AIRBORNE WIND ENERGY CONFERENCE 2021

22-24 JUNE 2022

MILAN

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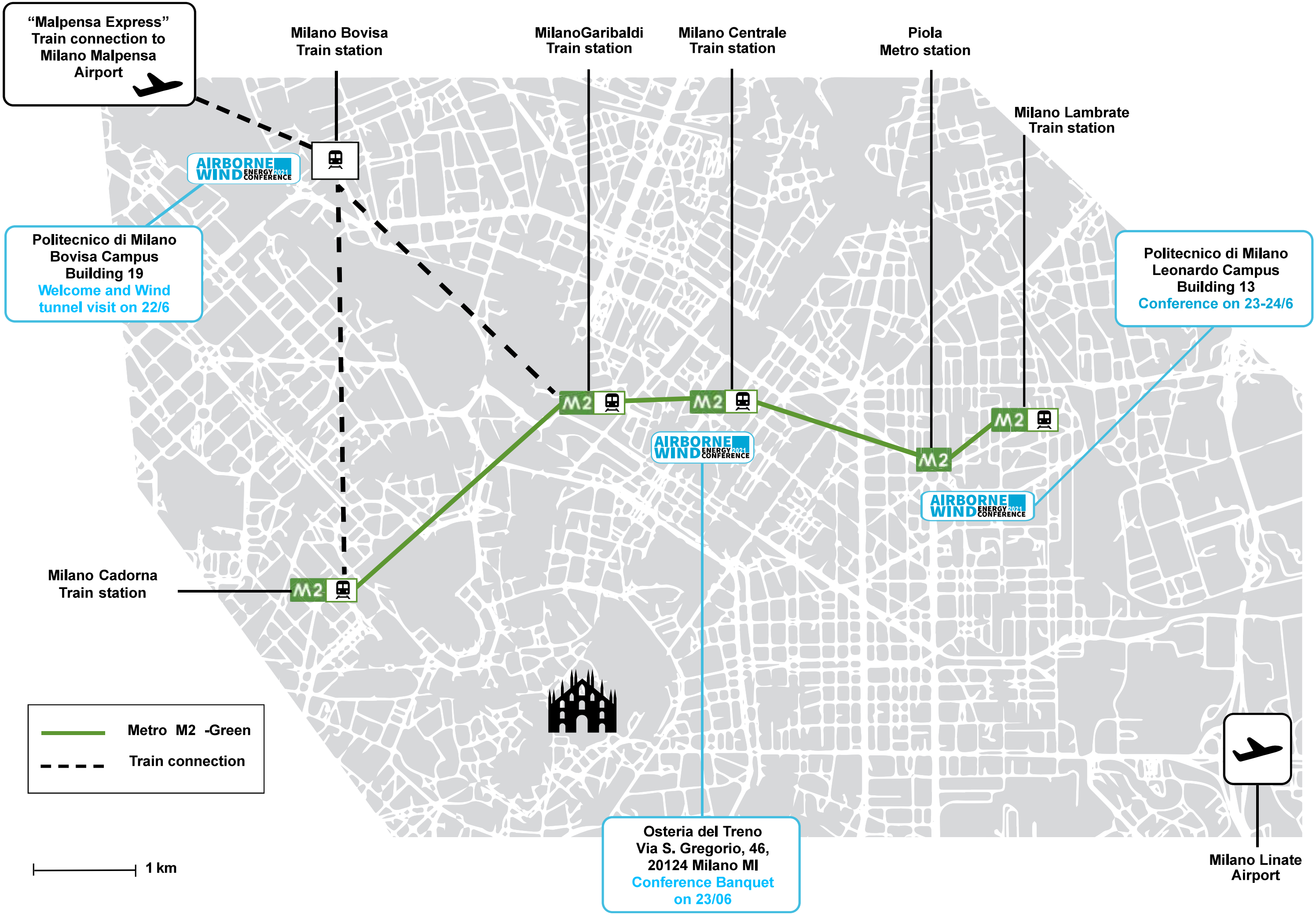
BOOK OF ABSTRACTS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AIRBORNE WIND ENERGY CONFERENCE 2021
Politecnico di Milano Bovisa Campus Building 19
Welcome and Wind tunnel visit on 22/6
Politecnico di Milano Leonardo Campus Building 13
Conference on 23-24/6
M2
Milano Cadorna Train station
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Osteria del Treno
Via S. Gregorio, 46,
20124 Milano MI
Conference Banquet on 23/06
Milano Linate Airport

