AIRBORNE WIND ENERGY CONFERENCE 2024

25-26 APRIL 2024

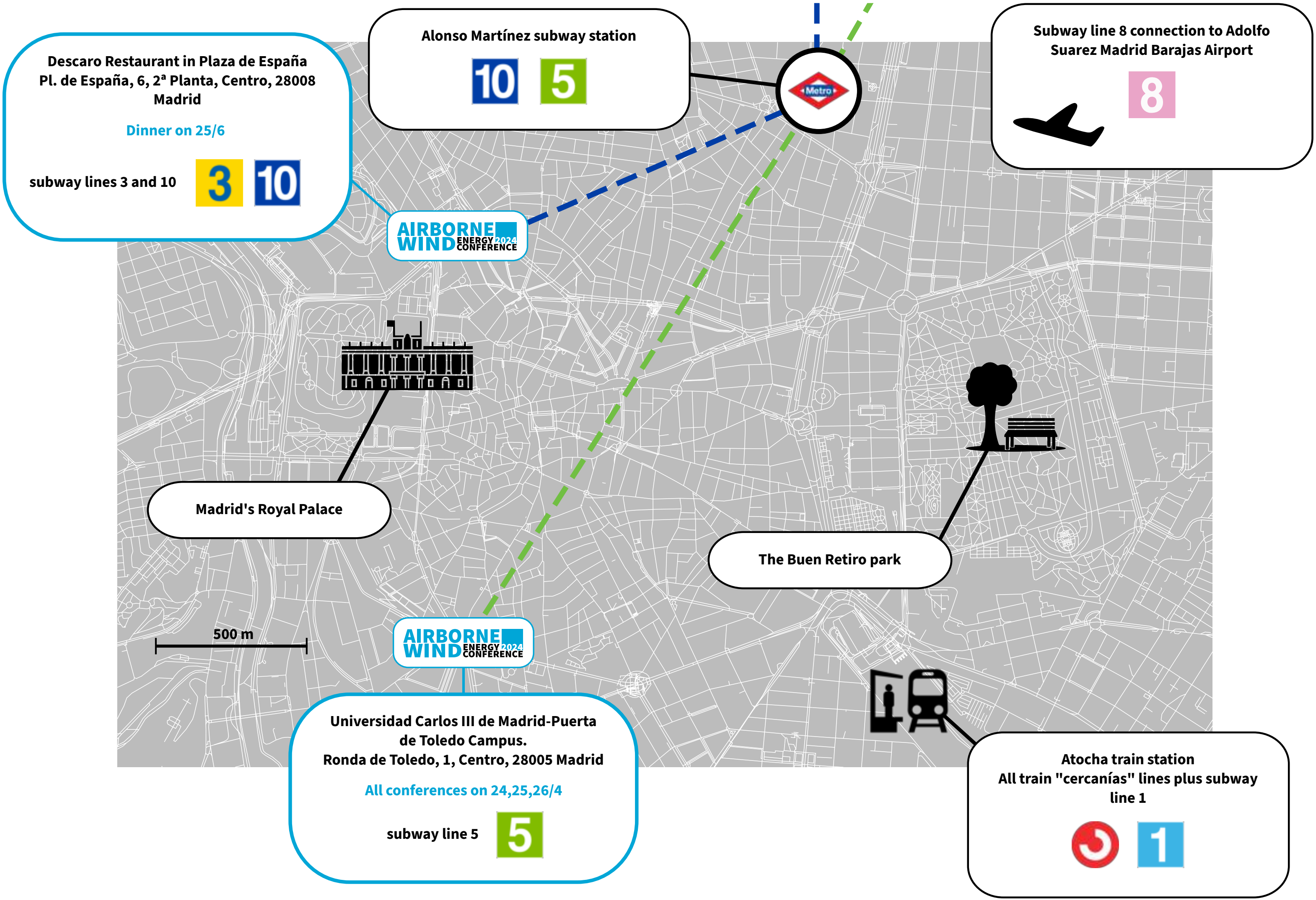
MADRID

Universidad Carlos III

AWEC2024.COM

BOOK OF ABSTRACTS



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Pl. de España, 6, 2ª Planta, Centro, 28008 Madrid
Dinner on 25/6
subway lines 3 and 10
3
10
Alonso Martínez subway station
10
5
Metro
Subway line 8 connection to Adolfo Suarez Madrid Barajas Airport
8
AIRBORNE WIND ENERGY CONFERENCE 2024
Madrid's Royal Palace
The Buen Retiro park
500 m
AIRBORNE WIND ENERGY CONFERENCE 2024
Universidad Carlos III de Madrid-Puerta de Toledo Campus.
Ronda de Toledo, 1, Centro, 28005 Madrid
All conferences on 24,25,26/4
subway line 5
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Atocha train station
All train "cercanías" lines plus subway line 1
1

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BOOK OF ABSTRACTS

Editors
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Technical Program - Thursday, 25 April 2024*

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8:00	REGISTRATION					[FOYER]	
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17:25	END-OF-DAY						
20:00	RESTAURANTE DESCARO					[PLAZA DE ESPAÑA 6 PLANTA 2, 28008, MADRID]	

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

Room naming scheme

Auditorium : LEVANTE
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-1.A.04 : SOLANO
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17:05	Farewell, including Poster Awards				[Levante]	

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

Welcome and Introduction to the Airborne Wind Energy Conference 2024

Gonzalo Sánchez-Arriaga[1], Stefanie Thoms[2], Roland Schmehl[3]
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[2]Airborne Wind Europe
[3]Faculty of Aerospace Engineering, Delft University of Technology

Gonzalo Sánchez-Arriaga
Universidad Carlos III de Madrid

Stefanie Thoms
Airborne Wind Europe

Roland Schmehl
Delft University of Technology

Dear conference participants, dear friends,

Welcome to the 10th International Airborne Wind Energy Conference AWEC 2024! The UC3M Puerta de Toledo Campus, located at the heart of Madrid provides a great environment for two inspiring conference days. Coming together creates the opportunity to make new ideas and collaborations to fly high, while keeping us grounded to the needs and challenges, the airborne wind energy (AWE) sector is currently facing. The program of the AWEC 2024 was composed with particular attention to promoting synergies and exchange of ideas between academia, industry, and stakeholders. We are glad to present:

- Four plenary sessions with keynote talks by prominent speakers working in the field of renewable energy and AWE, spanning policy and strategic visions, industrial and business developments, and academic research:

  Cristina Trueba Alonso, Head of Area, Spanish Ministry of Science and Innovation and Spanish delegate to the SET-Plan Steering Group;

  Paul Veers, Senior Research Fellow at the National Renewable Energy Laboratory (NREL) of the United States and Chief Engineer at the National Wind Technology Center of NREL;

  Sarah Barber, Head of the Wind Energy Innovation Division and Lecturer at the Eastern Switzerland University of Applied Sciences;

  David Lecoque, CEO of the Alliance for Rural Electrification (ARE), the global business association for distributed renewables in emerging markets;

  Romain Gellée, expert in wind and offshore marine renewable energy at ENGIE Laborelec;

  Fernando A.C.C. Fontes, Associate Professor at the Department of Electrical and Computer Engineering, Faculty of Engineering, University of Porto;

  Cristina L. Archer, Director of the Center for Research in Wind (CReW), Unidel Howard Cosgrove Career Development Chair in the Environment, Professor at the Department of Geography and Spatial Sciences and the Department of Mechanical Engineering at the University of Delaware;

  Reinhart Paelinck, Founder of Kiteswarms and Mozaero, with more than fifteen years of experience in R&D of AWE systems, both in academia and industry;

  Alexander Vandenberghe, Head of Innovation at WindEurope;

- Fifteen contributed talk sessions in three parallel tracks with altogether 72 oral presentations.
- One poster session, preceded by plenary spotlight presentations, with altogether 22 poster presentations.
- Two panel discussions, including 12 pitches by industry leaders of the AWE sector.
- An interactive role-playing game, exploring social conflicts that can occur when developing AWE sites.

The high quality of the scientific program is supported by the Program Committee and the work of the anonymous peer reviewers that provided valuable feedback to the

Puerta de Toledo Campus of Universidad Carlos III de Madrid.

authors. This book of abstracts, which acts as a summary of the contributions of the participants and the state of the art of the AWE sector, would not have been possible without the joint effort of authors and reviewers. We sincerely thank all of them. We also thank Ian van Coller for contributing an excerpt of his impressive photographic essay “Climate Work” to this book of abstracts. Acknowledging the commitment of the AWE community, this edition puts a particular photographic focus on the various teams that push the limits of technology development in a worldwide effort to contribute to the energy transition and to combat climate change.

The plenary talks and thematically compiled parallel sessions will take place in four different rooms – deliberately renamed after the famous Spanish winds:

- “Levante” is an easterly wind that blows in the western Mediterranean Sea. This wind is particularly strong in Spain when it blows through the Strait of Gibraltar. For this reason, Tarifa is a pole of attraction for kitesurfers, and “El Cabrito” is one of the oldest wind farms in Spain.
- “Nordés” is the name of a wind that blows from the north in Galicia, which is currently one of the Spanish regions with the highest renewable energy production.
- “Solano” is the wind blowing from the east in Castilla la Mancha, where locals used windmills since the 14th century. They inspired Miguel de Cervantes in the Spanish epic novel *El Ingenioso Hidalgo Don Quijote de la Mancha*.
- “Tramontana” is a cold and strong wind that blows in the northern Mediterranean coast (Catalonia and Balearic Islands), among others also in Girona, where the first Spanish wind turbine was installed in 1984 with a power of 15 kW.

In the last 40 years, wind turbines were scaled up more than two orders of magnitude in terms of rated power output, reaching a proud 10 MW for the currently largest commercial turbines. With an installed wind power capacity of about 30 GW, Spain is one of the leading wind power producers worldwide. In 2013, it was the first country to have wind power as its primary source of electrical energy. These figures were unthinkable when the first wind turbine was installed in Girona in 1984. In fact, at that time, some Spanish politicians claimed that wind turbines made no sense and the future of energy was fossil and nuclear. History often repeats itself and therefore we are looking forward to complement the established technologies with a new pillar for the future energy mix. AWE systems reached the tens of kW about a decade ago and today fully autonomous commercial products exist in the range of 150 kW. The AWE community is constantly evolving and continuously growing, thanks to the establishment of new research groups and incoming actors from the private sector. The currently ongoing Task 48 of the IEA Wind Technology Collaboration Programme (TCP) is a great example of multidisciplinary, multi-sector, international collaboration, and the AWEC 2024 presentations, fixed in the Book of Abstracts are indicators for the maturity reached in the AWE sector.

Spain and UC3M did not take part in the emerging phase of AWE technology but are prepared and can contribute extraordinarily to its stabilization and further development. Besides research, Spain offers a solid industrial framework and a long track record in wind energy that can boost AWE system development. Due to geographical reasons, the country is also suitable for hosting initial test sites.

The venue, Puerta de Toledo Campus, specializes in hosting international conferences and UC3M educating postgraduate students in economics, business, and law. Besides being at Madrid's heart, this offers a unique environment for fruitful discussions and a conference, dedicated to a technology focussing on industrialization and commercialization. In fact, new ideas and networking is strongly fostered by the social program that includes

- a welcome cocktail on 24 April at the Puerta de Toledo Campus;
- lunches and coffee breaks on the conference premises;
- a banquet at the *Descaro* restaurant, located at Plaza de España, one of Madrid's most emblematic locations.

The event would not have been possible without its sponsors (to learn about on pages 8–9), to which we express our sincere gratitude. We also warmly thank the local contributors of UC3M, in particular Ana Andaluz (logistics), as well as Francisco Cruz Pérez and Juan Fernández Lozano (both book editing).

We wish all AWEC 2024 participants a fruitful and inspiring experience in Madrid and much pleasure in reading this book.

Sincerely,

Gonzalo Sánchez-Arriaga
Universidad Carlos III de Madrid
Leganés, Madrid, Spain

Stefanie Thoms
Airborne Wind Europe
Brussels, Belgium

Roland Schmehl
Delft University of Technology
Delft, The Netherlands

Institutional Sponsors

Universidad Carlos III de Madrid Established in 1989, UC3M offers a broad range of BS, MS, and PhD programs in engineering and social sciences and law. According to the U-Ranking 2023, UC3M is one of the only two Spanish universities that are ranked in the top ten in teaching, research and innovation. UC3M has a strong international profile. It offers a broad range degree programs in English, nearly 20% of its students are international, and it is the first university in Spain and the third in Europe in the number of its students participating in the Erasmus program. AWEC 2024 is co-organized and co-hosted by the Aerospace Engineering Department and the Electrical Engineering Department, who have complementary expertise on AWE research.

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 2023 QS World University Rankings, it is the top-ranked university of the country and the third-best university worldwide in the field of engineering and technology. 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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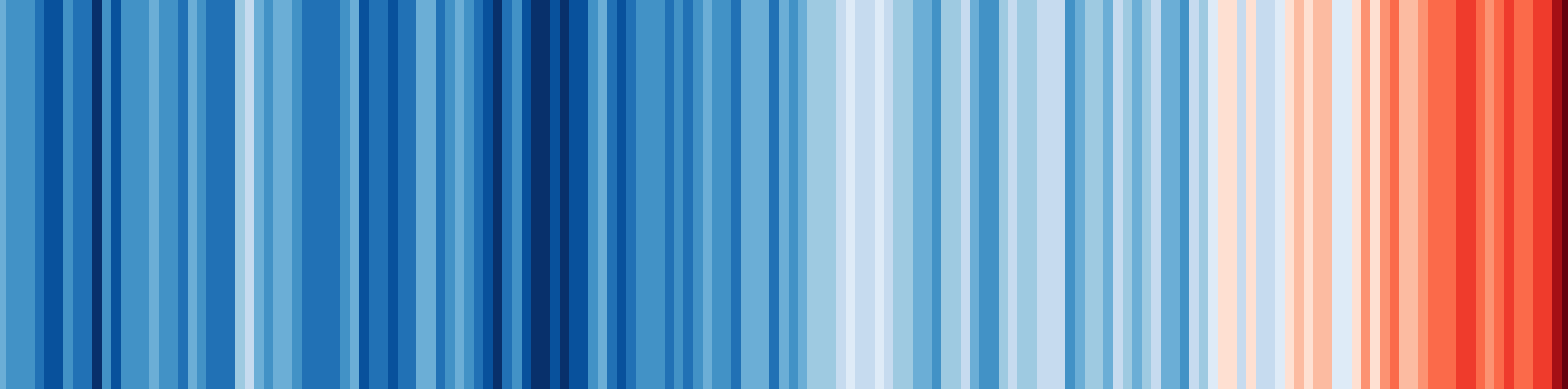
- Chris Vermillion, University of Michigan, USA
- Jochem Weber, NREL, USA
- Hong Yue, University of Strathclyde, UK

OEM Panel I "Soft & Semi-fixed Wing Systems"
Moderator: Kristian Petrick, Airborne Wind Europe

- Mark Hoppe, Skysails, Germany
- Eduard Ijsselmuiden, Kitepower, Netherlands
- Florian Breipohl, EnerKíte, Germany
- Giorgio Sella, Kitenrg, Italy
- Roderick Read, Windswept, United Kingdom
- Klaus Heudorfer, on behalf of Oceanergy, Germany

OEM Panel II "Fixed-wing Systems"
Moderator: Kristian Petrick, Airborne Wind Europe

- Thomas Hårklau, Kitemill, Norway
- George Hanna, TwingTec, Switzerland
- Christof Beaupoil, SomeAWE, Spain
- Florian Bauer, Kitekraft, Germany
- Garret Smith, Wind Fisher, France
- Reinhart Paelinck, Mozaero, Netherlands



Warming stripes graphic depicting annual mean global temperatures (1850-2018, from World Meteorological Organization data).

AWEC 2024 is dedicated to all climate change victims in the world

Climate disasters claimed thousands of lives globally in 2023 and forced people to leave their homes. Human-induced climate change is causing dangerous and widespread disruption in nature and affecting the lives of billions of people around the world.

Climate change is a grave and mounting threat to our well-being and a healthy planet. Our actions today will shape, how people adapt and nature responds to increasing climate risks.

Increased heatwaves, droughts and floods are already exceeding plants' and animals' tolerance thresholds, driving mass mortalities in species of flora and fauna. These weather extremes are occurring simultaneously, causing cascading impacts that are increasingly difficult to manage. They have exposed millions of people to acute food and water insecurity, especially in Africa, Asia, Central and South America, on small Islands and in the Arctic.

To avoid mounting losses of life, biodiversity and infrastructure, we need to take ambitious, accelerated action to adapt to climate change while making rapid, deep cuts in greenhouse gas emissions.

Climate change is a global challenge that requires local solutions. The urgency for climate action, focusing on equity and justice, must be addressed by adequate funding, technology transfer, political commitment and partnership, leading to more effective climate change adaptation and emissions reductions.

The scientific evidence is unequivocal: climate change is a threat to human well-being and the health of the planet. Any further delay in concerted global action will miss a brief and rapidly closing window to secure a liveable future.

The Airborne Wind Energy community is committed to fighting climate change and providing clean, renewable energy around the world.

Ian van Coller

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The Transparency of Time

Ian van Coller
Montana State University

Since 2012 I have been photographing landscapes around the globe that are rapidly changing due to climate change. These endeavors have focused primarily on glacier landscapes and other archives of earth's past such as ancient trees and mud cores. I am particularly entranced by the beauty of glacier ice and am fascinated with it as an archive of earth's atmosphere. Approximately 10% of glacier ice is air, that was trapped by falling snow, that then turned to firn, and then ice. In 2019 I was able to accompany a group of scientists to the Allan Hills of Antarctica where I was able to photograph them retrieving the oldest ice ever found by humans, approximately 3-4 million years old. The air in that ice can tell us quite precisely what earth's atmosphere looked like at that point in earth's past, a time when CO2 levels were similar to what they are now, and sea levels were at least 10 meters higher. As the climate warms and the glaciers melt, we are forever losing that essential archive to earth's past climate.

The rapid transformations brought on by climate change have compressed and conflated human and geologic time scales. I employ the metaphor of glaciers as "time machines" that capture, compress and conserve remnants of the planet's ancient atmosphere. Consequently, I have become interested in how human conceptualizations of deep time can be explored through visual exploration of glacier ice, the ephemeral contents of which can tell us much about our past, as well as our future. I have come to see my projects as both monuments and memorials to these vanishing landscapes.

I identify as an aesthetic activist. Beauty is a strong persuader, and I find great personal solace in the beauty of the natural world. I approach much of my work with the specific intent to reengage ideas related to the (Romantic) Sublime, which I see now as the Apocalyptic Sublime. As we face an impending environmental apocalypse, there is significant value in rediscovering Awe in Nature, and helping others (re-)discover that too. If people don't care about the natural world, it is all over. Our increasingly technological and urbanized world further serves to separate us from nature. Artists can and should help people bridge that gap and bring empathy to what Nature is left.

Photo essay:

Page 12: from the book "Kilimanjaro: The Last Glacier (2016/2018)"

Page 14: from the book "Bristlecones of the Long Now (2018/2019)"

Page 15: from the book "Kilimanjaro: The Last Glacier (2016/2018)"

Page 16: from the book "Kilimanjaro: The Last Glacier (2016/2018)"

MONTANA STATE UNIVERSITY

Media event on the UC3M Campus de Leganés, showcasing Kitepower's $40\ m^2$ kite (April 2024).

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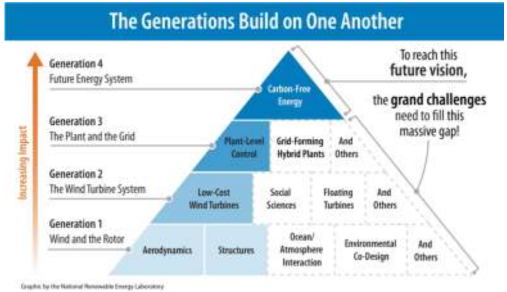
Generations in the Progress of Wind Energy: Foreshadowing a Pathway for Airborne Technology

Paul Veers
National Renewable Energy Laboratory

Traditional wind energy systems have progressed from stand-alone operations for off-grid and water pumping applications to a major source of global electricity supply over the last half century. An examination of this history could be informative for the future path of airborne wind systems. Figure 1 illustrates how achieving an increasing impact with wind energy requires an expanding base of scientific knowledge. While each generation's achievements increased wind energy's impact (shown in the blue blocks on the left side of the pyramid in the figure), some underlying science was left unresolved (shown in the white blocks on the right in Figure 1). In this work, Generation 1 delivered working energy conversion systems that can survive the most challenging operating conditions and focused on energy extraction with the rotor. The rotor also must be able to protect itself from extreme winds autonomously to enable continuous, unrestricted operation. Generation 2, the installation of large numbers of machines, requires low-cost and reliable wind turbines, and expanded the scope from aerodynamics to structural system optimization. Generation 3 is beginning to provide controllable wind plants that support the grid, requiring new capabilities in electrical and plant-flow controls. The aspirational goal of Generation 4 is a carbon-neutral future energy system, with deployments expanding into deep waters offshore and into low-resource sites on land that further expand the technical, social, and environmental demands. Wind energy can be the foundation for the fourth generation, but not until the gap left behind by the previous generations is addressed.

These generations will be required of airborne wind as well, but the sequencing may be somewhat different. For example, airborne wind uses less construction material (affecting system cost trade-offs) and the grid integration and support requirements are currently in flux. However, getting past Generation 1 remains crucial.



Generations in development leading up to wind as a foundation to a carbon-free energy system. Taken from [1].

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Upwind team of the University of Porto (December 2023).

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Development of a Fully Automated Airborne Wind Energy System at University of Porto

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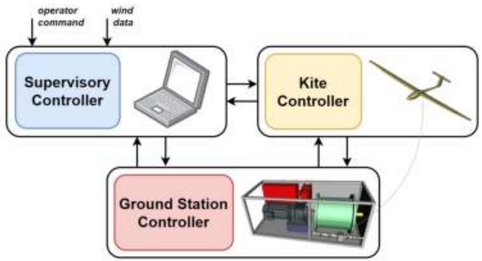
In this talk, we discuss the different stages of development of an Airborne Wind Energy System (AWES) that has been evolving as part of the UPWIND project at University of Porto. Our current system is a small-scale prototype, with on ground-generation, using a fixed-wing aircraft, operating crosswind, taking off and landing in a circular motion.

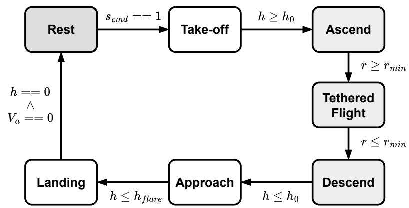
The stages of the development process range from the initial activities of modelling, simulation and optimization; the synthesis of control laws for both the kite and ground station; the design of the supervisory controller governing the transition between operating phases; as well as the prototype assembly.

More recently, we have been dedicating a significant part of our efforts into the design and implementation of an automatic circular takeoff and landing scheme. This last development is an essential step in achieving full automation of the entire process.

We acknowledge the support of FCT/MCTES-PIDDAC, through the projects KEFCODE, doi:10.54499/2022.02320.PTDC, and UPWIND-ATOL, doi:10.54499/2022.02801.PTDC.



The overall control architecture and its controller modules.



The several operational phases of the Airborne Wind Energy System with transitions governed by a Supervisory Controller.

Presenting at the AWEC in Milan (June 2022).

A Grand Vision of Wind Energy Digitalisation

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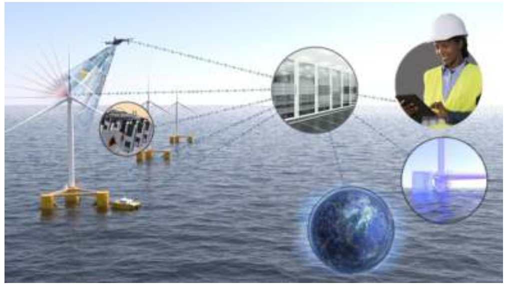
A successful digitalisation of the wind energy sector is key to reducing costs and increasing the value of wind energy. Digitalisation refers to creating value from data, for example by utilising AI methods to make faster decisions, by implementing easy-to-install IoT systems to monitor assets or by using advanced data analysis techniques to create innovative new business models. Data is becoming cheaper and easier to create, and thus more and more is becoming available. Organisations are therefore increasingly under pressure to exploit this data for business advantage.

In a recent review paper coordinated by IEA Wind Task 43 (Digitalisation) [1], the Grand Challenges in the Digitalisation of Wind Energy were defined as: (1) Creating FAIR data frameworks (FAIR: findable, accessible, interoperable and reusable [2]); (2) Connecting people and data to foster innovation; (3) Enabling collaboration and competition between organisations. This talk presents a new Grand Vision of Wind Energy Digitalisation, which is based on the Grand Challenges and on the work being carried out within IEA Wind Task 43. The Grand Vision of Wind Energy Digitalisation includes two aspects:

1. A world in which data analysts spend 80% of their time carrying out value-creating activities, rather than 80% of their time with data wrangling.
2. A world in the wind energy sector represents a diverse, inclusive, barrier-free digital environment in which everyone can flourish.

In this talk, I will discuss the details of these two aspects and then explore how the topic relates specifically to Airborne Wind Energy Systems.



Digitalisation in action. In this future floating wind energy plant, digitalisation enables a plant manager to take data-based decisions in real time, increasing safety and reducing the cost of energy. Image credit: NREL graphics team.

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Airborne Wind Energy Simulation Software - a Review

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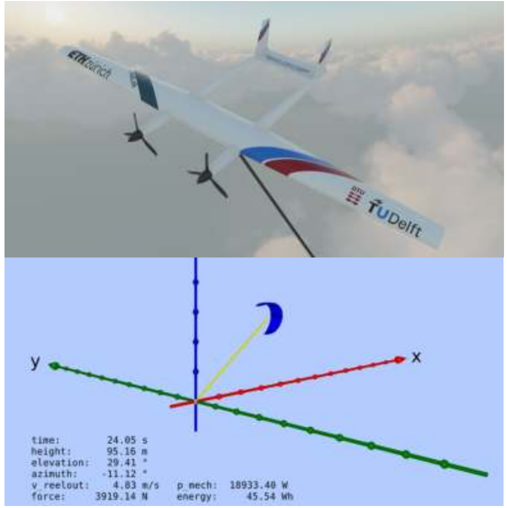
Various software packages exist for the simulation of airborne wind energy systems, but are they good enough to answer the basic question: How much energy can be harvested with a system of a given size at a given location?

I give a review of nine software packages with a focus on dynamic simulators, and also include one software that uses a quasi-steady model for wind resource analysis. Only fully or partially open-source software that allows the simulation of an AWE system is included in this review.

Dynamic simulators can be used for the design of a system, control research and to derive a power curve and cut-in and cut-out wind speeds. Furthermore they can be used to investigate the loads that have an impact on the lifetime and costs of a system, and also to derive other parameters that are needed to create and parameterize a quasi-steady simulation that can be used for wind resource analysis.

It was found that many of the software packages are very hard to install and/or unmaintained. Some of the simulators neglect the impact of the ground station or operate only at a few, discrete wind speeds which limits their use to derive a power curve. For the three major AWE concepts, pumping mode rigid wing, pumping mode soft wing and airborne generators working simulators are available, but many wishes remain open.

This work was inspired by our participation in the AWE working group of the International Energy Agency [2,3].



MegAWES and KiteSimulators.jl

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INNOVATIONSCAMPUS MOBILITÄT DER ZUKUNFT

Methodology to Compare the Potential of Two Concepts for an Energy Ship Using Airborne Wind Energy

Nicole Frommer, Po Wen Cheng
University of Stuttgart

This study focuses on flexible wing systems in the context of airborne wind energy (AWE), which holds promise for offshore wind energy generation due to its high mobility and ability to harvest wind energy from deep sea areas. Currently, various concepts exist for offshore energy ship systems utilizing AWE.

This work outlines a methodology to compare two distinct operational modes using mid-fidelity simulations. These operational modes diverge in how they harness the energy of the kite system.

The first concept employs a kite operating in a pumping mode, featuring adjustable tether lengths, while additional propellers propel the ship forward (Fig. 1). This concept utilizes Van der Vlugt et al. [1]'s quasi-steady kite model, which is integrated with two-dimensional drag force and velocity triangles depicting ship motion.

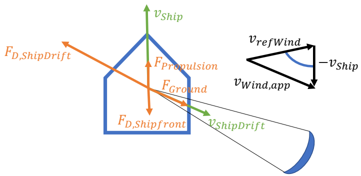

Figure 1: Concept sketch of the pumping mode, top-view

The second concept operates in a propulsion mode, where the kite pulls the ship, and underwater hydraulic turbines generate power from the ship's velocity (Fig. 2). This model is based on Pelz et al. [2]'s approach, which utilizes sails rather than an AWE system. This second model calculates forces using the force balance equation aligned with the ship's motion direction. This calculation contains the drag forces from the ship and hydraulic turbines, in addition to the propulsive force generated by the kite's interaction with the ship.

Detailed explanations of these modelling approaches will follow, accompanied by a discussion of the assumptions and limitations of this study. This work will contribute better possibilities to compare different operational principles, leading to better estimations of the influence of parameters on the performance of the system.

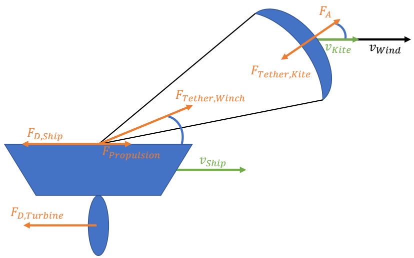

Figure 2: Concept sketch of the propulsion mode, side-view

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Deep Learning Investigation For Automatic Control and System Characterization for AWES

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CT Ingenieros

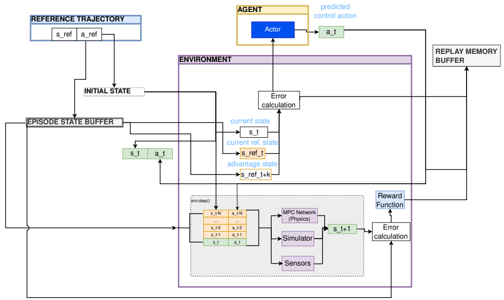
Automation plays a central role in AWE [1]. Despite extensive exploration of automatic control systems for AWE over recent decades [2], the integration of emerging machine learning technologies remains underdeveloped.

Reinforcement learning, a subset of machine learning, offers a spectrum of methodologies within AWE research. Some studies, like [3], emphasize power prediction instead of addressing optimal control or dynamic analysis. In contrast, other research, exemplified by [4], explores reinforcement learning, primarily in a theoretical context. This machine learning approach empowers machines to make decisions founded on accumulated experience.

The aim of this project is the creation of an automatic controller for AWES through deep and reinforcement learning. A data-driven model captures system dynamics, providing insights into the influence of different parameters. The data used to construct these models is a blend of experimental and simulated data. Simulated data is sourced from an AWE simulator developed within the CT simulation environment CT-sim. Experimental data is collected using a test bed jointly designed by CT and UC3M, deployed in the FTC area in Madrid and Castilla y Leon [5]. The tested configuration involves a 3-line machine with a delta kite, with a particular emphasis on flight control.

The developed models will undergo testing within a simulated environment and subsequently be validated in real-world test bed operations.

This project is for the 2021 call of the "Plan de Recuperación Transformación y Resiliencia" (PTRP) of the Spanish government and is funded by the EU Next generation program.



Reinforcement algorithm diagram

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A Sensor Fusion Approach for Accurate Wind Estimation and System Characterization

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Accurately estimating wind speed conditions at different operational heights is crucial for assessing a kite's flight state and controlling its trajectory effectively. Currently, wind measurements are typically taken at ground level and extrapolated to the kite's flying height. However, this approach overlooks atmospheric wind gradient and veer, leading to errors.

An alternative approach involves the installation of airborne flow sensors, specifically pitot tubes and wind vanes, to capture the apparent velocity vector, from which wind velocity can be calculated [1]. Nonetheless, substantial inaccuracies can occur, particularly if the pitot tube is significantly misaligned with the apparent velocity. The challenge becomes more pronounced in the case of soft-wing kites, where the entire structure is deformable, further contributing to potential inaccuracies.

To address this problem, the present study explores a sensor fusion approach. This technique combines real-time measurements with a detailed model of the system [2], incorporating factors like the tether's elasticity and the weight and inertia of the kite control unit, combined with an Extended Kalman Filter (EKF) to precisely determine the wind conditions at the kite's flying height. This integrated approach aims to provide a more accurate and reliable estimation of wind parameters, mitigating the limitations associated with traditional methods and enhancing the overall control and trajectory optimization of kites during flight.

