a commercial perspective declining energy prices led us to expand our business model towards offering sensing and telecommunication services from the platform.

We are looking for highly skilled aerospace and electrical engineers who share our vision for shaping a better world together.

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What Will it Take for AWE to be Successful in Remote & Mini-grid Applications?

Daniel Zywietz
Enerwhere

AWES show promise to greatly increase the potential of wind harvesting on a global scale. However, due to the significantly higher costs than other renewable energy sources like solar PV & conventional wind plants, many AWE system integrators target off-grid / mini-grid markets for their initial commercial products in the 100-500 kW range, as cost-constraints are believed to be less of a hurdle in these markets.

While this appears to be a viable strategy to increase the number of deployed units and drive down cost via learning effects, a number of critical real-world parameters need to be considered for the design of these initial products.

Modern mini-grids generally use a solar-battery system with diesel backup, achieving a 30-70% solar share. Adding AWES will increase the share of renewables at a cost below that of additional solar PV & storage. AWES will not be able to compete with solar PV during daylight hours in most locations, as PV costs are already very low (investment costs of <\$150 / kWh / day). Instead, AWES are needed at night and during bad weather, when solar PV would require storage, driving up investment costs to around \$500 / kWh / day (in 2019 but falling by 10% annually).

There are some requirements for early commercial AWES products:

(a) Ability to operate during night-time and bad weather need to be demonstrated early on.

(b) Initial mini-grid deployments will often be in remote, harsh (e.g. arctic, tropical, marine) environments and components need to be designed to withstand these conditions.

(c) Given that most potential clients will already have deployed solar and storage, in-house development of balance of systems and storage integration by AWES manufacturers is probably not required, as this task can be outsourced to existing technology providers.

(d) Fully autonomous operation is not a key requirement, as most potential clients have local operators for the diesel generators.

(e) Cost of business development for these applications is high, as customers are in remote locations. Suitable business development strategies, including commercial frameworks for distributors and local O&M providers, will need to be developed early on.

(f) While ground-space can be a concern on islands, airspace is often not a problem, but it makes a compact design (shippable in standard ISO containers) a must.

(g) Demonstrating the complementarity of AWE production with solar PV needs to be a priority for the industry, as this will provide a justification for further investment by both public & private funding sources.

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Report on Research and Development of Airborne Wind Power Generation at Niihama Kosen

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We have studied two types of airborne wind power generation.

Firstly, the Fly-Gen system for fixed-point meteorological observations in the Antarctic. The Japan Antarctic Research Expedition has observed the Antarctic weather using kites for several years. However, power supply and kite payloads have caused problems during these observations. Jointly with the National Institute of Antarctic Research of Japan we began research to address this. We developed a payload adjustment technology for kite trains. Legal restrictions on research using the Aviation Act including aircrafts, kites and drones in Japan restricts research on airborne wind power generation compared with other countries. Nevertheless, highly durable products can be supplied for generators and various other components.

Secondly we produced the design for a pumping kite ground station. The power generation used in the experiment was a high rotation type generator. Therefore, a centrifugal force variable flywheel was installed. We developed a mathematical representation that predicts the generated power. Using the rotational motion of the generator and flywheel, the tension in the kite tether, the speed of the kite and the generator settings we were able to predict the generated power. The simulation results agree with the experimental values.

Top: Fly-Gen Experiment, Bottom: Pumping-motion Ground-Gen Experiment

References:

[1] Hitoki, Endo.: Experimental Study on Design and Operation of Ground System for Airborne Wind Power Generation. Wind Energy 42(4), (2019, Japanese Language only)

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A Solution to the Pose Estimation Problem for Airborne Wind Energy Systems using Multiple Bluetooth 5.1 Devices

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The common approach to estimate the position and the attitude of a rigid body outdoors is to use an inertial measurement unit (IMU) providing measurements of the angular velocity and linear acceleration vector and combine it with a magnetometer to provide attitude estimates. The position is commonly measured using GPS signals and combining the IMU and GPS through sensor fusion leads to very good estimates of the pose of a rigid body.

Accelerometers estimate the roll and pitch angles by comparing the measurements with the expected gravity vector. However, accelerations generated by the tether will perturb these estimates and must be accounted for before using the measurements as part of the sensor fusion algorithm. Further, magnetometers are commonly used for yaw estimation by comparing the magnetic field with the expected direction of the magnetic field lines but suffers from inaccuracy (typically $1 - 5^\circ$) and is prone to perturbations from local magnetic fields generated from the electronics and power cables. It is also possible to find the yaw angle using positional history from GPS measurements or combine two GPS sensors and compare the change in position for each sensor over time. However, most GPS signals tend to drop out when exceeding 4G's (due to inherent design) and pose a major challenge for AWE systems that desire to operate at $10 - 15$G's or more. Kitemill has extensive experience with drifting in both position and attitude estimates and proposes a novel solution to pose estimation that mitigates most of these challenges.

Bluetooth 5.1 was announced 21 January 2019 and promises to provide centimeter positional accuracy [1] with a range of up to 1000 meters [2]. Using the angle of arrival and angle of departure enables the localization of Bluetooth devices and will result in a new array of product providing tracking of keys, cell phones, animals and other objects with high accuracy at a low cost (A Bluetooth 5.1 chip costs about €4). Another potential lies in pose estimation for AWE systems, where this solution can reduce the levelized cost of energy through cheaper navigation systems. The basic idea is to place multiple Bluetooth 5.1 devices inside the body of the kite oriented as its own reference frame representing the body frame of the kite. Then, position measurements can be used directly to recreate the reference frame that describes the attitude of the kite.

This work models the Bluetooth 5.1 devices as particles that move with the kite, showing how to combine four parallel Unscented Kalman Filters and some simple equations to find the pose of the kite. We share this work because this solution has the potential to become a standard for the AWE industry, however, it requires further R&D to create a complete system that is able to deliver the promised performance – something that can be performed through a joint project between the companies.

References:

[1] Bluetooth. Enhancing Bluetooth Location Services with Direction Finding, 2019.

[2] https://blog.nordicsemi.com/getconnected/things-youshould-know-about-bluetooth-range

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Design Space Exploration of a High Altitude Aerial Platform, “Mothership”

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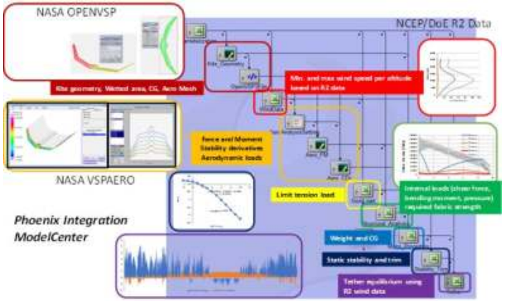
A global Toyota research team is investigating the feasibility of a futuristic high altitude aerial platform concept (called Mothership), envisioned to be reconfigurable to a variety of applications such as wind energy harvesting, atmospheric data acquisition, high speed communication relay, and payload transportation [1]. As a part of this endeavour, a preliminary system level analysis was conducted to gain initial insight into key system attributes as well as sensitivities with respect to design and technology parameters.

An integrated design and analysis environment was created by harnessing fast analysis tools covering key disciplines such as wind data, aerodynamics, inflatable structural analysis, mass properties, kite stability, and tether catenary. To expedite the design space exploration, a set of surrogate models was created from the integrated multi-disciplinary tool. Utilizing the surrogate models, a Monte Carlo simulation was performed to generate 30,000 different designs. The feasibility of those designs was evaluated against a set of design requirements including the internal pressure of the inflatable structure, kite stability, and tether tension. A baseline design, selected from a Pareto front, was further evaluated for impacts of design altitude and advanced technologies. This preliminary analysis indicates that access to high altitude (10km) requires a significantly large and lightweight kite and tether construction. In addition, advanced technologies are necessary for reliable operation at high altitudes. To cope with a wide seasonal variation of wind speed, advanced actuation system appears to be highly desired for stability augmentation, load alleviation and flutter suppression.



Integrated design and analysis environment for high altitude aerial platform concept design. OpenVSP was used to define wing geometry and to estimate wetted area. VSPAero was used to predict aerodynamic properties. Wing structure was approximated to a cantilever beam and analysed based on Euler beam theory. Once a kite design is defined, it was determined whether the kite can stay at 10km altitude for a variety of wind speed profiles derived from NCEP/DoE R2 data accounting for drag and weight of a tether.

References:

[1] Itakura E.: Save from Future Japan Social Crises! "Mothership" Project, AWEC, Glasgow, UK, 15-16 October 2019 (AWEC No. 65)

Drone perspective of Kitepower's 25 m^2 kite flying automatic figure-of-eight maneuvers, while the 40 and 60 m^2 kites are setup on the ground at the former naval airbase Valkenburg (8 May 2018)

Hysteresis Control of a Kite Flying Figure-of-Eight Maneuvers

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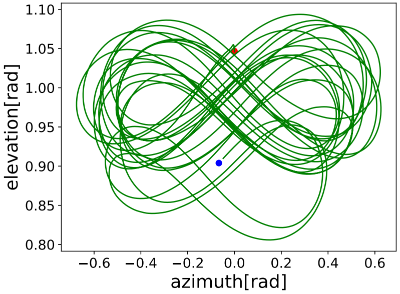
We are interested in wind power generation using a kite and the behavior of the figure-eight flight based on a simple controller. The kite flies dynamically, executing certain maneuvers instead of being stationary in air. Among the proposed maneuvers, a figure-eight flight path is considered to be the most efficient. In conventional methods to perform the figure-eight flight path, the kite needs to be controlled so that it follows a predefined trajectory. Moreover, the controller requires precise real time information on the kite position, on the kite orientation, and on the wind surrounding the flying object. However, the foil kite is susceptible to wind and requires precise control order to follow the target trajectory in response to wind conditions, which are difficult to predict.

We propose a simple switching/hysteresis controller based only on the attitude angle of the kite to realize a figure-eight maneuver flight. With this approach, the controller does not require any additional information, such as position or height of the kite in the air. We verified the feasibility of this method when realizing a figure-eight maneuver under wind disturbance with FreeKiteSim [1].

The foil kite is assumed to rotate around the z-axis at the top of the kite. The angle is called the attitude angle of the kite. We propose a hysteresis controller that controls the kite to rotate counterclockwise when the attitude angle exceeds a certain threshold θ or rotate clockwise when the attitude angle is less than $-\theta$.

We investigated the figure- eight flight trajectory and the stability of the kite under various wind conditions: no wind disturbance, sine wave change of the wind speed, and changes following the Dryden wind turbulence model. The figure below shows an example of the flight trajectory of the kite under the hysteresis control when subjected to the Dryden wind turbulence model.

All experimental results show that the kite can perform stable figure-eight maneuvers under various wind conditions when using the proposed hysteresis controller.



Flight trajectory under the wind condition based on the Dryden wind turbulence model (wind speed 6m/s base)

This work was supported by JSPS KAKENHI Grant Number 16K00647.

References:

[1] Fechner, U., van der Vlugt, R., Schreuder, E., Schmehl, R.: Dynamic model of a pumping kite power system. Renewable Energy ***83****, pp. 705–716 (2015). https://doi.org/10.1016/j.renene.2015.04.028*

NCSU’s marine hydrokite in the water channel (22 May 2019)

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Development of Iterative Learning Strategies for Optimal Crosswind Flight of Airborne Wind Energy Systems

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North Carolina State University

As is well known, effective crosswind flight is predicated on executing efficient circular or figure-8 paths and maintaining optimal lift and drag coefficients over the duration of each cycle. The optimal parameters for both the path and the aircraft trim are known to be dependent on environmental changes and are subject to significant uncertainties, due to the nascent nature of dynamic models for AWE systems. The present work leverages the repetitive nature of crosswind flight to utilize iterative learning control (ILC) strategies in improving average power production from one lap to the next. The proposed approaches present three challenges relative to existing iterative learning control techniques, however:

1. Environmental conditions (particularly wind conditions) can change from one figure-8 cycle to the next, rendering the previous cycle's path suboptimal for the new conditions.
2. While traditional ILC approaches assume the path to be followed to be fixed and merely seek to improve performance between pre-defined waypoints along the path, the proposed techniques in this work address the more fruitful problem of iterating on the path itself.
3. While most ILC tools work in environments where there is a pause during operation, the tools developed in this work are designed for continuous operation.