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BOOK OF ABSTRACTS

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TU Delft

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MILANO 1863

Airborne Wind Europe

Technical Program - Thursday, 23 June 2022*

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10.15	Ahmad Hably, *Grenoble-INP*	20	Kester Gunn, *RWE Renewables*	25	Mark Kelly, *DTU*	32
10:30	James Reed, *NC State University*	21	Stefanie Thoms, *Airborne Wind Europe*	27	Inés Coca-Tagarro, *BlueWise Marine*	33
10:45	Tareg Mohammed, *Politecnico di Milano*	22	Rudo Enserink, *enserinkdesign.com*	28	Helena Schmidt, *TU Delft*	34
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11.35	Manuel CRM Fernandes, *University of Porto*	36	Ignacio Oficialdegui, *Windsled*	53	Niels Pynaert, *Ghent University*	66
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* Schedule reflects the status at the time of printing of this book and may be subject to change.

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16.00	FAREWELL					

* 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 2021

Lorenzo Fagiano[1], Alessandro Croce[2], Roland Schmehl[3], Stefanie Thoms[4]
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Lorenzo Fagiano
Politecnico di Milano

Alessandro Croce
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Roland Schmehl
Delft University of Technology

Stefanie Thoms
Airborne Wind Europe

Dear conference participants, dear friends,

welcome to Milano and welcome to the 9th international Airborne Wind Energy Conference! We are excited to present you an inspiring program in a beautiful location.

A renowned, global excellence center of fashion and design, Milano is Italy's financial, commercial and industrial capital, at the heart of one of the most industrious regions of Europe. It hosts countless cultural landmarks, like the Duomo cathedral, the Castello Sforzesco, and Leonardo da Vinci's Last Supper in Santa Maria delle Grazie.

And on June 22-24, 2022 Milano is also the global hub of the Airborne Wind Energy industry! The scientific program includes:

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

  Stephan Barth, Chair of the International Energy Agency's Wind Technology Collaboration Program (IEA Wind TCP);

  Paula Nardone, Associate Professional at the International Renewable Energy Agency (IRENA), in the area of Renewable Energy Markets and Technology;

  Stephan Wrage, CEO and Managing Partner at Skysails Power GmbH;

  Christopher Vermillion, Associate Professor at North Carolina State University at Charlotte;

  Philip Bechtle, Privatdozent at the University of Bonn.

- Twelve contributed talk sessions in three parallel tracks with altogether 63 presentations
- Two poster sessions, each preceded by plenary spotlight presentations, with altogether 26 poster presentations
- Two panel discussions which include a further 5 presentations by AWE OEMs.

All abstracts presented in this book have undergone a peer review process, and we want to thank all authors and all reviewers for having contributed to a high quality scientific program, as we believe. We also thank all members of the programme committee for their work and support in the abstract reviewing process.

In the now well-stablished tradition of AWEC, we decided to rename the three main conference auditoria after renowned "researchers". We chose for the occasion three famous Italian explorers and pioneers:

- "Room Colombo" honoring Cristoforo Colombo (1451 – 1506), the Italian explorer and navigator who completed four voyages across the Atlantic Ocean and achieved the first European contact with the Caribbean, Central America, and South America;

Politecnico di Milano, view of the Building 1 from Piazza Leonardo da Vinci.

- "Room Vespucci" honoring Amerigo Vespucci (1451 – 1512), the Italian explorer and navigator from whose name the term "America" is derived;
- "Room Polo" honoring Marco Polo (1254 – 1324), the Venetian explorer, merchant and writer who reported for the first time in Europe many aspects of the then-mysterious culture of the Eastern World.