Furthermore, this methodology also enables a comprehensive characterization of the entire flight state of the system, including aerodynamic coefficients and tether sagging. These insights can be harnessed for various purposes, such as system identification and the validation of numerical models pertaining to the system. In essence, it offers a more holistic understanding of the system's performance and behavior.

Moreover, the versatile nature of the EKF permits the integration of various sensor setups. This adaptability is particularly valuable in determining the minimal sensor configuration required for accurate wind condition estimation.

As part of the Meridional project [3], several experimental campaigns will be executed, including measurement campaigns from LiDAR and drone-based systems. These campaigns will allow for the validation of the described analysis tool and the identification of the most effective sensor arrangement, which can rely solely on kite position, speed, and tether force.

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This work has been partially supported by the MERIDIONAL project, which receives funding from the European Union's Horizon Europe Programme under the grant agreement No. 101084216.

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On the Kite-Platform Interactions in Offshore Airborne Wind Energy Systems: Frequency Analysis and Control Approach

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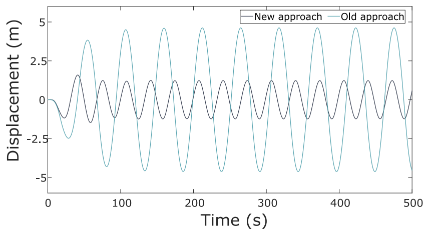
Politecnico di Milano

Airborne Wind Energy (AWE) research is currently focused on onshore applications to ensure the technology is mature enough before moving to the offshore environment. However, the marine environment will be attractive in future: this location is ideal for large-scale wind farms as it reduces issues with land occupation and community opposition. This study aims to explore the offshore kite-platform interaction, identify operational criticalities, and propose control strategies to address potential problems such as increased fatigue loads and damage.

The system includes a 360 m^2 soft-wing kite and a 10-meter-deep spar with four mooring lines. A point-mass model [1] is chosen for the AWE system, and a kite trajectory control strategy using two target points is employed [2]. The tether is modelled as a nonlinear spring. On the other hand, the platform model follows the assumptions of linear potential flow theory. The NEMOH software [3] and a system identification procedure are used to determine the hydrodynamic parameters.



Platform sway displacement with old and new control approach.

The two subsystems are linked by the tether, which makes the traction force the main subject of analysis. We focused at first on how waves affect the cable force and the kite's motion, highlighting the differences between onshore and offshore operations with different wave intensities. We also examined the platform resonances and discovered that the tether force frequency may belong to the same frequency range as the resonances. The proposed solution suggests identifying the trajectory targets for the kite's flight by choosing eight-path frequencies far from the platform resonances. The trajectory's frequency has to be maintained while the tether length increases; consequently, the target points will change during the traction phase.

We used MATLAB to simulate the system and test various wave types. Our simulations confirmed that resonance causes an increase in platform movement if the targets remain unchanged. The suggested approach proved to be effective in mitigating this issue.

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Toyota Mothership prototype (June 2023).

Toyota Mothership prototype (June 2023).

Toyota Mothership avionics prototype (June 2023).

Toyota Mothership team with prototype (June 2023).

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Toward Future Aerial Platforms
MOTHERSHIP PROJECT
SINCE 2018

TOYOTA

Development and Testing of an Airborne Wind Energy System

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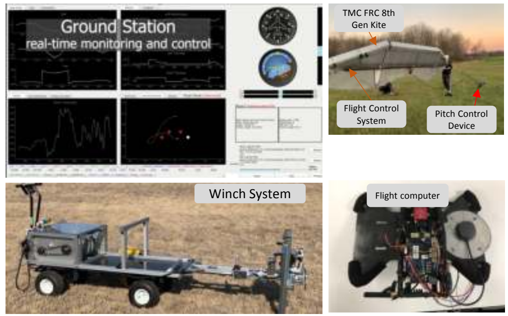
A research team from Toyota is currently exploring the potential of a futuristic concept known as the ’Mothership,’ which is a large, tethered wing designed to fly at altitudes of 10km or higher [1]. This aerial platform is envisioned for various missions that require long endurance and stationary capabilities including airborne wind energy (AWE) harvesting.

The Toyota team has developed a small-scale proof-of-concept for a single tether, ground-gen AWE system. The kite, with a wing area of 6m2 and a weight of 4kg, is equipped with a flight computer, four control surfaces positioned near the leading edge on each wing side, and a pitch control device. The AWE system also includes a winch system with a 1.5kW generator and a ground station for real-time monitoring and control.

Phase 1 (automated pumping cycle) and Phase 2 (parametric experiment) tests have been successfully accomplished by the team. The upcoming milestone is Phase 3, which encompasses evaluating an enhanced path planning algorithm, upgrading the winch system, and conducting system identification for flight control systems, with an anticipated completion date in March 2024.

The presentation will provide insights gleaned from prototype AWE system tests, comparative assessments with simulation outcomes, and the introduction of advanced features under development.

Images superimposed to depict the figure-of-eight flight path of the AWE kite during Phase 2 test (March 2023).



TRINA prototype AWE system.

References:

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Toyota Mothership control spoiler prototype (June 2023).

CPECC parachute-based prototype during take-off.


CPECC power unit at Jixi, Anhui Province, China (December 2023).

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A Parachute-Based Airborne Wind Energy System and Aerodynamic Characteristics

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High-altitude wind energy has abundant resources, high power densities, and more stable wind direction and speed compared to lower altitudes near the ground. In this work, we proposed an airborne wind energy system (AWES) based on parachutes, which utilizes a cascade of parachutes exploiting aerodynamic drag forces. For this technical approach, the generator is located on the ground, and the parachute-based power kites move upwards under the action of wind forces, driving the tether to pull the motor/generator, converting mechanical energy into electrical energy. After the airborne component ascends to the predetermined height, the power kite is de-powered, and the motor/generator reverses, retracting the kite to the deployment altitude. Currently, we have completed a 2.4MW pilot test in Jixi, Anhui. Such a conceptual design has a high power-to-weight ratio of the aerial components and is easy to scale up (possibly to the order of 10 MW, much greater than the nominal power of other AWES techniques).

The development of this technical approach requires breakthroughs in key technologies such as efficient wind energy capture, efficient energy transmission between air and ground, long-term stable coordinated control, integrated design,and demonstration. In the parachute-based AWES, the shape of the parachute and the distance between neighboring parachutes are key factors affecting the flow field, the aerodynamic drag force, and hence the efficiency in harvesting wind energy. It is conceivable that wake separation induced by the parachute cascade could be a major threat to the efficiency of downstream parachutes. However, due to the limited research in this direction, the wake influence on the whole parachute-based AWES unit remains largely unclear.

To tackle this problem, we numerically investigate the thrust coefficient (Ct) of the parachute cascade with a nominal power of 2.4 MW. The impacts of different states of the parachutes (open or closed) and the distance between neighboring parachutes are quantified. The results clearly manifest a large-scale separation flow that significantly damages the performance of downstream parachutes. It is demonstrated that an increase of the distance of neighboring parachutes (to 1000 m) substantially mitigates the wake effect and enhances the lift force of the whole system.

A parachute-based airborne wind energy system test.

UC3M and CT teams during a flight campaign (July 2023).

UC3M Airborne Wind Energy group (March 2024).

UC3M and CT Ingenieros flight test rig during testing (April 2023).

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A Small-Scale and Multipurpose Airborne Wind Energy Prototype

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Testbeds for AWE machines and full prototypes are being developed by research institutions and companies to study the system dynamics and control, characterize the aerodynamics of the aircraft, and investigate the mechanical-to-electric power conversion, among others (see a review in [01]). At UC3M, the first testbed aimed at the aerodynamic characterization of leading-edge inflatable (LEI) kites and delta kites [2] was recently updated with an automatic control system [3]. Leveraging on the experience gained with the testbed, this work presents an upscaled AWE prototype developed in close collaboration by UC3M and CT Ingenieros.

The yo-yo prototype, aimed at reaching 5 kW mean-cycle power generation at rated wind speed, has been designed to be a versatile platform for the testing of 1-line, 2-line and 3-line tethered aircraft (fixed wings, LEI and delta kites) and carry out research on dynamics, control and aerodynamics. It allows for the real-time measurement of the full kinematic state of the aircraft through onboard avionics and a camera vision system, in-situ measurement of the aerodynamic velocity, tether tensions, wind velocity, elevation and azimuth angles of the tethers, and full state of the control and electrical subsystems. The platform in its 1-line configuration is compatible with the integrated pod concept presented in [4]. Details of the electrical subsystem and its control are given in [5]. This work presents the design and top-level architecture of the prototype together with the results of a test campaign to validate its performance in open- and closed-loop control.

UC3M's testbed mobile platform and prototype render.

References:

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[4] González-García, J., et al.: AWE yo-yo fly-actuated machine control system using actuators to modify the geometry of the kite's bridle. AWEC 2024, Madrid, Spain.

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wind fisher

gipsa-lab

Dual-Cylinder Magnus Effect Kite: Fixed-Distance Flight Tests at Wind Fisher

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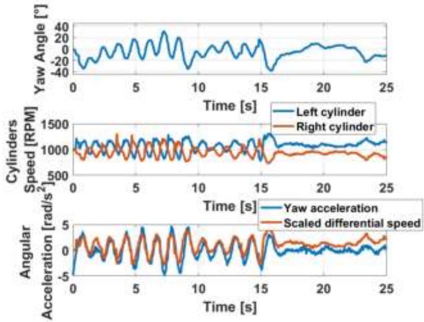
Today, most of the systems that we see in the Airborne Wind Energy landscape use similar designs based on soft or rigid kites. At Wind Fisher, we are working on a different system based on a dual-cylinder Magnus effect kite. Two helium-inflated balloons driven in rotation from the ground using the same drive-train units used to generate electricity. This pitchless, lighter-than-air cylindrical design provides a better gust response [1] and greatly simplifies the takeoff and landing phases. Moreover, it offers a good compromise between the performance of a rigid kite and the practicality of a soft kite [2].

Fixed-distance flight test with Wind Fisher's developmental prototype towed by a vehicle (left). Prototype ground-station (right).

Given that limited research has been conducted on this type of architecture. One of Wind Fisher's initial priorities was to design and build a small-scale prototype, in collaboration with the Gipsa-lab for the instrumentation and control aspects. The prototype is used as a test-bed to study the kite's behavior, test control algorithms, collect data, and validate simulation models. Fixed-distance flight tests were carried out either in real wind conditions or with artificially generated wind using a mobile wind tunnel setup where the ground station is attached to the roof of a vehicle, and the kite is towed at a constant speed, allowing to generate a more predictable wind. During the last flight tests, the prototype was successfully stabilized using a yaw control loop, previously validated in simulation. The presentation will give an overview of prototyping and flight testing at Wind Fisher, along with test results and conclusions.



Flight data showing the control of the yaw angle, the differential rotational speed acts on the angular acceleration and approximately stabilizes the yaw around 0° despite turbulent wind conditions.

References:

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Development of a Winch Separate-Type Tension Power Generation Device for Ground-Gen

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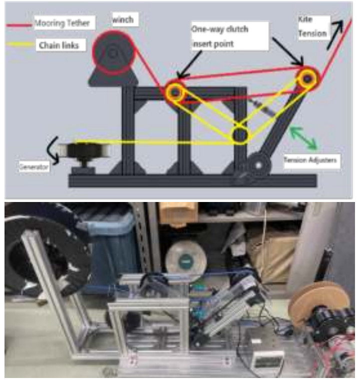
In this time, a novel approach to power generation is proposed, differing from traditional methods by separating the power generator and the winch into distinct units.

With a winch integrated, altering mechanical elements such as gears for kite flight control presents challenges. This method offers improved expandability and maintainability, as it is less likely to impact flight control mechanisms. Moreover, the utilization of existing winches aims to reduce costs.

Due to the specialized separation approach for power generation Ground Stations (GS), it is possible to design according to the power output specifications provided by generator manufacturers at various rotational speeds. For instance, in the experimental model used in this study, experiments were conducted to increase the generator's rotational speed while maintaining a constant input power by adjusting the number of teeth on the chain sprocket.

In the initial experiment, the power generation efficiency was approximately 13%, but it was possible to increase it to 23%. This indicates significant expandability. Furthermore, considering that the power generation efficiency of a winch-integrated GS developed previously using the same generator was approximately 17%, it is believed that this separation method offers superior energy conversion efficiency.



Top: Schematic diagram of winch separate-type tension power generation device, Bottom: Photo of experimental devic

References:

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Development of an Airborne Wind Energy Testbed in the United States

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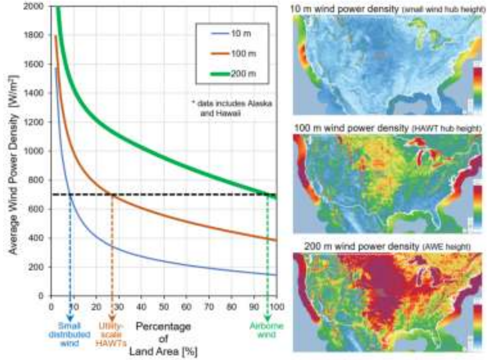
Transformative airborne wind energy systems (AWES) are now technically and economically viable due to efforts of many startup companies and parallel advancements in other unmanned aerial systems. Future AWES will work at heights with stronger, more consistent and widespread wind resources (see Figure). Along with a low transportation burden and strategies for storm avoidance, these advantages should facilitate future widespread, resilient, utility-scale deployment on- and off-shore, and offer significant impacts to deliver renewable power to historically disadvantaged communities. These also make AWES attractive for disaster-relief deployment [1].

Following the European creation of the first AWE test hub in Bangor Erris, Ireland, one or more potential AWE testbed sites are being identified in the U.S., open to any company for testing and validation. Previously identified challenges include "space, instrumentation, and expert personnel" and facilitating "collaboration among stakeholders to address airspace restrictions" [2].

Currently three tiers are envisioned: i) a very low TRL demonstration site, targeted to an educational institution with mutual outcomes for students and companies, ii) a well-instrumented site (lidar, met tower, power generated/consumed) to validate performance, reliability, and durability with produced power distributed at no or low cost to supplement operations, iii) an advanced site for airspace conflict studies. Feedback on social and ecological impacts are currently being collected, as are strategies for U.S. Federal Aviation Administration collaboration. These preliminary findings will be shared for feedback from AWE companies and IEA Task 48 members.

This work is supported by the U.S. DOE Wind Energy Technologies Office Incubator program. Sandia National Laboratories is managed and operated by NTESS under DOE NNSA contract DE-NA0003525.



U.S. wind resource as a function of land and near-offshore* surface area, with comparison of deployment of representative technologies at 700 W/m². Data from the Global Wind Atlas [3].

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[1] Naughton, B., Houchens, B., Summerville, B., Jimenez, T., Preus, R., Reen, D., Gentle, J. and Lang, E., Design Guidelines for Deployable Wind Turbines for Defense and Disaster Response Missions. J. Phys.: Conf. Ser. 2265 042074 (2022).

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[3] https://globalwindatlas.info

SkySails Power system in operation (July 2023).

Skysails Mauritus team (July 2022).

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Airborne Wind Energy Sites in Continuous Operation

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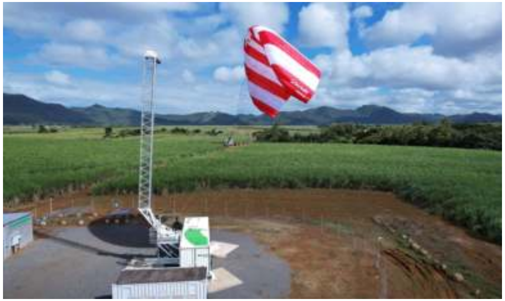
SkySails started out to operate kites for propulsion in 2006 and is developing Airborne Wind Energy (AWE) systems since 2016. Now, SkySails Power has managed to move from single operations of R&D systems to permanently installed AWE sites.

The systems in Klixbüll (Northern Germany) and Mauritius have launched operation in 2019 and 2021 respectively. Both feed produced energy into the local low voltage grid. The systems are operated between 1-3 shifts per day and used for research and development as well as endurance operation.

This is a major milestone for the entire industry as the technology is no longer in an experimental stage but has gathered experience and data from long-term operation. SkySails has learned to improve logistical processes, train local technicians, improve the spare parts supply chain and operate within the guidelines of local grid requirements.

During this presentation, SkySails will provide insights into the learnings of continuous operating AWE sites with regards to:

- Technological findings and advancements [1,2]
- Grid connection [2]
- Social acceptance [3]
- Operator training
- 3-shift operation
- Collaboration with local authorities.



SkySails Power System operating in Mauritius since 2021.

References:

[1] IEC 61400-1, Wind energy generation systems – Part 1: Design requirements.

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[4] Glossary – Airbornewindeurope, 10/2023. https://airbornewindeurope.org/glossary-2/

SkySails POWER

SkySails Power system nightflight with the moon (January 2024).

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AWE Resources over Spain: Potential Added Value with Respect to Conventional Renewables

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In the way towards fully renewable power systems, the variability of conventional renewables represents a fundamental challenge. One of the options to tackle this issue is to exploit the complementarity between different renewable energy sources and technologies. The aim of this study is to analyse the potential added value of AWE resources over Spain, in terms of temporal complementarity to mainstream renewables (onshore wind and photovoltaic energies) or good adaptation to demand.

Using data from a high resolution reanalysis (CERRA, Copernicus European Regional Reanalysis) and the AWERA tool [1] for analysing AWE resources, complementarity between AWE resources and conventional renewables is evaluated using actual PV and wind energy production data from the Spanish Transmission System Operator (Red Eléctrica Española), while demand data from the same source are used to explore adaptation to demand.

We focus on the summer season. This season is associated to particular problems, due to the clear seasonal decrease of conventional wind energy and the simultaneous increase in power demand, which may even exceed winter demand in the future due to climate change. Despite its summer production peak, PV energy covers only part of the day.

The high power demand in summer is associated with a particular seasonal low pressure system over the Iberian Peninsula, the Iberian thermal low [2, 3]. The corresponding wind fields show an interesting daily cycle, as well as a vertical distribution that might be advantageous for AWE in comparison to PV or conventional wind energy.

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Kitepower operating at RWE's airborne wind energy test center in Bangor Erris, Ireland (September 2023).

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Development of RWE's Airborne Wind Test Site in Ireland

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RWE is committed to exploring and supporting industry innovation and technological advances across all fields of wind power. Airborne Wind Energy is a new type of wind energy technology for which RWE has constructed a demonstration and test site in Ireland. After several years of development, the site came operational in September 2023 with Kitepower testing their system for the upcoming months. The test site will be available until 2028 with further test slots to enable enhancement of AWE technology.

The site was chosen after an extensive global search for a suitable location to support develop AWE systems. It is located in over 900 hectares of leased land and comprises of an onsite hangar, ground control centre and associated infrastructure including onsite roads, import grid connection and load bank.

This presentation outlines the key development processes required to achieve this operational site starting from site selection, environmental studies including landscape and visual assessment, ecology assessment, noise assessment, ornithology assessment and traffic impact assessment, permitting, stakeholder engagement and public consultation as well as import grid connection and construction.

RWE's airborne wind energy test center in Bangor Erris, Ireland.

RWE

The European Union AWES Centre of Excellence at La Gomera

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The EU AWES Centre of Excellence (EU-AWES-COE) at La Gomera is a unique and very much needed research infrastructure for AWES.

This initiative was started by CT Ingenieros (CT) early 2022 with the objective of developing several AWES technologies, such as:

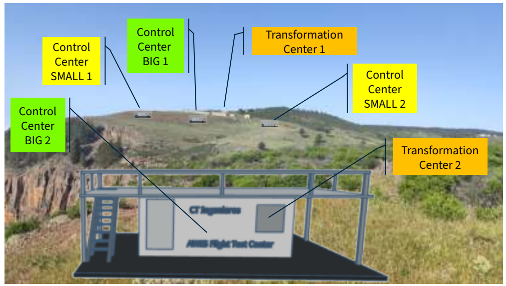
- Technologies that allow the conceptual design of AWES aircraft.
- Technologies that allow advanced modelling and simulation of AWES systems and their environment plus its "Software-In-The-Loop" (SWIL) integration of models and their synthetic validation.
- Technologies that enable:
  - Hardware-In-The-Loop (HWIL) integration of real and synthetic elements.
  - The integration of the avionics of high dynamic aircraft such as AWES vehicles.
  - The integration of AWES ground systems simulating the behaviour of the aircraft pulling the cable.

At the June 2022 Milan Airborne Wind Europe (AWE) meeting, CT proposed to incorporate to this initiative an infrastructure for in flight validation 24/7 of AWES (i.e. a Flight Test Centre - FTC) for our sector and it was unanimously accepted by associates [1]. Ten positive letters of interest were provided.

After a long negotiation process, at September 2023, Cabildo of La Gomera accepted its scope and budget as part of a national, regional and local initiative named "Estrategia Gomera 36" which is an instrument with more than 230 projects to be executed until 2036 on the island that will be financed in public-private collaboration.

The investment phase for EU-AWES-COE will last 3.5 years and will require some 5.9 M€. The operation phase for EU-AWES-COE has been extended to 2036 (in the scope of "Estrategia Gomera 36") and will require some 3.7 M€. CT has developed a return of investment scheme based on self-consumption of the energy produced at the FTC by a local energy community which allows to even provide an income to the company using the FTC.

This presentation will show the site assessment process and the different facilities of this unique R&D infrastructure and an update on its development status.



1.2 MW AWES Flight Test Centre in Arure, Valle Gran Rey, La Gomera.

References:

[1] https://greeningtheislands.org/groundbreaking-centre-of-excellence-in-la-gomera-will-help-make-airborne-wind-energy-a-reality-in-small-islands/

EnerKíte's V-shaped wing on the rotating mast (July 2023).

EnerKíte's V-shaped wing in flight operation (July 2023).

Close-up of EnerKíte's V-shaped wing in flight operation (July 2023).

EnerKíte team celebrating Christmas in front of the wind tunnel (December 2022).

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EnerKíte

The EnerWíng: Combining Performance, Longevity, Robustness, and Serial Production for Commercial EnerKíte Airborne Wind Converters

Florian Breipohl[1], **Jean Levevre**[2] **Jens Winter**[3], **Ashwin Candade**[1,4]
[1]EnerKite GmbH
[2]DLR
[3]TU Braunschweig
[4]Delft University of Technology

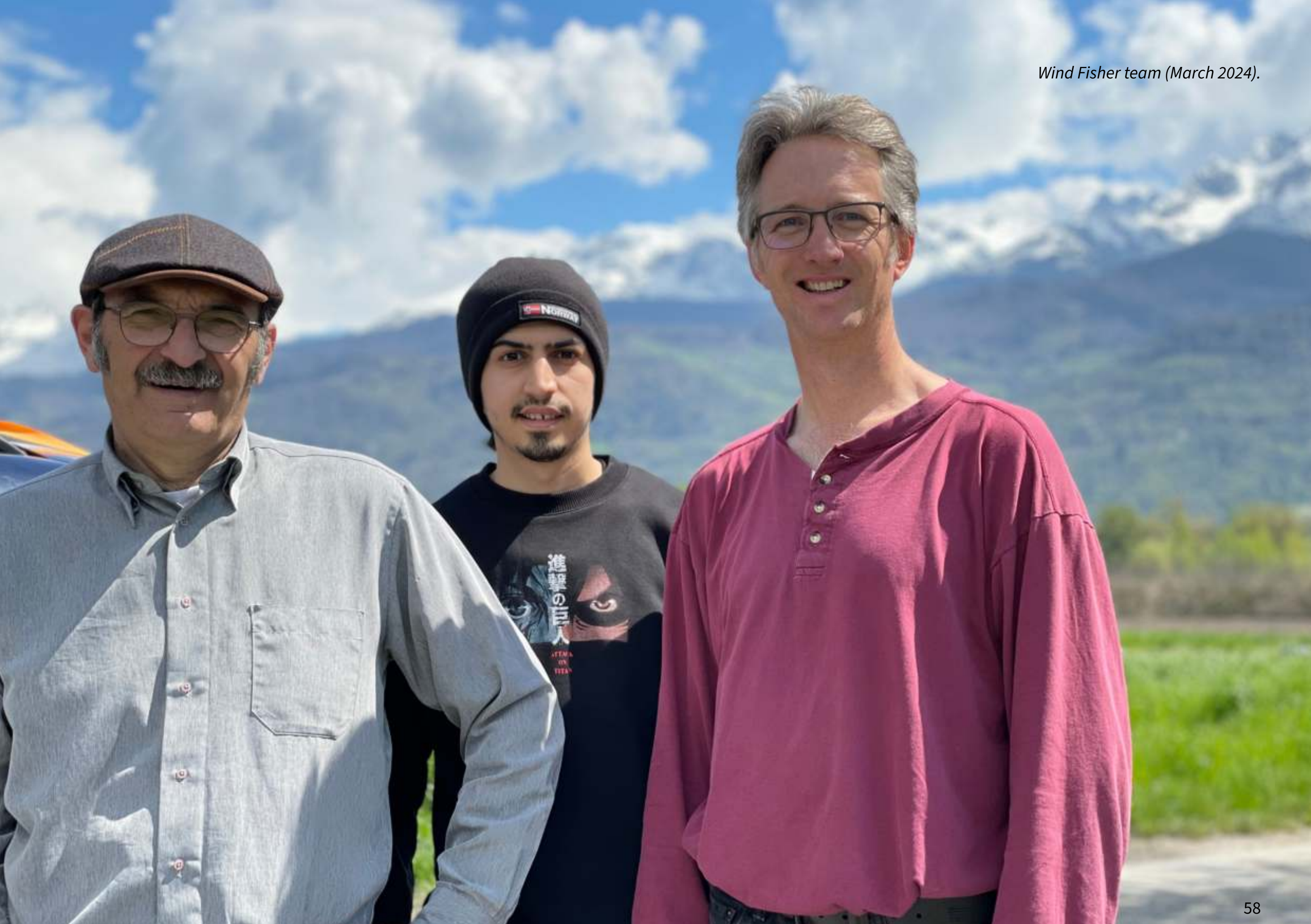
EnerKíte's high-performance wings are designed for maximum yield over an extended project lifetime. The wing has optimised aerodynamics and planform to realise long harvest trajectories with a short retraction phase. This poses a design challenge to achieve a stiff but lightweight structure capable of withstanding the forces from prolonged manoeuvre loads of the harvest phase.

These high-performance requirements have led to a novel structural concept called the gridshell. With the gridshell, EnerKíte has invented a new wing construction method that combines the following features:

- Material savings of 40% compared to a monocoque with comparable structural properties
- Reduction of parts for the wing to > 1/12 compared to differential construction methods
- Optimisation-friendly design
- Drastic reduction of steps in assembly
- Defined bonding surfaces and lower bonding areas
- High durability and robustness against mechanical impacts
- High degree of automation in mass production and wing assembly at low unit costs

Together with the German Aerospace Center (DLR), the Fraunhofer Institute for Manufacturing Technology and Advanced Materials IFAM, INVENT GmbH, and CTC (Airbus Company), EnerKíte is now addressing the mass production of the EnerWíngs. With the successful automated launch and landing with the rotating mast, the high-performance wing, and the gridshell design, EnerKíte is now well-positioned to bring the safest, most reliable, and most efficient system into product development for series production. The presentation aims to showcase the current state of development and to provide a perspective on the next steps and challenges on the path to the series production.

Modalanalysis (FEM) of the EnerWíng-Gridshell. EnerWíng-Gridshell docked on the mast of EK30



Wind Fisher team (March 2024).

Wind Fisher team performing tow tests of the Magnus rotor kite (February 2024).

Wind Fisher's Magnus rotor kite (August 2023).

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Size and Cost Modeling of a Ground-Gen Magnus Effect Airborne Wind Energy System

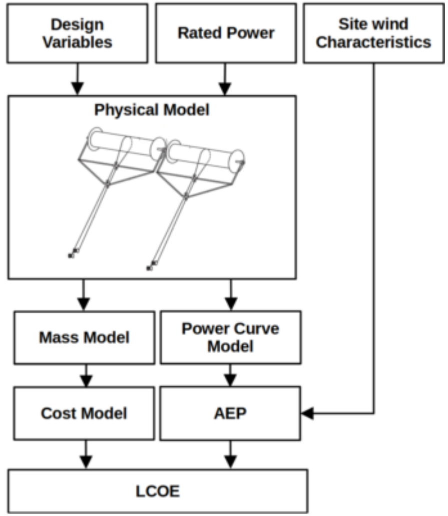
Garrett Smith, Armand Tardella, Yacine Boucheriguene
Wind Fisher SAS

One of our primary concerns at Wind Fisher is being able to prove the cost-efficiency of our system in order to ensure a successful entry in the energy market. To achieve this, we are developing a technico-economic model of our Ground-Gen Magnus Effect AWES.

Unlike most systems based on rigid or soft wing kites, our system consists of two cylindrical wings, which are helium inflated textile balloons with a rigid reinforcement structure. Wing rotation is driven from the ground using four drive-train units which simultaneously generate electricity. The winches are connected to four ends of the two cables wound around each cylinder. Models found in the literature, such as the reference model [1] currently under development, are not entirely suitable for our system architecture. We therefore need to establish our own model to account for the unique characteristics of our system.

The inputs of the model are the design variables (the most important being the aspect ratio of the kite), the desired rated power and the site wind characteristics (shape and scale parameters). The model's structure, as shown in the figure, contains a physical model which consists of simplified steady-state formulas [2] that are used to obtain the size of the kite and inputs for the mass and cost model such as maximum reel-out power and tether tensions, it also provides the power curve that is used to calculate the Annual Energy Production (AEP). Finally, Utilizing the system's cost (CAPEX and OPEX) and the AEP we can calculate the Levelized Cost of Electricity (LCoE). The aim is to be able to perform sensitivity analyses and optimize design choices to minimize the LCoE.

In this talk, we will give an overview of our model along with some results and conclusions.



Architecture of the size and cost model.

References:

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[2] Smith, G., Tardella, A., Boucheriguene, Y.: Magnus Effect Kites: Optimal Reel-Out Speeds for Cross-Wind Power Production Including Simulation and Test Results. Airborne Wind Energy Conference (AWEC 2021), Milan, 2022.

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NEON research

TU Delft

Developing a Reference Economic Model for Airborne Wind Energy Systems

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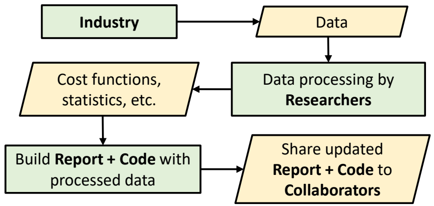
[2]Politecnico di Milano
[3]Airborne Wind Europe

For a successful diffusion of airborne wind energy (AWE) in the energy sector, the development of the technology should be aligned with the needs dictated by the market. Every market has different characteristics which can be suitable for different AWE concepts. For example, Soft-wing and fixed-wing systems, depending on the wind and site requirements, replacement costs, operation & maintenance costs, etc., could be suitable for different markets. Such trade-offs could only be evaluated by employing an economic model along with a performance model.

The IEA Wind Task 48 [1] aims at building a strong community that works together to accelerate the development and commercialisation of AWE technology. This work falls under Work Package 1, which focuses on identifying economic drivers and the potential of deploying AWE in different markets. We aim to develop a reference open-source economic model, which researchers and companies can use to assess the performances of their AWE concepts for different market scenarios. This was first introduced in [2].

The primary aspect of the economic model is the cost modelling of different concepts where we build cost functions parametric to key design parameters such as the kite wing area, span, aspect ratio, tether force, generator characteristics, etc. The process of developing this model is shown in the associated Figure. Airborne Wind Europe [3] acts as an intermediary to host the data collection, storage and dissemination.

The developed report and the code [4] can be used to perform techno-economic analysis, in system design optimisation studies, and to evaluate business cases for specific market scenarios. The model will also provide input to technology development roadmaps and inform policy-makers, organisations like the IRENA or the IEA, as well as the industry.