This presentation will review the ILC approaches pioneered by the team at NC State, which have been validated in simulation in [1], [2], and [3] using a unique "unifoil" model that accurately captures the translational dynamics of the system but incorporates unicycle constraints on the motion of the wing to simplify the underlying path tracking problem. The presentation will review these results, which have been obtained under both constant wind and realistic variable wind scenarios, and will present an outline for future simulation and experimental validation of the proposed approaches.

References:

[1] M. Cobb, K. Barton, H. Fathy and C. Vermillion, "Iterative Learning Based Waypoint Optimization for Repetitive Path Planning, with Application to Airborne Wind Energy Systems," in IEEE Conference on Decision and Control, Melbourne, Australia, 2017.

[2] M. Cobb, K. Barton, H. Fathy and C. Vermillion, "An Iterative Learning Approach for Online Flight Path Optimization for Tethered Energy Systems Undergoing Cyclic Spooling Motion," in American Control Conference, Philadelphia, PA, 2019.

[3] M. Cobb, K. Barton, H. Fathy and C. Vermillion, "2019," Iterative Learning-Based Path Optimization for Repetitive Path Planning, with Application to 3D Crosswind Flight of Airborne Wind Energy Systems (accepted), 2019.

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The Value of Airborne Wind Energy in a Zero-Emission Electricity System

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Airborne wind energy system (AWESs) harvest wind energy at high altitudes. In the future, AWE systems might be available at large scale, and part of the electricity generation systems. In order to assess the viability and economical value of AWESs in the power grid, the hourly power production and the related costs are of importance. The potential AWE power production can be estimated with the help of data on the local wind resources, and accurate mathematical models of the AWES. The costs, on the other hand, are hard to determine as no commercial installations exist yet. Alternatively, the marginal system value (MSV) of AWESs can be estimated [1]. The MSV defines the economic value of adding a certain technology to the electricity system.

In order to evaluate the MSV of AWE, first, the annual power generation of AWESs is calculated at an hourly resolution for one year. In this study the region of Ireland is chosen. The wind resource is obtained from ERA-5 wind data, available hourly in a $0.25 \times 0.25°$ spatial resolution. The vertical wind shear up to 800 m is obtained from wind speeds at 18 different pressure levels. For a realistic resource potential within a region, inaccessible areas are subtracted. The power production is obtained by an optimal control problem (OCP), that takes the hourly wind speeds as input and computes the average power production of one rigid wing during an optimized flight trajectory. As the OCP computation is time costly, a regression model is trained to map the vertical wind speed components to the computed power output to a high precision. The study is focussed on drag-mode AWESs. Taking into account the percentage of available area, the wind distribution over a wind farm, and efficiency losses due to wake and downtime, a power production potential estimate can be obtained for each grid point.

Further on, the hourly power generation profiles will be implemented into a regional cost-minimizing investment model for power production technologies, presented in [2]. The investment model is set up as a “green field study", i.e. assuming zero installed capacity and establishing a regional electricity generation system for the year 2050 that meets the hourly demand without emitting CO_2 at minimum cost. The inputs to the model are the regional electricity demand as well as the available renewable resources, storage devices, demand side management and different types of thermal power plants. The output gives the installed capacity per technology, the hourly power dispatch and the minimized annual cost of the electricity system. As a result, the economic value of the AWESs can be estimated based on the change in total annual electricity system costs.

References:

[1] V. Johansson et. al., “Value of wind power — implications from specific power”, Energy, 2017.

[2] L. Göransson and F. Johnsson, “A comparison of variation management strategies for wind power integration in different electricity system contexts”, Wind Energy, 2017.

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Configuration Optimization of a Generic Crosswind Airborne Wind Energy System

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The aim of this work is to address fundamental questions related to crosswind airborne wind energy systems with hard wings: are the ground generation or the fly generation airborne wind energy system most cost efficient? In which cases are one better than the other? Which subsystems are crucial in terms of overall performance and costs?

To investigate these topics, the two crosswind generation types are studied with a unique model. A generalization of the Loyd power equations[1] into one expression is thus derived to leave a gradient-based optimization algorithm to range continuously within the two types. This expression is derived with the assumption of steady-state flight, the power losses due to mass are included with an analytical model. The optimizer can then design the geometry and the aerodynamics of the system while choosing some performance parameters, describing the generation types. To refine the model, the main subsystems and physics are considered. The model computes the power curve taking into account reel-in phase, drag penalty of the tether, wind shear, structural design of the tether and of the kite, take-off strategies and presence of tower. A cost and an operational life are finally assigned to these subsystems to make the optimizer to maximize the economic profit.

Unfortunately, or interestingly, many aleatory uncertainties and many epistemic uncertainties, related to different design strategies, are present in such a problem. Thus, a global sensitivity analysis involving physics and cost parameters is a suitable tool to analyze how these uncertainties influence the design. After the uncertainty quantification, the sensitivity analysis is carried out to determine the conditions for which one configuration is better than the other in terms of annual energy production and levelized cost of energy.

The main outcome of the present work is to give a quantitative overview of which subsystems are driving the design and under which conditions a fly generation could be preferable to a ground generation and *vice versa*.

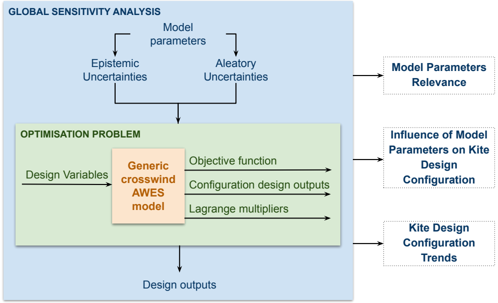

Diagram of the methods used to evaluate the generic crosswind AWES model.

References:

[1] Loyd, M. L.: Crosswind Kite Power. Journal of Energy ***4****(3), 106-111 (1980)*

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Airborne Wind Energy System Optimizer (AWESOpt) for Fly-gen Analysis and Optimization

Mark Aull, Andy Stough
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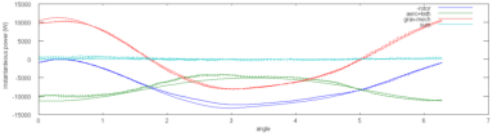
A performance analysis tool fast enough to be feasible for system design optimization is important for fly-gen AWE technology to mature. Design trade-offs are difficult to analyze with traditional tools; using simulations to iterate through parameters for design optimization is undesirable. The analysis tool developed is better suited for this task. It analyzes AWE performance as an 'inverse problem' to controls-focused models: the path, velocity, and lift of the aircraft are input as Fourier series coefficients, guaranteeing a closed, steady state cycle (rather than iterating to converge to a steady state solution). The gravitational & inertial forces for the trajectory and aerodynamic forces for the aircraft & tether are calculated, the roll angle to balance lateral force is determined, then tether tension and rotor force are calculated to balance the lateral forces, allowing power to be calculated. No controller design or tuning is required for each set of system parameters, and there are no deviations from the proscribed trajectory or instabilities due to a controller.

Constraints can be applied to tension, rotor force, roll angle, roll rate, and wingtip angle of attack, etc. to ensure that the trajectory is realizable. Analyzing one system on one trajectory requires no iteration, though ensuring constraints are met may. Comparing different system designs is relatively computationally inexpensive, therefore iterating over system designs to minimize a cost function is feasible. Other analyses have optimized flight paths, however fly-gen system performance requires optimization of turbine drag or flight speed and requires accounting for mass (another analysis concluded that mass is an important parameter in ground-gen performance[1] and fly-gen aircraft generally have higher mass than comparable ground-gen aircraft).



Power transfer calculated and simulated

A validation against a high fidelity simulation matches well, despite simplifications such as a straight rigid tether, constant lift and drag coefficients, and a simplified rotor model. A design optimization focused on tether parameters is presented. The tether plays a central role in system performance. In a simplified model, increasing allowable tether tension, power transmission capability, and length increase rated power. However, the associated increase in tether weight and drag reduce output throughout the power curve. The AWESOpt tool determined optimal tether length and conductor and strength member sizes in order to maximize system-level capacity factor.

References:

[1] R. van der Vlugt, A. Bley, M. Noom, R. Schmehl: Quasi-Steady Model of a Pumping Kite Power System. Renewable Energy, Vol. 131, pp. 83-99, 2019. doi:10.1016/j.renene.2018.07.023

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Avian Collision Risk Modelling: A Comparison of Methods for Airborne Wind Energy Devices

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Kite technology provides an innovative contribution to the renewable energy industry, allowing previously inaccessible wind resource to be harnessed for energy generation. Assessing the environmental impact of kite devices will inevitably constitute a key concern when planning deployment sites. One key consideration which has shaped the wind energy industry has been the potential for bird mortality through collisions. In Europe, avian collision risk modelling is often a mandatory requirement of the planning phase for wind farms and this will likely also apply to airborne wind energy. However, modelling the collision risk of a kite device presents new challenges since their movement is somewhat more complex than that of wind turbines.

We will present two models to predict the avian collision risk of a rigid-wing kite device. The first uses bird characteristics to assign species-specific collision vulnerability indices. These are combined with information on recorded mortality rates from power lines (a proxy for the tether) and small aircraft (a proxy for the kite itself) to predict fatalities per species [1]. The model is based on observed fatality rates and is simple to apply. However, it relies on the similarity of the collision risk posed by the device to the surrogates used. The second model uses bird flight activity data from the proposed deployment area, and flight path data from the kite device. This model is more complex to implement and cannot readily be validated but provides a general framework which can be adapted for different device types and scenarios.

We will discuss lessons learned from the wind farm industry, current knowledge gaps in collision risk assessment for kite technology, and potential monitoring strategies and validation methodology.

References:

[1] Bruinzeel L., Klop E., Brenninkmeijer A., Bosch J.: Ecological Impact of Airborne Wind Energy Technology: Current State of Knowledge and Future Research Agenda. In: Schmehl R. (eds) Airborne Wind Energy. Green Energy and Technology. Springer, Singapore, pp. 679–701 (2018). https://doi.org/10.1007/978-981-10-1947-0_28

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Rare Event Prediction for Enhanced Control System Reliability of AWE Systems

Sebastian Rapp, Roland Schmehl
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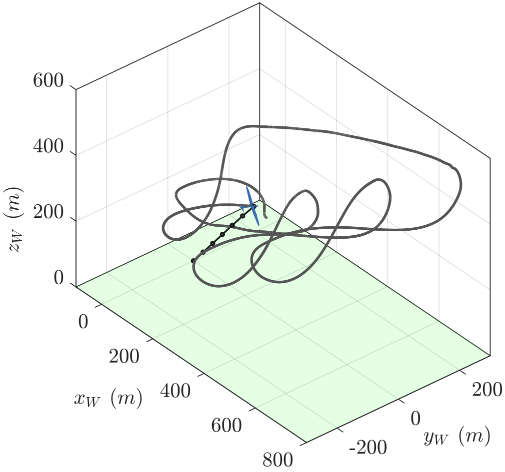
Reliable autonomous operation of Airborne Wind Energy (AWE) systems requires control algorithms that are able to attenuate the effect of stochastic disturbances on the control performance in continuously changing wind conditions. Assessing the stability and robustness of the control system is in general carried out using simplified system models where the real stochastic nature of the control problem is neglected. Therefore, a direct Monte Carlo approach is used in practice to increase the confidence in the control system's reliability. However, this approach performs poorly if it is used to estimate the effect and the probability of *rare events* such as strong gusts. Statistically, these events are located at the tails of the underlying joint probability density function. Consequently, only a few samples leading to rare events can be identified in a reasonable amount of time which leads to a biased probability estimate. In addition, it is difficult to recognize and leverage patterns if only a small set of samples is available that lead to a violation of a critical control requirement.

In this talk, we present an approach to predict rare events in the context of AWE using a combination of *Subset Simulations* (SS) [1] and time series classification. SS will be used to systematically create samples that lead to the violation of a specified closed loop performance criteria. Furthermore, based on the identified samples a time series classifier is trained that is able to detect critical situations using on-board sensor measurements before the AWE system enters an unrecoverable state. The approach will be evaluated by means of simulations of a generic AWE system operated in pumping cycle mode in randomly generated wind fields.



Pumping cycle flight path.

References:

[1] Au SK, Beck JL: Estimation of small failure probabilities in high dimensions by Subset Simulation. Probabilistic Engineering Mechanics (2001).