Indeed, the people that attend and present their work at the conference are the explorers and pioneers of Airborne Wind Energy Science and Technology, which is today in a clear and well-sustained transition from an early-stage concept to a commercial renewable energy solution. Amid up and downs, we see a steady increase of support and interest in AWE, resulting in solid and growing activities of research and development, testing, standardization, and global collaborations. Today, we witness the first commercial systems in the 100-kW range in operation, the development of joint worldwide collaborative projects such as the IEA Task 48, several sector studies carried out or being started and a growing number of projects featuring public-private collaborations.

When it comes to industrialization and commercialization, engineering and design are key elements, which are remarkably represented by the conference venue. The main conference building is in the Leonardo Campus of Politecnico di Milano, named after the Italian polymath, draughtsman, engineer, scientist, theorist, sculptor, painter and architect Leonardo da Vinci (1452-1519). The Politecnico di Milano is a founding member of Airborne Wind Europe and active participant in the ongoing IEA Task 48 as well as in several projects and collaborations with AWE companies and research groups. We are sure that the conference venue and environment, in the classrooms where thousands of students daily participate to lectures in STEM disciplines, will stimulate fruitful discussions and exchange of experiences among all attendees.

An important aspect of a -finally again!-in-presence conference is the social program, to foster collaborations, new ideas, and networking. That of AWEC 2021 includes:

- a visit to Politecnico di Milano's wind tunnel, one of the largest in Europe, and a welcome cocktail on June 22 in Politecnico's Bovisa campus;
- lunches and coffee breaks at the conference premises;

- a banquet in the Liberty-style Osteria del treno, a piece of Milanese history, built as a club for railway workers at the nearby Stazione Centrale.

The event would not have been possible without its sponsors (listed on pages 8–9), to which we express our sincere gratitude.
We also warmly thank the people at Politecnico di Milano who contributed to the local organization, in particular Laura Brambilla and Martina Spinelli (DEIB communication), Francesco Esposito (logistic services), Isabella Pedone, Rosa Petrelli (DEIB admin), and Luigi Esposito Feudale (CIT services), and the people who contributed to the editing of this book, Filippo Trevisi and Nicolas Kessler.

AWEC 2021 takes place at a unique point in history, after two years since the Covid-19 pandemic outbreak. At the same time, a war that most people in the world thought impossible is raging in Europe since more than four months, exposing once more the geo-political implications -besides the environmental ones- of a society that heavily depends on non-renewable and geographically concetrated fossil fuels to supply most of its primary energy demand.
Hoping that peace will return soon, in these dreadful times we like to attribute to AWEC 2021 an additional value, as a symbol of a new beginning and restart of in-presence interactions towards the common goal of making the abundant, widespread, renewable and sustainable high-altitude wind resource reliably available to humanity.

We wish all AWEC 2021 partecipants a fruitful and inspiring experience.

Sincerely,

Lorenzo Fagiano

Politecnico di Milano
Milan, Italy

Alessandro Croce

Politecnico di Milano
Milan, Italy

Roland Schmehl

Delft University
of Technology
Delft, The Netherlands

Stefanie Thoms

Airborne Wind Europe
Brussels, Belgium

Institutional Sponsors

Politecnico di Milano Politecnico di Milano is the first technical university in Italy and among the first in Europe and worldwide, and its Departments cover all of the engineering and design aspects involved in Airborne Wind Energy. The conference is co-organized and co-hosted by the Dept. of Aerospace Science and Technology and the Dept. of Electronics, Information and Bioengineering, who have complementary expertise and collaborations in 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 2019 QS World University Rankings it is among the top 20 universities for engineering and technology. It is the highest ranked university of the country. Founded in 2004 by Wubbo Ockels and continued in 2009 by Roland Schmehl the Airborne Wind Energy Research Group is a pioneer and international leader in this innovative technology.