Flowchart showing the adopted process to build a reference economic model for airborne wind energy systems

References:

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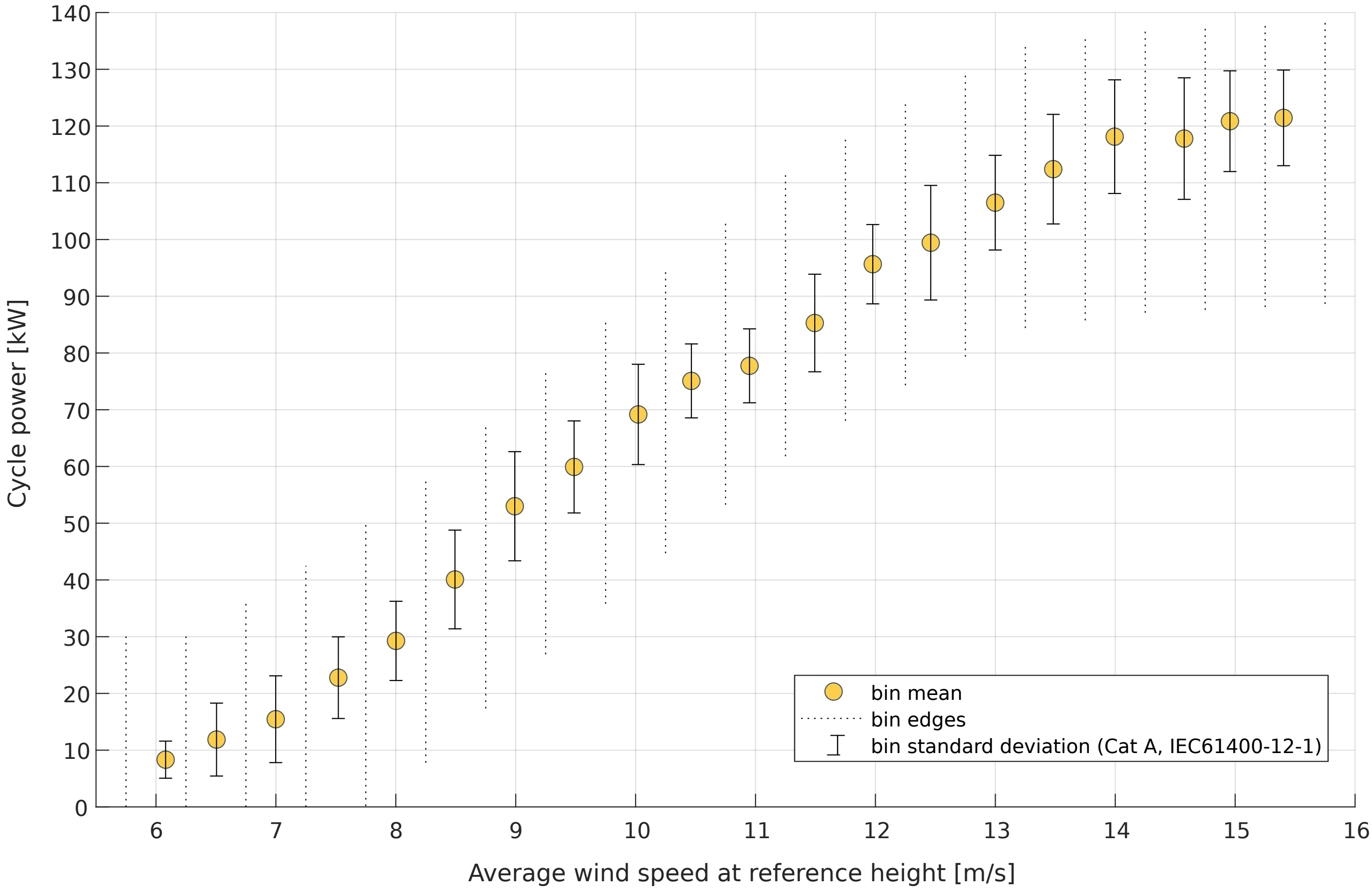
This work was supported by the Dutch Research Council (NWO) and Kitepower B.V. under grant number 17628.

SkySails Power system standard landing (May 2023).


Cycle power [kW]
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90
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16
Average wind speed at reference height [m/s]
bin mean
bin edges
bin standard deviation (Cat A, IEC61400-12-1)

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SkySails PN-14 Power Curve Measurement

Thorben Bartsch, Philip Knipper, Stefan Grazianski, Rafal Noga, Xaver Paulig
SkySails Power GmbH

Skysails Power GmbH is the leading manufacturer of light and efficient power kites that harness the wind's untapped supplies at high altitudes aiming at profoundly altering wind energy's impact in achieving the global energy transition. The key characteristic to describe the output of wind electricity producing systems is the power curve. Here we will present recent results on power curve measurement on our PN-14 System.

The experimental setup based upon standard IEC 61400-12-1 [1] for power performance measurements of conventional electricity producing wind turbines. Benefits and limitations of this standard for airborne power applications are discussed in the talk. With the presented measurement method, we propose a procedure for future specified power curve validations for ongoing discussion to the community [2,3]. The presented data are collected on our test site in Klixbüll in the north of Germany. We will discuss the data collecting method, the site assessment, as well as the statistical evaluation of the data base based upon standard IEC 61400-12-1 [1]. Different concepts of averaging the instantaneous power are compared.

Finally, we show that the data are in good agreement with our theoretical predictions based on three-dimensional model simulations.

SkySails PN-14 System in Klixbüll, Northern Germany.

References:

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Composite Material Database for Fixed-Wing Airborne Wind Energy Kites

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The HAWK Project (Hibernian Airborne Wind energy Kites) is led by Composites Testing Laboratory (CTL) and is funded by Sustainable Energy Authority of Ireland.

This project will address the use of industrial-grade composite materials in AWE systems and aims to improve the predictions for CAPEX and OPEX of AWE systems through four main activities:

1. Material and process characterisation
2. Techno-economic assessment of the manufacturing supply chain
3. Assessment of the durability of the composite wing
4. Development of a certification strategy for AWE airframe structures

This abstract is focused on material and process characterisation. CTL has conducted surveys with many of the fixed wing AWE developers and has gathered information on the composite material systems that are currently in use, along with their use during full-scale production.

From these surveys, four composite materials have been selected for testing. The focus is on novel composite materials, which aren't already included in existing databases.

1. Pultruded UD carbon fibre/Epoxy
2. Natural fibre (Flax) fabric/Epoxy
3. Carbon fibre fabric/Reprocessable thermoset
4. Carbon fibre fabric/Power Epoxy

The next phase of this work package is to perform mechanical testing on the selected materials to obtain the mechanical properties.

The open-source database will then be generated and populated with this material data. This will give developers a head start when it comes to material selection. It will also allow other material suppliers to populate the database in the future.

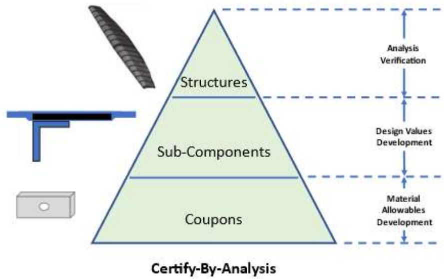

Diagram of the stages of material characterisation for composite structures.

This study has been supported with financial contribution from Sustainable Energy Authority of Ireland under SEAI RDD 2022, Grant number 22/RDD/893.

Composite Materials and Manufacturing Methods Tradespace Analysis of AWES

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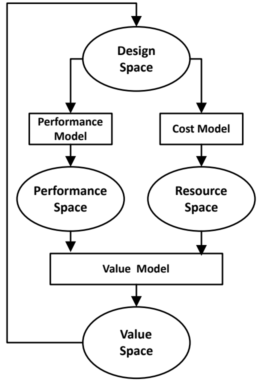
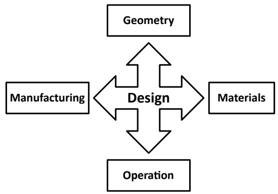
Total system optimization is important to the ultimate success of AWES. A great amount of research has been done on performance modelling and optimization. Less research has been done on a total value model for AWES. Airborne Wind Europe is developing a reference economic model for AWES using input from manufacturers and researchers [1].

Important components of any cost model for composite AWES are the material costs and the manufacturing costs. These components also affect the performance of the AWES. Both the performance and the costs factor into the total value of the system. Ideally, maximizing the total system value of an AWES would involve optimizing all the design variables by iteratively executing the Design-Value Loop. See Fig. 1.

This research focuses on the design variables related to composite materials and manufacturing methods used in AWES. The composites used in towered wind are impressive and well optimized through years of development. However, the composite materials and manufacturing methods used in AWES are very different. They are similar to traditional aircraft! A tradespace analysis of several advanced materials and manufacturing methods is presented. Materials such as infusible thermoplastic resins combined with multi-axially braided carbon fiber preforms, and manufacturing methods such as reusable vacuum bagging and ultrasonic bonding are analyzed.



Design-value loop.



Design variable interactions.

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Performance vs. Mass of Box Wing Designs Using Parametrised Finite Element Modelling

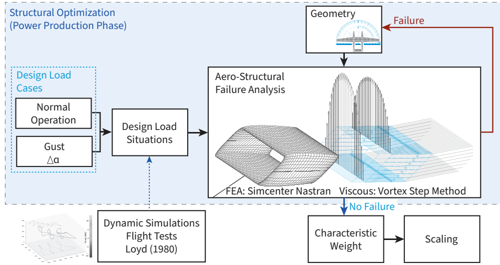
Dylan Eijkelhof, Roland Schmehl
Delft University of Technology

A big challenge for scaling up airborne wind energy fixed-wing kites is their mass. As we scale towards Megawatts, the need for larger kites becomes clear, inevitably leading to increased mass. Gravity is consistently highlighted as a critical concern, especially in relation to power production scalability [1, 2]. Consequently, it becomes imperative, during the preliminary design phase, to gain a comprehensive understanding of the scaling properties and potential limitations that may be encountered in the design process.

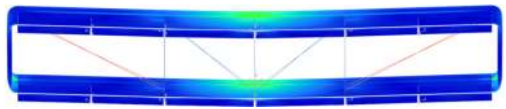
To gain a thorough understanding of the scaling process, it is crucial to use a reliable structural analysis tool for assessing the design's performance. This tool is also tailored to support the objectives of Work Package 4 (WP4) within the HAWK project, funded by the Sustainable Energy Authority of Ireland involving both industry and academia. WP4 is dedicated to evaluate the performance of the wing structure, leveraging material properties obtained through experimental testing.

The framework comprises of an open-source parameterised fixed-wing kite design and a finite element (FE) meshing tool, both developed within a Matlab environment. These tools are seamlessly integrated with an automated failure analysis interface specifically designed for use in Siemens Simcenter Nastran. Validation is performed using the Kitekraft 2.5m wingspan box wing kite.

Subsequently, an optimiser is employed to determine the material thicknesses needed for each scale while adhering to a defined objective function that encompasses both minimising weight and ensuring the quality of power output.



Flowchart of the framework developed to obtain the characteristic weight at each design scale.



Stress results of a box wing made from aluminium plate material. Highest stresses occur at the root and the cant region.

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Preliminary Investigation on AWES Structural Loads Due to Turbulence and Significant Transient Wind Events

Michael McWilliam, Mac Gaunaa, Mark Kelly
Technical University of Denmark

The performance and reliability of AWES depends strongly on the structural loads of the aircraft wings and the tether. A lighter structure can be more power efficient, however, sufficient structural integrity is needed to avoid catastrophic failure. Thus, to minimize the weight, it is important to understand the load statistics to avoid failure. Typically transient flow events are ignored in the preliminary design of an AWES device. The work of Kelly [1] shows the importance of improved turbulence statistics in the upper atmosphere. The goal of this study is to understand how transient flow events increase the loading compared to steady wind.

This work looks is the final part of a 3-part study. The study is based on the AMPYX AP2 aircraft. This is a 30kW device with a 5.5m wing-span. AWEBox was used to solve the optimal flight path over a range of wind speeds. The lifting line code by Mac Gaunaa was used in conjunction with turbulence statistics and transient wind events collected Mark Kelly [2,3]. This work provides a set of unsteady aerodynamic load time series. The details of these studies are given in separate talks by Gaunaa and Kelly.

A medium fidelity structural dynamics model was used to assess the structural loads due to the unsteady aerodynamic forces. The tether model is based on Arbitrary Lagrangian Eularian (ALE) formulation of Absolute Nodal Coordinate Formulation (ANCF) cable model [4]. This is a high-fidelity finite element cable model that can vary in length. The structural model for the aircraft wings is based on Geometrically Exact Beam Theory (GEBT) [5]. The cross section modelling is based off of BECAS.

The structural dynamics code will be used to collect the load statistics on the wing root flap-wise bending moment and the tether tension and compared to stead loads. Furthermore, the research will show what parts of the device are most sensitive to transient loading. Similarly, the research will also show what type of transient events generate the highest loads.

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Aero-Servo Simulations of an Airborne Wind Energy System Using Geometry-Resolved CFD

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Properly understanding the unsteady interaction between the wind and the aircraft is critical to developing reliable airborne wind energy (AWE) systems. High-fidelity simulation tools are needed to accurately predict unsteady aerodynamics, providing insights into the design and operation of advanced and efficient AWE systems.

This work considers the reference multi-megawatt AWE system megAWES [1]. A two-way aero-servo coupling between AWEbox [2] and a geometry-resolved CFD model, which consists of the wing, ailerons, rudders, and the elevator, is established. We opt for the Chimera/overset technique, which has shown its ability to reproduce the motion of AWE systems in the flow domain [3]. Each component can move according to the combination of the aircraft's motion and its relative orientation. Each component is meshed separately and the Chimera/overset technique detects the overlapping cells between each component and applies interpolation to exchange flow data between the components. The aerodynamic forces and moments of the CFD model are fed to the dynamics simulator of AWEbox to compute the flight path. The model predictive controller (MPC) returns the rates of control surface deflections to the CFD model to track the reference flight path.

This novel approach effectively captures how the large aircraft motion, the deflection of control surfaces, and their interactions with the flow field influence the unsteady aerodynamics of the aircraft during operation. It allows to perform CFD simulations of complete power cycles in the atmospheric boundary layer.

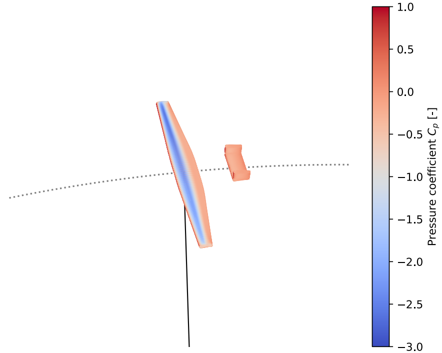

Figure 1: Pressure (C_p) distribution over the aircraft for a 1- loop power cycle prescribed to the CFD model.

In future work, the aero-servo model presented here will be coupled to a structural model of the MegAWES aircraft to obtain a high-fidelity aero-servo-elastic model.

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Investigation of Controlled Airborne Wind Energy System Flying in Turbulent Atmospheric Conditions Using Large Eddy Simulation

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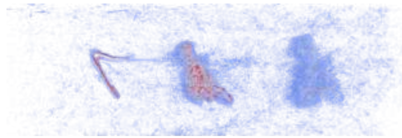
Rigid-wing ground-gen airborne wind energy systems (AWES) fly complex trajectories. This therefore calls for accurate modeling of the dynamics and for advanced control. Flying in atmospheric conditions also requires a high fidelity modeling of the turbulent scales. Such a framework was first developed by Haas et al. [1], where they used Large-Eddy Simulation (LES) to study AWES farms in realistic turbulent winds. Each AWES was represented by its main wing, modeled as an actuator sector. The system dynamics were computed using a 3-DOF point-mass model coupled to a closed-loop path-tracking non-linear model predictive controller from the optimal control toolbox AWEbox [2].

In the present work, we aim to develop a LES framework to study more accurate AWES models in turbulent winds and assess the robustness of the controller against flow perturbations. The toolbox AWEbox is also used for trajectory generation and control. Here the device is flown with a closed-loop controller using a 6-DOF aircraft model; the control surfaces are thus also modeled.

The reference rigid-wing AWES from [3] is considered and is modeled using an actuator line (AL) for the wing. The control surfaces cannot be discretized using an AL because the LES flow solver grid size is too coarse relatively to their span; they are thus modeled using their lift slope. The tail control surfaces (elevator and rudders) are each a lifting surface of small aspect ratio and they are modeled using their effective lift slope. The effect of the main wing ailerons is also modeled: the local lift is modified following the aileron deflection angle. The addition of the control surfaces allows for the evaluation of the aerodynamic moments; as is required by the 6-DOF aircraft model.

The AL-based model is used to study the behavior of controlled AWES when flying in turbulent atmospheric flows; also with shear as for the atmospheric boundary layer (ABL). The performances are then compared to those from the idealized conditions, evaluated with AWEbox. More complex scenarios will also be investigated, where the AWES encounters additional perturbations such as the wake from a wind turbine or from another AWES.



Volume rendering of the wake vorticity field produced by a rigid wing AWES flying a 4-loop trajectory in a turbulent inflow.

References:

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Aerodynamic Analysis of an Airborne Wind Energy System in Turbulent Wind Conditions

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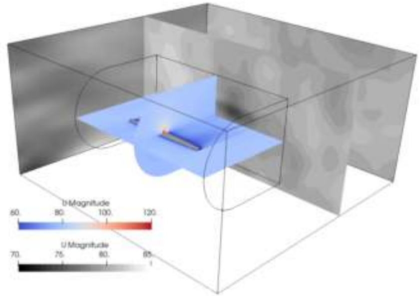
Airborne wind energy (AWE) systems operate in the turbulent atmospheric boundary layer (ABL) by flying complex manoeuvres. The systems are therefore subject to unsteady flight conditions which affect their flight dynamics and overall performance. In particular, this work focuses on the effects of the inherent wind turbulence on the unsteady aerodynamic performance of the system's lifting surfaces.

For this aerodynamic analysis, we consider the multi-megawatt reference AWE system, MegAWES [1]. Pynaert et al. investigated the aerodynamic performance of the MegAWES system in crosswind flight using unsteady Reynolds-Averaged Navier-Stokes (RANS) in [2]. While the effects of large motions on the system's aerodynamic characteristics can be evaluated, the turbulence modelling inherent to the URANS method falls short at capturing the unsteady effects of resolved wind turbulence. In the present contribution, an aerodynamic analysis of the MegAWES aircraft is performed in the presence of added freestream turbulence. Resolved synthetic turbulence is fed as transient inflow condition to the simulation domain to emulate the flow characteristics of the turbulent ABL. The flow is simulated using hybrid RANS/LES (Large-eddy simulation) techniques in order to capture the large structures of the turbulent and separated flows. The local aerodynamics around the AWES are computed on a boundary-layer resolving body-fitted mesh, which is subsequently coupled to the ABL domain using the overset mesh coupling technique, see the figure.

This contribution investigates the effects of wind turbulence on the system's performance during level flight, in particular on the spanwise distribution of aerodynamic loads. This study ultimately helps assessing the feasibility of using hybrid RANS/LES capabilities in combination with overset techniques for the future investigation of complex flight configurations, including large crosswind motions, and wing deformation.



Instantaneous turbulent wind flow past the MegAWES wing computed using overset and hybrid RANS/LES.

References:

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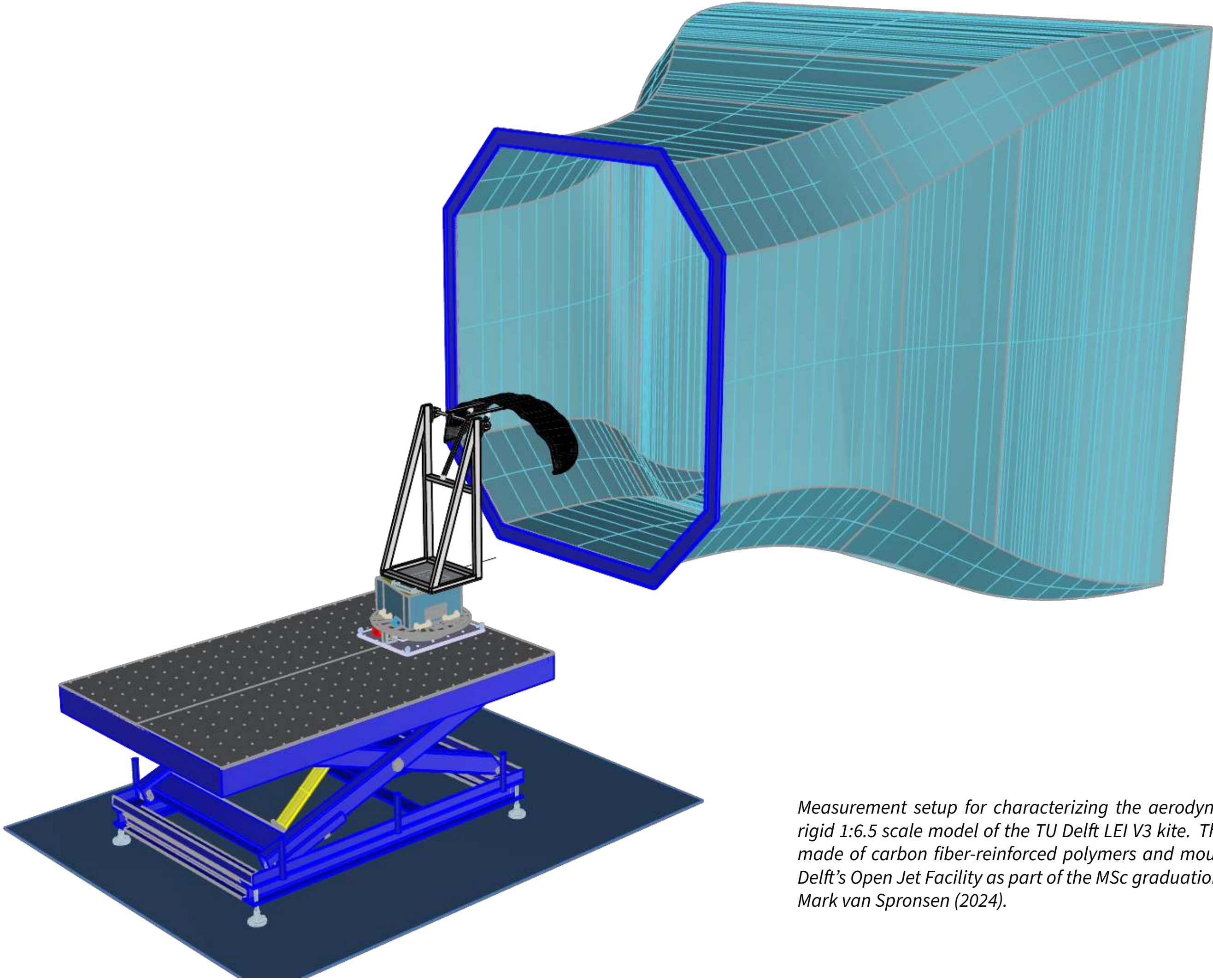

Measurement setup for characterizing the aerodynamics of a rigid 1:6.5 scale model of the TU Delft LEI V3 kite. The model is made of carbon fiber-reinforced polymers and mounted in TU Delft's Open Jet Facility as part of the MSc graduation project of Mark van Spronsen (2024).

Rigid scale model of the V3 kite in TU Delft's open jet facility (April 2024).

Rigid scale model of the V3 kite in TU Delft's open jet facility (April 2024).

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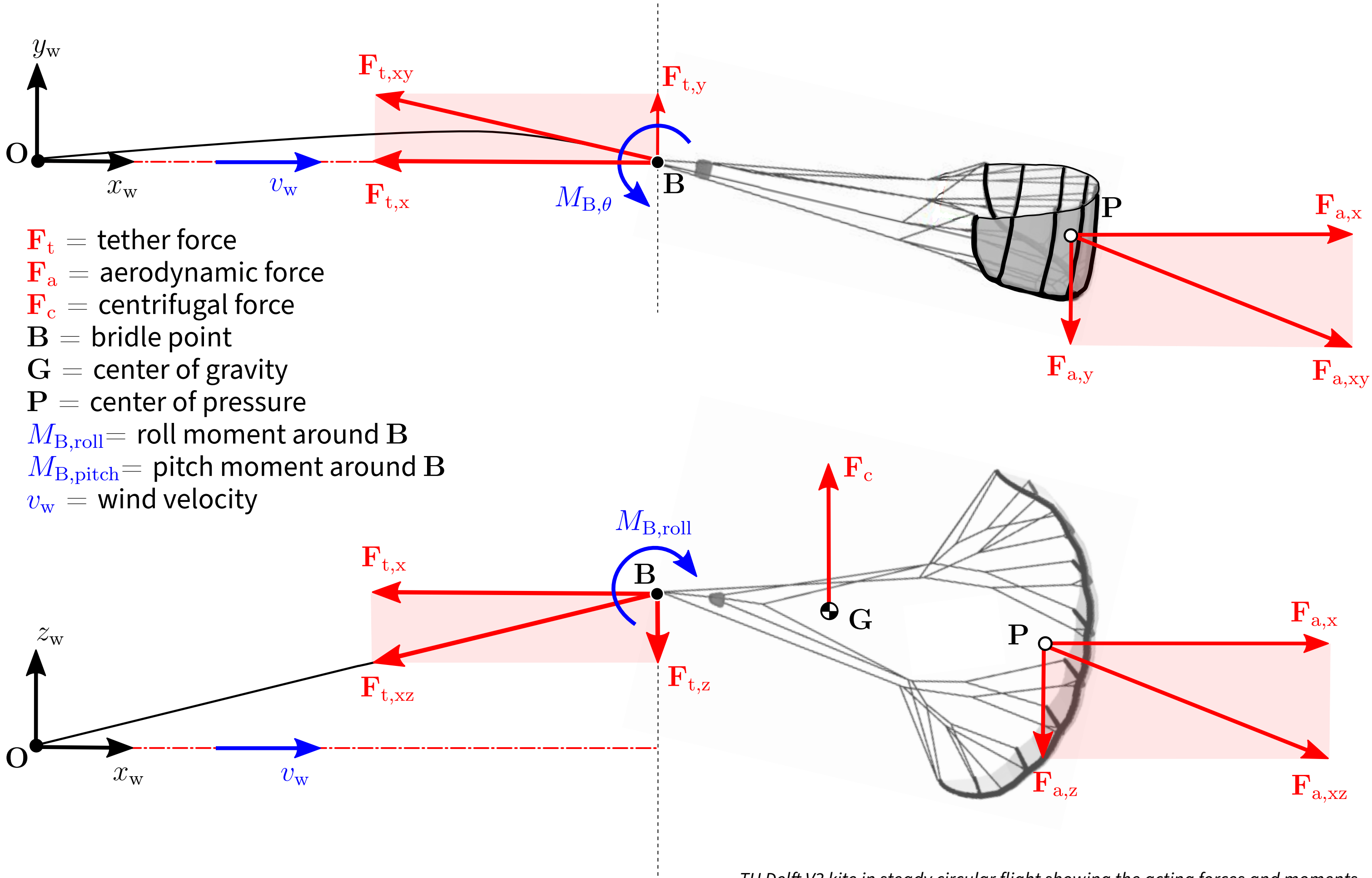

TU Delft V3 kite in steady circular flight showing the acting forces and moments.

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Symmetric and Asymmetric Aero-Structural Coupled Soft-Wing Kite Simulations

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Simulations are essential for optimizing the design of soft-wing airborne wind energy (AWE) kites. They aid in addressing the inherent design challenges associated with soft-wing kites. For example, generating high force and power necessitates a flat-wing kite, whereas precise and stable steering calls for a wing with substantial curvature. The simulation environment, denoted as virtual wind tunnel (VWT), allows for cheap, fast, safe and sustainable testing of new designs.

Instead of modeling the entire AWE system, only the kite is placed in the simulation domain. The VWT flies with the kite along its trajectory. The flight path is discretized into operating points; for each point, a separate analysis can be made, assuming a quasi-steady state. A boundary condition is placed at the origin that, like the bridle point, holds force in the tether direction but offers no rotational resistance. Without rotational resistance, the yaw, pitch and roll moments at the bridle point must be zero. An equilibrium over the six degrees of freedom is necessary for the simulation to converge to the quasi-steady state. In each operating point, the resulting forces are calculated using an Aero-Structural coupled framework [1]. A structural model is included as soft-wing kites are controlled by morphing the wing and are prone to aero-elastic deformations. A particle system model [1] is loosely coupled to an aerodynamic Vortex-Step Method [2] with integrated pre-computed 2D CFD data [3].

There are operating points, e.g. during the straight part of the reel-in phase, for which one can assume the presence of a symmetry plane at mid-span, i.e. where the left and right half of the kite are equal. The kite is pitch static stable and finds a 'trim-angle' at which the pitch moment is zero. With symmetry, the yaw and roll moments are zero; equilibrium is thus found and the simulation converges.

Without symmetry, the kite must also find an equilibrium position for yaw and roll. The backward swept wing aids positively towards yaw static stability. Finding a roll equilibrium is not trivial, as the anhedral wing shape makes the kite roll statically unstable. The instability requires continuous control input and has limited previous analysis to symmetric cases.

A novel solution is to evaluate a special crosswind flight case in which the kite flies a circular pattern. To remain in a circular flight, the sum of the forces in the radial direction must be zero. In the radial direction, there is a tether force component and a centrifugal force. The centrifugal force equals the sum of the radial components of the tether force and aerodynamic force and must be included because the VWT reference frame is rotating. After some deformation, a constant turning radius is found where the positive aerodynamic and negative centrifugal roll moment contributions cancel out. With a zero roll moment at the bridle point, equilibrium over six degrees is found, enabling the first converging asymmetric VWT simulations.

References:

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Airborne Wind Energy as a Viable Solution to Further Rural Electrification

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As of 2023, the global decentralised renewable energy (DRE) scene has seen remarkable progress and widespread adoption, marking a transformative phase in the transition towards a sustainable and clean energy future. Across the globe, countries and communities are increasingly recognising the benefits of decentralising their energy systems, and renewable sources are playing a pivotal role in this paradigm shift towards achieving Sustainable Development Goal 7 (SDG 7).

In developing countries, DRE has emerged as a game-changer in addressing energy poverty and improving energy access. Offgrid and remote communities that were previously left unserved by conventional grid systems are now benefiting from standalone renewable energy generation systems. These systems are providing clean electricity to schools, healthcare facilities, households and businesses, fostering economic development and enhancing the socio-economic standards of life in these areas.

An estimated 675 million people around the world, however, still lack access to electricity as of 2021. Despite the progress on energy access, the current pace is not adequate to achieve any of the 2030 targets.

Airborne Wind Energy is one of the viable solutions that can address lacking energy access in rural areas as it harnesses the steady winds high above the blade tips of today's wind turbines. The technology is a promising addition to the more common existing technologies today.

The low use of materials gives it an advantage for use in remote areas and reduces CAPEX costs. In addition, the fact that the technology has a high capacity factor and is complementary to other renewables in both stand-alone but also hybrid installations will allow it to be integrated as an additional element to current solutions. Going forward the sector can still benefit from significant further development funding to deploy at scale as well as from specific policy support to reach its full potential like other renewable energy technologies in the past.

In conclusion, the nature of the technology makes it an ideal solution for rural electrification, increase energy access for millions of people, and as a result have a positive impact on socio-economic developments in remote areas and on climate change.

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Challenges in Advancing AWES Development and Permitting

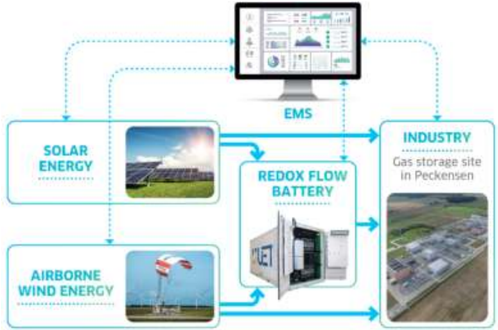
Romain Gellee, Christophe Merlo
ENGIE Laborelec

Aquilon is a collaboration project of Storengy Deutschland GmbH and ENGIE Laborelec with the aim to develop a 100% renewable-powered, continuous energy system for the Peckensen gas storage site in Germany.

Aquilon embodies an innovative approach to achieve complete greenhouse gas emission reduction at an industrial site, integrating Airborne Wind Energy (AWE), solar PV, and a Redox-flow Battery (RFB) storage system. However, challenges arise in technology development and asset integration. ENGIE Laborelec's expertise is vital for coordinating these components into a seamless energy provision scheme, including an intelligent Energy Management System (EMS).

Recognized by the EU's Innovation Fund with grant agreements innovation fund, Aquilon is poised to drive significant progress toward a sustainable energy future.