Safe Testing of Airborne Wind Energy Systems

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ver the past years, TwingTec has accumulated an excellent safety record in the testing of Airborne Wind Energy systems through the adoption of suitable operational procedures. A methodology to assess the effectiveness of such procedures and to assign the additional operational safety requirements in order to ensure the operation stays under control have been formalized through the Specific Operational Risk Assessment (SORA) process. This process was developed for the civil drone industry by the Joint Authority on Rulemaking for Unmanned Systems (JARUS) and is being adopted by Civil Aviation Authorities (CAAs) throughout Europe.

This process starts with the development of a Concept of Operations (CONOPs) which describes the not only the system to be deployed but also the organization itself and the various procedures and risk mitigation measures to be applied in order to sufficiently mitigation the various ground and air risk inherent to the operation. Working together with the Swiss Federal Office of Civil Aviation (FOCA), TwingTec has secured an Operational Approval (OA) for pilot system (see picture) test operations at multiple sites in Switzerland. An overview of the SORA process which was followed to apply for this OA will be presented along with some general guidelines for the safe testing of AWE systems.

TwingTec pilot system.

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MAKANI

Airborne Wind Energy Systems as an Obstruction: Makani's Journey with the US Federal Aviation Administration

Neal Rickner
Makani

Sustained engagement with the US Federal Aviation Administration (FAA) resulted in the announcement that Airborne Wind Energy (AWE) systems in the United States will be regulated as obstructions under 14 CFR Part 77. This means AWE systems will be regulated in a similar way to large buildings, towers and Horizontal Axis Wind Turbines (HAWTs).

Makani's 10+ years of engagement with the FAA began with early conversations about how AWE systems present an obstruction that would be perceived by pilots as such—always in the same geographic location. This led to a collaboration with the FAA to develop a lighting and marking scheme for Makani's 20kW demonstrator; which was flown with the FAA observing at Makani's Sherman Island test site in 2013.

The Makani-FAA collaboration continued as Makani developed the M600, a 600kW 26m wingspan kite. In 2016 the FAA issued a temporary determination of no hazard (DNH) for Makani's Hawaii test site, allowing Makani to operate for a limited time. This DNH also provided the basis for the Norwegian Civil Aviation Administration to issue a permit for Makani to operate at Metcentre in Norway.

In late 2018/early 2019 the FAA observed the M600 in Hawaii and reached final conclusions. As a result, Makani's DNH is on track to become a permanent—marked as an obstruction in a similar way to other wind turbines on aviation charts.

Makani M600 energy kite in flight in Hawaii. April 2019.

References:

[1] "Notification for Airborne Wind Energy Systems". Docket ID: FAA-2011-1279. https://www.regulations.gov/docket?D=FAA-2011-1279

[2] "Title 14, Code of Federal Regulations (14 CFR) Part 77" https://www.ecfr.gov/cgi-bin/text-idx?SID=c957224f6e2b4fb1f2fc236f5da09558&node=pt14.2.77&rgn=div5t

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Advances in Aerodynamic Modelling of Crosswind Kite Power Systems

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We present numerical results from an ongoing research on the aerodynamics of crosswind kite power systems (CKPS). These results have been obtained from a computational fluid dynamics (CFD) simulation ($\sim$ 51 days of CPU time) for a large-scale kite ($\sim$ 5 MW) flying on a prescribed circular trajectory in the simplified straight downwind configuration, where the tether elevation angle is assumed to be zero. The CFD simulation was performed using a URANS flow solver combined with the $k - \omega$ SST turbulence model. Also, the kite exact geometry was modelled. The results uncover interesting aspects of the flow behaviour in the vicinity as well as downstream of the kite. Most studies on the aerodynamic modelling of CKPS neglect the effects of flow retardation or 'induction factor' as well as the wake flow developed downstream of a crosswind kite. However, results from our previous [1,2] and current studies confirm that such effects exist and may significantly degrade the aerodynamic performance of CKPS, and thus should be considered when designing and optimizing a kite farm layout, as well as when predicting the economical returns of such system.

Our numerical results for the above-mentioned kite system show that the average induction factor over the annular area swept by the kite is a = 0.12, which also agrees well with the analytical solution obtained from the theory developed in [2]. If this induction factor is ignored, for example, it will result in nearly 20% power output overestimation and consequently considerable underestimation of levelised cost of energy. In addition, it is found that the span of the near-wake region, within which static pressure is recovered to the freestream pressure, is of the order of 3 to 4R; R being the gyration radius. Beyond the near-wake region, the wake expands almost linearly with the streamwise distance from the rotor plane, x (positive in the downwind direction) towards the centre of the annulus, while it expands with a lower rate towards the outer flow region. Inside the wake region, it is observed that the flow velocity undergoes a deficit which in shape looks like a Gaussian profile. At $x = R$, the peak flow velocity deficit is around 25% of the freestream velocity. The flow deficit then gradually decreases with x; for example, at $x = 10R$, the peak flow velocity deficit is nearly 10%.

The present results are intended to provide some insights about why the effects of the flow retardation and wake flow of individual kites, which have been ignored so far, should be taken into account for kite farms layout design and optimization. This new requirement should be met in addition to the geometrical interference which is commonly considered as the sole requirement. Further research is certainly warranted on the effects of the tether aerodynamic interference, non-zero tether elevation angles as well as energy harvesting modes on the aerodynamic performance of CKPS.

References:

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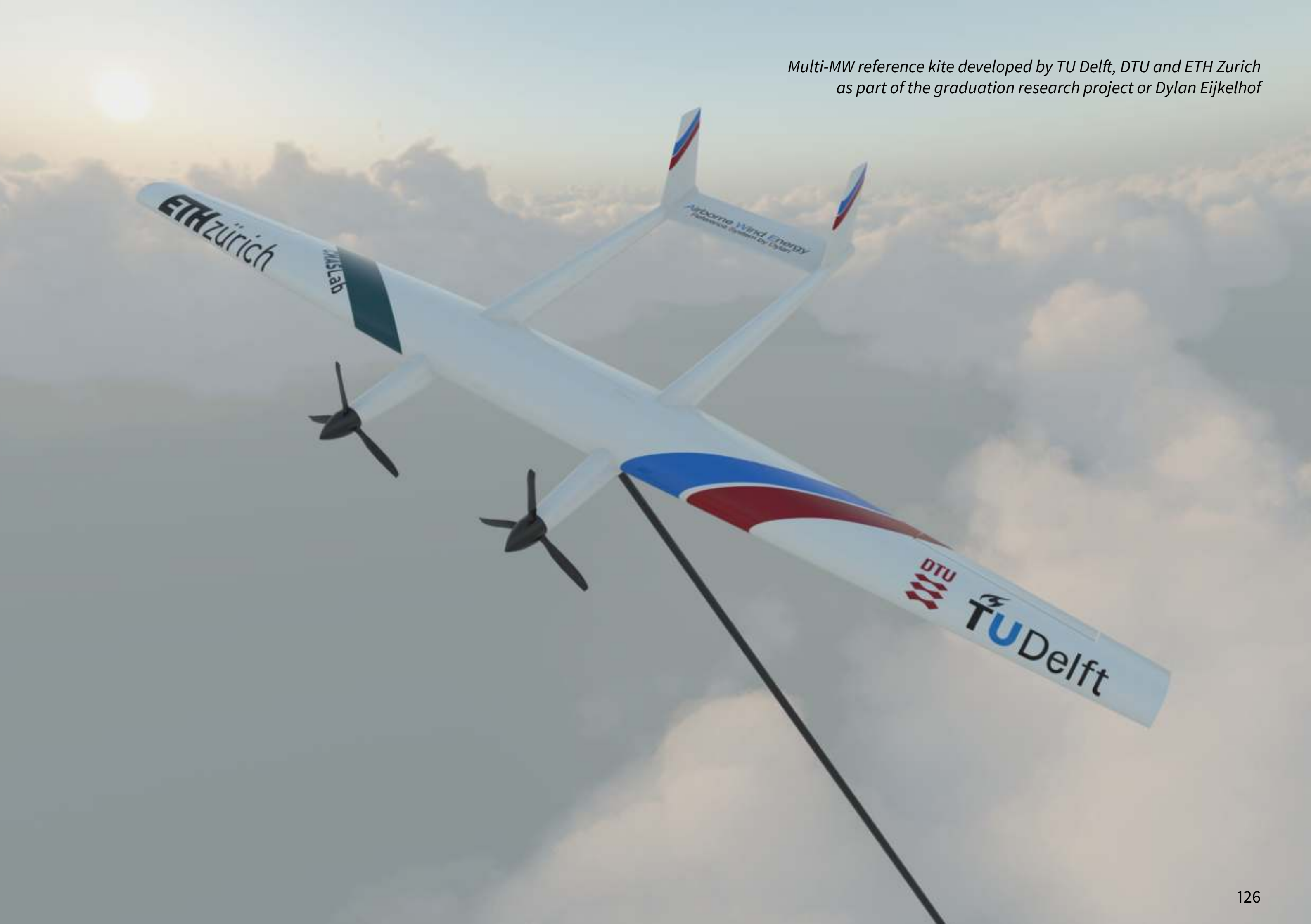
*[2] Kheiri, M., Bourgault, F., Nasrabad, V.S., Victor, S.: On the aerodynamic performance of crosswind kite power systems. Journal of Wind Engineering and Industrial Aerodynamics **181**, 1-13 (2018).*



Multi-MW reference kite developed by TU Delft, DTU and ETH Zurich as part of the graduation research project or Dylan Eijkelhof

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Aeroservoelastic Analysis and Optimization Framework for Morphing AWE Wings

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Morphing wing AWE aircraft based on compliant internal structures – compared to aircraft equipped with discrete wing control surfaces – show great potential in increasing the power production capabilities of AWE systems [1]. Potential benefits of morphing wings range from greater adaptability to different flight conditions to reducing the drag – and therefore increasing the power harvesting factor – due to the smooth wing surface. Furthermore, a reduction in parts count and complexity can be achieved, especially when applying novel additive manufacturing techniques. The greatest challenge in applying morphing to AWE are the contradicting requirements of high stiffness and strength to withstand the aerodynamic loads, while simultaneously maintaining compliance to allow for the desired shape adaptation. Therefore, it is of great importance in the design of morphing wings to consider the full system dynamics from an early stage.

In this work, a design methodology is presented that allows to concurrently analyze and optimize the control, structural, and aerodynamic design parameters of an AWE morphing aircraft. The numerical model presented in this work couples a dynamic system model, consisting of a ground station, tether, and aircraft dynamics model, with a two-way fluid structure interaction (FSI) simulation of the wing [2]. The FSI model consists of a detailed 3-D finite element model to assess the structural behavior, coupled with a 3-D panel method to calculate the aerodynamic characteristics of the wing.

To increase the computational efficiency of the simulation, reduced order modelling (ROM) techniques are applied to the structural and aerodynamic model of the wing. The structural ROM relies on a mode superposition method, whereas the aerodynamic model relies on a Taylor-expansion of the aerodynamic influence coefficient matrix in the direction of the structural modes. The Taylor-expansion can be efficiently computed using the Sherman-Morrison. This allows the ROM to deliver speed-up factors of about 180, when compared to the full simulation, at virtually no decrease in accuracy. The ROM is coupled to the dynamic system model and a flight controller consisting of an aircraft and ground station controller is included in the dynamic simulation, enabling the tethered aircraft to follow predefined trajectories.

To identify the optimal system parameters, the introduced dynamic model is embedded in a genetic optimization framework [3]. With the proposed framework, optimizations can be performed, maximizing the power production capabilities of morphing AWE aircraft. Furthermore, the framework is not limited to morphing wings, but can also be used for the design and optimization of conventionally actuated AWE aircraft of arbitrary size, with arbitrary flight trajectories and control strategies.

References:

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[2] Fasel, U., Tiso, P., Keidel, D., Molinari, G., and Ermanni, P., "Reduced Order Dynamic Model of a Morphing Airborne Wind Energy Aircraft," AIAA Journal, 2019.

[3] Fasel, U., Keidel, D., Molinari, G., and Ermanni, P., "Aeroservoelastic Optimization of Morphing Airborne Wind Energy Wings," AIAA SciTech Forum, 2019.

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Development of a Toolchain for Aero-structural Design of Composite AWE Kites

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The earlier in the design process the trade-offs between a system's cost and its performance can be determined, the easier it is to narrow in on an optimal final design. In order to explore the initial design space for composite carbon kites, it is imperative to assess the load couplings effects and its impact on the aerodynamics of the wing, and ultimately the performance of the system's yield. CFD and 3D finite element methods are currently too computationally expensive to efficiently explore the design space at such an early stage of the design process. This leads to the need for a toolchain that has sufficient modelling fidelity while being efficient enough to be used for conceptual design. An efficient aero-structural toolchain is the focus of this work.