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

ELO-X The Marie Skłodowska-Curie network ELO-X, "Embedded Learning and Optimization for the neXt generation of smart industrial control systems" is funded by the European Commision under the Horizon 2020 program, grant agreement No. 953348. The network comprises top universities and industrial research centers in Europe and will train 15 PhD students in the areas of control, optimization, and machine learning. The goal of the network is to develop reliable and efficient control solutions to enable innovative industrial systems such as AWE generators.

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- Roland Schmehl, TU Delft, Netherlands
- Stefanie Thoms (chair), AWEurope, Belgium

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- Axelle Viré, TU Delft, Netherlands
- Jochem Weber, NREL, USA
- Hong Yue, University of Strathclyde, UK
- Udo Zillmann, AWEurope, Belgium

OEM Panel I

- Kristian Petrick, Airborne Wind Europe, Belgium
- Stephan Wrage, Skysails Power, Germany
- Rolf Luchsinger, TwingTec, Switzerland
- Rod Read, Windswept & Interesting, United Kingdom
- Alexander Bormann, Enerkíte, Germany
- Stephan Barth, Forwind, Germany
- Agustin Arjonilla, CT Engineering, Spain

OEM Panel II

- Kristian Petrick, Airborne Wind Europe, Belgium
- Florian Bauer, kiteKRAFT, Germany
- Johannes Peschel, Kitepower, The Netherlands
- Gian Mauro Maneia, Kitenergy, Italy
- Asgeir Løno, Kitemill, Norway
- Mike Blanch, BVG Associates, United Kingdom
- Jochem Weber, NREL, USA

Henk Hutting (1952–2021)

AWEC 2021 is dedicated to Henk Hutting, Pioneer of Wind Energy and Ambassador of Airborne Wind Energy

Henk Hutting is widely regarded as one of the founders of the modern wind energy industry in the Netherlands. He began his career in wind energy in 1982 when he got involved in developing the first wind farm in the country. He then coordinated a comprehensive research and development program covering all aspects of wind farming, after which he set up and managed the wind energy department of energy consultancy KEMA. He continued as managing director of the joint venture Smart Tower, specializing in developing support structures for offshore wind turbines, after which he became CEO of WinWind, a wind farm development company.

In 2007, Henk started his own company, Hutting Windenergie BV, and continued as CEO and shareholder of Growind, a company to develop and own a 63 MW wind farm in the Netherlands and as CEO of Lake Turkana Wind Power Ltd, a company to develop and own a 300 MW wind farm in Kenya. In early 2008, he led the founding of the Vader Piet entities to build and operate the wind farms on the Caribbean island Aruba. The same year he joined NuCapital as CEO, specializing in developing, financing and commissioning wind energy projects in the Caribbean and Central and South America.

As an investor and board member, Henk was also pushing for the improvement of the efficiency of solar panels, and his interest in renewable energies broadened when he joined Futerra in 2015 as an investor and Chairman of the Board, develop a factory in Portugal to produce Bio-Coal out of waste wood. In 2018, Henk joined the board of Kitepower BV to prepare the technology's commercial viability.

We would probably not be where we are today if it were not for his engagement and drive, guidance and experience. We are fortunate to have known and worked with him.

The team of Kitepower: Johannes Peschel, Joep Breuer, Jacques van Haaster, Roland Schmehl, Astrid de Jong, and colleagues.

Marjolein Hutting (left) and Samara Hutting (right) in front of the portrait of their father Henk Hutting on the V9 kite of Kitepower, taking over their fathers commitment, heritage and vision (16 June 2021).

Marcello Capra

Senior Expert
Department of Energy
Italian Ministry of Ecological Transition

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MINISTERO DELLA
TRANSIZIONE ECOLOGICA

The Strategic Role of Research & Innovation to Implement the Italian Energy and Climate Plan

Marcello Capra
Italian Ministry of Ecological Transition

Italy is part of the EU SET-Plan and is a promoter of Mission Innovation launched at COP21 to boost frontier projects for clean energy technologies

Mission Innovation is an International partnership joined by 25 Nations (plus the European Commission) with the aim to promote technology innovation to support energy transition by means of doubling of public funds for clean-tech research. Italy committed to double public funds for R&D for clean energy (from 222 Million € in 2013 to 444 Million € in 2021). Italy has a co-leadership role in the development of the new Mission “Power in the Future” MI 2.0 and is also member of the Mission Clean Hydrogen.