Securing permits for innovative green technology can be arduous due to regulatory frameworks ill-suited to accommodate emerging technologies. Stakeholder concerns and unfamiliarity with novel solutions often lead to resistance and prolonged approval processes. Additionally, navigating diverse regulatory landscapes and inconsistent environmental evaluation procedures further complicates the process. Overcoming these challenges requires proactive engagement, collaboration, and flexibility in regulatory frameworks to expedite the deployment of sustainable solutions.



Project Scheme of Aquilon.

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Airborne wind energy (AWE) systems can harness the power of the wind at high altitudes without the need for big and expensive supporting towers. As wind speed generally increases with height above the ground, AWE systems can tap into the rather phenomenal wind resource available above the atmospheric boundary layer.

In this talk, I will review the methods that have been proposed to assess the global wind energy resource available for AWE applications [1], from the first study that used reanalysis data at coarse resolution and included winds up to the jet streams, to more recent higher-resolution evaluations that focused on lower levels (<1 km) [2,3].

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AP3 shortly after takeoff from Oostwold Airport, The Netherlands, during an untethered flight performance test in The Netherlands (November 2023).

AP3 ascending to circuit altitude during untethered flight performance tests in The Netherlands (November 2023).

AP3 overflying the runway at Oostwold Airport, The Netherlands, during an untethered flight performance test (November 2023).

Mozaero team (November 2023).

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MOZ AERO

Progress Along the Long and Windy Road

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With the dissolution of Ampyx Power in 2022, more than a decade of research and development on airborne wind energy was jeopardized along with the possibility that the AP3 demonstrator aircraft would ever fly. Rather than let it all go to waste, a few determined engineers took a leap of faith and resolved to finish the development, integration and testing of the largest fixed-wing pumping cycle system to date.

The 12 m span, 475 kg aircraft with an estimated average power production capacity of 150 kW and its ground equipment have been under construction since 2017. The model validation campaign has been kicked off by the first untethered flights in the Netherlands in November 2023, making AP3 one of the largest privately built UAV's to fly in Europe.

This talk discusses the path that led to the first flight of AP3 from an engineering, operations and business development perspective, as well as gives an outlook on product design and scaling for our take on Airborne Wind Energy, leveraging the lessons learnt from building and flying a demonstrator at relevant scale.

First flight of the AP3 demonstrator aircraft at Oostwold Airport, the Netherlands (November 2023).

Mozaero's prototype in untethered flight (November 2023).

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Will it Fly? An Interactive Role-Playing Game for Exploring Social Conflicts in Airborne Wind Energy Siting

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Developing airborne wind energy (AWE) requires more than just technical and economic expertise. As an energy technology, AWE must be embedded in society, and the technology's success depends on wider social factors [1]. Experience with other renewables has shown that opposition to local energy projects can slow down, halt, and even hinder their realization. Some AWE developers have already encountered objections to planned or existing test sites, including the withdrawal of site permits. As AWE approaches commercialization, it is important that developers meaningfully engage local communities and other relevant stakeholders in deploying AWE [2]. A one-size-fits-all approach for good engagement does not exist because the particular socio-economic, political, and historical contexts shape responses to a given project. However, the types of stakeholder and the nature of their concerns and needs can be similar [3]. We have developed a role-playing game that allows participants to immerse themselves in the social conflicts and dilemmas frequently encountered during the proposal of renewable energy projects. In this session, participants will be asked to imagine a fictional but realistic scenario: An AWE project is being planned in a small town, and some regional stakeholders have found out and are raising concerns. The project developer invited them to a typical 'town hall meeting' to mitigate concerns and address unresolved issues. Participants will simulate the meeting by playing a pre-defined role from a set of selected stakeholders (e.g., concerned resident, local council, nature conservationist, landowner, and airport manager). Guided by a facilitator, the participants will explore whether and under what conditions the AWE project can be realized. After the role-play, participants will jointly reflect on what the game has taught them about social conflicts that can occur for proposed AWE projects. Spots are limited and will be assigned on a first-come-first-serve basis. Join the game to understand better the societal implications of siting AWE projects.

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Variable Mass Tether Modeling of Airborne Wind Energy System

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Tethers, critical components in AWE systems, are particularly important for safety and stability in challenging high-altitude environments. The tether modeling mostly adopts the discrete rigid body modeling method [1-2]. This method has advantages in reducing computational complexity but can cause model errors. Meanwhile, it is also challenging to accurately describe the tether dynamic characteristics. In addition, the tether length change needs to be considered because it undergoes significant changes during the release or recovery stages [3].
This research aims to present an accurate tether dynamic model with the variable mass of an axially moving tether. A semi-open control boundary, which is characterized by the steady form of the Hamilton principle, is defined to establish the tether dynamic model. The model can be described as

$$\int_0^t \left(\delta\left(E_k - E_p\right)_s + \delta W_s + \delta M_o\right) dt = 0 \qquad (14.1)$$

wherein

$$\left(E_k - E_p\right)_s = \frac{\rho_c S}{2}\int_0^{l+\Delta l}\left[\left(\dot{v} + v_{\mathbf{R}_1} v'\right)\left(\delta\dot{v} + v_{\mathbf{R}_1}\delta v'\right)\right]dx + \frac{1}{2}\int_0^{l+\Delta l} ES\delta v' dx + \int_0^{l+\Delta l}\rho_c Sg dx \qquad (14.2)$$

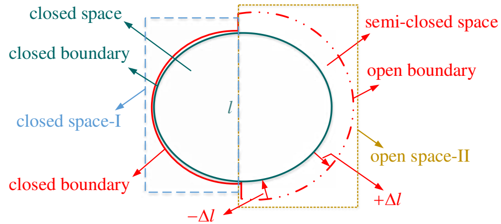
,

$$\delta W_s = \delta W_c + \delta W_o,$$

$$\delta W_o = ESds + \iint_{B_o} c\dot{v}\delta v \cdot \mathbf{n} ds,$$

$$\delta M_o = \left[\rho_c S\left(\dot{v} + v_{\mathbf{R}_1} v'\right)\delta v\right]\Big|_0^{\Delta l}.$$

The open boundary condition is used to describe the variable length behavior of a tether accurately during the release and recovery stages. Moreover, we have further considered and established tether model with the wind loads. Finally, an analysis of the tether characteristics, including the effects of the axial excitation and the stability of axial velocity, has been conducted



A semi-closed space domain for variable mass tether.

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A Bayesian Model for the Prediction of Extreme Winds

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In airborne wind energy engineering, the installed system must be able to fly autonomously over a long period of time without being adversely affected by atmospheric turbulence and wind gusts [1]. The aim is to predict the extreme wind quantiles, which may helpful in airborne wind energy engineering.

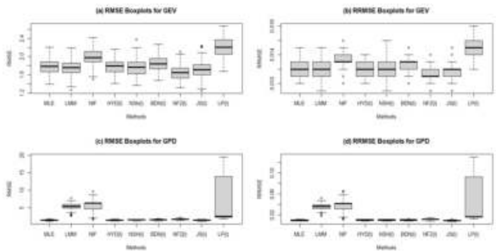
Extreme value theory (EVT) is a valuable tool for estimating model-based quantiles, particularly when analyzing maximum wind speeds at various meteorological locations. Accurate estimates of these quantiles are essential for modeling and predicting extreme winds. This study employed frequentist and Bayesian modeling approaches to develop an efficient framework for analyzing daily and annual maximum wind speeds.

For the modeling of yearly maxima, we utilized the generalized extreme value (GEV) model, while the generalized Pareto distribution (GPD) was employed to model daily exceedances over a high threshold. We estimated the model parameters using the maximum likelihood and linear moments methods in the frequentist framework. In contrast, the Bayesian approach involves the use of the Markov Chain Monte Carlo procedure with the Metropolis–Hasting algorithm.

We empirically construct informative priors for both models in the Bayesian paradigm by examining wind speed data from neighboring areas. Our analysis focused on the wind speed data from Pakistan. The results indicate that Bayesian modeling offers distinct advantages, including improved parameter estimation accuracy and more reliable return level estimates.

Furthermore, our Bayesian analysis reveals that the choice of areas used to formulate informative priors can influence posterior inference. When considering uncertainty in parameters and return levels, the GPD model fitted with Bayesian informative priors proved to be a superior estimation strategy in terms of precision compared with other frameworks.

By incorporating prior information from bordering regions of neighboring countries, such as China, Afghanistan, India, and Iran, our methodology can be readily adapted and applied to different regions.



Comparison of estimation methods and models for GEV and GPD

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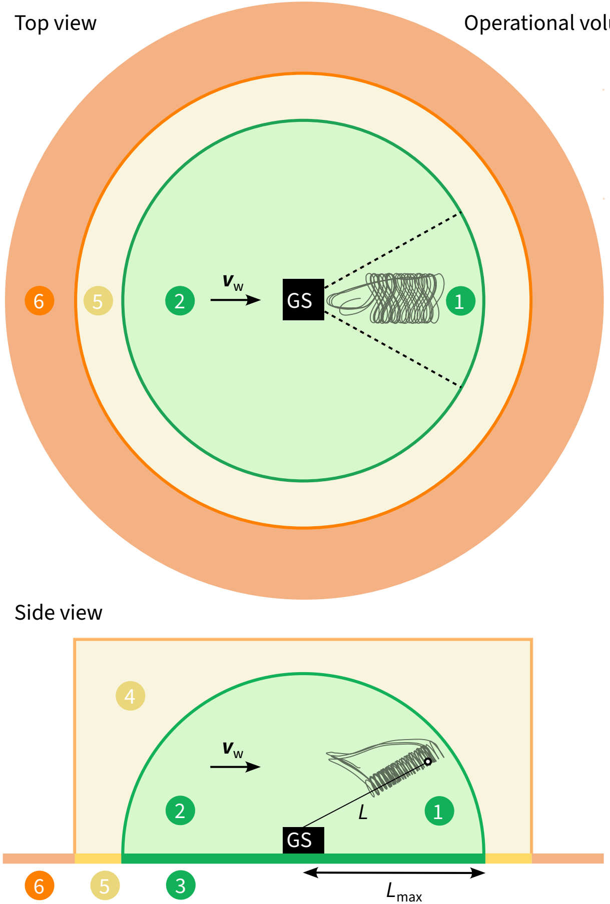
Kitepower's V5.40 kite with 40 m^2 wing surface area operating on the former naval airbase Valkenburg (July 2018).



Operational volume = Tethered flight trajectory + Contingency volume

1. Flight trajectory and flight boundaries for a specific wind direction.
2. Tethered flight geography for all wind directions. Radius = maximum tether length L_{max}.
3. Tethered flight geography area.
4. Contingency volume.
5. Contingency area.
6. Ground risk buffer (GBR) based on affected area in tethered crash situation.

v_w: Mean wind velocity at flight pattern heigth.

GS: Ground station / tether attachment point.

Definition of the operational volume for AWES and related terminology. The ground risk buffer is calculated according to JARUS' ground risk model with a significant safety factor. Source: Salma, V., Schmehl, R.: Operation Approval for Commercial Airborne Wind Energy Systems. Energies, ***16****(7), 3264, 2023. doi:10.3390/en16073264*

IEA WT48 WP3 Update on AWES Regulations

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The IEA Wind Task 48 on Airborne Wind Energy (AWE) was kicked off on 27-28 October 2021.

The objective of the Task is to tackle various of the specific challenges for this new technology on a global level by addressing and including stakeholders who are not primarily AWE developers, i.e., policy makers, authorities, regulators and other wind energy and technology experts.

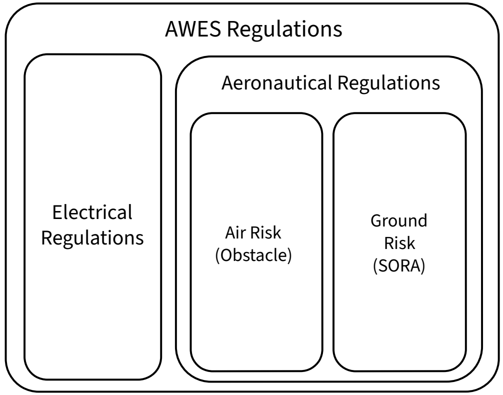
Expected results are:

- Enhanced international collaboration and coordination in the field of AWE to leverage the work being done in the AWE sector.
- Studies and reports in five focus areas/work packages (WPs).
- Updated library of Task publications, collaborative journal articles and list of relevant studies and other publications.
- Open-source dynamic models, with corresponding documentation and training opportunities, for common use in AWE research and development.

Work Package 3 addresses safety and regulation of both aspects of AWES: the aeronautical and the electrical regulations [1].

Due to its dual nature (i.e. an obstacle and a tethered UAV), in order to allow its autonomous operation in future, AWES should be classified as obstruction from the air risk perspective and UAS from the ground risk perspective, but in the end, AWES will have to be regulated as AWES.

This presentation will show current strategy of having AWE-specific aeronautical regulations (i.e. not to follow UAS one) although using UAS related tools such as SORA. Moreover, "Safe Operation and Airspace Integration of Airborne Wind Energy Systems" whitepaper shall be presented and an upgrade on current status of the initiative shall be provided.



AWES Regulations.

References:

[1] IEA Wind Task 48 [AWE], Work Package 4 [Safety and regulation. https://iea-wind.org/task48/task48-activities/task48-activities-wp3/

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Modeling and Control of a Magnus Effect Kite: Pumping Cycle with Reversing Rotation

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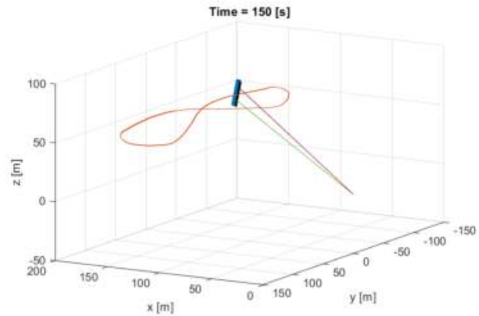
Wind Fisher is developing an airborne wind energy system based on an innovative dual-cylinder Magnus effect kite. The system utilizes cross-wind flight and optimizes wing lift during reel-in and reel-out phases. Developing a simulator enables to test control strategies to ensure prototype stability during our flight test and also to simulate and estimate the pumping cycle energy production of the future 100kW to MW scale systems. The model includes two cylinders with a rigid reinforcement structure, two tethers and four drive-train units connected to each end of the tethers.

At AWEC 2021, we presented our first simulation results of in-plane pumping cycles [1] obtained with a simplified 2D point mass model and a non-optimized basic control. In this talk, we will present the evolution of our control strategy leading to an optimized production with variable wind speeds.

Given the special architecture of our system, which requires reversing the rotation of the cylinders every half-cycle, a complex control with multiple phases is required (two reel-out phases, two reel-in phases and multiple transition phases including rotation inversion). Indeed, during a pumping cycle, after a reel-out phase in one direction the cylinders rotation is reversed during a reel-in phase in order to start again a second reel-out phase in the other direction and follow a figure-eight trajectory. Also, we upgraded to a 6-degrees-of-freedom 3D model that considers the six aerodynamic forces and moments, using coefficients from Badalamenti experimental results [2]. Work on yaw control to improve flight stability has been carried out and validated during flight tests with our prototype.

To conclude this presentation, simulation results (power curves, flight trajectory, etc...) obtained with different simulation models will be presented.



Simulated figure-eight flight trajectory of a Magnus effect kite during pumping cycles.

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Optimal Flight Pattern Debate: Circular vs. Figure-Of-Eight

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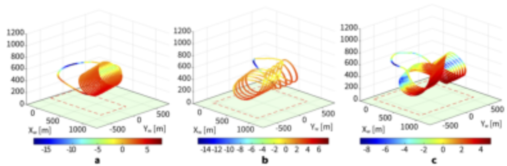
The debate about the optimal flight pattern for AWE dates back to the beginning of the technology development in the late 2000s. The industry appears undecided, with circular and figure-of-eight patterns both being prevalent. Tether winding seems to be the key reason for the latter, but other factors could influence the choice.

This work attempts to provide a better understanding of the effect of each pattern on the system's performance when using a simple flight control strategy. The performance is studied using three criteria: average cycle power, power quality (oscillations) and projected ground surface area. Three patterns are considered: the circular path; the figure-of-eight with down loops(DL) at the outer edge; and the figure-of-eight with up loops(UL).

The MegAWES reference kite (150 m^2 fixed-wing) [1] is used in conjuction with a new improved and modified flight controller developed in [2], based on [3]. The navigation strategy, based on a variation of the widely used L_1 logic [4], is proposed, tuned and tested in conjunction with a cascaded PID control loop for the attitude control of the kite. Furthermore, the winch design and controller is implemented as developed in [5]. The new flight controller is simple and robust under diverse wind conditions, and highly satisfactory path tracking capabilities.

Early results highlighted that circular paths are comparable, if not superior, with higher average power (1.175 MW) than both figure-of-eight paths (DL: 0.998 MW, UL: 0.847 MW). Even though the figure-of-eight up loop is most commonly used, it proved to be less advantageous for this type of airborne wind energy system.

Finally, the flight path is projected on the ground and the produced average cycle power per square meter of land surface area is compared. The results show a higher power density per land surface area for the circular path compared to the others.



Mechanical power (colorbar, [MW]) and ground coverage for three patterns at 15ms^{-1} and 36^{o} elevation: (a) Circular, (b) Down loop and (c) Up loop.

References:

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Performance of Fixed-wing Airborne Wind Energy Systems: A Parametric Study

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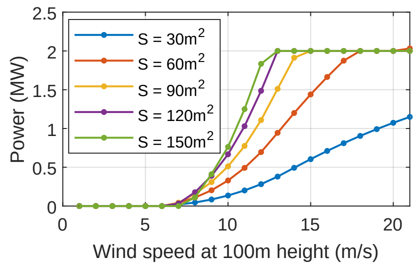
Airborne wind energy (AWE) systems are complex multi-disciplinary systems with many interdependencies within their components. To better understand the systems' behaviour and performance, it is necessary to identify the critical links and the associated trade-offs between design parameters. This work focuses on fixed-wing ground-generation AWE systems.

For example, increasing the kite wing area will directly increase the aerodynamic force, but it will also increase the kite mass, thereby increasing the loss in performance to counter its weight. The Figure shows the computed power curves for a fixed electrical rated power and a range of kite wing areas. It shows a diminishing performance improvement with increasing wing areas since the effect of mass is more pronounced than the increase in the aerodynamic force. These power curves are generated using a quasi-steady model implemented as an optimisation problem, maximising the electrical cycle power of fixed-wing ground-gen AWE systems [1,2].

The objective of this work is to understand the impact of various system design parameters, such as the kite wing area, span, aspect ratio, airfoil polars, tether material, drum, generator properties, etc., on the performance of the system. A systematic parametric study is performed for the same. The performance can be compared purely based on power production or comprehensive metrics such as the levelised cost of electricity (LCoE). Generally, all renewable energy technologies designed to minimise LCoE are comparable. Hence, it could also be one of the key design objectives for AWE systems. For LCoE, besides a performance model, cost models are also required. A reference economic model [3] is being developed as a part of the IEA Wind Task 48 on AWE and is used in this analysis. The LCoE results are expected to further the understanding of dominant design drivers and variables.



Computed power curves for a range of kite wing areas.

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This work was supported by the Dutch Research Council (NWO) and Kitepower B.V. under grant number 17628.

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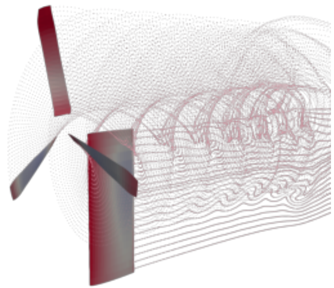
Towards Mid-Fidelity Aero-Servo-Elastic Simulations of Airborne Wind Energy Systems

Gianni Cassoni, Filippo Trevisi, Pierangelo Masarati
Politecnico di Milano

The dynamic problem of airborne wind energy systems is intrinsically multidisciplinary, where the aerodynamics, the control and the structural elasticity determine the system motion and thus the generated power. In the literature, the aerodynamics is approached using precomputed aerodynamic models or coupling flight simulators with high-fidelity computational fluid dynamics solvers; the control is developed by modelling the AWES as a rigid body and the structural dynamics is studied in idealized cases. To study how these disciplines combine during operations, NREL researchers developed *KiteFAST*, a aero-servo-elastic simulator for airborne wind energy [1]. *KiteFAST* is based on MBDyn, an open-source multibody dynamics code available at https://mbdyn.org/, and was coupled with the other OpenFAST modules.

We approach the aero-servo-elastic problem by leveraging the versatility of MBDyn and DUST, a free wake vortex lattice method accessible at https://www.dust-project.org/. This coupling yields a mid-fidelity simulation, proficiently operating without substantial computational overhead. A similar combination technique was previously introduced in [2] for tiltrotor applications. Both MBDyn and DUST are developed at the Department of Aerospace Science and Technology in PoliMi.

This study introduces an open-source mid-fidelity aero-servo-elastic simulator tailored for the airborne wind energy community. The modeling approach incorporating distributed masses, beam elements, and an aerodynamic model. Such simulations have previously been utilized in the analysis of tiltrotors, particularly in the investigation of instabilities such as whirl flutter. In our study, we create an initial model to examine diverse operational settings, offering insights into the aerodynamic interaction between onboard turbines and the wing (as shown in the accompanying figure), and analyzing aerodynamic loads and power forecasts.



Vorticity trailed by a wing and a wing-tip rotor.

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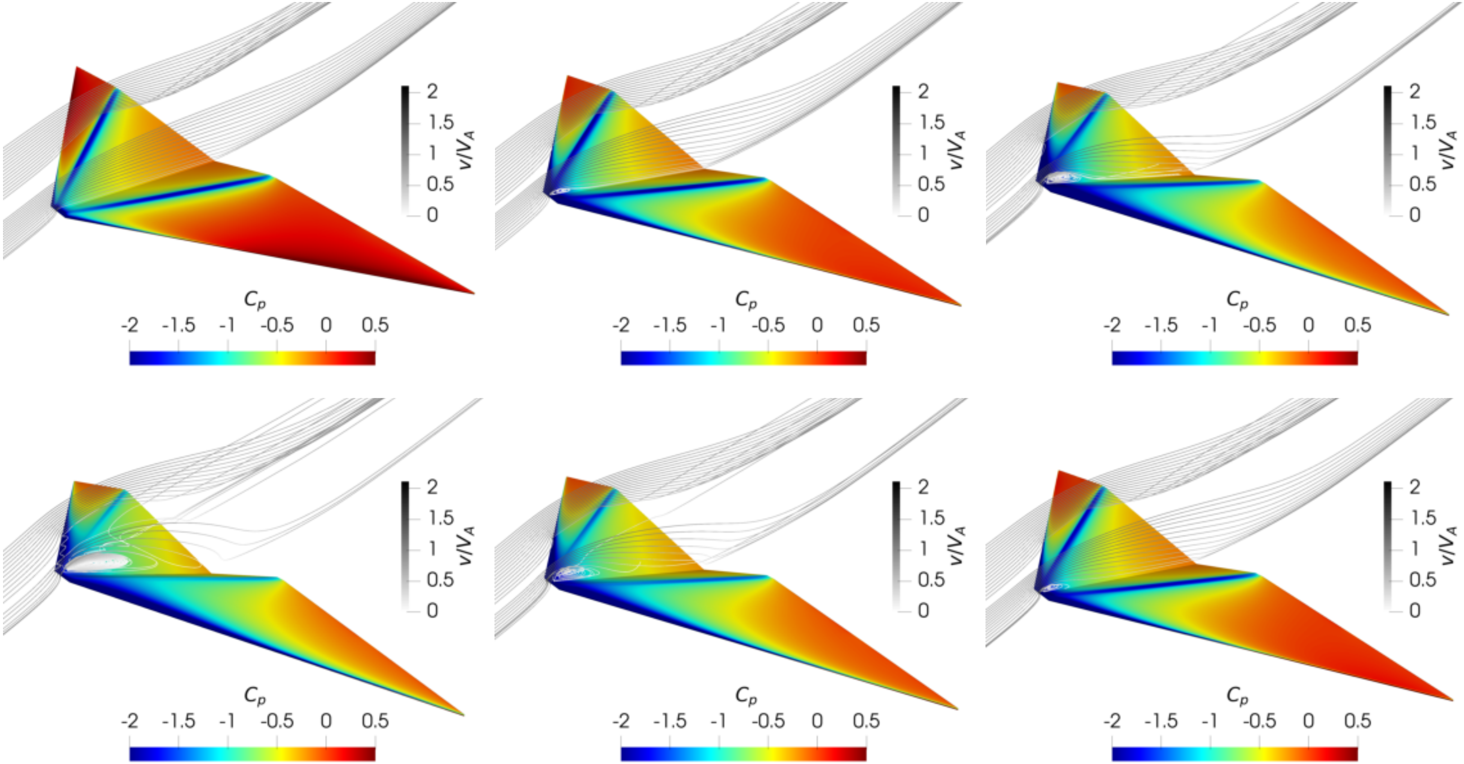

Unsteady RANS simulation for the pitching motion ($\dot{\alpha} \neq 0$) of a representative cycle. Panels (a)-(f) correspond to angles of attack of 23° (upstroke), 30° (upstroke), 35○ (upstroke), 38° (downstroke), 35° (downstroke) and 30° (downstroke), respectively. The streamlines are colored with the normalized velocity (local velocity over aerodynamic velocity. Castro-Fernández, I.: Unsteady Aerodynamics of Delta Kites applied to Airborne Wind Energy Systems. PhD Dissertation, UC3M, 2024.

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Fluid-Structure Interaction Analysis of a Rigid-Framed Delta Kite for Airborne Wind Energy

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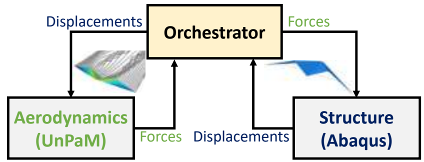
Fluid-structure interaction (FSI) plays a major role in membrane and semi-rigid wings applied to AWE systems. Besides their inherent flexibility, the aerodynamic pressure presents significant variations induced by large changes in the aerodynamic velocity (angle of attack, sideslip angle and airspeed) during crosswind operation [1]. Owing to its relevance in AWE, FSI of leading-edge inflatable [2] and ram-air [3] kites was extensively studied. Unsteady aerodynamic performance of rigid-framed delta (RFD) kites, like the one used by the AWE group of UC3M, was characterized through experiments [1] and simulations [4,5]. However, their aeroelasticity has not been investigated yet despite significant aero-structural deflections having been experimentally observed.

This work analyzes the aero-structural behavior of an RFD kite through a computational FSI framework that consists of two modules coupled through an ad-hoc orchestrator as shown in the figure. The aerodynamic module is a potential-flow steady solver within the in-house suite UnPaM [5]. It was benchmarked against the computational fluid dynamics software SU2 showing a good qualitative agreement on the pressure field over the RFD kite at low to moderate angles of attack. The structural module is a detailed finite element model built with the commercial software Abaqus. The rigid frame made of carbon fiber bars is modelled with beam elements joined with connectors, and the canopy with geometrically nonlinear membrane elements. The quasi-steady FSI analysis allows to assess the relative importance of aeroelastic and unsteady aerodynamic effects on the aerodynamic coefficients versus the angle of attack of the RFD kite. Moreover, the framework constitutes a mid-fidelity aero-structural code ready to be coupled with any kite flight simulator to enhance the predictions.



Depiction of the FSI framework.

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UC3M and CT Ingenieros flight test rig during testing (January 2024).

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An Aircraft-Integrated Control System Based on Bridle Actuation for AWE Machines

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Flight dynamics control systems for crosswind airborne wind energy (AWE) can be classified as ground-actuated and fly-actuated [1]. Ground-actuated control systems present a higher drag because these involve more than one tether, but they are simple and allow for lighter aircraft. Fly-actuated systems have the advantage of just involving one tether. They typically use flight control surfaces in fixed wing aircraft and an external pod for changing the bridle geometry in Leading Edge Inflatable (LEI) and delta kites. This work proposes a fly-actuated control system that changes the geometry of the bridle but, instead of being separated in a pod, the mechanism is integrated in the aircraft (see Fig. 1).

The study presents a theoretical framework based on a previous work on bridle control [2] and a trade-off analysis of the design parameter of the control mechanism based on simulation with the LAKSA software [3]. After a detailed design, and manufacturing, the structure and the mechanism are integrated in the delta kite of UC3M testbed [4]. The system involves a base structure, a battery that supplies power to a motor controller, an electric brush-less motor with a gearbox, and a pulley system that is attached to the gearbox on one side and to two control lines reels of the other. Its design reduces the load on the motor by balancing the tension of two lines of the bridle. The control system has been verified through static tests in the laboratory and flight tests using UC3M testbed. A comparison between simulation results and the experimental data of the flight testing campaign is presented, demonstrating the system's viability and reliability.

Bridle control system integrated in a delta kite.

References:

[1] Cherubini, A.: Advances in Airborne Wind Energy and Wind Drones. 2015

[2] Alonso-Pardo, J & Sánchez-Arriaga, G.: Kite Model with Bridle Control for Wind-Power Generation. Journal of Aircraft, vol.52, n.º3, pp. 917-923, may 2015.

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Material Scaling for Direct-Driven Permanent Magnet Synchronous Generators for Airborne Wind Energy Applications

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One of the most competitive advantages of Airborne Wind Energy (AWE) systems when compared with other renewable energy sources is the limited amount of required materials.

The deployment of low-speed, direct-driven Permanent Magnet Synchronous Generators (PMSG) further enhances the possibility of reducing the material investment for the gear system, at the cost of a greater mechanical complexity and more significant torque ripples. The proposed work aims at providing an effective way for evaluating how the electric machines scale, and the related bill of materials, depending on the average cycle power P_{cycle} of a pumping AWE system. The analysis of the contribution of each element to the mass of the electric machine is instrumental to carry out a rigorous Life Cycle Assessment (LCA) study of the whole system, to assess quantitatively its environmental impact (e.g. [1],[2]). The outcomes indeed contributed to an LCA study with functional unit 1 *GWh* of electric energy and system boundaries defined by a *cradle to grave* approach, developed according to the ISO standards 14040 and 14044. The mass breakdown of a PMSG with P_{cycle} = 1 MW is reported in Figure 1 as an example.

The obtained results shed lights on the crucial aspects to consider when scaling these machines in energy production applications, such as the extensive use of rare-earth permanent magnets, and provides a preview of the machine dimensions for potentially marketable solutions.

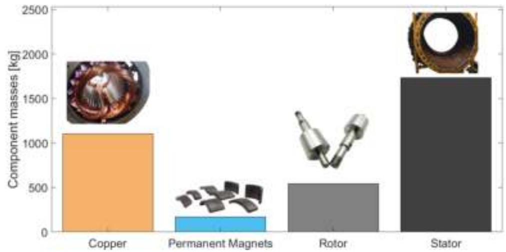

Figure 1: Mass breakdown of the different components of PMSG for an AWE application with 1 MW cycle power.

References:

[1] Wilhelm, S.: Life Cycle Assessment of Electricity Production from Airborne Wind Energy. In: Schmehl, R. (eds) Airborne Wind Energy – Green Energy and Technology, 727–750, Springer, Singapore (2018). doi:10.1007/978-981-10-1947-0_30

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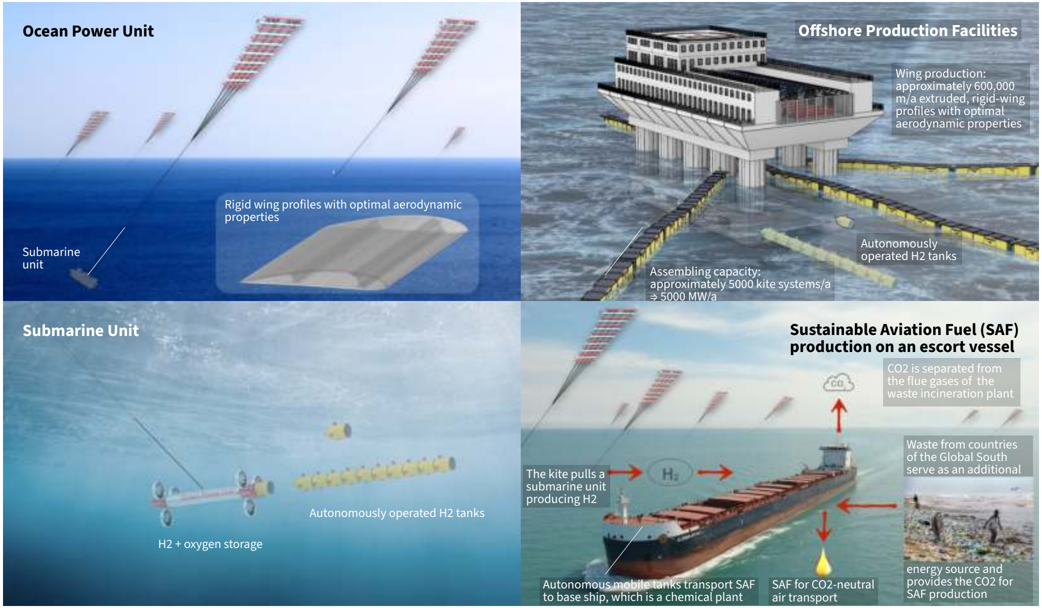
ParCy
Paradise Cycle

Harvest Ocean Energy

Franz Ringelhan
ParCy

Making the energy resources of the world's oceans usable is the goal of our considerations and concepts. Decisive for the realization are economic efficiency and reliability. These general conditions led us to develop an autonomous and mobile kite system. It consists of extruded, rigid wing profiles with optimal aerodynamic properties. In offshore production facilities, the kite systems can be efficiently manufactured, assembled and commissioned in large quantities. The kite system is connected to the underwater unit with a 400 m long rope. This is pulled through the water. Rotors generate electricity, which is directly converted into hydrogen by an electrolyzer. Which is stored in autonomously operated H2 tanks and transported to an escort vessel. There the H2 is converted with CO2 into SAF (Sustainable Aviation Fuel).