In order to analyse the composite structure of the kite efficiently, instead of a traditional 3D finite element method, a 2+1D method that can capture the effects of fibre orientation, stack up sequence, and other aspects of the internal structure of the wing with sufficient fidelity, while being computationally efficient is employed[1]. This structural model is coupled with the aerodynamics of the kite via a 3D nonlinear vortex step method[2]. The toolchain also includes the effects of the underwing bridle configuration and is able to model the influence of different bridle and pulley configurations on the aero structural performance of the kite. A design space exploration exercise using the toolchain is carried out for a typical EnerKíte wing.

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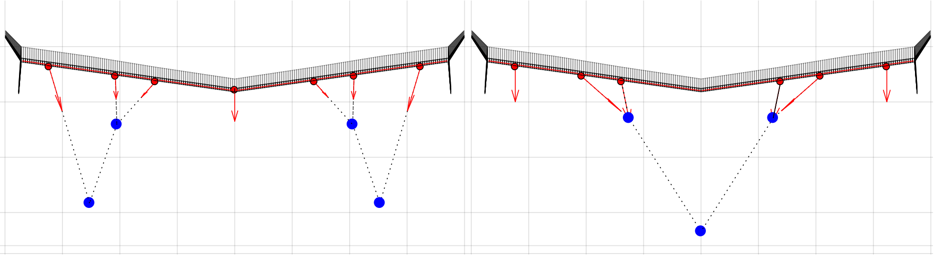
[1] A. A. Candade, M. Ranneberg, R. Schmehl: Structural Analysis and Optimization of a Tethered Swept Wing for Airborne Wind Energy Generation. Wind Energy (in review), 2019.

[2] M. Ranneberg, "Direct Wing Design and Inverse Airfoil Identification with the Nonlinear Weissinger Method," Cornell Physics.FluDyn, pp. 1–13, Jan. 2015.



Bridle design space exploration using the described toolchain.

Computer rendering of the Skysails Power 200 kW AWE system

Skysails Power 200 kW AWE system in operation as rendering (left) and in the workshop (11 September 2019)

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Steady-State Solver for a Ram-Air Kite Aeroelastic Model Based on Dynamic Relaxation

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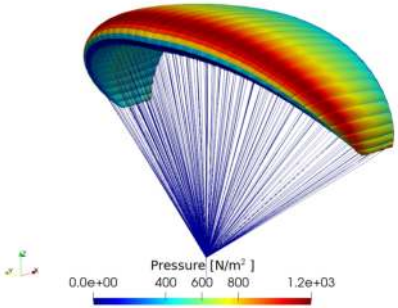
We present a computationally efficient steady-state solution method to model the aeroelastic deformation of a ram-air kite for airborne wind energy applications. The kite's weight in comparison to the aerodynamic forces is small which justifies a quasi-steady analysis, neglecting gravitational and inertial force effects [1]. The approach is suitable to efficiently determine the deformed configuration of a ram-air kite for design and optimization purposes as found in [2]. Because of the expected large deformations and changes in the flow field, fluid-structure interaction has to be taken into account in the analysis.

Ram-air kites have been modeled in the past using explicit time integration, such as in [3], to study transient flight behavior and maneuvers. At SkySails Power we aim to model the steady-state for specific angles of attack using dynamic relaxation (DR) by finding the equilibrium state between flow and structure. The steady-state solver ignores transient effects and therefore dramatically reduces computation time.

The kite's deformations are computed with the finite element method. Membrane elements with a non-compression and orthotropic material model are used for the canopy, and the bridle system is modeled using cable elements. The aerodynamic forces are computed with a 3D inviscid panel method which allows a fast pressure field computation.

The solver is used to determine the deformed shape and forces acting on the kite's structure during flight and can be used for geometric parameter optimization.



Deformed ram-air kite under pressure load determined by fluid-structure interaction.

References:

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[2] P. Thedens, et al., Ram-air kite airfoil and reinforcements optimization for airborne wind energy applications., *Wind Energy 22.5 (2019): 653-665*

[3] R. Flores, E. Ortega, E. Oñate, Simple and efficient numerical tools for the analysis of parachutes, *Engineering Computations, Vol. 31 Issue: 5, pp.957-985, 2014.*

AWEsome: An Airborne Wind Energy Learning Platform Using Open Software and Open Hardware

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AWEsome (Airborne Wind Energy Standardized Open-source Model Environment) [1,2] is a test platform for airborne wind energy systems that consists of low-cost hardware and is entirely based on open-source software. It has been implemented on two different flight control platforms and tested on two different model plane airframes. It can be used without the need of large financial investments (< 1000 $), in particular by research groups and startups to acquire first experiences in their flight operations, to test novel control strategies or technical designs, for academic student training or competitions, or for usage in public relations and for raising awareness for AWE.

The system consists of a modified off-the-shelf model aircraft that is controlled by the pixhawk autopilot hardware and the ardupilot software for fixed wing aircraft. The aircraft is attached to the ground by a tether. We have implemented new flight modes for the autonomous tethered flight of the aircraft along periodic patterns. We present the principal functionality of the algorithms, a simulation environment to test and develop the flight controller, and report on first successful tests of these modes in real flights [3] and on the analysis of the flight data.

In addition to using the flight control software Ardupilot, some of the original flight control algorithms of the AWEsome project were implemented in the PX4 software. A tether coupling mechanism was designed, leading the tether vertically through the fuselage. The ability to release the tether offers more safety in critical flight situations and for landing, which has been proven in test flights.

Tethered test flight of an AWEsome vehicle, Stuttgart.

References:

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[2] https://arxiv.org/abs/1704.08695

[3] https://www.ifb.uni-stuttgart.de/en/institute/news/videos/Airborne-Wind-Energy-Successful-test-flight/]

Flight Testing, Aerodynamic Parameter Identification and Dynamic Simulation of Rigid and Flexible Kites Applied to Airborne Wind Energy systems

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Simulation, state estimation, and aerodynamic parameter identification from in-flight data are actual research topics in AWE [1,2]. This work summarizes the status of four infrastructures developed at Universidad Carlos III de Madrid that are related with them: (i) a portable experimental rig for the acquisition of flight data like kite position, velocity, Euler angles, angular velocity, aerodynamic speed, angle of attack and sideslip angles, tether tensions, and wind velocity, (ii) an estimator of the state of the system, including the aerodynamic force and torque (iii) an optimization algorithm to compute the aerodynamic parameters from the estimated state variables, and (iv) the open-source simulator LAKSA, that contains modules aimed at the dynamic simulation and control of fly-gen and ground-gen generation systems, 2-line acrobatic kites, four-line kitesurf kites, and a train of N stacked kites.

These four tools have been applied to two four-line flexible kites of different surfaces and stiffness (Cabrinha switchblade, 10m^2, 5 struts and Cabrinha Contra, 13 m^2, 3 struts) and a 2-line acrobatic rigid frame kite (Fazer XXL, 3.6m wingspan). The full state vectors of the three kites were reconstructed and a data set with the aerodynamic force and torque, angle of attack and side slip angle for different maneuvers was created. However, difficulties arose for the aerodynamic parameter identification because the kites spent most of the time in a post-stall state during the flight. This conclusion, which is evident from the lift and drag coefficients versus angle of attack curves, was corroborated by the direct measurement of the angle of attack. Experimental and simulation results are presented together with a critical review of the capabilities of the infrastructures.

Flight testing of an acrobatic rigid framed kite.

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Hardware-in-the-Loop (HIL) and System Identification of a Pumping Kite Power System

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Airborne wind energy (AWE) is an emerging renewable energy technology which uses flying devices that are tethered to the ground. So far AWE has been demonstrated at tens of kilowatts level, a scale much smaller than what would be commercially viable in the utility sector [1]

Figure 1: Kite power system: KCU, and Real Flight Test.

In Kyushu University, we established our kite system with the aim of designing and manufacturing a small-scale prototype to generate a maximum power of 7kW using an inflatable wing with 10 m^2 surface area [2,3]. The system consists of a kite connected with a Kite Control Unit (KCU) to steer the kite wirelessly and follow a designed path of flight called Figure-of-Eight as depicted in Fig. 1. In the current stage, the KCU is acting as a ground anchor, not flying with the kite.

To obtain autonomous flight for the kite, it is required to design and manufacture a measurement unit for the position and attitude. GPS, IMU, Xbee, and arduino microcontroller were used to manufacture the circuit installed on the kite during flying. This unit collects the data, kite's position and attitude, then send them wirelessly to the ground station through the XBEE with sample time of 0.15 second. Several field tests have been performed and the respective data has been analysed for the system's performance. The current experiments aim to let the kite perform as HIL technique; the data of the kite are sent to the ground station and the control action is calculated, then the control signal is sent back again to the KCU to steer the kite during flight.

Finally, the technology used in our project will be described, and an update on the overall progress of the project will provided. The system is designed to produce $7kW/10\ m^2$. Our largest kite is 10 m^2 surface area and has a KCU with weight of 3 kg. The key lessons learned in the current project and the planned future work will be described.

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[2] Dief T.N., Fechner U., Schmehl R., Yoshida S., Ismaiel A.M., Halawa A.M.: System identification, fuzzy control and simulation of a kite power system with fixed tether length. Wind Energy Science. ***3****, pp. 275–291 (2018). https://doi.org/10.5194/wes-3-275-2018*

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Prototype AWE system built by the ftero student team of ETH Zurich

ftero student team of ETH Zurich with their prototype AWE system (2019)

Fast Prototyping Morphing Wings for Airborne Wind Energy

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The student project ftero, from the Swiss Federal Institute of Technology (ETH), has developed, designed and prototyped a fully functional small scale Airborne Wind Energy (AWE) system. The system relies on a ground-based power generation approach and an adaptive composite fixed-wing aircraft. In contrast to other research projects, ftero is entirely run by engineering students as part of the final year of their undergraduate education. Within the two semesters of the project, the current team had to raise the required financial means, fabricate a new aircraft, adapt the ground station and implement the necessary controllers for full autonomous power production. The additional implementation of a morphing wing, replacing the control surfaces of a conventional design by a continuously deforming carbon-fibre reinforced plastic (CFRP) structure, enabled decreasing drag and allowed an adaptation of the wing profile for different flight conditions.

The limited resources in combination with the ambitious goals created a unique and demanding, yet comprehensive learning experience, while setting up an experimental framework for innovative ideas in the field of AWE.

To meet the given challenges, rapid manufacturing and ease of repair were key elements in achieving 141 conducted flight tests with three self-manufactured CFRP and three styrofoam aircraft. The innovative manufacturing approach uses additively manufactured (AM) parts and the newly developed manufacturing technique Cured Carbon Folding (CCF). In combination with a modular design, the proposed concept provides sufficient mechanical and aerodynamic performance while minimizing the manufacturing and repair time. In fact, a morphing wing with a span of two meters could be produced within only two manweeks.

The latest build prototype has a total wingspan of 4.6 *m* consisting of a 2 *m* base wing and 1.3 *m* wing-extensions, making use of a modular assembly concept. With this aircraft, all flight phases were flown manually, using the chosen quadplane approach for vertical take-off and landing (VTOL) as well as the implemented morphing structure. Furthermore, with a smaller prototype, a tethered autonomous power cycle was flown, yielding usable electrical energy on the ground station.

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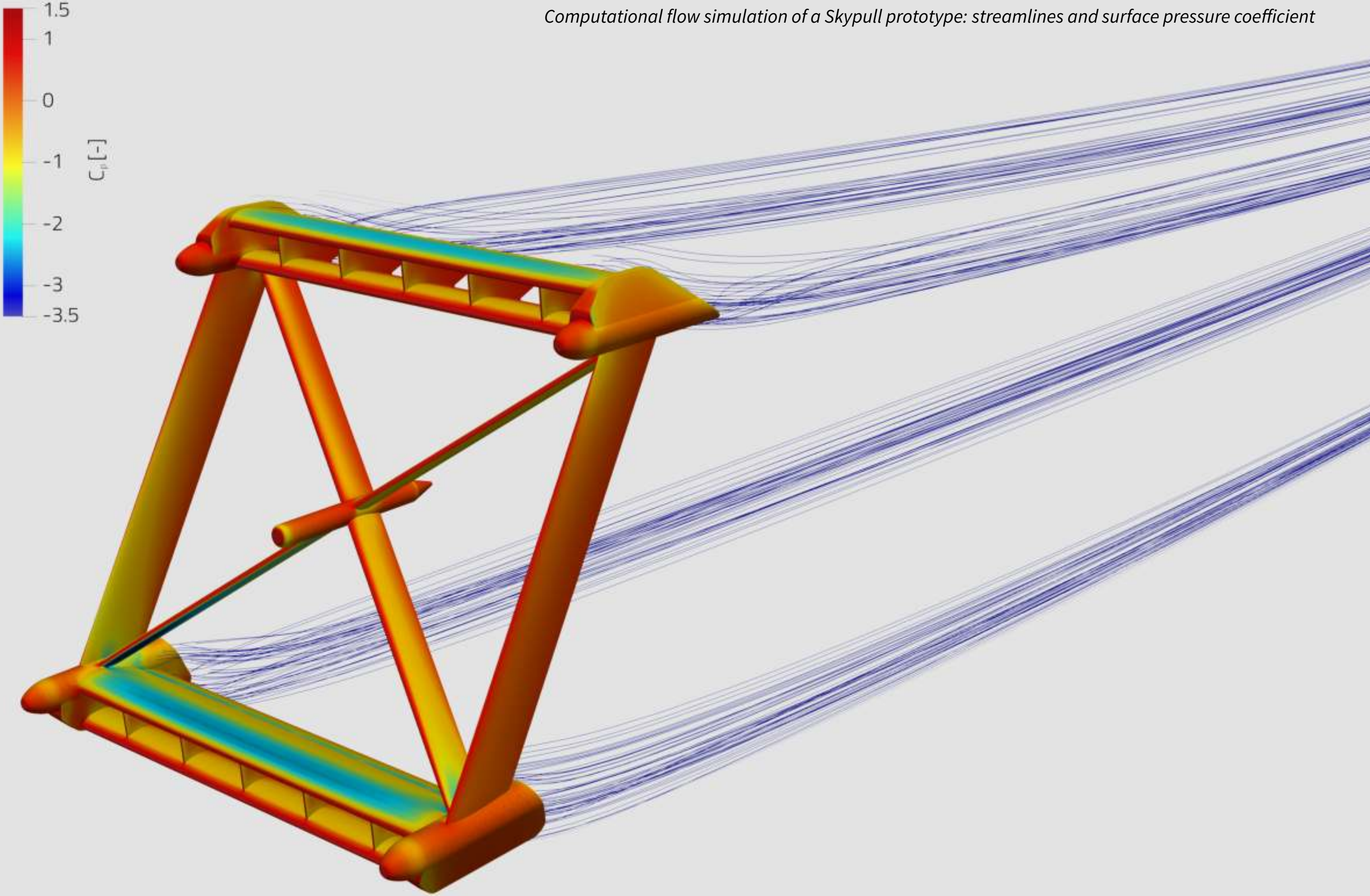
Computational flow simulation of a Skypull prototype: streamlines and surface pressure coefficient



Skypull's AWE system ready for launch (1 December 2018)

Composite photo of a successful test flight of the Skypull system (May 2019)

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Control of Vertical Take Off, Pumping Operation and Vertical Landing of Hybrid Drones for Airborne Wind Energy

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[1]Politecnico di Milano
[2]Skypull SA

A control design approach for a tethered, hybrid multi-copter/box-wing drone for pumping airborne wind energy is presented. The drone, designed by Skypull SA [1] (see Figure), features four propellers and multiple aerodynamic control surfaces, and can operate either as multi-copter or as an airplane. The goal is to achieve fully autonomous vertical take-off, transition to dynamic flight and pumping operation, and vertical landing. A model-based, hierarchical feedback controller is proposed, with linear inner control loops to stabilize the drone's attitude, and outer nonlinear loops to obtain the desired flight trajectory. A switching strategy is employed to transition from hovering mode (i.e. multi-copter) to dynamic flight mode (i.e. airplane), and vice-versa. Each mode has a different outer controller, while the low-level loops are the same. Simulation results with a realistic system model indicate that the controller can achieve good performance and robustness in all flight conditions, notwithstanding its simplicity and ease of implementation, and carry out the wanted pumping cycles. This work builds on a recently presented contribution [2], where an untethered system was considered.

Example of prototypes of the considered hybrid drones during tests in the Swiss Alps

References:

[1] Skypull SA. [Online]. Available: https://www.skypull.technology (last accessed September 2019)

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On Using Drones for the Take-off and Landing Phases of an AWE System

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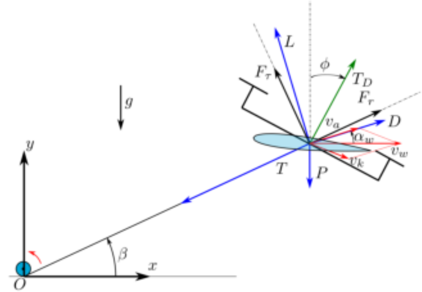
Modeling, control and optimization of AWE system have been extensively studied theoretically, in numerical environments and through infield experiments. Despite of these above-mentioned developments, several relevant and urgent aspects have to be addressed for the technical feasibility and commercial success of AWE systems. One of such aspects is the take-off and landing of the airborne platform, especially for on-ground production systems with rigid airfoils.

In this work we have studied the control design of the take-off and landing of a rigid-wing airborne wind energy system using a multicopter. First a 2D model was developed including the drone and the airborne airfoils. The system is subject to aerodynamic forces but also to the thrust force of the drone. From this model a controller was designed using an output feedback linearization method. The aim is to transform the nonlinear tracking problem to a linear stabilizing problem. Then, an intermediate linear control law is computed to ensure the asymptotic stability of the tracking error. The position of the drone is controlled thanks to the winch torque and the lateral force of the drone, while the tension in the tether is controlled with the radial force of the drone.

A simulation on a specific scenario is performed including a take-off, a disturbance due to the wind and then a landing. The obtained results show the efficiency of the proposed control policy in simulation environment of a hybrid tethered system that is composed of a rigid wing attached to multicopter drone both attached to on-ground winch where the torque is controlled.

In the near future, we are working on implementing a tether model [2] and test the algorithm in a ROS/Gazebo simulation environment. Meanwhile, a small-scale prototype is under development to validate the approach experimentally.



The airborne wind energy system with the drone connected to the on-ground station. All forces acting on the system are shown.

References:

[1] Lorenzo Fagiano and Stephan Schnez. On the take-off of airborne wind energy systems based on rigid wings. Renewable energy, 107:473–488, 2017.

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Kitemill's Vertical Take-off and Landing System for the KM1 Model

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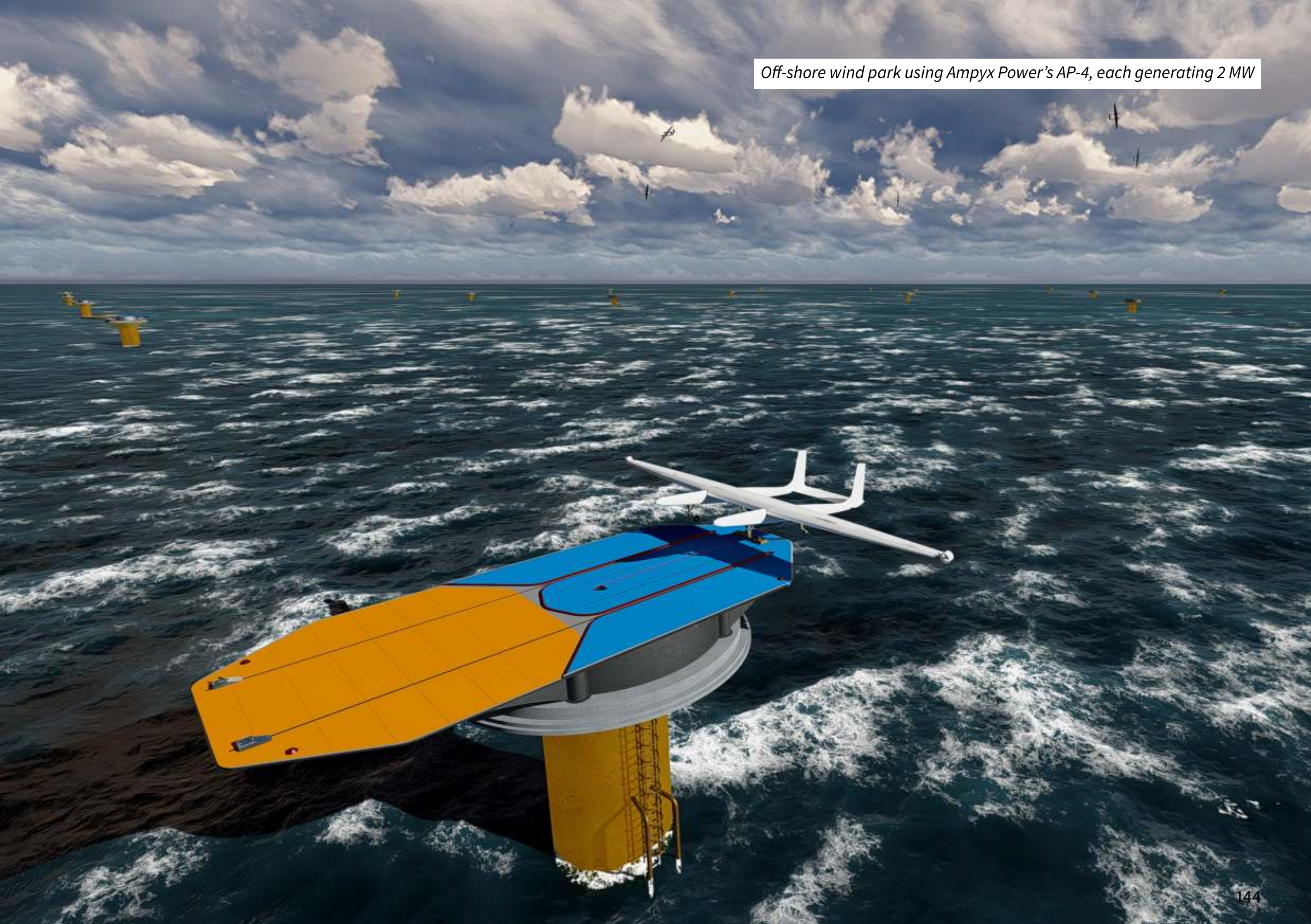
Kitemill AS

There are many different launching systems for airborne wind, ranging from catapult launches, spiral launches and vertical take-off and landing (VTOL) solutions. After a thorough analysis, Kitemill found VTOL to be the best means for launch and recovery of their kites and has invested much time and effort to develop an autonomous VTOL system for airborne wind leveraging the research within drone technologies.

The KM1 model called the Spark model has a wing span of 7.4 meters, and four different motors, two large motors fixed to the fuselage, and two smaller motors on the wings that can be tilted to produce a forward thrust to enable a transition from VTOL mode to production mode. The tilt-motors can also be used in regenerative mode to enable recharging of the batteries onboard the kite during the return phase to enable 24/7 continuous autonomous operation. In addition to the four motors, the kite has multiple control surfaces that work together with the motors to control the kite in high wind conditions.

This work presents how the combined sets of actuators are used to control the attitude and altitude of the kite, how to reach a desired position through a novel guidance strategy specifically designed for airborne wind energy systems that minimizes the required power, how the team has developed and tested the system, as well as the experiences obtained through this work. Experimental results show the performance of the system.

Experimental testing of the VTOL system for the KM1 model.



Off-shore wind park using Ampyx Power's AP-4, each generating 2 MW

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Autonomous Takeoff and Landing of Rigid Wing Airborne Wind Energy Systems

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An overview of the design of an autonomous horizontal takeoff and landing approach for AWES utilising a rigid wing aircraft is presented. Ampyx Power's approach uses a combination of ground-based and aircraft-based system components to provide and remove energy from the system, specifically a catapult mechanism for injecting kinetic energy into the system during launch, and an arresting system that utilises the tether for removing energy during the landing. The design approach is rooted fundamentally in minimising the system footprint.

The methodology for sizing of the catapult is presented, as well as the means for ensuring the tether does not collide with the aircraft body during the initial climbout. A mathematical model for simulating the catapult interaction with the aircraft is presented, together with simulation results of the launch phase over all operational wind speeds.