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Flight Path Optimization for Airborne Wind Energy Applications Using Multiple Tethered Aircrafts

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Generating electricity can be more efficient and cost-effective through the utilization of multi-aircraft systems in the process of airborne wind energy (AWE) applications. This approach involves the operation of multiple tethered aircraft connected by a shared main tether. In this way, the lateral motion of the shared tether is reduced, thereby minimizing aerodynamic drag and maximizing the harvested energy. Extensive research on tethered multi-aircraft systems has revealed significant efficiency improvements. These conceptual extensions offer advantages such as scalability, more consistent power output profiles, and increased power densities within the entire farm structure. However, they are accompanied by a set of challenges, including increased complexity, optimization of path trajectories of the system to avoid collisions during flight, and handling the process of reeling in and out of the tether during take-off and landing.

For any AWE system, efficient flight paths are critical for path planning, system optimization, and controller design. While previous research in this area has been primarily conducted through simulations, our work introduces practical outcomes derived from real-world experiments to optimize the flight trajectory of two tethered unmanned aerial vehicles (UAVs).

In this talk, I will present the initial setup of our multiple-tethered aircraft system, including the hardware configuration of each tethered UAV, controller design, and optimization of their flight paths to maximize lift when flying across the wind in a figure-of-eight pattern. Furthermore, I will discuss the conclusions obtained from our work with this configuration and outline future steps to enhance our model to maximize its power generation capabilities.

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Evaluation of High-Voltage Submarine Transmission Lines and Battery Integration for Offshore Airborne Wind Energy Systems

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This study aims to survey the challenges and potential solutions in the field of submarine electrical transmission for Offshore Airborne Wind Energy Systems (OAWE). The analysis is undertaken to perform a thorough Life Cycle Assessment (LCA) investigation of a specific OAWE system, with the aim of quantitatively evaluating its environmental footprint rigorously.

It is considered a hypothetical OAWE power plant near Sicily in the Mediterranean Sea. This site has been chosen to carry out comparisons with a traditional wind power installation [1]. This OAWE site faces challenges in its 220 kV power grid, connecting Palermo and Messina, therefore a connection to the 380 kV power grid in Campania is being explored.

The analysis also takes into account the integration of batteries in the offshore electrical substations as a crucial component of the infrastructure, to ensure continuous and stable power output. To this end, the battery sizing will be carried out by also considering the possibility to properly synchronize more systems on the same bus, such that the overall power output is always positive.

(Left): Offshore electrical substation with battery integration, own illustration. (Right): Investigated site of the hypothetical OAWE farm and its connection to the grid

The integration of batteries aims to enhance the reliability and efficiency of offshore wind energy generation while mitigating the intermittent nature of wind resources.

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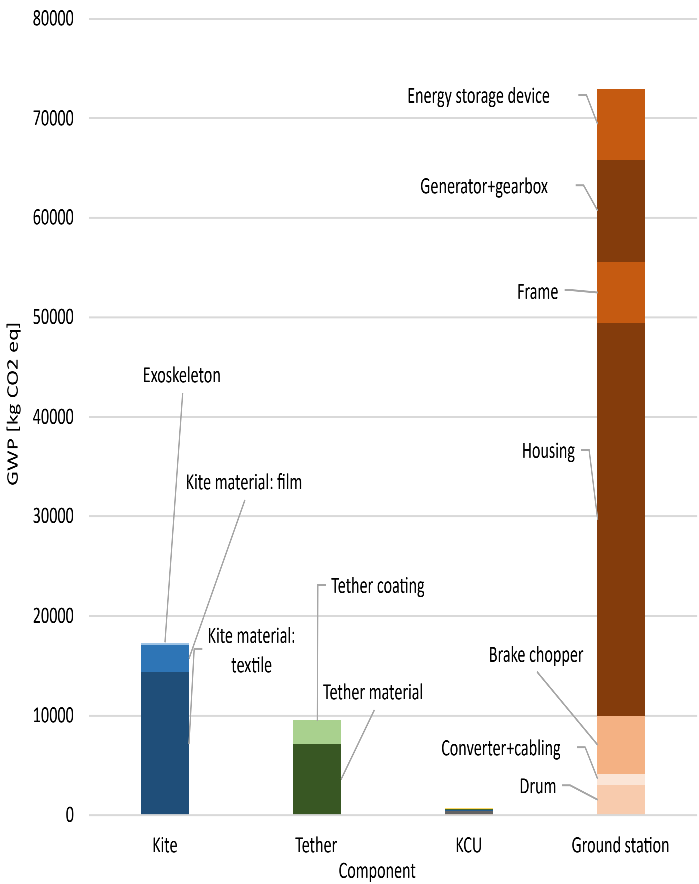
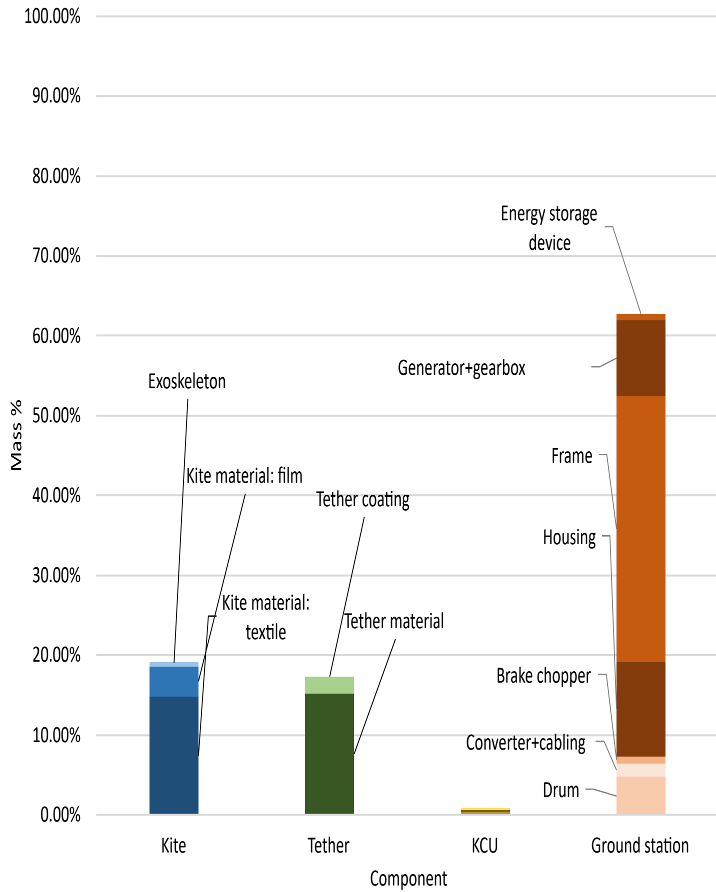
Distribution of global warming potential (left) and mass (right) over the components of the AWE system, with replacements over system life time included.





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Life-Cycle Analysis of a Soft-Kite Airborne Wind Energy System

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The European Commission's roadmap for transitioning towards a fully renewable energy system includes ambitious goals to install 60 GW of offshore wind energy by 2030 and 300 GW by 2050[1]. This accelerated capacity scale-up will entail a massive consumption of raw materials to manufacture the required wind turbines, including the foundations and installation infrastructure. One of the key advantages of airborne wind energy (AWE) is the low material demand of the technology, which should not only lead to a further reduced carbon footprint of renewable electricity but also to a reduced environmental impact [2].

The goal of the present research is to assess the environmental performance of a commercially developed 100 kW soft-kite AWE system by quantifying its global warming potential (GWP100) and material intensity. The presently pursued target market for soft-wing AWE systems in the 100-500kW range is for off-grid remote areas – coupled with solar PV and batteries, primarily for displacing diesel generators. The starting point of the research is an earlier sizing study for this type of novel kite-powered hybrid power plant (HPP) [3], expanding this now by a life-cycle analysis of mainly the AWE component. The research is conducted as a graduation project at TU Delft within the larger scope of the doctoral training network NEON, funded by the Dutch Research Council NWO.

To quantify the hypothesized environmental benefit of AWE systems, a comparative LCA study of a hybrid power plant configuration with and without AWE will also be performed. The LCA will use the methodology as provided in ISO 14040 and 14044 [4][5]. The LCI modelling framework used is an attributional LCA with system boundaries from cradle-to-grave. The functional unit is: 'Annual electricity production of 450 MWh, generated by an airborne wind energy system'. Activity browser and EcoInvent are used as the LCA modelling software and database respectively. The research will also aim to provide better insight into whether recycling kite and tether materials is beneficial in the overall environmental impact of the system. Initial findings show that the ground station contributes the most to environmental impact despite the kite and tether requiring the most replacements over the 25 year lifetime.

References:

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[5] ISO 14040: Environmental Management – Life Cycle Assessment – Principles and Framework

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Integrated Design of Offshore Airborne Wind Energy System: the Floating Platform and the Aircraft

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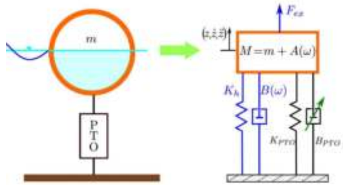
In order to guarantee the correct functioning of an offshore AWE system, an integrated design of the floating platform and the aircraft – also referred to as kite in the literature – is required.

After the initial sizing of the aircraft for the desired rated power, the tension in the tether during operations is used in the iterative design of the platform. The integrated design of the offshore system is carried out considering the wind and wave distribution over the year, and some relevant extreme load cases.

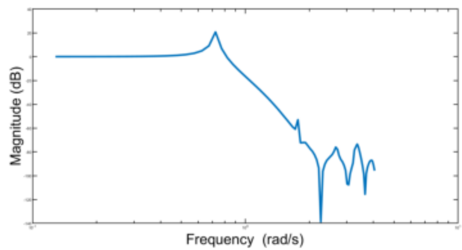
As the platform response to the tether force and the wave excitation is expected to influence the energy production [1], the floating platform shall be designed to limit the vertical displacement. The hydrodynamic characteristics of a simplified platform, such as its stiffness, radiation and excitation forces are evaluated with NEMOH, a boundary element solver based on linear potential flow and the linear theory of waves [2].

Then, the response of the platform in distinct offshore locations is assessed, using ERA5 data of a specific site (i.e., wave height and wave period) [3].

Finally, a frequency analysis is performed, to study the critical frequencies and vibration modes. Using absorbing materials, together with a mooring system, a change in the natural frequency of the structure is obtained, avoiding instabilities. The results highlight the importance of modifying the design depending on the specific environmental conditions.



Simplified model of the platform.



Bode diagram of the magnitude response.

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Power Smoothing and Energy Storage System Sizing Strategy for Airborne Wind Energy Farms

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We tackle the challenge of balancing the power output from an Airborne Wind Energy Farm to ensure a stable power flow into the grid. This is crucial to prevent the imbalances commonly seen in ground-gen systems, given the significant oscillation between power production and consumption during the reel–in and reel–out phases.

We analyse two synchronization strategies regarding the units of a farm. The first approach creates groups of synchronized units according to wind direction, e.g. [1], with all units in the same group operating simultaneously and phased in the same cycle step. In the second approach, the reel–in phase occurs inside the flight envelope, which allows kites in different phases to operate independently, mitigating high–amplitude oscillations in the farm power output [2].

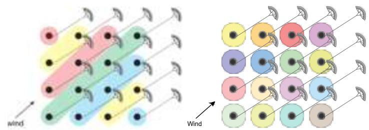
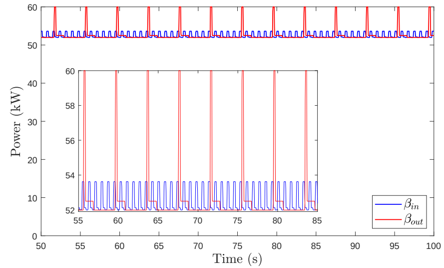


Illustration of the different arrangement approaches. Left: four synchronization groups (one for each colour). Right: sixteen synchronization groups (all different)

Additionally, we enhance power output smoothing by implementing an energy storage system (ESS). We then compare the ESS performance under both approaches. The first approach results in larger power deviations implying a larger ESS, while the second approach reduces deviations but increases oscillation frequency, potentially impacting degradation rates.

This study compares both methods, aiming to identify the best suitable approach for the large–scale integration of the wind farm with the grid.



Resultant power waveform for each approach

References:

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A Discussion on Automatic Take-off and Landing Approaches for Airborne Wind Energy Systems

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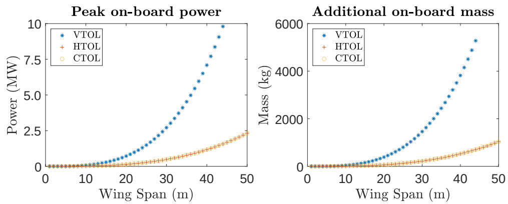
A scalable, robust, and cost-effective airborne wind energy system (AWES) should rely on a completely autonomous operation, including a fully automatic launch and landing scheme. The take–off and landing (TOL) schemes are significantly different for AWES with soft wings and with rigid wings, and in each of these systems a consensual specific scheme is yet to be established (see e.g. [1]). In this work, we study different automatic TOL (ATOL) techniques for rigid–wing aircrafts, with self-propulsion, to be used in ground-gen AWES, detailing the analysis for three schemes: VTOL – Vertical TOL, HTOL – Linear Horizontal TOL (which can be aided by a catapult during take-off and by an arrest device during landing), and CTOL – Circular TOL. For each scheme, we evaluate a range of criteria, including the facility to relaunch, the possibility to reuse existing technology, ground area needed, peak on-board power, and the consequent additional on–board mass. These characteristics are examined for various aircraft dimensions, with scaling factor indexed by the wingspan. In the case of the CTOL system, we have used as basis a small–scale prototype developed within the UPWIND group [2,3].

While the VTOL scheme shows advantages regarding the needed ground area, the facility to relaunch and the possibility to re–use existing technology (e.g. from drones), it requires significantly more peak power and additional mass. This can be justified since the on-board motors have to generate lift that overcomes the aircraft weight, while in horizontal approaches the on-board motors have essentially to overcome just the aerodynamic drag. HTOL and CTOL schemes require a much larger ground area. In HTOL, the take–off speed, capable of generating sufficient lift, has to be attained within the runway length, and during landing a robust control scheme should be designed to guarantee touch-down within a small predefined area. These requirements can be relaxed in CTOL due to the endless nature of the runway. However CTOL has a much lower possibility of reusing existing similar technology, requiring further research on the topic.



On–board peak power and the additional on–board mass as a function of the wingspan for each of the three ATOL schemes.

References:

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EnerKíte's swept wing on the rotational mast (July 2023). The right half of the wing shows several tell tales that are used for flow visualization.

Topology optimized EnerKíte wing (2024).

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Multifidelity Design Optimisation Models for Composite AWE Wings

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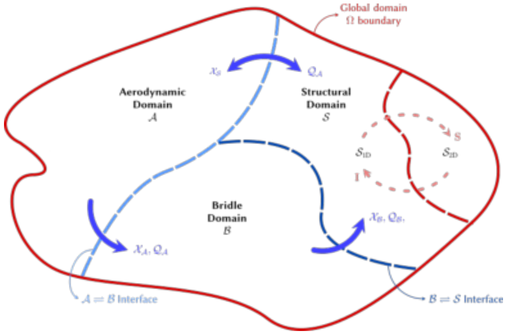
Composite materials are the standard choice for fixed-wing AWE wings, given their high stiffness-to-weight ratios. These anisotropic materials typically undergo complex load-deflection couplings, further complicated by the wing geometry. These complicated deflections could give rise to undesirable aeroelastic phenomena and hence require consideration, already in the initial design stages. EnerKíte utilises ultra-light, slender carbon composite wings to minimise airborne mass. A set of multifidelity models is presented that builds upon the toolchain consisting of a group of 2+1D solvers for the aerodynamic A, bridle B and structural S domains [1,2]. The aeroelastic response is determined by a steady-state coupling of the solvers [3]. An approach is suggested that describes the structural domain S in varying levels of complexity, facilitating solving for the complex lamination layer plan only as the final step. This allows for the rapid screening of design candidates without having to prescribe detailed lamination layups and other manufacturing constraints that are typically unknown at the initial design stage. This proposed method can thus probe the vast initial design space, considering configurations in the aerodynamic A, bridle B and structural S domains [4].



Partitioned approach and information exchange for coupling of the different AWE domains.

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Wind Resource Analysis For Airborne Wind Energy Systems

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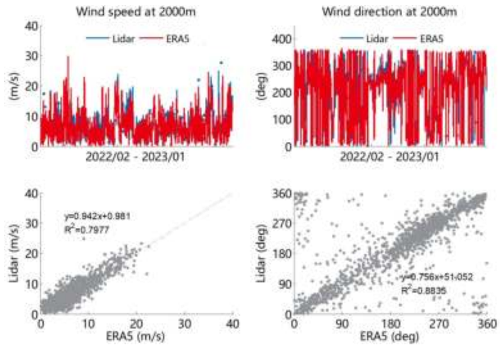
High-altitude wind energy has a rich resource, high power densities, and more stable wind direction and speed than close to the ground. Different from many existing airborne wind energy systems (AWES), we consider in this paper a parachute-based AWES containing a cascade of parachutes exploiting aerodynamics drag forces. Such a conceptual design has a high power-to-weight ratio of the aerial components and is easy to scale up (possibly to the order of 10 MW, much greater than the nominal power of other AWES techniques). In this paper, the principle of parachute-based AWES will be present.

Wind resource assessment is a critical step for site selection of high-altitude wind farms, and its accuracy is crucial for the future actual operation and benefits of wind farms. For studying the wind energy that could be captured by the Airborne Wind Energy System (AWES), we conducted year-round monitoring of wind speed, wind direction at heights between 300 meters and 3,000 meters using laser wind profilers and wind profiling radars at the test site. The spatial distribution, vertical profile, and temporal variation of wind speed and wind power density between 300 and 3,000 m were analyzed using the monitoring data and the ERA5 reanalysis data from 2012 to 2021. As shown in the figure, the laser wind profiler monitoring data and the ERA5 data for wind speed and wind direction have a good match. We also proposed a method for assessing high-altitude wind resources:

1. Data collection and organization
2. Statistical analysis of basic wind condition parameters
3. Analysis of wind energy resource characteristics
4. Estimation of equivalent wind power density
5. Evaluation of high-altitude wind energy resources



Correlation of wind speed and wind direction between laser wind profiler and reanalysis data (at 2000 m).

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MERIDIONAL

POLITECNICO
MILANO 1863

A Preliminary Estimation of the Absolute Wind Vector in AWE Systems

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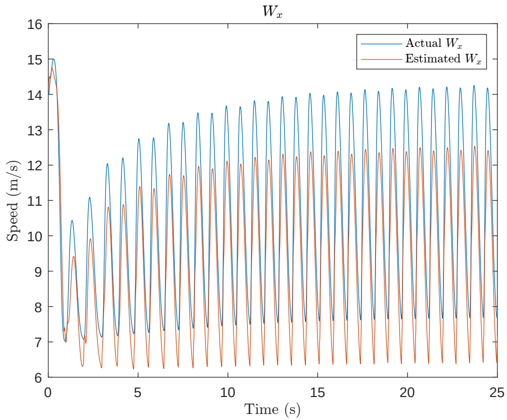
An accurate estimation of the wind vector at operational height is essential for the design, control, and optimization of AWE systems. However, the nonlinear and stochastic nature of altitude wind, the limited and noisy measurements from the onboard sensors, together with the complex aerodynamics of a tethered aircraft pose serious challenges to the task.

Inspired by an initial work at Kitemill [1], the main objective of this work is to develop and evaluate novel methods for wind speed estimation for AWE systems in a simulation setting. This paper proposes and compares two different approaches for wind vector estimation, without using any dedicated wind sensors and exploiting only the measurement of dynamical quantities of the kite. Under the assumption of perfect knowledge of the simulation model, the first approach utilizes a solver capable of handling nonlinear equations, minimizing the difference between the measured derivatives of the state and the estimated derivatives of the state computed with the unknown wind. On the other side, the second approach solves a nonlinear minimization problem where the model used for the estimation is different from the simulation one.

Although the Nonlinear Solver approach generated promising results, its reliance on strong assumptions and susceptibility to noisy measurements, causing a fast divergence, led to its performance being considered inferior to that of the optimization approach. Indeed, the latter proved to be robust in the presence of uncertainties and flexible in the employment of constraints, derived from aerodynamic considerations.

The algorithms developed in this work will be further tested in a more complex simulation environment to test and improve their robustness, and the wind vectors estimated could be exploited to reconstruct a wind field.



Estimation results of optimization method

References:

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POLITECNICO
MILANO 1863

Modeling and Control of an Airborne Wind Energy Microgrid

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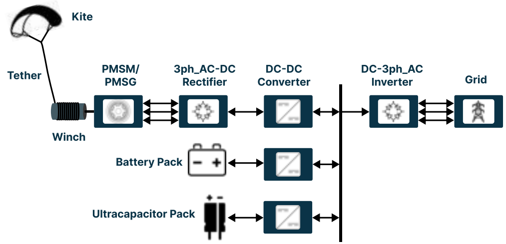
The contribution investigates the use of Airborne Wind Energy to deliver electrical power to remote areas. The focus is on the utilization of soft-wing kites with pumping operation; it is assumed that the AWE employs a Permanent Magnet Synchronous Machine (PMSM) for efficient conversion of mechanical energy into electrical power[1].

The presentation will encompass the technical aspects of mechanical to electrical power conversion, highlighting the efficiency and viability of PMSMs in AWE systems. Furthermore, the discussion will extend to the various stages of electrical power conversion necessary to render the output suitable for grid connection. This includes an analysis of the technical considerations and challenges involved in integrating AWE-generated power into the existing power grid infrastructure.

An essential aspect of our research is the incorporation of an energy storage system. This system is designed to ensure a consistent and smooth delivery of power to the grid, particularly focusing on maintaining stability during the power generation and recovery phases of the AWE cycle. The presentation will offer insights into the design, implementation, and benefits of the storage system, emphasizing its role in enhancing the reliability and efficiency of power delivery. The findings are supported by simulation results on a detailed model developed by the presenter.



AWE Microgrid System

References:

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Feasibility Analysis to Find an Appropriate Financing Strategy for a 25 KW Kite Generator in the Iran Energy Market

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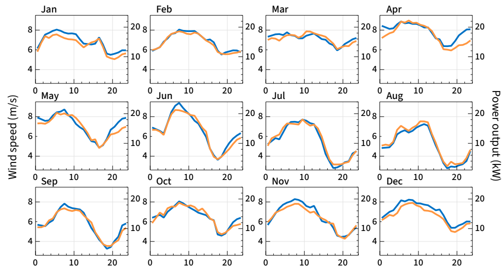
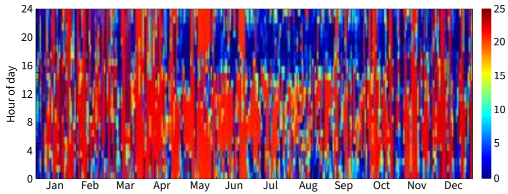
This study examines the feasibility of a 25 kW kite power system located in Abhar, a city in Northwestern Iran. The system operates at a wind velocity of 8 m/s and is situated at an elevation of 100 meters. The cost of the supply was estimated by applying cost models that are compatible with the market conditions in Iran. The study aimed to investigate the best economic factors to adjust the most appropriate financing strategy [1]. In addition to examining the feasibility of the model, financing strategies such as receiving the facility from the National Development Bank, utilizing facilities granted by the Ministry of Energy from the collection of customer tax (governmental purchasing tariff), securing capital from the Special Fund through Sukuk (physical asset-based bonds), and exploring overseas financing options were taken into account. According to the figures, the AWES system consistently produces energy throughout the day and across different months of the year. This consistency is evident in the hourly data on electricity being fed to the grid, the daily comparison of wind speed with system power generated, and the heat map of hourly system power. Additionally, a suitable financial strategy was determined through an analysis of the cash flow model. This strategy includes allocating loans in percentages of 75%, 50%, and 25%. The chosen model incorporates Sukuk, an incentive tariff of 1.5 cents per Kwh, a 25% loan allocation, and overseas financing, taking advantage of the favorable Euro to Rial conversion rate [2].



Daily profiles of wind speed and power output.



Daily power production (kW) over the year.

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Aerodynamic Shape Optimization of Airfoils and Wings for Crosswind Kites

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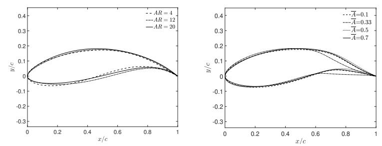
This paper reports on an ongoing research on the aerodynamic shape optimization of airfoils and wing planforms for rigid-wing crosswind kites. In the present airfoil optimization framework, developed in MATALB, the improved geometric parameter (IGP) method is used for airfoil geometry parameterization, XFOIL is used to obtain aerodynamic forces, and the Non-dominated Sorting Genetic Algorithm II (NSGA-II) is employed to generate random airfoils. In the wing planform optimization framework, OpenVSP is used to create the wing geometry and to obtain aerodynamic forces acting on the wing, and NSGA-II is used to create random planforms.

Most existing airfoils and wing planforms in the open literature have been designed and optimized for the use in conventional aircraft, where the objective is typically maximizing the lift-to-drag ratio, (C_L/C_D), or minimizing the induced drag. While the conventional airfoils and wing planforms may still be used for crosswind kites, they cannot guarantee optimal power generation. It is well known that the power output from a crosswind kite is proportional to C_L^3/C_D^2 which may be a more reasonable quantity to be maximized. In addition, in contrast to conventional aircraft, kites are tethered to the ground, which may necessitate optimal airfoils and wing planforms different from those for conventional aircraft.

Few studies, such as Refs. [1-3] exist on the aerodynamic shape optimization of airfoils and wing planforms for airborne wind energy applications. In contrast to these studies, in the present study, the IGP method has been used to create airfoil shapes, which significantly reduces the computational burden and increases the versatility of the design and optimization framework. Pareto-optimal airfoils were obtained for three different scenarios including the effects of: (i) neither wing's aspect ratio (*AR*) nor tether drag, (ii) wing's aspect-ratio, and (iii) tether drag. For example, as seen from the left figure, the optimal airfoils for scenario ii (i.e., including *AR* effects) have a cusp at their trailing edge. From the right figure, the resulting shape for scenario iii, particularly for $\overline{A} = 0.33$ ($\overline{A}$ is the tether-to-kite area ratio), is reminiscent of a flapped airfoil, suggesting a multi-element airfoil design. The aerodynamic behaviour of optimal airfoils and wing planforms are examined through comprehensive CFD analysis. The methods and results from this study are useful for developing more efficient crosswind kite systems.



Optimal airfoils when including the effects of: (left) wing's aspect ratio (scenario ii), and (right) tether drag (scenario iii).

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Lifting-Line Aerodynamics for Airborne Wind Energy on a Prescribed Path

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Lifting-line aerodynamic models are attractive for a number of reasons. First, the computational load relative to CFD is small enough for it to be viable for a wider range of studies and engineering design application. Furthermore, the lifting-line framework is suitable for exploring the effect of different chord, twist, sweep and dihedral distributions.

A previous work [1] by the author used the unsteady thin airfoil framework to reveal the necessary implementation details for a consistent coupling between the "inner" 2D (airfoil data) representation and the "outer" 3D lifting-line representation of the method. This allows for properly capturing the correct local and total aerodynamic forces and moments for both steady and unsteady situations. This contribution is a preliminary investigation on the use of this model for Airborne Wind Energy (AWE).

As a preliminary investigation, this lifting-line model is set-up to calculate the aerodynamic forces from an Airborne Wind Energy aircraft on a prescribed path. The Ampyx AP2, 5.5m 30kW system will be the basis of this model and the prescribed path is solved using AWEBox [2]. The forces from the lifting-line model will be compared with the predicted forces from the linear aerodynamic model in AWEBOX. Unlike, with simplified models, the present work include the full nonlinear coupling effect of the loading on the wings as well as the possibility of including the effect of full 3D unsteady flow fields (turbulence/gusts) as well as flight path and dynamics.

Most engineering models for kite aerodynamics are not capable of simulating the fully coupled effect of sweep and dihedral with these effects. This contribution will try to show how these geometric variations affect the aerodynamic forces. Additionally, the model can be enhanced with spiral vortex wake models, this work will also try to investigate these enhancements.

The lifting-line model is also the basis for two additional conference contributions. The first by Kelly [3,4] investigates the impact of upper atmospheric flows on the aerodynamic forces. The second by McWilliam [5] applies the model in to investigate the impact of these aerodynamic forces on the structural dynamics.

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TÉCNICO LISBOA

Using Leading-Edge Protuberances for Dynamic Stall Control of an Airborne Wind Energy Wing

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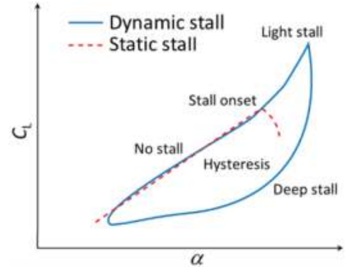
Many passive and active techniques have been proposed and investigated with the aim of achieving dynamic stall control [1]. Recently, vortex generators in the form of leading-edge protuberances have demonstrated to be very effective for the foregoing purpose when applied to a small vertical-axis wind turbine [2]. The use of this passive control technique in Airborne Wind Energy (AWE) wings may be expected to allow smoothing out dramatic fluctuations in aerodynamic loads, as well as reducing the strong hysteresis in the deep stall regime (see figure).

During the energy-producing (or reel-out) phase, “figure-of-eight” flight maneuvers are the trajectory of choice for AWE wings, thus subjecting these to periodic pitching motions [3]. In this context, different approaches may be considered to study the occurrence of dynamic stall phenomena. Vortex methods are usually fast, but three-dimensional geometrical complexities may be difficult to implement. Coupling inviscid techniques with semi-empirical models such as the Leishman-Beddoes method allows circumventing the latter difficulties, but empirical information must be fed into the calculations. Despite their high computational burden, viscous (Navier-Stokes) methods have shown capabilities to fully describe the unsteady flow phenomena. This approach has allowed to provide detailed predictions of the use of leading-edge protuberances in the control of static stall for a finite wing [4], and it is also applied here for the intended analysis of an AWE wing subjected to dynamic stall.



Schematic comparison of static stall versus dynamic stall.

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University of Ghent's Fluid Mechanics team (March 2024).

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Multi-Component Overset Simulations of Airborne Wind Energy Systems

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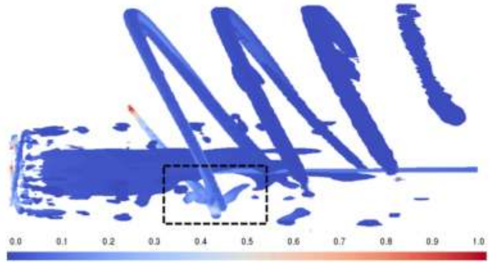
Several types of Airborne Wind Energy Systems (AWESs) execute a pumping cycle and thus perform a large rigid-body motion in the atmosphere. Additionally, the flying device will typically deform due to the wind loading [1] and can have moving or deforming control surfaces. Finally, also farms of AWESs [2] and their combination with Horizontal Axis Wind Turbines (HAWTs) [3] are of interest.