During landing, the aircraft is guided to the landing point without active propulsion, with control of airspeed provided by tether tension. Unlike conventional piloted aircraft that fly an inertial glideslope, our system flies a flight path that is determined as a function of wind speed, and optimised to minimise the effective landing dispersion. This results in approach paths that are not a constant angle in the inertial frame. In the final stages of the landing, the winch is decelerated and locked to allow the tether to be used for braking the aircraft. However, using the tether directly without any additional damping leads to forces on the aircraft along the longitudinal axis that would significantly increase the design requirements for the tether attachment point. To prevent this, an arresting mass is used to cushion the impact. The arresting mass is attached to a passive damper that allows for the deceleration forces transmitted to the aircraft to be tailored. The optimisation process for choosing the damper profile, together with Monte Carlo simulation results are presented to illustrate the robustness of the landing approach.

Tether-arrested landing, showing aircraft landing on a platform with tailored arresting system.

someAWE Labs' continuous torsion-based power transfer from rotor to ground (10 March 2019)

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Practical Experiences with a Torsion Based Rigid Blade Rotary Airborne Wind Energy System with Ground Based Power Generation

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Rotary airborne wind energy systems that use rotors similar to conventional wind turbines and ground based generators combine some of the known benefits of Loyd [1] based crosswind kite power systems with potential additional benefits such as continuous energy generation, no tether drag from crosswind flight, passive control, use of "cheap" lift and easier launch and landing.

Airborne wind energy systems without crosswind motion typically have a bad power/blade area ratio. The talk discusses a rotor design that can alleviate this disadvantage. It treats the blades of the rotary wing as independent airborne wings that are only connected for easier control and launch. The airfoils start at some distance from the hub thus achieving high tip speeds with smaller blade area than conventional rotors.

Our implementation of such a rotor uses rigid blades. The rigid design provides a better power coefficient and stable operation in turbulent air. Thereby allowing us to focus on the stability of the energy transmission.

For continuous torsion-based power transfer from the rotor to the ground a tensegrity based torsional stiff structure ("helix") has been developed and tested.

This design has been chosen over the pure Tensile Rotary Power Transmission (TRPT) of the DAISY system [2,3] as it allows for linear scaling with constant diameter. The power transfer lines are being held in a squared helix shape reducing twist induced lag and oscillations.

A 300 W demonstrator system with 60 cm blades, a rotor diameter of 4.8 m and a helix length of 30 m has been designed, build and tested for more than 10 hours.

This talk shares practical experiences with this torsion based rigid blade rotary airborne wind energy system.

The talk discusses the design rationale, lessons learned, successes and dead ends. It presents field test footage (also available here https://bit.ly/2maLiLs) and provides an outlook.

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[3] Tulloch, O.: Development of Safe and Efficient Operation for an Airborne Wind Energy (AWE) System - A Rotary Design, (2019)

kiteKRAFT founders (from left to right): Max Isensee, Florian Bauer, André Frirdich, Christoph Drexler (13 February 2019)

kiteKRAFT onboard turbines that are also used for propulsion (13 February 2019)

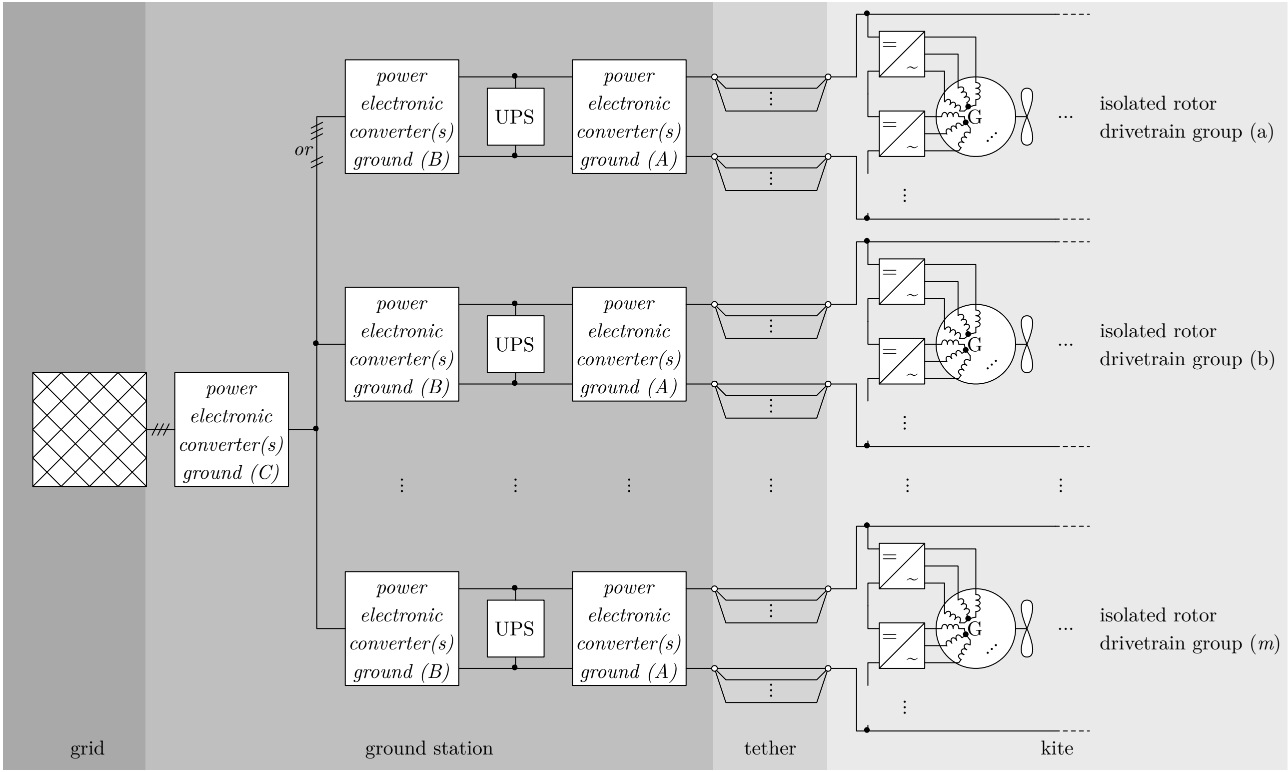

Fig. 1: Proposed power electronic topology for a drag power kite.

Power Electronic Topologies of Drag Power Kites

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Drag power kites belong to the class of crosswind kite power systems, which harvest energy from the wind with onboard turbines [1]. All electricity is generated onboard the kite and transmitted to the ground through electrical cables integrated in the tether. For a high power extraction efficiency, the tether must be thin and light. Optimizations of the tether design reveal the optimal transmission voltage at around 8 kV [2], though with a relatively low sensitivity for off-optimal voltages to around 2 kV [3]. Several kV transmission voltage is a challenging demand for the design of the power electronics, in particular for the airborne part. Besides the goals of low costs, high efficiency, and low weight, the topology and components must be fail-safe and have a low complexity.

In this talk, recently published power electronic topologies are presented and assessed, including those specifically targeted for drag power kites [2,4–7]. To achieve all of the above stated goals, a promising topology is a combination of concepts, visualized in Fig. 1: The different rotor powertrains are electrically isolated from each other as in [5] to achieve a very high fault tolerance with no single point of failure—even a short circuit in the tether has no harm (assuming there are enough isolated rotor-drivetrain groups). Additionally, the electrical machines (motors/generators) have several three-phase windings (multiphase machines), each of which is connected to a voltage-source AC-DC converter, whereas these converters are connected in series on the DC side. This allows to obtain not only the advantages of [4,7] being low-cost and high-efficient, but also having a lower complexity and higher modularity. In particular, no high-power DC-DC converters or transformers are required onboard the kite.

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Towards a Modular Upscaling Strategy for Utility-Scale Airborne Wind Energy

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The prevailing industrial upscaling strategy towards utility-scale AWE systems is based on single-kite systems and relies on increasing aircraft size until the desired power output in the MW range is reached. This strategy suffers from many of the drawbacks associated with the upscaling of conventional wind turbines, such as increased costs related to production, transport, repair, challenging structural mechanics, etc.

It has been shown in simulation that AWE systems based on multi-kite topologies could drastically reduce the required aircraft size for a given power demand due to the intrinsically low main tether drag [1]. However, safety and efficiency concerns limit the amount of kites that can be added to a single multi-kite system.

Hence the idea of extending the design space to multi-layer multi-kite configurations, obtained by stacking multi-kite systems on a shared main tether, as illustrated in the Figure. This concept naturally allows to increase the total amount of harvesting area together with the number of aircraft in the system. It results in an efficient and modular upscaling strategy, effectively decoupling aircraft sizing from power demand. Therefore, multi-layer topologies could enable the realization of utility-scale AWE systems based on relatively small, mass-producible aircraft.

This research aims to assess the upscaling advantage of multi-layer relative to single-layer multi-kite topologies for rigid-wing aircraft systems. Optimal control is applied to simultaneously optimize both system design and flight trajectories for a large set of possible topologies. The models are based on 6DOF aircraft dynamics and low-order layer-wise induction models, similar to those presented in [2]. The optimal control problems are formulated and solved using the open-source AWE optimization framework `awebox` [3]. The results are computed for different power output requirements associated with industry-relevant wind sites. Flight trajectories and required aircraft size are compared for considered topologies. Finally, results for both drag-mode and pumping-mode systems are compared and discussed in detail.

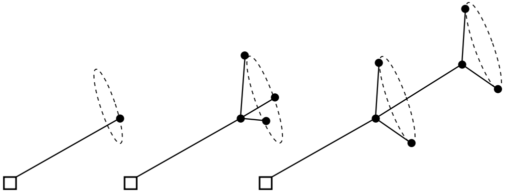

Illustration of the topology of a single-kite (left), single-layer-triple-kite (middle) and two-layer-dual-kite (right) AWE system.

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Model-Based Development and Verification of Ampyx Power's Airborne Wind Energy System

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The systematic processes used by Ampyx Power to evaluate conceptual design choices, perform detailed algorithmic design, and conduct simulated-based verification during the development of its Airborne Wind Energy system are presented. Ampyx Power is currently simultaneously working on different parts of the development cycle for a rigid wind AWES: 1) Flight test and evaluation of a small-scale prototype (AP-2), 2) Detailed design and manufacture of a medium-scale prototype (AP-3), and 3) Conceptual design of a large-scale commercial prototype (AP-4). Each of these phases requires a different approach so as to properly balance process rigour taking into account efficiency, accuracy of output, and risk.

A detailed description of the methods and lessons learned used by Ampyx Power during the development of its AWES are presented. The main development framework utilises MATLAB/Simulink with a set of customised tools developed specifically for AWES. The approaches used by Ampyx Power are presented together with representative examples of the output of the processes for the AP-2, AP-3 and AP-4 projects. For context, the aviation-industry design guidelines SAE ARP 4754A for complex systems, and DO-178C/DO-331 for software incorporating model-based design elements are used to provide a methodological approach to design and development, with the ultimate aim to deliver a certifiable product that meets stringent safety standards. Ampyx Power believes that this currently provides the best context for development of AWES, with some specific tailoring, so as to meet the high reliability and safety requirements that a commercial AWES should be capable of meeting.

Ampyx Power employs physics-based modelling of the rigid-wing aircraft, with a major focus on the aerodynamic and actuator modelling, which drive the stability and control performance of the system. Combinations of CFD, nonlinear lifting line, and a vortex-lattice method are used to derive the static and dynamic aerodynamic coefficients for the bare airframe. Detailed models of the electromechanical actuators, characterised by extensive experimental testing, are employed. In-house sensor characterisation is performed to derive models for all sensor components. The control systems for the on-ground and in-air computers are implemented as design models and incorporated into the simulation test harness that simulates the complete airborne wind energy system. The design models are converted into embedded C code via Simulink Embedded Coder. The algorithms and ultimately the generated source code are verified by a three-tier testing strategy: 1) Functional, robustness, and requirements-based testing of the design models against requirements, 2) host-based source-code tests against the design models, and 3) Hardware-in-the-loop tests of the integrated software on the target processor.

Investigating Offshore Markets for AWE Technologies

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The offshore market is a key target for utility scale AWE operation. Lower foundation moments could lead to early opportunities for AWE: re-powering fixed foundations and floating foundations. Initial investigations have focused on potential technical, financial and safety show-stoppers.