For all of the reasons above, overset simulations are considered a suitable technique for high-fidelity computational fluid dynamics (CFD) and fluid-structure interaction (FSI) simulations of AWESs. Such overset flow simulations consist of a large rectangular prismatic background grid for the Atmospheric Boundary Layer (ABL) and a body-fitted grid around each of the flying components. These components can be the main wing but also a control surface. Furthermore, the component grids can move relative to each other and even deform, and they overlap the background grid. Interpolation and iteration between the different grids ensures that the obtained flow field takes the ABL and all flying components into account.

After analysing the deformation of the main wing of a single MegAWES [4] device using FSI simulations [1], this technique has been applied to analyse its flight through the wake of a HAWT [3]. These simulations provide insight in the wake interaction and the reduction in generated power during the wake crossing. Likewise, multi-kite CFD simulations are planned and the influence of the component grid resolution on the produced power and generated forces is assessed.



Vorticity [1/s] on an iso-surface of the Q-criterion equal to 0.1 for an AWE behind a HAWT [3]. The dashed box shows accelerated breakdown of vortical structures by wake interaction.

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SkySails Power System in operation under a cloudy sky (July 2023).

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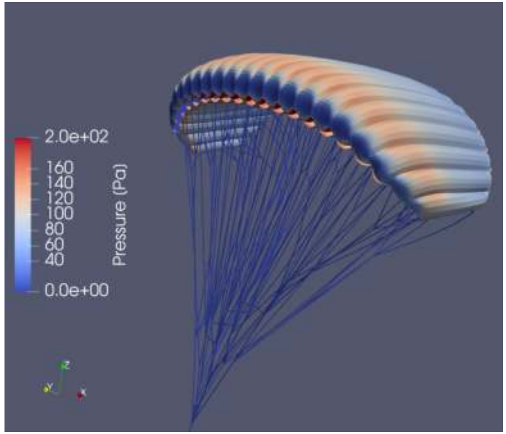
Towards an Optimal Ram-Air Kite Design for AWE: Recent Advances in the Coupled Aero-Structural Model

Paul Thedens
SkySails Power GmbH

SkySails Power utilises tethered ram-air kites to harvest wind energy. During the power phase the kite is trimmed for maximum lift while the control pod steers the kite's trajectory. During the reel-in phase, the kite is depowered to reduce lift and minimise the glide ratio, ultimately shortening the reel-in time and minimising tether force.

The design of the canopy and bridle system is of paramount importance for an efficient power cycle and minor alterations can yield unintended canopy geometries and flight behaviours. Thus, the process of crafting an effective canopy and bridle design is an iterative process that blends analytical approaches, field testing, and simulation.

A sophisticated simulation environment based on a coupled aero-structural model [1-2] has been developed over the years and it is capable of modelling our kite's performance and structural deformations. Introducing new features to refine our model and achieve more accurate results throughout all flight phases is an ongoing process. During the presentation, we will showcase our most recent findings, comparing them with field measurements to validate our model. With our evolving simulation capabilities, we aim to gain a deeper understanding of how design modifications impact the entire airborne system and further integrate the simulation environment in the design process loop.



FSI simulation of the depowered SkySails kite.

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SkySails Power system in operation above the clouds (April 2023).

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Multi–Objective Layout Optimization for Airborne Wind Energy Farms

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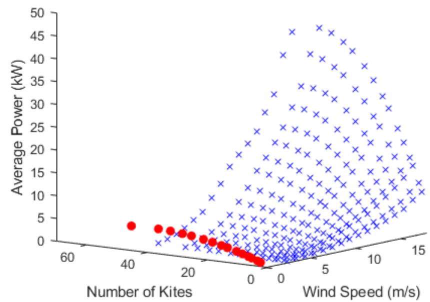
We address the problem of designing an airborne wind energy farm, which involves deciding the number of kites, their flight envelope and their location.

The main challenge is to maximize the average power generated by the kite farm while minimizing the number of units to be installed on a pre–defined area, considering the positive correlation between the number of units and the overall cost. This Multi-Objective Optimization Problem involves two conflicting optimization goals, which we solve using a combination of the Non-dominated Sorting Genetic Algorithm-II (NSGA-II) and the Biased Random Key Genetic Algorithm (BRKGA) [1, 2]. This integration uses essential elements such as elitism, biased uniform crossover, the introduction of mutants, as well as non-dominated sorting and selection criteria that use crowding distance to maintain solution diversity.

As in [3], we explore different farm layouts, including square and hexagonal patterns, to determine the best number of units in the kite farm. In the results, we obtain a discrete approximation of the Pareto front. Furthermore, we fit a Weibull distribution to a wind data set of a location in northern Portugal, which is used to estimate the average power output of the kite farm.

We can further refine the number of units needed by considering different decision factors, such as the maximization of Annual Energy Production (AEP) per unit. With our proposed methodology, we have been able to improve on the results reported in [3].



Pareto surface for a hexagonal layout (blue). Average power regarding local wind distribution (red).

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Simplified Optimal Path–Planning for Airborne Wind Energy Systems

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We address the problem of Path–Planning and Optimization for Ground Generation Airborne Wind Energy Systems (AWES) during the Power Productive Phase.

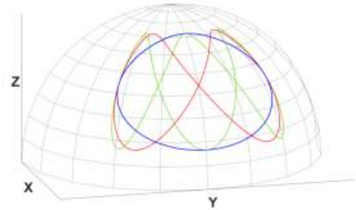
In order to produce as much power as possible, the kite must perform a quasi–crosswind periodical flight. There is a vast literature regarding trajectory optimization, for instance using Optimal Control, in order to maximize power production during the productive phase. This trajectory can then be converted into a time–independent path which can be used as reference for path–following controllers [1].

Although Optimal Control can be a very useful tool to find these optimal trajectories, it can be difficult to solve a problem with such a complex system. Since the trajectory of the kite in applications of AWES must be periodical, there have been attempts of simplifying the Optimal Control Problem (OCP) by formulating it in the frequency domain and thus simply optimizing for the main harmonics, reducing the problem dimension [2].

In this work, we aim at simplifying the trajectory optimization problem by defining the path as a Lissajous Curve in the plane consisting on the azimuth and elevation angles (ϕ,β) in a spherical coordinate system, thus optimizing simply for the curve parameters.

This separates the path definition and the speed at which the kite performs the periodical flight, defining the path as simple harmonic functions shown in the following equation.

$$\begin{cases} \phi(\tau) = A \sin(\omega_1 \tau + \delta_1) \\ \beta(\tau) = B \sin(\omega_2 \tau + \delta_2) \end{cases}, \tau \in [0, 2\pi]$$



Path defined as Lissajous Curves with $\delta_1 = \pi/2$, $\delta_2 = 0$ and ratio $\omega_2/\omega_1 \in \{1, 2, 3\}$ in blue, red and green, respectively, projected onto a spherical surface centred at the ground station and with radius equal to the tether length.

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Optimization of Long Trajectories of Dual-Wing AWE Systems with Many Cycles

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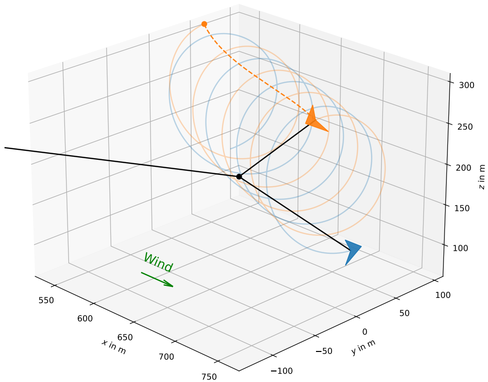
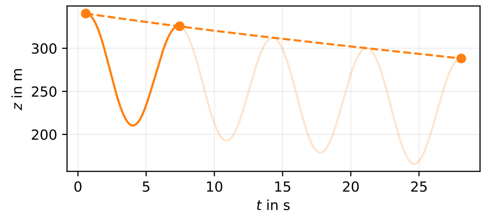
The reel-out phase of pumping AWE systems is usually composed of a sequence of fast cycles (circular loops or lemniscate patterns) superimposed on a smooth reel-out trajectory (slowly changing average flying height or tether length). For a large number of such cycles, the optimal control problem of finding power-optimal trajectories becomes increasingly more computationally expensive to solve.



The reel-out phase of the trajectory of a dual-wing AWE system consists of many similar loops.

Instead of exactly simulating all cycles of an oscillating trajectory, we only simulate a subset of them to approximate the slow change that occurs over the time horizon. Although restrictions with respect to the geometry of the trajectory have to be added, the number of variables in the resulting optimization problem as well as the time to solve the problem is reduced notably.



Only a subset of cycles have to be simulated to approximate the slow change of the z-position of one kite.

This method was presented in prior publications [1] where it was utilized for the trajectory optimization of a single-wing system with low-fidelity models. By integrating the method into the toolbox AWEBox [2], we can make use of the toolbox's high-fidelity models and reliable solution strategies to optimize the trajectory of a dual-wing AWE system.

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Rigid-Wake Lifting-Line Vortex Modeling in a Single-Kite AWE Optimal Control Problem

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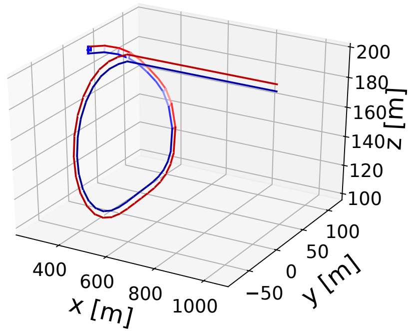
Two common assumptions about airborne wind energy (AWE) systems - that kites will experience a high cross-wind factor, and that kites will experience negligible induction effects - appear to be mutually inconsistent. It may, therefore, be reasonable to worry that the solutions of an AWE optimal control problem (OCP) whose dynamics are built upon the simultaneous application of both of these assumptions, could be unphysically optimistic.[1] That would, in turn, be a problem for AWE companies - and potentially the field as a whole - since the offline solution of OCPs is a common method of predicting performance metrics.[2]

This leads to the question: for a single-kite, lift-mode AWE system, is the solution of an average-power-maximization OCP significantly different if the constraints include a rigid-wake, lifting-line representation of the vorticity in the flow, or no representation of induction effects at all?

In order to answer that question, we will include a lifting-line vortex model, with a partially-resolved rigid-wake (convected with the free-stream) and vortex strengths chosen to be consistent with the trajectory, into the awebox[3]. How much of the included wake is resolved, as well the discretization of that resolution, will be determined according to the tradeoff between computation cost (time and memory) and modeling error (as estimated due to truncation and discretization).



An example of the vorticity distribution within the flow behind a single-kite, lift-mode, power-maximizing AWE system, using a partially-resolved, rigid-wake lifting-line vortex model, as formulated and solved in the awebox[3].

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Performance and Control of a Rigid Twin-Kite System for Power Generation

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Conventional ground-gen airborne wind energy systems (AWES) usually use a reel-in phase to pull the kite back upwind for the next power-generating phase. This reel-in phase raises the levelized cost of energy (LCOE) and increases the cycle complexity. We propose a twin-kite single generator configuration that eliminates the conventional externally powered reel-in phase. The system consists of a tether linking two kites, one at each end, and a ground generator positioned near the middle of the tether.

The contribution of this work is a simulation-based study that reveals two interesting properties of the configuration. First, somewhat surprisingly, a 13-degree-of-freedom (DOF) simulation with 6-DOF per kite and 1-DOF for the generator shows a stable cyclic pattern using only a bridle for roll and pitch stiffness and generator damping (Fig 1). The existence of this cycle, which does not use active control, suggests that the system may be relatively easy to control in practice.

Second, a more abstract simulation (3-DOF for each kite) yields a performance estimate for the twin-kite configuration. This simulation compares trajectories for a twin-kite system and a single-kite system both optimized with the trapezoidal collocation method. For the single-kite system, the optimized power curve during the reel-out phase is similar to the power curve developed by Houska and Diehl [1] under the same conditions and aircraft parameters. Based on the preliminary results, the twin-kite configuration eliminates the need for a powered reel-in phase, and nearly doubles the energy output (Fig 2).

We are currently working to improve the optimization approach to find optimal trajectories for the full 13-DOF system. With optimized trajectories for the full system, we plan to evaluate its performance and control in the presence of realistic disturbances using an MPC controller for tracking an optimized flight path.

Figure 1: Stable flight path of a twin-kite system that uses only passive control mechanisms.

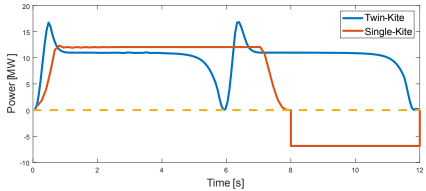

Figure 2: Power curve comparison for one cycle.

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Oceanergy’s kite being winded onto its storage truss (January 2024).

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Preliminary Design and Scaling Methodology of Flexible Kites for Airborne Wind Energy Applications in the Maritime Sector

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As far as climate goals are concerned, renewable energy sources play an important role. Concepts and systems in the field of Airborne Wind Energy (AWE) provide the potential to harvest the enormous available energy of high-altitude wind resources.

The KITE GAS/FUEL SHIP is a mobile AWE-system which exploits the high altitude winds on the open ocean [1]. Within the ICM-autoKite project the research is focussed on providing the basics of automated kite flight as a means of propulsion for Airborne Wind Energy systems in the maritime sector [2].

For maximization of the energy yield, the kite design must account for the high loads encountered, while providing the desired flight characteristics and flight performance during operation. The design of such tethered AWE kites requires appropriate methods that take into account the flexible characteristics and in-flight deformation during operation, in contrast to the fixed-wing design in classic aviation.

In this work, a preliminary design and scaling methodology of flexible kites in the field of AWE is developed. The methodology is structured in several sections, which allow an iterative design with an increasing level of detail. First of all a design point can be selected based on requirements of the overall system. Then an initial sizing is done to determine the relevant geometric parameters. In the following steps, the geometry will be further refined, focusing on the shape of the kite canopy, the bridle line geometry and the structural design. Furthermore, flight tests with a prototype system of a 4 line kite with integrated sensors were conducted and evaluated. The results are used to optimally adjust the kite design already at the first phase of the design process.

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Pumping Mode Rotary Airborne Wind Energy Systems: Exploration and Experimentation

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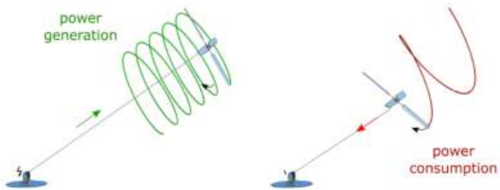
Pumping mode rotary airborne wind energy (AWE) systems have been described in literature [1,2] but despite their potential advantages over single-wing AWE systems, they have not been comprehensively researched or explored yet. Due to the high crosswind speed of the tether the efficiency of a single-wing AWE system breaks down as the tether length increases. Single-wing systems also have to fly acrobatic trajectories close to the ground at high speed during take-off and landing.

Rotary AWE systems on the other hand use a quasi-stationary tether and achieve crosswind motion by orbiting multiple connected wings around a center. As shown in the figure the tether of a pumping mode rotary AWE system only performs a reel-out and reel-in translational motion thus, significantly reducing tether losses and the complexity of the control system.



Working principle.

The feasibility of torque-based rotary AWE systems with lifter kites has been successfully demonstrated [3]. However, the use of a lifter kite and the tensile rotary power transmission (TRPT) provide significant challenges in automation and up-scaling [4]. The implementation of cyclic pitch control for rotary AWE systems [5] has removed the need for a dedicated lifter kite and has opened the path to pumping mode rotary AWE systems. Evaluating their viability, someAWE has been exploring, conceptualizing and experimenting with pumping mode rotary AWE systems. Searching for solutions for some of the functional requirements, different architectures and design options have been explored for:

- Rotor designs with cyclic and collective pitch mechanisms
- Methods for launching and landing
- Ground station designs with a generator and launch and landing capability
- On-board power systems

This talk presents different designs being evaluated and the current results with functional demonstrators

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Economic Value of Dual-Wing AWE Systems: a Case Study

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Airborne wind energy (AWE) systems based on dual wings consist of a near-stationary main tether, which is connected with shorter secondary tethers to two individual wings flying tight crosswind loops around each other. The low tether drag allows a high harvesting factor for small wings, even when operating at high altitudes.

Previous simulations have indicated that this feature allows for a system upscaling with significantly lower wing material investment and a higher power-to-mass ratio, theoretically leading to a lower levelized cost of electricity (LcoE) compared to single-wing systems. When exploiting the low sensitivity w.r.t. to altitude and harvesting wind energy "vertically", also an improved power density per ground area in farms is to be expected [1].

Recent investigations [2,3] showed that other performance metrics (such as, e.g., capacity factor, cut-in wind speed) besides LcoE should be taken into account as well to determine the value of AWE systems in an electricity market with fluctuating prices.

This work extends previous case studies to quantify the increase in system value, measured by the levelized profit of energy (LPoE), when transitioning from a single- to a dual-wing topology for pumping, rigid-wing AWE systems. The case study rests on the following pillars: a wind resource based on ERA-5 wind data; optimized, time-resolved flight trajectories taking into account realistic operational constraints; a parametric cost model; and an energy price model provided by the ENTSO-E platform.

Example of an optimized, time-resolved pumping flight trajectory of a dual-wing, rigid-wing AWE system.

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Towards Atmospheric Event-Driven Loads for Rigid AWES

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The highly variable and complex flow at operational AWE heights (of $\sim$ 200˘500 m or more) impacts the loads on a given AWES design. This involves different flow regimes which can involve turbulence and other phenomena,[1] producing transient events that may dominate AWES loads as well as operation. As reported previously, flow accelerations over length- and time-scales relevant for AWES systems are different than those for conventional wind turbines, and so are the appropriately filtered flow statistics.[2]

Following the work of Gaunaa *et al*. presented here (at AWEC2024) using lifting-line simulation/code, and in conjunction with the parallel work of McWilliam *et al*. using AWEbox[3] (this is 1/3 of a joint investigation), we examine the statistics of aerodynamic forces on a rigid AWES device—and their relation to corresponding flow acceleration statistics.

The analysis is done for a modelled device based on the AP2 system by AMPYX (nominal power 30kW, wingspan 5.5m). The python-based framework AWEbox[3] is used to solve for optimal flight paths over a range of conditions corresponding to AWES regimes. From observations, transient events at different scales, due to phenomena not always seen at lower heights, are embedded in the inflow; this can include gradients not represented in mesoscale-model or re-analysis data.[4]

The inflow timeseries to simulations includes all three velocity components, capturing effects specific to AWES. Significant accelerations in multiple directions affect AWES, while HAWTs act as larger-scale filters, mostly responding to / affected by streamwise fluctuations[2].

In this study we start pragmatically by neglecting the dynamic interplay between flow field, flight paths, and control system; this will be investigated in later studies. The sensitivity of forces or stresses on the rigid AWES to transient inflow (i.e., filtered velocity and acceleration component statistics) will be examined, for the first time; this also includes analysis relative to 'typical' turbulent flow at operational AWES heights. Timeseries of simulated forces will also be further fed to loads calculations (primarily wing flap-wise bending moment and tether tension), analysed and described by McWilliams et al. in an accompanying presentation.

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Trajectory Optimization of Dynamic Soaring Considering Closed-Loop Dynamics

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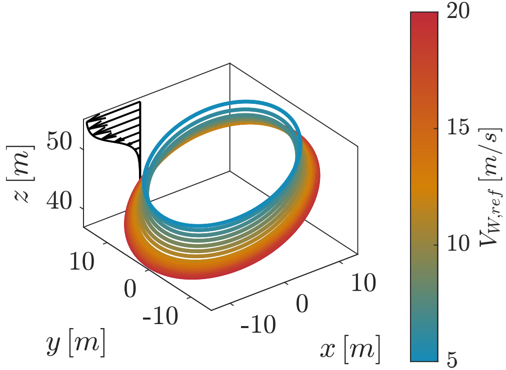
Dynamic soaring, a bio-inspired flight technique observed in wandering albatrosses, is a natural way of harvesting wind energy. In future applications, leveraging dynamic soaring may allow unmanned aerial vehicles (UAVs) to increase their range and endurance.

Autonomous dynamic soaring requires possibly optimal trajectory planning and precise tracking to maximize the energy gain in shear winds. Following a widely used approach to generate open-loop optimal control trajectories based on reduced order models (e.g. point mass models) results in poor energy extraction in closed-loop evaluations. Therefore, we directly include the closed-loop model into the trajectory planning process. This model contains a higher fidelity aircraft model and a tracking controller developed in [2]. Due to the complexity of the model (e.g. discontinuities) no analytical gradient information is available. Thus, the gradient is approximated numerically by forward finite differences. This leads to increased computational cost in the planning process. To counteract this, the trajectory is parameterized to reduce the number of decision variables in the optimization. The simplest parameterization of a loitering dynamic soaring trajectory is an inclined circle resulting in three parameters, the inclination angle δ, the reference height h, and the radius r. This reduces complexity, however, comes with a loss in optimality as the shape of the trajectory is preset.
The optmization objective is the mean total energy performing closed-loop dynamic soaring for 150 seconds and indicates the energy extraction capability of the planned trajectory. The optimal parameters are determined by single shooting using a Quasi-Newton method. The solution takes several minutes on a standard notebook, however, adaptation strategies exist to adjust the parameters online. The figure below shows the optimized trajectories for different shear wind speeds $V_{W,ref}$, indicated by the color of the trajectory. $V_{W,ref}$ is the wind speed prevailing in the free stream. The shape of the shear wind layer and the wind direction is plotted in black.



Optimal trajectories for different shear wind speeds.

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Safe Operation and Airspace Integration of Airborne Wind Energy Systems

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The safe operation and integration into the airspace is critical for the successful commercial deployment of airborne wind energy systems. In early 2023 a survey of leading AWES developers was carried out to investigate the state of the art of this topic. The survey aimed to characterize the current approaches being used by developers for the mitigation of air and ground risks as well as their outlook on how these mitigations will evolve going forwards.

Overall, 11 developers participated in the survey, representing most mainstream AWES architectures including both soft kites and rigid wings as well as ground-based and on-board generation. This survey was performed in the context of a project funded by the Swiss Federal Office of Civil Aviation (FOCA) entitled “Safe Operation and Airspace Integration of Airborne Wind Energy Systems”.

The survey also aimed to develop a consensus on how a commercial AWES should be classified from a regulatory perspective, as well as understanding the largest challenges facing developers in terms of safe operations of commercial AWES. The survey was supported by Airborne Wind Europe and UASolutions, and key results have been included in a white paper available on the AWEurope website [1]. Over the last month, policy and regulatory recommendations were further discussed and developed with in the IEA Wind Task 48 on AWE. The current status of the White Paper will be presented along with other relevant learnings from the overall project.

Overview of survey participants grouped by AWES architecture.

References:

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Certification Roadmap for AWE Aerostructures

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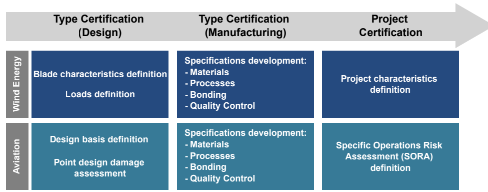
Certification of AWE aircraft systems in the EU will be handled by the joint efforts of the European Union Aviation Safety Agency (EASA) and the National Aviation Authorities, while in the United States the Federal Aviation Authority (FAA) will likely be the responsible party [1]. Certification of commercial AWE wind farm projects will also require approval from organisations such as DNV, TÜV SÜD or Lloyd's Register. The whole certification process will therefore include requirements from both civil aviation and conventional wind energy sectors. Both industries provide guidance on the design, manufacturing, and maintenance of composite structures, each with industry-specific requirements and guidelines. The Hibernian Airborne Wind Kites (HAWK) Project seeks to identify the key challenges for predicting the capital and operating costs of composite airframe structures for AWE systems [2]. As part of the HAWK Project, the project team will map the requirements for certification for AWE aerostructures.

In this project activity, both industries' approaches to the certification of composite structures are reviewed and compared, with major deviations between the relevant standards analysed for the AWE context. The standards assessed include AMC 20-29 for aircraft composite components and the DNVGL-ST-0376 design standard for wind turbine rotor blades. The objective of the project is to develop a roadmap for certification of AWE system aerostructures which will contain (i) an overview of the development process, (ii) major deliverables and development milestones and (iii) risks and trade-offs for each industry's approach. The assessment of certification requirements and standards will complement the ongoing analyses of AWE safety and regulation in Work Package 3 of the IEA Wind Task 48 on Airborne Wind Energy [3].



Comparing the wind and aviation industries' approaches to certification for AWE systems/projects.

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Conceptual Design of Windplanes

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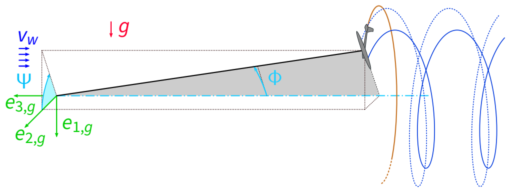
This abstract summarizes the main findings of the Ph.D. thesis *Conceptual design of windplanes* [1]. The thesis focuses on the design of windplanes (i.e. Fly-Gen AWESs), and the methods can be later applied to other AWE topologies (Ground-Gen and rotational).

The first part addresses the research question: "**Given a wingspan, which design maximizes power?**". In this part, the plane is modelled as a point mass flying circular crosswind trajectories and a periodic solution to the tangential equation of motion is found. Since the design problem is formulated for a given wingspan, the optimal aspect ratio is finite and airfoils with high lift-to-drag ratio are optimal. Large radii trajectories decrease the generated power because of the gravitational potential energy exchange. Small radii trajectories decrease the generated power because of the aerodynamic induction. It exists then an optimal mass, as this is the main parameter determining the trajectory radius.

The second part investigates the research question: "**Can windplanes fly stable orbits?**". In this part, the plane is modelled as a rigid body, the non-linear equations of motion are solved with a harmonic balance method and the aerodynamics model is linearized about non-linear operating points. The design framework *T-GliDe* (Tethered Gliding systems Design) is developed with an "all-at-once" formulation, allowing the use of automatic differentiation. If the gravity is removed from the model, the problem has a steady solution. The windplane is trimmed in the circular crosswind trajectory which maximizes the projected area. If the gravity is included in the model, the simplest control strategy is to trim the horizontal stabilizer, the vertical stabilizer and the turbine thrust coefficient to constant values, to actuate the ailerons cyclically and to control the vertical stabilizer in closed loop. The cyclic control of the ailerons rolls the plane and redirects the lift to compensate gravity and to stay airborne. The vertical stabilizer is controlled in closed loop to increase directional stability and damp the precession mode. A moderate reduction in power coefficient between the steady case and the dynamic case with this simple control is found at low wind speed. A complete stability analysis is carried out, showing that the pendulum mode is lightly damped and the precession mode needs feed-back control.



Schematic view of the windplane flying circular trajectories.

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Rotational kite system of Windswept and Interesting (2019).

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Windswept

Navigating Mass Scaling and Low-Wind Lift Challenges for 20 kW Single-Rotor Kite Turbines

Roderick Read
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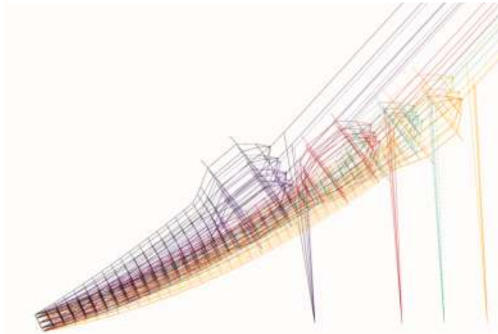
Kite Turbines previously relied on static lift kites for launch, alignment, and enhanced line tension. Standard off-the-shelf KAP (Kite Aerial Photography) kites are posing a challenge to low wind performance as we scale Kite Turbines. KAP line tensions are not scaling as well as expected in the quest to develop a 20 kW minimal viable product with a generation cut-in of 4m/s. The poor low-wind performance shown by standard KAP lift kites makes systems reliant on static lift less marketable.

The talk will cover mass scaling of automated Kite Turbines up to 20 kW. Additionally, we explore alternative lifting mechanisms, with a focus on improving low-wind performance and market reach.

Simulations of Kite Turbine network flown forms were conducted using results from lift kite trials, and using know tension parameters from Airborne Wind Energy Systems (AWES) publications. The flown form simulations are analysed for line tension, sag and overall lift angle achieved. Parametric design allows us to study how mass scaling alters efficiency and feasibility for various designs.

Our findings indicate that dynamic lifting kite mechanisms will significantly outperform static lift kites for Kite Turbine deployment in low-wind conditions at scale. The combination of dynamic lift kites and Kite Turbines is likely to outperform classic dynamic lift kite AWES. This advancement should enhance the broad marketability of Kite Turbine systems larger than 20 kW.

By addressing these performance challenges, we open new avenues for kite turbine design, making them more efficient and broadly marketable as they scale and automate. By incorporating the valuable legacy of AWES science into dynamically lifted Kite Turbines, new levels of AWES performance can be achieved.



Modelling the catenary sag effect of four lift tension variations for five different kite turbine model configurations.

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Industrialization of Fluid Power Ground Station

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Diinef AS and Imenco AS in close partnership are developing ground stations for pumping kites. Our ground station benefits from highly efficient fluid power transmission and power smoothing.

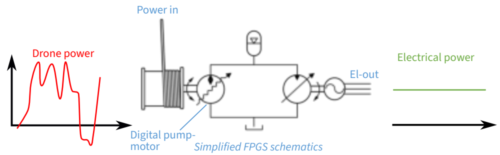
Diinef has background in the wind turbine industry, developing fluid power (hydraulic) drive trains to replace gearboxes and frequency converters. It was found that fluid power drivetrains had potential to reduce Levelized Cost of Energy (LCOE) of wind turbines with a two-digit percentage. When applied to Airborne Wind Energy, the advantages are significantly larger. Some key-components for ground stations in the 100-200 kW power range are currently being tested for lifetime, others are existing commercial products. Based upon proven product platforms from maritime industry, our technology scales favourably to MW size.

A large diameter winch is directly connected to digital pump-motors, eliminating losses and vulnerability of gearboxes and frequency converters. We use existing 4-quadrant high-torque pump-motors and enhance their controllability and efficiency by incorporating electronic valves on each cylinder. They provide cost effective torque with an efficiency up to 95%, and above 90% even at part load. The inertia of these drives is negligible, enabling rapid acceleration and precise tension control.

Energy storage with compressed nitrogen and almost infinite life is decoupling the winch from the electrical Power Take Off (PTO). The choice of PTO is flexible yet preferred to be a hydraulic motor driving a synchronous generator at constant speed and varying torque. Absence of power electronics improves robustness and enables output voltages up to 15kV. The high voltage option is especially valuable at utility scale/farms, where cabling costs are minimized.

We have developed scaling methods and a range of tools to estimate LCOE contribution of the ground station, as well as simulation models to predict behaviour when operating in an AWE system.

In the presentation, we will elaborate on the advantages offered by the technology, the component principles and identify the drivers for cost and LCOE.



Simplified diagram of a fluid power ground station.

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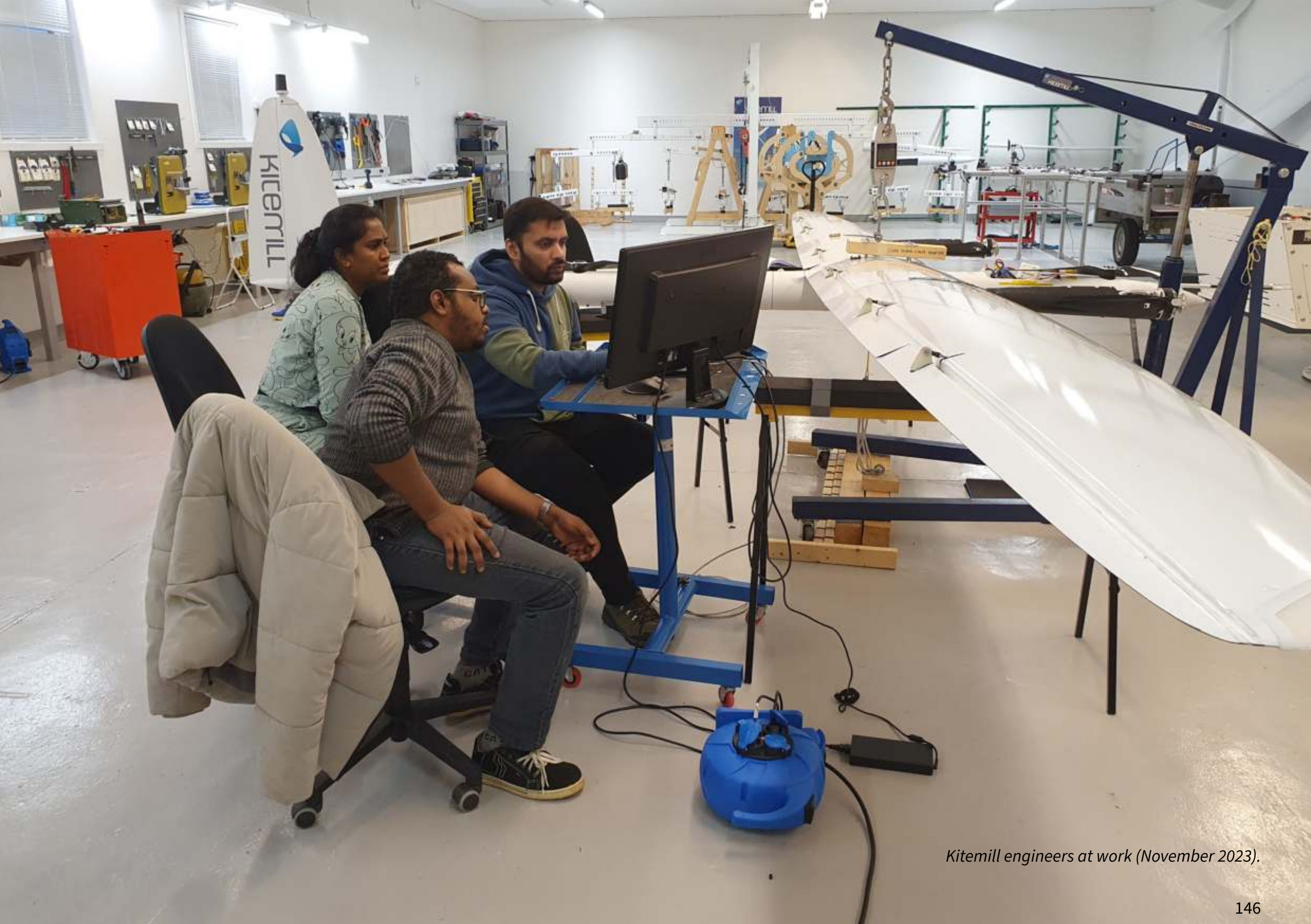
Kitemill prototype in flight (October 2022).



Kitemill engineers at work (November 2023).

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Reverse Pumping for Rigid Wing Airborne Wind Energy Systems at Large Scale

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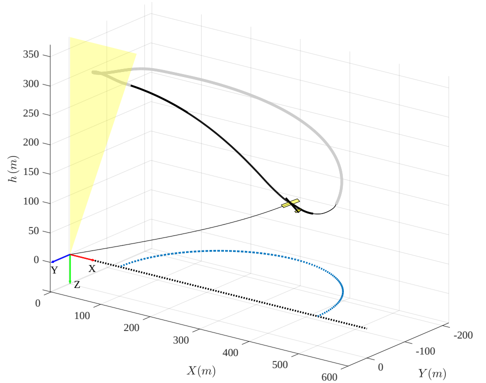
The problem of continuous flight of pumping Airborne Wind Energy Systems (AWES) with rigid wings in low-wind conditions is addressed. The considered operational mode, referred to as "reverse pumping" in the literature, aims to keep the kite airborne in case of low wind, instead of carrying out a time-consuming vertical landing. In [1], the authors investigated optimal reverse pumping in open loop in connection to a carousel launch maneuver for a small-scale system. In [2], reverse pumping is studied theoretically, considering a twin-kite setup and a laboratory-scale experimental setup.

In this work, we propose an approach to design a feedback control system to obtain reliably a large-scale reverse pumping maneuver, with tether length of the order of hundreds of meters, at the same time being relatively easy to implement and tune. The strategy features four phases: a pre-winch-launch, a winch-launch, a linear-glide, and a turn-away phase. A high-level state machine governs the switching among the four phases with a feedback strategy, while low-level control loops on the ground station and on the kite carry out the maneuvers prescribed for the current phase. Simulation results obtained with a high-fidelity model showcase the feasibility and effectiveness of the approach. The method's main advantages are: enabling operation below cut-off wind speed, reducing the hysteresis losses by making a smooth transition between cut-in and cut-off wind speed, and reducing the system mass; since the approach enables launching the system with a shorter tether length than a standard winch launch method, it decreases the hovering time required to enter production and allows the designers to down-size the onboard energy storage for the VTOL system.



Simulation results: flight trajectory in the 0 m/s wind speed scenario for three full cycles.

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Disturbance-Learning Predictive Control of the Ground Station of an Airborne Wind Energy System

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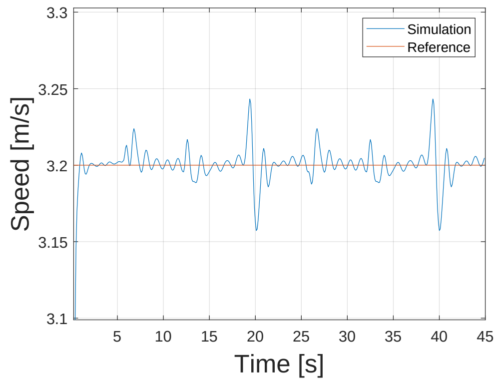
The field of automatic control for Airborne Wind Energy Systems (AWES) is in continuous development [1]. In particular, flight control design and optimization have been extensively addressed in the last years [2].

This work is focused on the development of an efficient control strategy for the ground station of an AWES, which is crucial for ensuring an effective and safe operation of the whole system. Moreover, an efficient winch control strategy helps preventing excessive wear and tear of the system's components.
To this end, a novel Model Predictive Control (MPC) formulation is presented, aimed at exploring the integration of periodic disturbances rejection techniques into the MPC framework. The issue of compensating for periodic disturbances in dynamical systems is still open, especially when a model of the disturbance is not available. In this simulation-based application, the goal is to track the reference speed given by the flight dynamics, while compensating for disturbances on the tether load, possibly deriving from sources such as turbulence or, in a hypothetical off-shore context, wave motion.

The approach is to learn the periodic component of the disturbance by means of real-time measurements and predictions, then exploit this model to recursively update the prediction model of the MPC at any step of the optimization process. Key performance metrics, including disturbance rejection amplitude, control effort and tracking accuracy have been used to assess the effectiveness of the proposed approach. Besides, a comparison with traditional offset-free-based MPC has been performed to show the enhancement of the control performance.



Ground station control simulation result: tether reeling speed reference tracking in pumping operation using disturbance learning model predictive control.

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Cascaded Control Approach for a Ground Steered 4-Line Kite System

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Airborne Wind Energy (AWE) offers a promising approach to harness wind power at higher altitudes where winds are stronger and more consistent. In the AWE framework, an automated control system plays an important role in optimizing energy generation, ensuring the stability and safety of tethered kites, and providing precise control for propulsion or towing tasks. By continuously analyzing environmental variables and adapting to changing wind conditions, the control system enables AWE systems to efficiently capture renewable energy while offering versatile and adaptable performance. This automation is essential for unlocking the full potential of AWE as a clean and sustainable energy solution.

The ICMautoKite project is focused on the automated kite flight as the core propulsion system for the KITE GAS/FUEL SHIP, a mobile AWE system designed to harness high-altitude winds in the open ocean [1,2].

In this project, the first step is the automatic position hold of the kite, which will be analyzed and presented in this work. This maneuver can not only be used as a defined starting position for dynamic figures of eight, but also to be able to hold the kite in a stationary position during operation. The control law was implemented using a cascaded PID controller, and manual flight data from real flight tests were used to design the controller parameters. The control law was controlled from a ground station. Since this setup encounters more delay than a kite controlled by a control pod placed beneath the bridles, the time behavior will be analyzed in more detail as well.

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Loss-Minimizing Model Predictive Control for the Power Conversion System of an Airborne Wind Energy System

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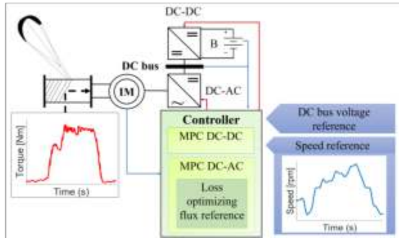
The mechanical-electrical power conversion system in AWE Systems (AWES) is crucial for efficiently generating and storing electricity [1]. When selecting the machine for power conversion, Permanent Magnet Synchronous Generators (PMSG) are often favored for their high efficiency [2]. However, Induction Machines (IM) can be competitive due to lower manufacturing costs if their control optimizes electrical performance.

This work introduces a loss-minimizing model predictive control (MPC) strategy tailored to IMs in AWES applications. It is specifically suited for this application since it employs a power converter switching strategy to minimize electromagnetic torque noise and enhance dynamic response. Unlike conventional methods, where the reference stator flux for the IM is kept constant, this MPC dynamically adjusts the stator flux reference to reduce total electric loss across varying speed and torque ranges relevant to the AWES application. This is achieved without added computational overhead of offline optimization.

The developed simulation framework is schematically shown in the figure. Its main building blocks are the mechanical model of the kite, the IM, the DC-AC converter which controls it and a bi-directional DC-DC converter which connects a battery with the constant DC bus feeding the aforementioned DC-AC converter. The proposed control was tested and compared to a MPC without the torque noise minimization strategy and stator flux reference optimization for the optimum mechanical cycle of an AWES. The proposed electric topology and control is suited for two AWE prototypes with 3 lines and onground control [3] and 1-line and onboard control [4]. The enhancement features proposed for the control improve the total electrical cycle energy efficiency of the AWES up to 35% in this case study. Matching the electrical efficiencies reached when using a PMSG instead of a IM.



Topology and proposed MPC for an AWES power conversion system

References:

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Analysis and Experimental Validation of a Low-Complexity Enhanced Orientation-Based Controller for Tethered Energy Harvesting Systems

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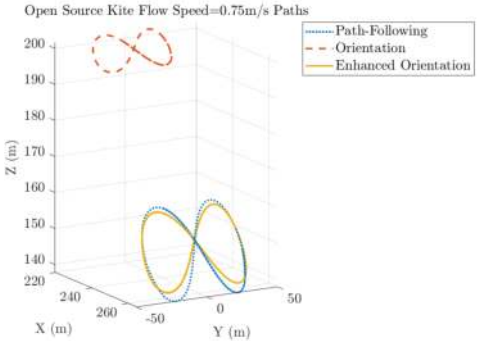
This work introduces a new flight control technique for kites that combines the simplicity and robustness of orientation-based control with the performance of more sophisticated hierarchical path-following controllers. Conventional orientation-based control strategies guide a kite to track periodic, open-loop roll and yaw setpoint trajectories. In the proposed control strategy, termed "enhanced orientation-based control," the roll setpoint trajectory is modified continuously to track a desired elevation angle. Orbital stability is validated in a low-order simulation framework (presented in [1]) for a proprietary and open-source kite model under multiple flow conditions via a Floquet analysis. Using both kite models, the performance of the proposed controller is benchmarked in a medium-fidelity simulation framework (using a dynamic model derived from [2]) to both an orientation-based and path-following controller (wherein a desired 3D flight path is tracked). In simulation, the proposed strategy was shown to generate 88.4%–97.3% and 81.1%–86.5% of the power generated by the path-following controller for the open source and proprietary kite models respectively, without requiring high-precision, real-time localization. Meanwhile, the orientation-based strategy generated 48.9%–53.6% and 68.7%–69.9% of the power generated by a path-following strategy for the open source and proprietary kite models respectively. The proposed strategy was tested experimentally on an underwater kite towed behind a boat to simulate an ocean current where this strategy outperformed an orientation-based strategy by 9.6%–18.8%.



Flight paths flown by the open-source kite for a flow speed of 0.75m/s and a tether length of 500m. As shown, the enhanced orientation-based controller drives the kite to a comparable elevation angle to the path-following controller, which results in much more efficient flight than orientation-based control alone.

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Magnus Effect-Based Quadcopter AWES of Gipsa-lab, Grenoble INP (December 2023).

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Optimizing Take-off and Landing Control of Magnus Effect-Based Quadcopter AWES in Challenging Wind Conditions

Zakeye Azaki, Jonathan Dumon, Nacim Meslem, Pierre Susbielle, Alexis Offermann, Amaury Negre, Ahmad Hably
Gipsa-lab, Grenoble INP

The take-off and landing phases of airborne wind energy systems (AWES) are critical, particularly in extreme wind conditions. Ensuring the safe operation of AWES during these phases presents a significant challenge. This work centers around the Quadcopter/Magnus effect wing hybrid UAV configuration [1,2]. While less efficient than traditional fixed-wing configurations, the Magnus effect offers increased robustness by enabling precise control over the speed of cylinder rotation to produce the desired aerodynamic forces. Instead of relying on the angle of attack dependent on apparent wind, this control over rotation speed eliminates the complexities associated with wind estimation.

Our presentation discusses ongoing research efforts that employ control allocation strategies for Magnus effect-based quadcopter AWE tethered flight and studies how it can guarantee safe take-off and landing in extreme and turbulent wind conditions. Initially, we introduced a position controller based on 3D robust sliding mode control (SMC) [3]. This foundational structure was then upgraded to a nonlinear constrained optimization-based control allocation strategy. The optimization problem centers around the objective, primarily minimizing power consumption during take-off and landing. This is achieved by giving a higher contribution to the Magnus aerodynamic forces through precise control of its rotational speed while allocating the remaining forces to the drone's thrust.

Our novel control strategy showcases adaptability to various wind conditions, including no wind and high wind speeds up to 20m/s, thus enabling the AWE system to take off safely and land across various scenarios. In experimental tests conducted under different wind conditions, we demonstrate the effectiveness of our strategy.

Magnus effect-based quadcopter system

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Automatic Circular Take–off and Landing of Self–Propelled Kites

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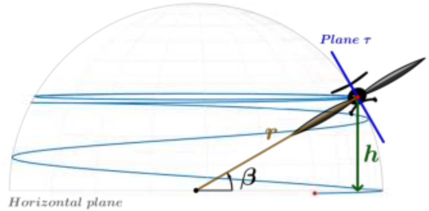
Within Airborne Wind Energy Systems (AWES), the ability to perform controlled, reliable, and safe Automatic Take-off and Landing (ATOL) maneuvers stands as a crucial requirement for autonomous operation. We address one of the least researched ATOL techniques – the Circular Take–off and Landing (CTOL) – which, from our viewpoint, shows interesting and promising features.

We consider a self–propelled fixed–wing kite connected to the ground–station via a flexible and constantly taut tether, where the take-off and landing is performed with a circular motion approximately in an horizontal plane, with constant tether length. The Take-off phase is divided in three sub–phases: 1) Acceleration, where the kite gains speed until it reaches a specific reference airspeed, 2) Rotation, in which it tilts upwards until it attains a specific reference pitch angle, 3) Climbing, where its speed and pitch angle are controlled until it achieves a threshold altitude. That is defined taking into account the maximum possible elevation angle that the tethered plane can sustain for the current tether length. After that, it loiters in a level flight. The Landing procedure follows analogous sub–phases in reversed order: Approach, where the kite performs a descent glide until it reaches a a predefined altitude related to its wingspan; Landing, in which it tilts upwards in a flare maneuver and touches down.

We propose a hierarchical control architecture, which, at its higher–level layer, has a discrete–event system, incorporating a path–planner and a supervisory controller that oversees and sets references to the lower–level modules responsible for executing each phase of the process [1]. The control of the kite parameters in each of these sub-modules, such as speed or altitude, is ensured by a variety of controllers, ranging from simple PID controllers addressing a single variable loop during short duration sub–phases, to multivariable optimization–based controllers during longer and steadier sub–phases.

A small–scale self–propelled prototype was assembled, demonstrating the adequacy of the developed controllers as well as the overall viability of the concept [2,3].



Circular take-off kite trajectory [1].

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Swift Airgen rotational launcher and kite (February 2024).

Swift Airgen kite being attached to launcher (February 2024).

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Progress on a Rotational Launch and Recovery System for a Fixed Wing Kite

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Swift Airgen

The launch and recovery of fixed wing airborne wind energy (AWE) systems can be achieved by several methods, each with its advantages and disadvantages. This talk presents theoretical and experimental work on a rotational launch system for a ground generator type fixed wing AWE kite. Our approach avoids the mass penalty of vertical launch motors, and the runway infrastructure required for horizontal take-off.

The challenges of this approach in the launch and recovery phases, predictions of performance and experimental results are presented and discussed in-turn.

The launch phase sequences through centrifugal rotation, transition to aerodynamic flight, tether payout, and then transition to the energy generation path. The sequence of the recovery phase is transition to rotational flight around the launcher, tether recovery, centrifugal rotation, initial capture of the kite to the launch system cradle, and then final docking of the kite. Challenges include controlled transitions between steps, stable operation in wind, and achieving high levels of automation.

A prototype system has been built that comprises of a ground launch rotating frame, a motorised reel with tether, a control system and a fixed wing kite. The system includes real-time control software of the launcher, working in synchronisation with the on-kite flight control software.

We present the expected performance from simulations of the rotating launcher and kite at the various launch and recovery stages, and then compare with experimental results. We then present conclusions and outline our next steps.

Swift Airgen rotational launch system

Flight Guidance Concept for the Starting Phase of a Flying Wing Within an Airborne Wind Energy System

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In the search for a suitable flight system configuration for airborne wind energy, no configuration has yet prevailed. The use of "flying wings" in these specialized wind energy systems is a promising approach in terms of system performance. Because these flight systems have less drag intensive components, they are expected to have particularly high aerodynamic performance. In addition, when designed as tailsitters, they offer vertical takeoff and landing capabilities. However, the handling of these particular flight systems, especially at low airspeeds during vertical takeoff and landing, as well as during the transition from such a thrust-borne state to a wing-borne state, poses great challenges in terms of controllability [1].

In order to safely operate such a flight system during this transition, a guidance controller must take into account the controllability at high wind speeds and the constraints imposed by the tether. In accordance with [2], a curved yaw-roll maneuver is selected to operate the flight system through this transition. As shown in Fig. 1, when performing this maneuver, the flight system accelerates with a yaw motion in a tangential upwind direction until sufficient airspeed is reached and it initiates a roll dominant motion. In doing so, it transitions from thrust-borne to wing-borne flight while the tether is sagging and the flight is considered to be close to untethered. Subsequently, the transition to a fully tethered flight is achieved by increasing the turn radius. A trim calculation with an element-based flight dynamics model of the flight system is used to determine the flight envelope for this maneuver at different wind speeds. Based on this specific envelope, an appropriate guidance controller is developed.

This guidance controller forms the top level of the cascaded flight controller, while the lower levels consist of a translational and a rotational Incremental Nonlinear Dynamic Inversion controller. The control performance of the overall controller is analyzed using model-in-the-loop simulations. It is shown that the developed controller architecture allows the control of this multi-axial transition maneuver at different wind speeds.

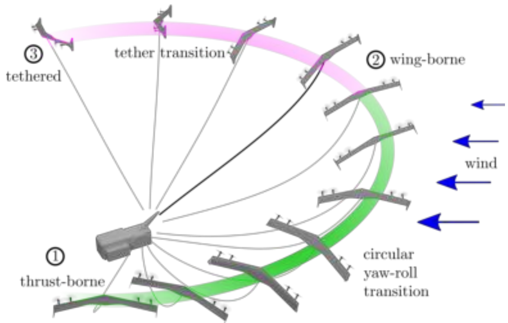

Illustration of the circular yaw-roll transition followed by a transition to a tethered flight.

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Lift Kite Operation Requirements of a Rotary Airborne Wind Energy System

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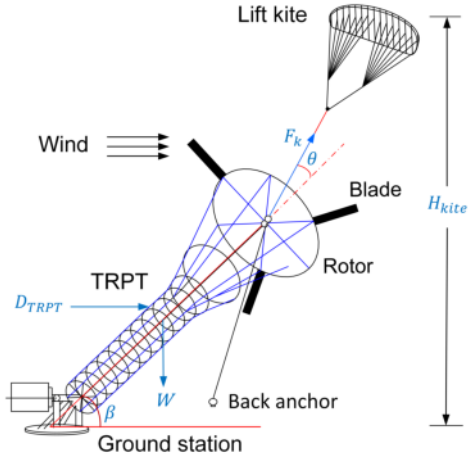
A rotary kite airborne wind energy system is equipped with a tensile rotary power transmission (TRPT) system that can transmit torque from the airborne components to the ground [1,2]. The TRPT section has several equally spaced connecting tethers linking all concentric rings from the top end to the bottom end, the top ring acts as the rotor with multiple rigid blades, and the bottom ring is connected to a fixed ground station. A lift kite is applied to lift the rotor and TRPT system and provide tension as the axial force, the latter directly influences the TRPT transmission performance.

The lift kite plays central roles during system operation in the air, launching and landing. The aim of this work is to investigate the operation requirements of the lift kite. At any given wind speed, the equilibrium point of the system is achieved by the operation of lift kite. A small deflection angle, θ, is induced between the TRPT's central axis and the tether connecting the rotor to the lift kite. The tension force exerted by the lift kite, F_k, counterbalances the drag force on TRPT, D_{TRPT}, and the lumped gravitational force of the AWE system, W, leading to the moment equilibrium. To enable effective torque transmission and aerodynamic performance, the lift kite force, F_k, and its deflection angle, θ should be determined to achieve the designed TRPT elevation angle, β, and the required tensile force. Hence, both axial and normal components of F_k are determined, and considering the drag force, the requirement for the design of the lift kite and its operating altitude, H_{kite}, can be calculated.

The understanding of the lift kite operation requirements is not only necessary for system design optimisation and control, but also critical for automated launching.



Rotary kite AWE system with a lifting kite.

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Enerkíte swept wing after rotational launch (July 2023).

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EnerKíte

AWEC 2024: Markets of a 100 kW-AWE-System and EnerKíte's Pilot-Projects for a Perfect Market Entry

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EnerKíte's 100kW-System has many advantages compared to other renewable systems of that size, such as transportability and a high availability. The last is mainly given through the ultra-lightweight wing design. In this work it will be briefly explained what impact this has on potential markets and why those systems still should be seen as an addition to the existing renewable systems, not as a competition. park, a small wind turbine and biogas plant. In this work, the current status of the project will be shown such as the status and first results of the projects in the field of self- supply.

With these properties, there can be identified three main markets for a 100kW-AWE-System:

- Self-Supply e. g. of farms or small companies
- Micro-Grids and Diesel replacement
- E-Mobility charging stations

These three markets and their stakeholders will be described in this work. Furthermore, the expected worldwide market volume will be given, according to the current research state. EnerKíte has pilot customers and/or funding projects for all three markets. For example, the E-Mobility Market is currently being researched in the form of a study regarding the technical design and economical potential of an EnerKíte-powered charging station together with Volkswagen Group Charging daughter Elli in a BMBF-founded project. The Micro-Grid Market is researched together with the energy supply company following years the pilot operation will take place in Brandenburg, Germany in combination with a solar park, a small wind turbine and biogas plant. In this work, the current status of the project will be shown such as the status and first results of the projects in the field of self- supply.

Looking to the future: An EnerKíte powered charging station in a rural area.

Offgrid-charging a battery electric vehicle with kite power in Dirksland, the Netherlands (July 2023).

Kitepower operating at RWE's airborne wind energy test center in Bangor Erris, Ireland (September 2023).

Kitepower team during flight testing in Dirksland, the Netherlands (July 2023).

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KITEPOWER™

Kitepower Wind Energy: RWE Test Site Insights

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Kitepower, a pioneering force in renewable energy, is rewriting the rules of clean energy generation with its airborne wind energy technology. This abstract provides a concise overview of Kitepower's progress at the RWE Test Site in Ireland, with a specific focus on their commitment to extending kite flight times and preparing to scale up to MW-class systems.

Kitepower's innovative approach, employing kites, offers a trifecta of benefits: cost-effectiveness, adaptability, and eco-friendliness in wind energy generation. The RWE Test Site, renowned for its good wind conditions, serves as an ideal proving ground for Kitepower's technology and prepares its ventures into the MW-class domain.

This abstract explores Kitepower's relentless pursuit of longer flight durations, delving into advancements in kite design, control algorithms, and energy conversion. It also addresses the challenges encountered when adapting the technology to varying wind patterns and harsh weather conditions, offering insights into the innovative solutions that have emerged.

Furthermore, we highlight the environmental and societal advantages of Kitepower's airborne wind energy systems, underlining their potential to deliver clean energy in challenging areas while minimizing ecological impact. Join us at the AWEC in 2024 for an insightful discussion on how Kitepower's dual mission– to extend flight times and validating the feasibility with a 1/30 model of a MW-class system.

Kitepower's 60 m^2 kite during the second flight in Ireland (September 2023).

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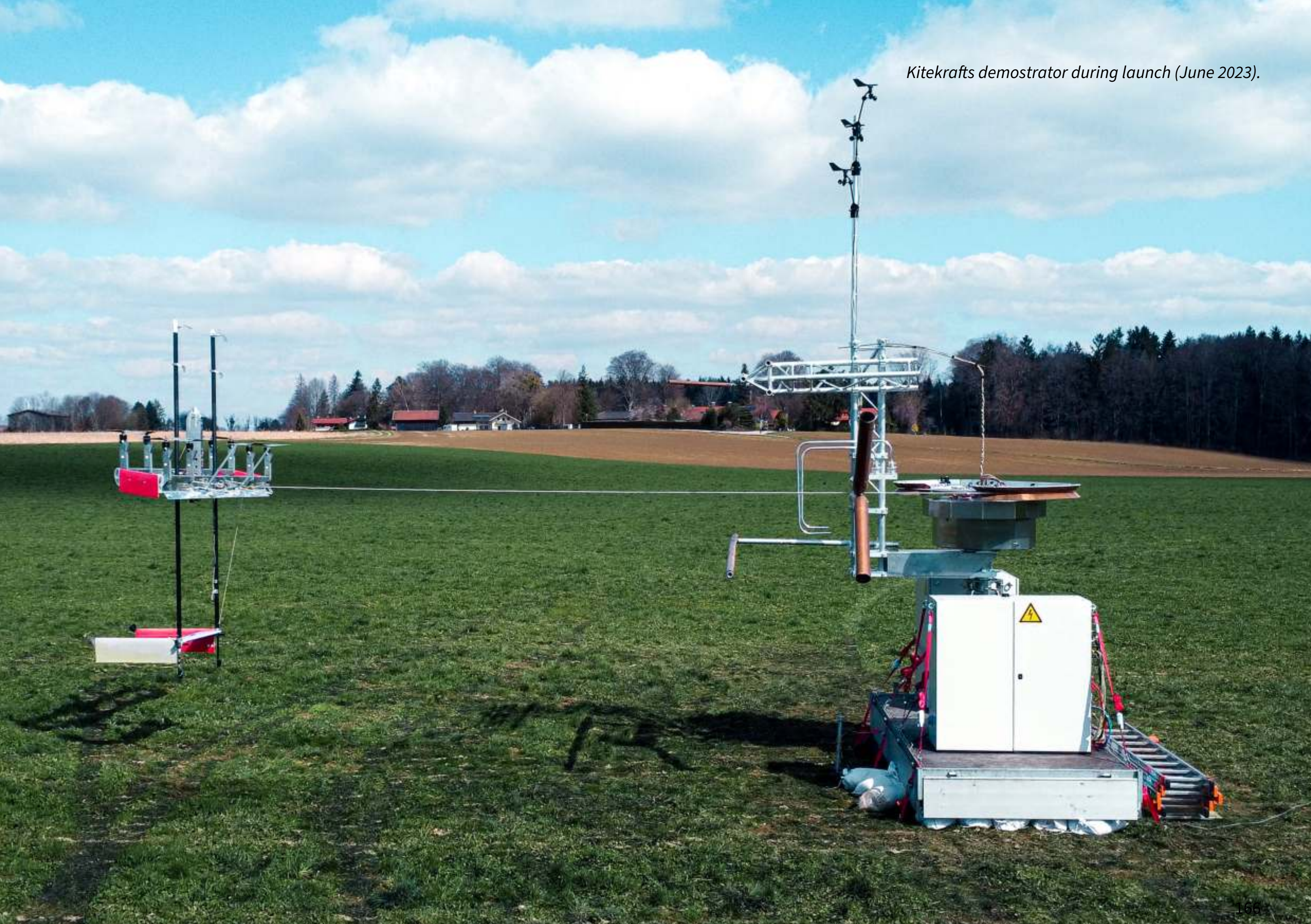

Kitekrafts demostrator during launch (June 2023).

Bird's eye view on Kitekrafts demostrator during launch (June 2023).

Kitekraft's demonstrator during flight, seen from the tailplane (June 2023).

Kitekraft's demonstrator during flight (March 2023).

Kitekraft team (March 2023).

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An Update on Kitekraft's Progress

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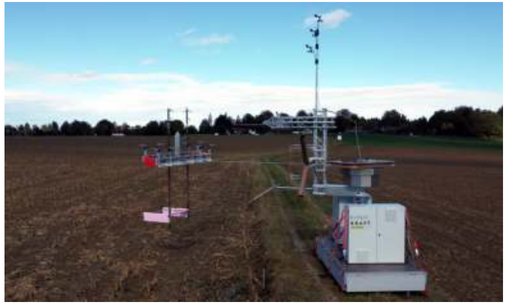
Kitekraft was founded in 2019 as a spin-off from Technical University of Munich. After research on various airborne wind energy topics, incl. concepts [1], crosswind kite power with onboard generation ("drag power" [2]), with a boxplane airframe kite made from rigid materials, has been selected as the most promising concept for an industrial product. The technology has been developed step by step towards market requirements. The main advances, so far, have been (i) the development and validation of required key features, e.g., a high-lift multi-element airfoil, the ground station with autonomous undocking and docking mechanisms, or the power electronics down to a grid connection, and (ii) the increase of the robustness for safe, reliable, autonomous operation in all phases. The latter includes the selection and validation of low-cost and reliable sensors as well as redundancy and fail-safe mechanisms, such that the system remains always in a safe state, even during component failures ("no single point of failure", see also [3]), i.e. the kite remains always able to perform a hover-landing on the ground station. Fig. 1 shows the demonstrator in flight shortly after take-off from the ground station during a test flight in October 2023. The ground station has a 30kVA bidirectional connection to the public grid [4] and can supply the kite during hover phases and feed power into the grid during figure-8 flight. Fig. 2 shows the kite during figure-8 flight. In this talk, further details on achieved milestones, videos, telemetry data, and plans are discussed

KITE//KRAFT



Kitekraft demonstrator shortly after take-off from grid-connected ground station, October 2023.

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Kitemill's Drive: Pioneering Wind Energy Innovations with the AWE Community for Net Zero 2050

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To achieve NET Zero by 2050, IEA's projections for wind energy have been revised from 390 GW annually to 300 GW. This shift emerges from a crisis in the wind energy sector, driven by the race to scale turbines to greater heights. Reaching higher allows for access to more wind resources from the same ground area. Even at 20 kW, AWE prototypes already tap into resources that conventional wind turbines cannot yet reach.

Recognition of AWE as an enabling technology for net zero is crucial. The primary hurdle for AWE is not the absence of R&D results, it's the lack of funding to generate these outcomes. Notably, fusion power and air taxi companies have individually secured more funding than the entire AWE sector combined.

A shift in the energy mix towards more solar means a corresponding increase in storage, an adjustment that promises to be both challenging and costly. If AWE can achieve a higher capacity factor with fewer materials, it positions itself as a contender to lead the energy market.

However, such claims demand verification. Kitemill's latest operational achievements and our extensive LCA study provide solid evidence supporting these assertions. These findings not only bolster our claims but also reinforce our belief in the transformative potential of AWE, especially as guided by Kitemill.

Despite the clear potential of AWE, its overshadowing by other energy alternatives in both attention and funding is puzzling. Yet at Kitemill, we envision a scenario where the swift and deliberate scaling of AWE is essential. Our goal is not just about technological advancement, it's about aligning robustly with the global sustainability vision.

Kitemill, driven by our vision to lead in wind energy, is merging global ambitions with AWE advancements, anchoring its crucial role in reaching Net Zero by 2050.