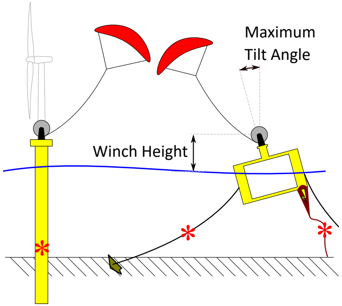
Re-powering offshore windfarms offers possible CAPEX savings from re-using major components (foundations, array cables, etc). This could offset costs associated with immature technology and provide a proving ground for AWE operations. Learnings and supply chains could accelerate development of new-build AWE sites.

Floating foundations offer the potential to exploit new markets, with AWE allowing smaller, lower cost, foundations than conventional turbines. Decoupling of the sensitivity components (the airframe) and wave motions further reduces requirements. Static modelling (excluding waves) has been used to size foundations, and understand trade-offs for several classes of AWE device (based on data provided by AWE developers). Financial modelling has then been carried out.

Fatigue life is a key challenge in all cases due to the cyclic loads of lift devices. For re-powering, the majority of the fatigue life of the foundations will have been used, and assessing remaining life for AWE is challenging. For floating foundations, fatigue of moorings and export cables is key, as foundations move under cyclic loads. Mitigating these loads may be a requirement in either case.

Trade-offs found to have a significant impact on foundation design, especially for floating, include: the height of the winch above the waterline; the angle to which the "ground station" can be tilted; and the amplitude of cyclic loads. Accounting for these early in design could have a significant impact on cost.

Finances are unfavourable for re-powering due to the short operational life and the high OPEX associated with immature technology. However, realistic levels of support (feed-in tariffs) could overcome these shortcomings. Early floating shares similar shortcomings, however mature AWE with more generation per foundation ($\geq$6MW) could outperform conventional floating, and potentially compete with conventional fixed foundation.



Key parameters for re-powering and floating AWE. Red $*$ indicate locations of fatigue.

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Global Prospects for Airborne Wind Onshore

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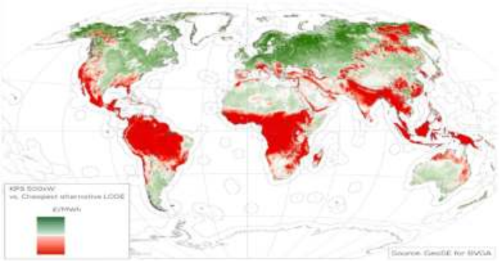
Airborne wind energy (AWE) technology is evolving rapidly and could become mainstream in the next decade. The major target is generally regarded as offshore, particularly on floating platforms at deep water sites. This is for three main reasons: there is less competition from other energy sources, there are significant cost savings compared to conventional wind due to lower material mass, and there are anticipated to be fewer planning issues as the devices will be located away from populated areas.

Onshore markets are also important, giving a low-cost opportunity to demonstrate proof of concept and accelerate cost reduction. There are also many areas of the globe without access to electrical power from a reliable grid; these give AWE technology developers opportunities to build volume and evolve technology at smaller scales.

In this study we characterised the global potential for onshore AWE compared to alternatives. Using GIS software, we calculated the levelized cost of energy (LCOE) of conventional wind, solar and diesel gensets across the world. The geospatial variance of the technologies was captured using global datasets: annual average wind speed, solar irradiation and country-scale diesel price, which were combined with benchmark system costs. The costs were fixed across all locations; this represented an assumption as in reality these will vary according to regional factors like logistical costs, tax regimes and local labour cost.

The output of the analyses were ‘heatmaps’ of LCOE. At each point analysed the lowest cost technology was identified. The LCOE for an AWE device was also calculated and compared to the conventional case to identify the most suitable areas for the technology. An example of this output is presented in the Figure.

A further analysis considered socioeconomic and environmental exclusion zones. Examples included proximity to airports and urban areas and remote areas far from road infrastructure. This allowed priority markets for AWE onshore to be identified. Conclusions are drawn as to the size and location of the markets and the likely role they will play in the development of AWE.



LCOE of the AWE device vs the cheapest conventional technology. The green areas indicate where the AWE device is cheaper, the red areas where the conventional technology is cheaper.

Coupled Kite-Ground Station Simulink Model for Optimal Flight Path Following Assessment

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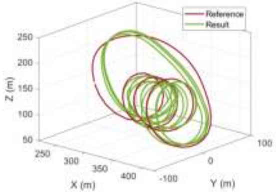
Crosswind Kite Power Systems (CKPSs), a specific type of airborne wind energy systems, will operate at higher altitudes than conventional wind turbines. CKPSs will fly through a significant portion of the atmospheric boundary layer, and therefore encounter a wide range of incident wind profiles corresponding to wide ranging atmospheric stability conditions resulting from synoptic and diurnal weather conditions. This study aims to demonstrate an approach to considering realistic wind speed profiles for a lift mode (a.k.a. pumping mode) CKPS. The focus is on a time-domain simulation of tethered flight to follow optimal trajectories solved for both simple and realistic wind speed profiles. The pre-computed trajectories may not be optimal, or even achievable, when considering forward-marching flight dynamics compared to the necessarily simplified optimization flight model. In particular, ground-station tether reel-in/out speed and torque envelopes and control directly affect the power harvesting performance, longevity and robustness of the system. An approach is being developed to support ground station control coupled with tether and flight dynamics, to explore controller synthesis solutions that do not excite the coupled kite–tether–ground-station system dynamics, especially during transitions between harvesting and retraction flight phases.

In the proposed approach, the wind speed profiles from the mesoscale Weather Research and Forecasting (WRF) model [1] are first implemented in the open source AWEbox [2] which is then used to determine optimal flight paths for a range of wind profiles. A flight controller is implemented in a Matlab's Simulink model to follow the pre-computed optimal trajectories generated with the AWEbox in a time-marching dynamic simulation. Dynamic tether tension, structural loads and energy harvesting performance are estimated and compared with the offline, idealized control actions obtained with AWEbox.

The ultimate goal is to integrate both the base-station and flight controllers in the combined system dynamic model in Simulink, assess the ability and robustness of the control system to follow those optimal paths, and evaluate the differences between optimal idealized performance and that achievable dynamically in the presence of wind disturbances. This evaluation will also form the basis for assessing lifetime structural fatigue loads and sizing requirements.



Sample dynamic simulation trajectory result compared to optimal reference trajectory generated with AWEbox in wind field in x-direction with log profile starting at 8 m/s for z_{ref} = 10 m with exponent α = 1/7, and winch at (0,0,0).

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Fluid-Structure Interaction of Inflatable Wing Sections

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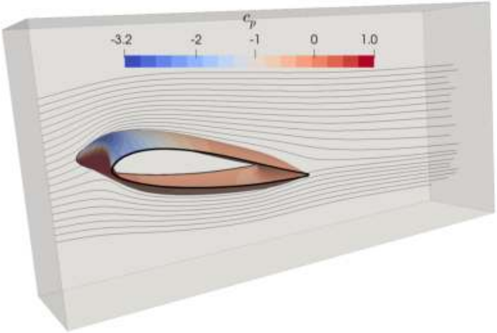
We investigate inflatable kites made of membranes such as ram-air [1] and leading edge inflatable [2] kites. The kites are very flexible and therefore exhibit a strong coupling between fluid and structure. An accurate aerodynamic model is essential to design kites which are aerodynamically efficient and of high steering capability.

In this work, a fluid-structure interaction methodology is developed to study the steady-state aerodynamics of inflatable kites. The aerodynamic load distribution is calculated using computational fluid dynamics toolbox OpenFOAM. Steady-state solver with RANS based turbulence model $k - \omega$ SST is used. The structural deformation is calculated with mem4py [2] finite element solver for membranes which uses dynamic relaxation method to find the static shape. The two solvers are coupled with preCICE [3] coupling tool. Each solver is connected to preCICE through an adapter and thereafter preCICE takes care of the coupling such as the parallel communication, the data mapping for non-matching meshes and the coupling algorithm to accelerate the convergence.

The fluid and the structure solvers are validated against relevant experiments and the coupled simulation framework is used to study the aerodynamics of a ram-air wing section with uniform pressure inside. The results show large deformations and therefore the aerodynamic loads highly depend on the structural deformations. The coupled framework shows a good compromise between fidelity and efficiency.



Pressure coefficient around the kite section and streamlines at the symmetry plane with $\alpha = 10^\circ$.

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Windswept and Interesting Ltd. rotary network AWES with rigid blades (15 September 2019)

Modeling Studies on Tensile Rotary Power Transmission for Airborne Wind Energy Systems

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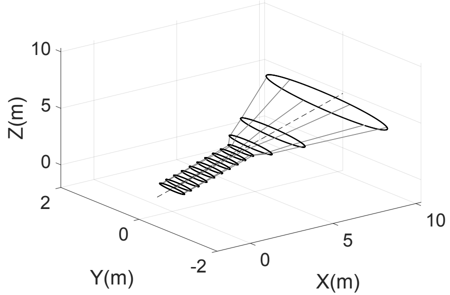
Rotary airborne wind energy (AWE) systems are a class of AWE that utilize multiple wings arranged to form a rotor. They rely on auto-rotation to provide both aerodynamic lift and torque. There are several rotary systems currently under development, among them the Daisy Kite developed by Windswept and Interesting Ltd, introduced in [1]. A rotary AWE system must transfer power from the airborne components down to the ground, either mechanically or electrically. The Daisy Kite employs a mechanical method referred to as tensile rotary power transmission (TRPT) system.

TRPT takes the aerodynamic torque produced by the rotor, and through a series of taut lines held apart by rigid components, transmits the torque down to the ground. From model-based analysis of the steady state case of the Daisy Kite, it can be stated that the line tension, the diameter of the rings and the distance between the rings are the three key factors affecting torque transmission performance. By analyzing the steady state line drag it is found that the transmission efficiency varies greatly depending on the operating condition. Based on the operating conditions during field tests the current Daisy Kite prototype has drag losses of around 7% within the TRPT.

A dynamic representation of the Daisy Kite's TRPT was developed through derivation of the non-linear equations of motion. The dynamic response was then analyzed using a numerical integration method. While the steady state analysis gives the maximum allowable steady torque that the TRPT can transmit, the dynamic representation can additionally show the maximum change in torque that can be transmitted and the transmission time for a given operating state. The dynamic representation can be used to improve the Daisy Kite's design and optimize the systems operating strategy.

This research has been funded by EPSRC, award no. EP/L016680/1, a Scottish Funding Council Innovation Voucher and the Energy Technology Partnership.



Graphical representation of the TRPT used in the Daisy Kite system.

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Investigation of the Effect of Modeling Different Degrees of Detail in the Key Elements in a Crosswind Kite Wind Energy System

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The present work investigates the effect of modelling different degrees of detail of the key elements of a crosswind kite wind energy system. The key performance parameters on which the effect is evaluated are effective lift-to-drag ratio, tether tension force and power production.

To some extent there is also a pedagogical/didactic scope of this work, for students and those less experienced with crossflow kite wind energy systems to familiarize themselves with how important the different key elements are for the key output parameters of the system.

The models used in the study are simple engineering models, modelling the main key behaviour without drowning in an unnecessarily large amount of model details and/or tweakable constants. For instance, the aerodynamic model that is used for relating the aerodynamic drag to the aspect ratio and the chosen lift coefficient is the classic lifting line theory with the addition of a viscous profile drag part. The line force and power production is evaluated using the expressions from Loyd [1].

As an example of the “first part of the story”, the figures show as function of C_L and kite aspect ratio *AR* the effect on effective *L*/*D* from aspect ratio effects only (Fig. 1), aspect ratio + viscous drag (Fig. 2), aspect ratio + viscous drag + line drag penalty (Fig. 3). The power production capability (Loyd expression) based on aspect ratio + viscous drag + line drag penalty is shown in Fig. 4. It is seen that for the given kite area (20 m^2), wind speed (12 m/s) and tether length (500 m) the favored lift coefficient and aspect ratio is as high as possible if a maximization of the power is sought.

The main outcome of the present work is to give a quantitative understanding of the relative importance of modelling different key elements in crosswind kite wind energy systems. *References:*

*[1] Loyd, M. L.: Crosswind Kite Power. Journal of Energy **4**(3), 106-111 (1980)*

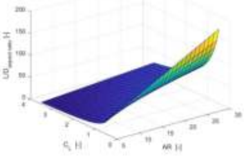

Fig. 1: Aerodynamic lift-to-drag ratio *L*/*D* from aspect ratio contribution only.

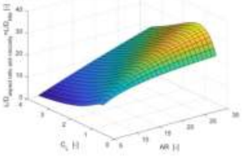

Fig. 2: *L*/*D* from aspect ratio and viscosity contributions = *L*/*D* for kite alone.