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Scaling of rigid wing Airborne Wind Energy Systems to MW

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TwingTec AG

Airborne Wind Energy Systems (AWES) using soft kites are heading towards commercialization with first products in the range of 100 kW, achieving a major milestone in the AWE sector. Product-market fit studies TwingTec has done with potential large-volume customers in the decentralized power/offgrid sector clearly indicate, that products in the range of 100 kW start to become commercially attractive, however, systems in the range of one MW allow for considerably lower LCOE values while still offering a high degree of mobility due to containerized transport, both key USP's of AWE for this market segment. TwingTec assesses the total addressable market for AWES in the decentral and off-grid market in the order of EUR 70 B/y with the biggest share resulting from systems in the MW range, making the scalability of the chosen technical AWE concept a key driver for a high-volume market penetration.

It is TwingTec's ambition to develop and commercialize a technical AWES concept which can be scaled to several MW. To this end we have done a detailed study of a rigid wing VTOL AWES in the MW range in a project partially funded by Innosuisse and supported by external aviation experts. A major tool for this study has been our proprietary simulation tool KITESIM [1], which we have developed over the last ten years and validated with experimental data from our small-scale prototypes. The study shows that rigid wing VTOL AWES can be scaled to MW, enabling TwingTec to develop a stepwise commercialization road map from smaller scale systems to the MW scale based on the same technical concept. Results from this study will be shown in this presentation.

Rendering of TwingTec's 1 MW system.

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Bibliometric Analysis of Airborne Wind Energy for the Last Decade

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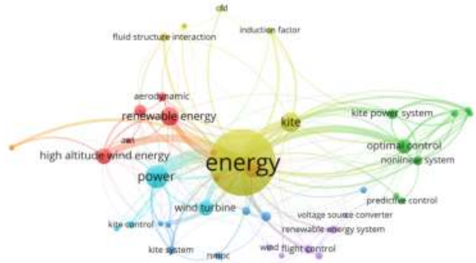
Bibliometric analysis is an accurate approach for exploring and analysing large scientific data. It allows us to uncover the subtle changes and developments within a given research field, emphasising emerging topics.

Scientific papers serve as a primary way to showcase scientific and technological achievements, and bibliometrics provides a quantitative analysis method that focuses on the external characteristics of scientific literature. Bibliometric analysis is widely used to analyse the current research status, cutting–edge directions, and future development trends of specific fields. Using these computer–assisted review techniques, we can identify the key results and/or authors within the predefined research field, and reveal their relationships by examining all the publications related to specific (sub)topics.

We apply this analysis to the Airborne Wind Energy (AWE) research field. Since the AWE has seen an increase in publications after 2013, our bibliometric analysis was focused on the last decade. Our proposed methodology consists of three phases: (1) planning and preparation, (2) data collection, and (3) analysis and findings. Initially, we defined the main parameters for developing the analysis, namely keywords and the digital repositories (Scopus, Web of Science, Google Scholar, etc.). Afterwards, we search the scientific documents, and we export and filter data from digital repositories, registering relevant information about documents such as title, authors, citations, source, publication date, country. In the last phase, we perform a quantitative analysis and develop a science–based mapping through clusters and network analysis visualisation.

The clusters resulting from the analysis reveal interesting subtopics relationships as shown in the figure.



Clusters resulting from the bibliometric analysis.

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Airborne Wind Energy Technology Assessment: Method and Tool

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Airborne wind energy technology development is both, supported and challenged by the diversity of operational concepts, engineering designs and technological implementations. Furthermore, the technology development process is complex, most certainly requires high development cost, time and is exposed to technical and commercial risk. This is the case for most renewable energy forms.

Given these circumstances, that are based on the fundamental technological challenges, it is critical that the technology development process is delivered through the most efficient and effective methodology. Therefore, clear and applicable formulations of technology development progress metrics and technology assessment tools are required. Technology Readiness Levels (TRL) are widely used to express the progress of a pre-commercial technology towards product readiness. However, TRLs entirely miss to consider, express and assess the techno-economic performance potential of at technology at all stages of the development. Within an equally diverse renewable energy technology development domain, ocean wave energy, these circumstances have been alleviated by the introduction of the Technology Performance Levels (TPL) [1]. This techno-economic assessment system has been developed to satisfy principal requirements for realistic and effective technology performance assessment criteria and metrics. It is build on the basis of a holistic representation of all cost and performance drivers, both of qualitative and qualitative nature [2]. This approach, that takes preference of completeness over accuracy delivers an assessment tool that provides robustness against failure in the technology development process. The combined use of both, TRL and TPL as independent metrics and also serving as coordinates to span up the technology development plane that clarifies the vastly different technology development trajectories and offers orientation for identifying and following the most cost, time and risk effective path towards successful market entry. In ocean wave energy a series of TPL assessment tools has been developed [3] and effectively supports primarily technology developers as well as private and public funders. The system engineering methodology, the identification of capability criteria and the development of such assessment tools are clear and can readily be applied to develop a TPL assessment system for airborne wind energy technologies, delivering similar and critical benefits to this technology domain.

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HAWK
Hibernian Airborne Wind energy Kites

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Development of an Open-Source Techno-Economic Model for Fixed-Wing Airborne Wind Energy Kites

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AWE uses kites or drones that are tethered to the ground to generate electricity. While AWE has the potential to generate significant amounts of renewable energy with less variability than conventional ground-based wind turbines [1], the technology is still at an early stage of development. The main aim of the Hibernian Airborne Wind energy Kites (HAWK) project is to determine the key challenges and barriers for AWE system developers in predicting the capital and operating costs of composite airframe structures by developing techno-economic analysis models supported by data for candidate materials.

This study develops an open-source techno-economic model for AWE. At first, a survey of AWE developers is conducted to achieve their expected range of production volumes and system sizes to support component manufacturers. Based on the feedback from developers, a suitable concept of the manufacturing line design for the airframe composite structures is being defined that provides the necessary input data for the manufacturing cost model. Then, the obtained cost model is incorporated into the open-source software (MegAWES) [2].

Moreover, the material and manufacturing process data found in a previous investigation are processed into a suitable format for the cost model. Furthermore, a techno-economic cost analysis is conducted for the series production of megawatt-scale AWE systems.

Finally, a full description of the manufacturing line and factory layup required to produce full-scale AWE systems are presented to outline the requirements for a supply chain of the composite components. The developed open-source techno-economic model in this study can be employed as an applied tool for the cost assessment and supply chain mapping of AWE kites. Moreover, this model will help AWE system developers predict the capital and operating costs of composite airframe structures.

Rendering of the airborne component of the MegAWES large-scale AWE system [2].

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TV crew recording Kitepower's operation at Dirksland, Netherlands (June 2023).

TU Delft's Airborne Wind Energy Research Group (February 2024).

The Potential Future Role of Floating Wind Turbines and Airborne Wind Energy Systems in the North Sea Region

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In light of the energy transition to a fossil-free energy system, Europe is experiencing a substantial shift toward renewable energy generation. To facilitate this shift, new conversion technologies and energy resources are being investigated. Novel airborne wind energy (AWE) and floating wind turbines have the potential to unlock untapped wind resources and contribute to the balancing of the energy system in unique ways. So far, the techno-economic potential of both technologies has only been investigated at a small scale, while the most significant benefits will likely play out on a system scale. Demonstrating the economic viability and additional benefits of emerging technologies in an energy system context is vital to accelerate political support and funding.

This research aimed to find the main system-level trade-offs in integrating AWE systems and floating wind turbines into a highly renewable future energy system [1]. We developed a modeling workflow consisting of future costs and performance estimations and wind resource assessment integrated into a high-resolution large-scale energy system cost-optimization model based on the Calliope modeling framework [2]. The investigated region contains 10 countries in the North Sea region. The wind resource and system balancing are hourly-resolved.

The results show that onshore AWE can achieve higher capacity factors than conventional onshore wind turbines due to higher wind resource availability and hourly generation profiles that are different and sometimes complementary. The main limiting factor in large-scale onshore AWE deployment is the achievable power density per ground surface area. Offshore AWE shows highly identical performance compared to offshore wind alternatives. Therefore, its deployment is driven by whether it can compete on costs. Floating wind turbine technology demonstrates great potential because of the high capacity factors that can be achieved in high wind resource areas where conventional offshore wind technology is not technically feasible.

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Kitenergy 25 m^2 ram-air kite clean configuration).

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Product Carbon Footprint of a 100 kW AWE Generator

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Today, among the many options available within renewable sources, solar and traditional wind technologies are well-established solutions capable of generating the 12% of global electricity.

Despite this, small islands and remote/isolated areas often rely solely on diesel generators for energy supply. Depending on the operational scenarios and external constraints, a mix of different renewable energy technologies would help to mitigate the impacts of fossil fuel generated energy and provide 24-hours grid quality electricity.

Regulatory emission controls on diesel generators and intense debate over the actual impacts of solar PV and wind energy open the way to innovative technologies. Airborne Wind Energy (AWE) generators, thanks to their peculiar characteristics, are almost ready to offer a highly competitive solution from an environmental and economic perspective, while overcoming many of the concerns associated with other technologies. A Product Carbon Footprint (PCF) method has been adopted to preliminary assess the Kitenergy AWE generator system and estimate the greenhouse gases (GHGs) emitted throughout its life cycle.

Then, the PCF of Kitenergy's 100 kW AWE generator is firstly compared with those of potential alternative solutions such as Solar Photovoltaic (PV) and traditional wind power and, finally, used to estimate the potential reduction of GHG emissions resulting from the substitution of a diesel generator with a Kitenergy AWE generator of the same rated power. The system architecture, combined with the ability of harvesting winds at altitude, results in extremely high performance in terms of use of materials and quantity of electricity produced with low impacts:

- in order to manufacture and install a 100 kW Horizontal Axis Wind Turbine (HAWT), 27.6 t of materials such as steel, copper, glass and polyester with the addition of 190 t of concrete for foundation are needed. Our AWE generator design allows a material weight reduction of 90% for the same rated power and a Carbon Intensity (g CO_2eq/kWh) 5.6x lower than a wind turbine;
- solar PV plant at global scale has on average a Capacity Factor (CF) of 16.1%. On the contrary, thanks to altitude winds, it is easy for Kitenergy AWE generators reach a CF of more than 50% with lower day to night production variability. This results in a Carbon Intensity up to 16x lower than solar PV.
- adopting an average carbon emission factor of 695 g CO_2/kWh for diesel gensets and, taking into account only the fuel necessary to operate a 100 kW diesel generator unit, the emissions reduction achieved by installing a Kitenergy AWE generator can reach 292 tonnes CO_2/year.

TV crew recording Kitepower's operation at Dirksland, Netherlands (June 2023).

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NEON research

TU Delft

Noisy Kites? Exploring Noise Annoyance for Airborne Wind Energy Systems with a Laboratory Listening Experiment

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Placing renewable energy infrastructure close to homes can impact people negatively, leading to low acceptance and hindering the expansion of renewables. The experience with wind turbines has shown that especially noise emissions can burden residents and cause annoyance and stress [1]. It is, therefore, critical to understand how people perceive noise emissions from airborne wind energy (AWE) systems and which factors influence annoyance to be able to mitigate noise impacts of AWE systems if needed. Only one field study has investigated residents' experiences of noise impacts for AWE [2]. The study showed that a small but considerable number of residents (7.5%) are highly annoyed by the noise emissions of a nearby AWE system. While the findings suggest that noise could be an important acceptance factor for AWE, they are limited to one AWE prototype and do not elucidate the relationships between acoustic metrics and reported annoyance. To address this knowledge gap, we conducted an experiment in the Psychoacoustic Listening Laboratory at Delft University of Technology. We recruited 75 participants who listened to 11 randomly ordered sound fragments (25 seconds long each) of four different operational AWE systems (i.e., using both soft-wing and rigid-wing kites). In response to each recording, participants rated their perceived annoyance on the standardized ICBEN scales (International Commission on Biological Effects of Noise) [3]. The resulting data was analyzed to investigate to what extent people experience noise annoyance with AWE sounds, how the prevalence of annoyance differs across various AWE systems, and which personal variables (e.g., noise sensitivity, age) and acoustic metrics (e.g., tonality) predict annoyance. The preliminary findings will be presented. Regarding the implications, we recognize that AWE is a rapidly evolving technology and that many unintended side effects, such as noise emissions, will be automatically eliminated with scaling up and design modifications. However, the present results can still direct efforts to mitigate noise emissions. Moreover, they emphasize that ongoing prototype testing already impacts residents, which, if not accounted for, can negatively affect technology acceptance in the long run.

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Life Cycle Assessment of Floating Offshore Airborne Wind Energy Systems

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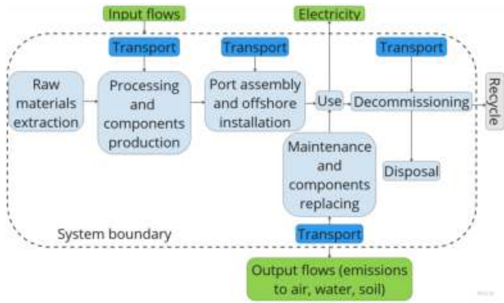
Airborne Wind Energy (AWE) appears to be a promising option for green energy production, in terms of efficiency and also land use, especially if Offshore Airborne Wind Energy (OAWE) systems are considered. However, systematic studies on the environmental impact and sustainability of such a technology are still rather rare in the literature. The research presented in this contribution, developed jointly by Politecnico di Milano and Politecnico di Torino, aims to design an OAWE system and exploit the design of the different components to come up with a life cycle inventory and perform a Life Cycle Assessment (LCA) of a hypothetical offshore wind farm. The farm includes 500 OAWE systems and is located in the Mediterranean Sea, about 60 kilometers off the western Sicilian coast. The LCA methodology, applied in this work to assess the environmental sustainability, is defined in the ISO standards 14040 [1] and 14044 [2].

The goals of the LCA are determining the potential environmental impacts of the OAWE and the life cycle hotspots as well as compare it with a study on an Offshore Horizontal Axis Wind Turbines (OHAWT) farm in the same location. The functional unit of the study is 1 GWh of electricity generated by the offshore farm and delivered to the grid. The system boundary is illustrated in the scheme on the right: natural resources as energy and raw materials taken from the environment and emissions to air, soil and water are both taken into account to quantify the environmental burdens. The majority of inventory data rely on the components design, conducted from scratch; also, an iterative approach is applied on the choice of the floating platform materials and the design phase to pursue lower environmental impacts. Likewise, sensitivity analyses are done on the two wing options (flexible and rigid) and on different alternatives for the end of life phase.

The investigated impact categories align with the EU environmental footprint (EF) 3.0 [3], a life cycle impact assessment (LCIA) method which covers 16 impact categories, divided in 3 main groups: environment, human health and resource consumption.



Schematic representation of the system boundary, own illustration

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Community Perspectives on Offshore Airborne Wind Energy: A Survey Study

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Airborne Wind Energy (AWE) aspires to tackle the increasing demand for sustainable energy. Along with the technological demands, it is important to consider the social needs and concerns related to AWE deployment to smoothen its introduction into society. The available literature provides many optimistic assumptions about the social acceptance of AWE but no empirical evidence [1]. On this basis, our work aims to measure how a local community evaluates a hypothetical large-scale deployment of offshore AWE systems (OAWES). The method used to survey a local community, and the preliminary results are presented.

The development of the survey was guided by existing methodological literature [2], established questionnaires on wind energy acceptance literature [3,4], and the expertise of one of the authors (H.S.) in social scientific inquiry. The survey questions specific to the OAWE investigation will be shared for transparency and further use.

The researched community lives in County Mayo, an Irish county bordering the sea. This location was chosen because an AWE test site was established there in the context of the EU Interreg project MegaAWE, and the community has been familiar with conventional wind farms for a few decades. This allows us to limit the bias related to technological unawareness and to compare community members' responses for AWES and OAWES. Regarding the comparison, a decreased safety concern is expected for OAWES, given the lower immediate impact of a possible system failure (i.e., an offshore kite crash is not directly dangerous for human beings and their properties). Other aspects analyzed in relation to the social acceptance of the OAWES include visual disturbance, noise annoyance, ecological impact, impact on leisure activities and the local fishing industry, and attitude toward the energy transition.

Notably, as technology evolves, social acceptance also changes [5]. Thus, the survey aims to explore residents' evaluation of an OAWE pre-construction. Such a phase is crucial for the engagement and collaboration of the local population, and the results obtained through the survey could entail recommendations for AWE developers. From this perspective, AWEC2024 will represent a testing ground to understand how sector experts perceive and weigh the above-mentioned factors.

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Policy and Regulatory Outlook Towards AWE Deployment

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Airborne Wind Europe and its members have stepped up activities towards policy makers on the European, national and regional level in order to raise awareness for the need of AWE-specific policy and regulation. This includes targeted approaches towards the European Commission, Members of the European Parliament, members of national parliaments, ministries, energy associations, regulators, etc. Moreover, the sector has elaborated a number of policy papers, for instance

- the White Paper on the AWE sector in general [1],
- the White Paper on Airspace Integration [2],
- position papers on inclusion of AWE in certain national laws like the German EEG [3]
- the identification of the potential of AWE sites [4],
- the call for a European Strategy on Airborne Wind Energy and
- the inclusion of AWE in National Energy and Climate Plans (NECPs), especially with respect to the newly defined 5% target for innovative renewable energy technologies by 2030 (EU RED III).

Together with the efforts and advancements of the AWE technology developers with regards to improving and commercializing their systems, the AWE community has become increasingly outspoken on the urgency to support the AWE sector in terms of R&D funding programs, AWE-specific remuneration schemes and adequate regulation. The AWE sector can scale up fast due to the possibility to mass produce the systems (with minimized environmental impacts [5]) and to install them both in a centralised and a distributed way. Therefore, AWE's disruptive nature will allow it to get on a very steep deployment curve – once the initial policy and regulatory barriers have been overcome. This presentation will recap the AWE sector's strategy and explain the various activities underpinning it, provide an update on the deployment roadmap in the short, medium and long-term. The presentation is thus targeting policy and industrial decision makers to provide them with a comprehensive picture of the current status and future outlook of the AWE sector.

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Preparing AWES Deployment by Onboarding RE Stakeholders with Regards to Social Acceptance

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Airborne Wind Europe

Airborne wind energy (AWE) is about to become a key element in the future energy system. Due to the high resource potential and the low material consumption, it is one of the most promising technologies to provide reliable renewable energy, bringing down energy cost at the same time. However, by now the social acceptance of AWE systems (AWES) is largely unknown [1]. In order to evaluate stakeholder positions and foster their involvement to prepare for commercialization and large scale deployment of AWES, Airborne Wind Europe aims to involve not only in stakeholder engagement but also to actively communicate the need of action on all levels. In October 2021, Task 48 on Airborne Wind Energy was established within the IEA Wind TCP framework. One of the work packages focuses on the social acceptance, also with regards to the limits, the deployment of wind turbines faces today, due to obstructions by citizens, refusing renewable technologies as such or individually suffering their impact. To early and appropriately address such issues, Airborne Wind Europe got involved in research projects, like the JustWind4All Horizon Europe project, that aims to integrate insights from different academic disciplines and societal perspectives, supporting synergies and exchange among people and organisations to coordinate and participate in actions around wind energy deployment [2]. The project aims for findings to implement just and effective governance for accelerating wind energy.

Another approach to evaluating the future landscape of integrated renewable energy is conducted within the project GrowFlowFly, funded by the German Federal Ministry for Economics and Climate Action to explore the Acceptance potential for area-extensive renewables such as Agri PV, Floating PV, and AWE compared to established renewable energy technologies. Implementing a gamification approach by developing a GIS-based augmented reality surrounding, focussing coal downstream areas, incorporating the view of landscape architects, psychologists and other research fields, social acceptance factors, like land use and landscape changes are to be addressed with regard to the following questions:

- safeguarding food production
- nature conservation and ecology
- landscape image with the new visual perspectives of fields, skyline, sky, water
- enjoyment of nature, experience and recreation
- regional and local identity.The presentation will give an insight of the latest findings and milestone achievements from all activities, providing proof and inspiration to obtain and maintain AWES research and deployment.

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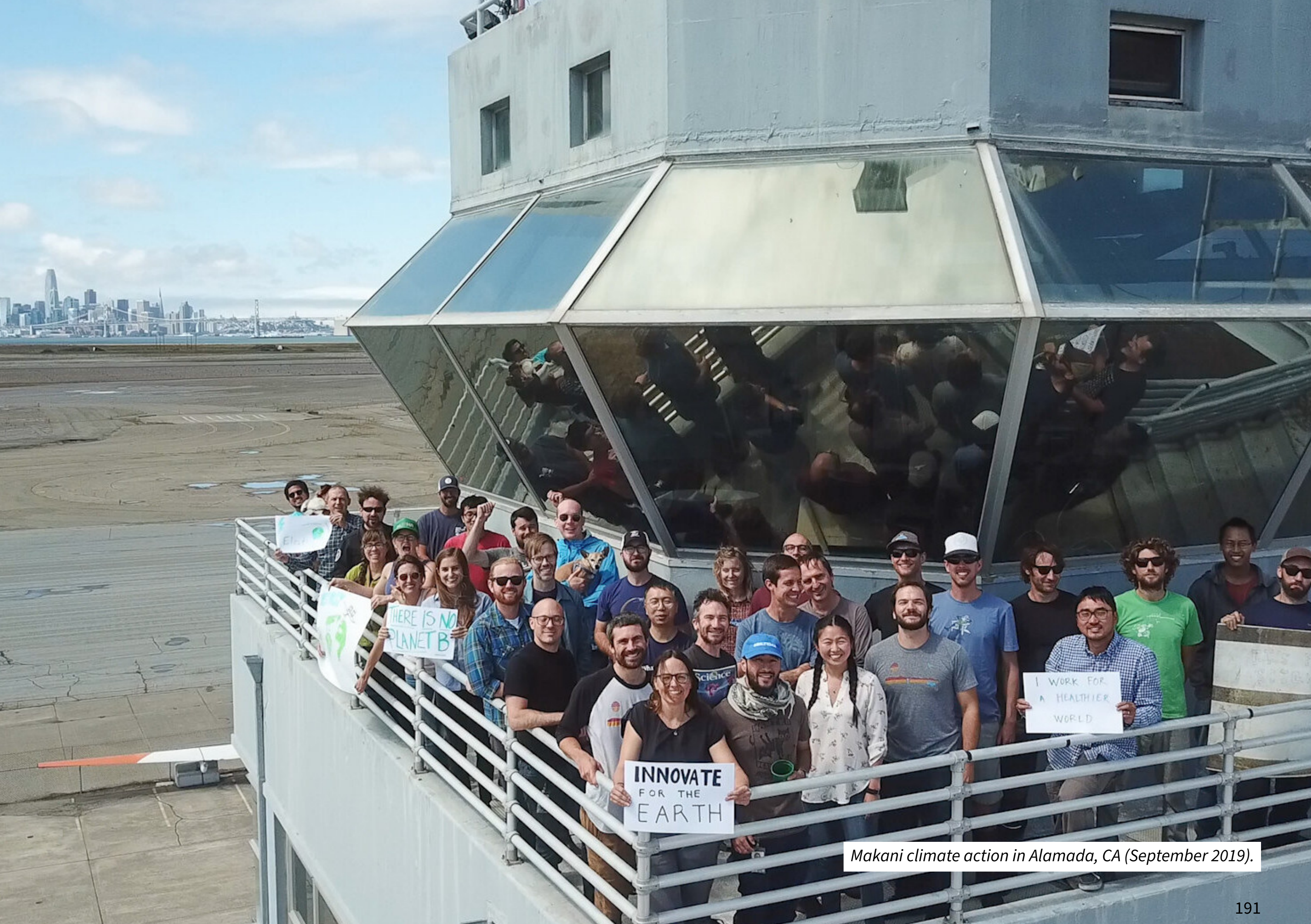
Windlift team (March 2024).



Makani climate action in Alamada, CA (September 2019).

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Third Party Materials

AWEC Archive

The Airborne Wind Energy Conference (AWEC) is hosted as an international public event since 2010. The following archived documentation is openly accessible:

AWEC 2011, 24-25 May 2011, Leuven, Belgium
Book of Abstracts, edited by Jacqueline De Bruyn, Moritz Diehl, Reinhart Paelinck, Richard Ruiterkamp, 73 pages.
ISBN 978-94-6018-370-6
DOI 10.4233/uuid:54a23dff-74f9-4007-b1d6-e92e0c458491

AWEC 2013, 10-11 September 2013, Berlin, Germany
Book of Abstracts, edited by Guido Lütsch, Christian Hiemenz, Roald Koch, 77 pages.
ISBN 978-94-6186-848-0
DOI 10.4233/uuid:f91af52c-4e76-4cf5-917a-129455b3fca9

AWEC 2015, 15-16 June 2015, Delft, The Netherlands
Book of Abstracts, edited by Roland Schmehl, 123 pages.
ISBN 978-94-6186-486-4
DOI 10.4233/uuid:6e92b8d7-9e88-4143-a281-08f94770c59f

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https://collegerama.tudelft.nl/mediasite/Showcase/Channel/conference-airborne-wind-energy

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Book of Abstracts, edited by Lorenzo Fagiano, Alessandro Croce, Roland Schmehl, Stefanie Thoms 188 pages.
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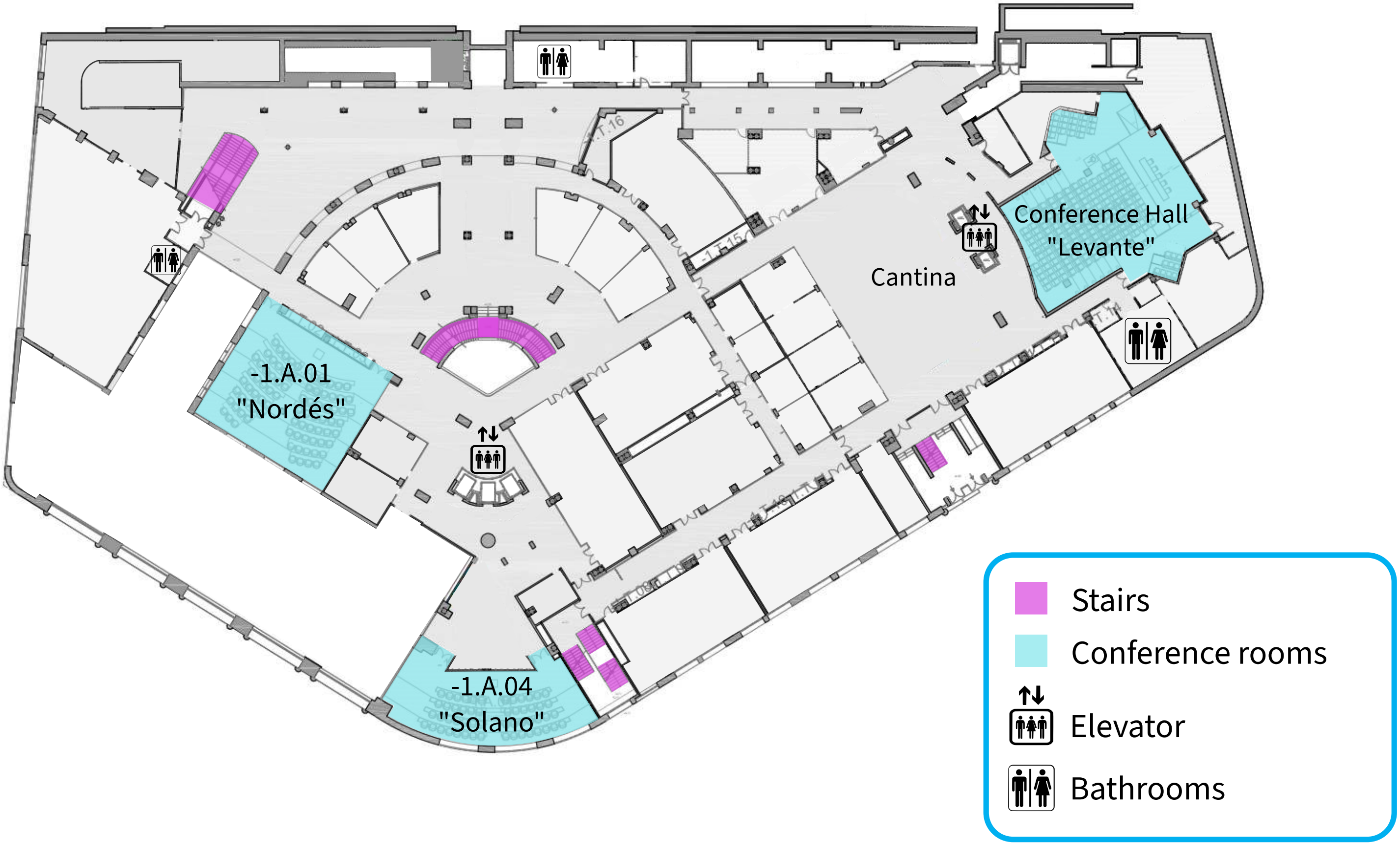
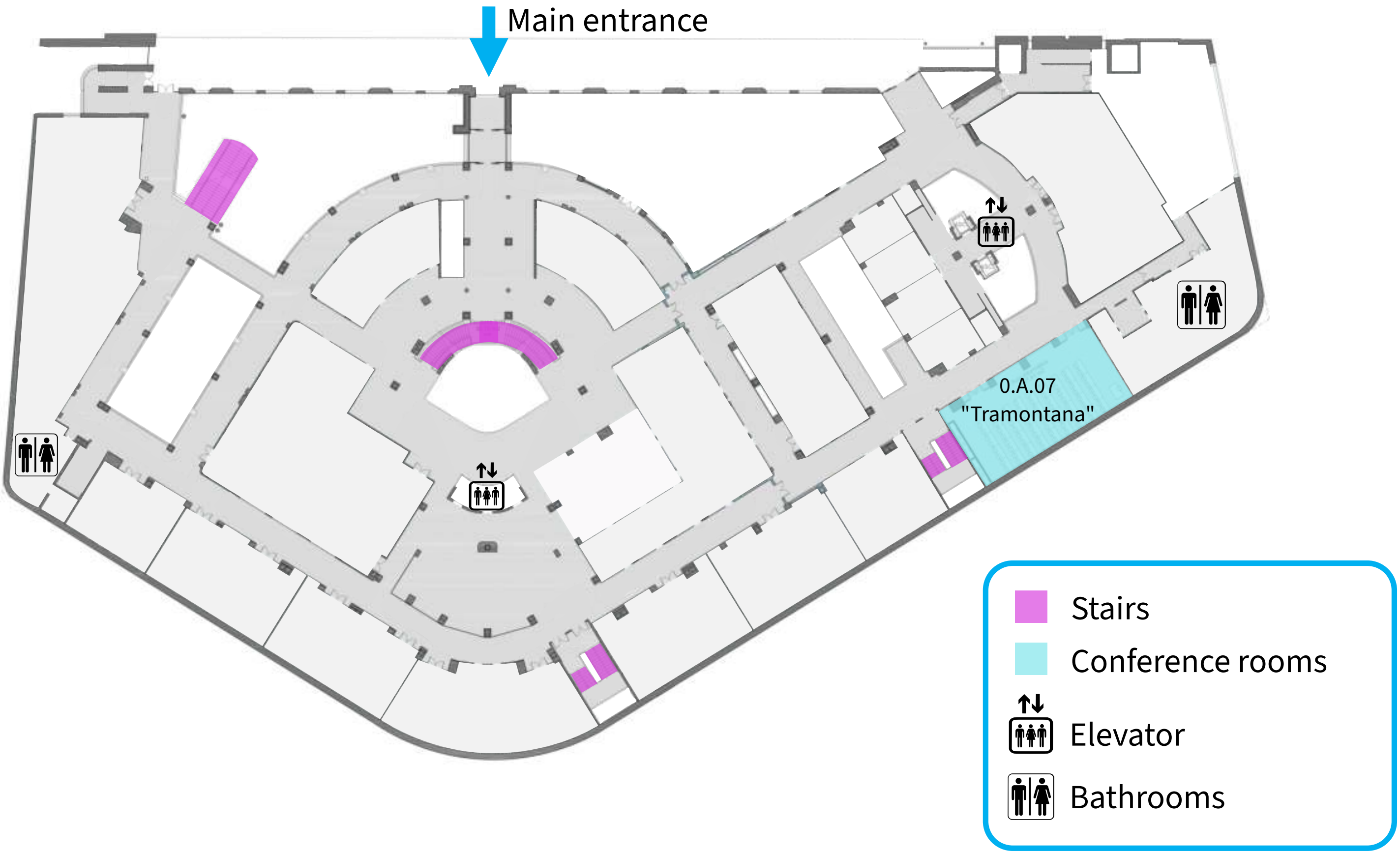
Building Puerta de Toledo
-1 floor



Building Puerta de Toledo
Ground floor



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