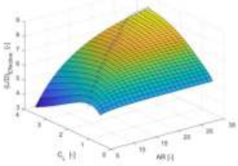

Fig. 3: Circles represent the C_L that maximize $(L/D)_{eff}$ for a given *AR*.

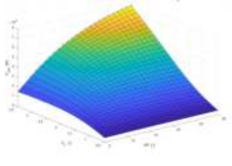

Fig. 4: Power produced when pulling with a reel out vel. that is 1/3 of the wind vel. Circles represent C_L values that maximize power for a given *A*.

Author index

Ahbe, Eva, **46**
Ainsworth, David, 155
Anderson, Russell, 76
Aregger, Damian, 105, 123
Aull, Mark, 45, **120**
Bättig, Rik, **137**
Börngen, Hannes, 151
Bauer, Florian, **151**
Beaupoil, Christof**,** 147
Bechtle, Philip, **94**, 132
Bezard, Florian, 105, 123
Bigi, Nedeleg, 79
Birr, Michelle, 94
Bonnin, Vincent, 43, **98**
Borm, Anika, 154
Bormann, Alexander, **101**
Borobia-Moreno, R, 133
Bosch, Jaap, 19, 121
Bosman, Rigo, **91**
Bourgault, Frédéric, 95, 125, **156**
Breuer, Joep, **41**, 93
Breukelman, Pim, 43
Brodrick, Tim, 76, **97**
Bronnenmeyer, Thilo, 85, 152
Bungart, Merlin, 131
Candade, Ashwin, 101, **128**
Carnel, Lode, **42**, 70, 143
Cattano, Aldo, 141
Cobb, Mitchell, **117**
Coleman, Joseph, 81
Costa, Dino, 105, 123
Crawford, Curran, 95, 156
Creighton, Robert, 45
Dangel, Manuel, 46
De Schutter, Jochem, 85, **92**, 96, **152**
Dief, Tarek, **134**
Diehl, Moritz, 85, 92, 96, 152
Dumon, Jonathan, **82**, 142
Endo, Hiroki, 84, **111**
Ermanni, Paolo, 127, 137
Fagiano, Lorenzo, **35**, **141**
Falkena, Wouter, 153
Fasel, Urban, **127**, 137
Fechner, Uwe, 73
Fernandes, Manuel C.R.M., 87
Feuchtwang, Julian, 159
Folkersma, Mikko, **157**
Fontes, Fernado A.C.C., **87**
Frost, Ciaran, **155**
Fujii, Hironori, **47**, 84
Göransson, Lisa, 118
Gallacher, Daniel, 86
Galliker, Manual, 137
Galliot, Cédric, 105, 123
Garry, Kevin, 75
Gaunaa, Mac, 119, **160**
Gebhard, Christian, 101
Ghandchi, Shadi, 153
Gohl, Flavio, 105, 123
Gow, Graham, 155
Grini, Jo, 42, 70, 143
Gros, Sébastien, 85, 118
Gunn, Kester, **154**
Gupta, Yashank, 82
Hårklau, Thomas, 42, **70**, 143
Haas, Thomas, **96**
Hably, Ahmad, 82, 142
Hagemann, Tim, 132
Halawa, Amr M., 134
Hanna, George, 105, 123
Hatakeyam, Ryo, 84
Heilmann, Jannis, 105, 123
Hensen, Micha, 137
Hessberger, Steffen, 105, 123
Houle, Corey, 105, **123**
Ife, Max, 154
Itakura, Eiji, **71**
Jochum, Christian, 79
Jones, Colin, 80
Kader, Barzy, 137
Kazemi Amiri, Abbas, 159
Keidel, Dominic, 127, 137
Kennel, Ralph M., 151
Kheiri, Mojtaba, **125**, 156
Klein Miloslavich, Andreas, 156
Klop, Erik, 121
Koenemann, Jonas, 92
Kruijff, Michiel, **43**, 145
Kusagaya, Tairo, 47
Le Pense, Solenn, **76**
Leroux, Jean-Baptiste, 79
Leuthold, Rachel, **85**, 92, 152
Licitra, Giovanni, 92
Listov, Petr, **80**
Logan, Andy, 155
Luchsinger, Rolf, **105**, 123
Macuglia, Mael, 137
Malz, Elena, 94, **118**
Marl, Jonas, 137
Maruyama, Yusuke, 84
Mcleod, Doug, **33**
Merkel, Kevin, 132
Meslem, Nacim, 82, 142
Meyers, Johan, 96
Micheli, Claudio, 141
Mizzi, Marco, 154
Mortimer, Alan, **86**
Morvan, Antoine, **79**
Nam, Taewoo, **113**
Narikawa, Masafumi, **115**
Nordstrom, Charlie, 33
O'Donnel, Cathal, 81
Oficialdegui, Ignacio, **51**
Okubo, Hiroshi, **84**
Oland, Espen, 70, 83, 112, **143**
Onodera, Hidemi, 84
Paelinck, Reinhart, 152
Pagani, Michele, 137
Paiva, Luís Tiago, 87
Paulus, Fiona, 94
Paz, Marcos, 145
Perlberger, Michael, **109**
Peschel, Johannes, **69**
Petrick, Kristian, **61**, **99**
Philibert, Cédric, **34**
Quack, Manfred, **53**
Rafter, Jessica, 154
Ramiro-Rebollo, D, 133
Ranneberg, Maximilian, 128
Rapp, Sebastian, **122**
Read, Roderick, **59**, 159
Rebbeck, Henry, 97
Rementeria Zalduegui, Alex, **75**
Rickner, Neal, **124**
Rueger, Maximilian, 94, **132**
Rushdi, Mostafa A., 134
Salari, Mahdi Ebrahimi, **81**
Sanchez-Arriaga, Gonzola, **133**
Sato, Tsuyoshi, 84
Schanen, Audrey, 82, **142**
Schelbergen, Mark, **93**, 94
Schläfli, Florian, 137
Schlothauer, Arthur, 137
Schmehl, Roland, **5**, 73, 93, 94, 122, 128, 131, 133, 157
Seki, Kazuichi, 84
Sieberling, Sören, **19**
Sieg, Christoph, 132
Siegwart, Roland, 46
Sigron, Pirmin, 137

Skutnik, Stefan, 101
Smidt, Sture, 42, 70, 143
Smith, Roy S., 46
Soliman, Mahmoud, 53
Sommerfeld, Markus, **95**, 156
Spieler, Michael, 80
Stastny, Thomas, 46
Steenhuizen, Durk, 145
Stough, Andy, **45**, 120
Svenkerud, Christer, 42, 70, 143
Tabor, Samuel, 76, 97
Takahashi, Yasutake, 84, 115
Tateson, George, 76
Thedens, Paul, **131**, 157
Tiso, Paolo, 127
Toal, Daniel, 81
Todeschini, Davide, 141
Tomita, Takumi, 47
Trevisi, Filippo, **119**
Tulloch, Oliver, **5**, 59, **159**
Tveide, Tallak, 42, 70, **83**, 143
Vallejo, Gillian, **121**
Vermillion, Chris, 117
Victor, Samson, 125
Vire, Axelle, 157
Vollmer, Claus, 101
Waibel, Johannes, 132
Weber, Jochem, **57**
Westenberger, Jelle, 83
Wilhelm, Stefan, 19
Williams, Paul, 43, **145**, **153**
Yamamoto, Hiroki, 47
Yoshida, Shiego, 134
Yue, Hong, 159
Zemp, Cédric, 137
Zhang, Yannan, 43
Zillmann, Udo, 61, 94, 99, 132
Zywietz, Daniel, **110**

Photo Credits

Ampyx Power B.V., 12, 13, 14, 15, 16, 17, 18, 144
Bauer, Florian, 60
Beaupoil, Christof, 146
Beyond the sea®, 77, 78
Charaf, Peter / Race for Water, 54
University of Cranfield, 74
Eijkelhof, Dylan, 126
EnerKíte, 100, 102
FTERO / ETH Zurich, 135, 136
Kitepower B.V., 6, 36, 39, 40, 65, 67, 68, 114
Makani, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32
Perlberger, Michael, 108
Peschel, Johannes, 68
NCSU, 116
NREL, 56
Read, Rod, 58, 158
Skypull AG, 138, 139, 140
Skysails Power GmbH, 52, 129, 130
Studio Roosegaarde, 88, 89, 90
Trombitas, Daniel, 62
TU Delft, 55, 64, 72
TU Munich, 148, 149
TwingTec AG, 103, 104, 106, 107
University of Freiburg, 11
Werij, Henri, 37, 38, 63, 66
Windlift, 44
WINDSLED, 48, 49, 50

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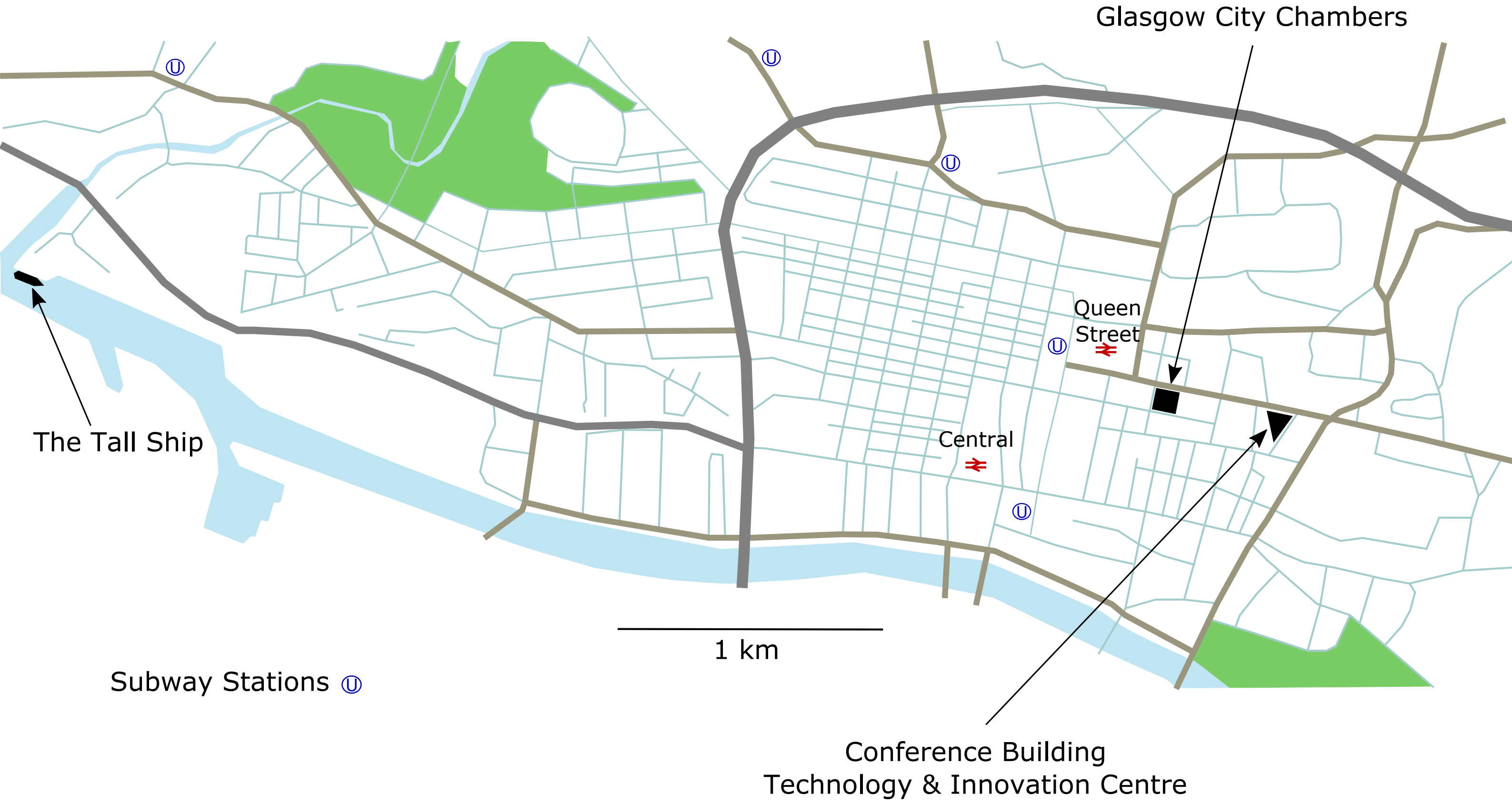

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