The Strategic Energy Technology (SET) Plan is the reference program for investment at EU level, and for private investment to support R&D and innovation in the energy sector. The main implementation program of the SET Plan is Horizon Europe 2021-2027.

The National Energy priorities for Italy are:

1. The development of products and process technologies for the energy transition;
2. The development of models and systems for energy transition and security.

The main policies and measures will be briefly described, including:

- The Recovery and resilience facility;
- Mission Innovation;
- The power system research Fund

Marcello Capra is Senior Expert of the Department of Energy of the Italian Ministry of Ecological Transition.

After obtaining the Laurea Degree in Nuclear Engineering in 1980 at the University of Rome La Sapienza, he started his career in the power generation sector in F.B.M.-HUDSON ITALIANA S.p.A., Milan, Italy, where he worked until 1984 on R&D of heat exchangers for power plants.

In 1984 he entered ENEA, the National Agency for R&D in Energy and Environment, where he took on many responsibilities as Experimental Areas manager and R&D projects manager. In 2001 he was appointed Head of the Division for Energy-Demand Technologies.

In 2002 Mr. Capra has been appointed by the Ministry of Economic Development Member of the Secretariat of the Department of Energy of the Italian Ministry of Economic Development (now Ecological Transition).

He represents his Ministry in many international organisations, such as the Carbon Sequestration Leadership Forum (CSLF), the International Partnership on Hydrogen Economy (IPHE) and the Steering Group of the Strategic Energy Technology Plan (SET Plan) of the European Commission.

He has been also appointed by the Ministry of University and Research (MUR) in 2001 Member of the Italian Delegation of the Horizon Europe Programme – Cluster 5.

Stephan Barth

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How Wind Energy can Lead the Global Transition to a Decarbonized Energy Supply

Stephan Barth
ForWind

The world's energy systems are changing faster than ever before. There are and there will be different recipes for different regions, countries or zones of the world. But there is no doubt that wind and solar energy will be at the heart of any of those transition strategies. In the International Energy Agency Wind Technology Collaboration Programme (IEA Wind TCP), we set out the vision of ”wind energy leading the global transition to a decarbonized energy supply”. The programme fosters an international co-operation of 24 countries and sponsors members that share information and research activities to advance wind energy deployment. Achieving this goal is obviously very ambitious and we need to pool all the expertise that exists. IEA Wind TCP provides a unique framework for global collaboration in wind energy research and development, where grand challenges and potential barriers are addressed and worked on in international working groups - the IEA Wind Tasks. These cover areas from resource, site characterizations and external conditions to advanced technologies and energy systems with high amounts of wind energy. The less technical areas social, environmental, and economic impacts as well as communication, education and engagement are equally important. Task 48 provides a platform for the open exchange of ideas, experiences, and techniques for airborne wind energy systems. Launched in 2021, IEA Wind Task 48 on Airborne Wind Energy aims to build a strong community working together to identify and reduce barriers to the development and deployment of airborne wind energy systems. In doing so, it contributes to our mission of advancing wind energy research and communication through international collaboration.

References:

[1] IEA Wind Task 48. Airborne Wind Energy. https://iea-wind.org/task48/

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World Energy Transitions Outlook: 1.5°C Pathway

Paula Nardone
International Renewable Energy Agency

To keep the global temperature increase below 1.5°C, the world needs to significantly increase renewable electricity capacity, rapidly scaling renewable energy share in electricity generation to 65% by 2030. Wind power together with solar PV are abundantly available and are already the lowest-cost electricity sources in most parts of the world. They create the opportunity to replace fossil fuels for power generation, reducing both emissions and the cost of electricity [1].

Between 2010 and 2021, wind energy installations expanded by more than fourfold. Despite this, the wind's exploitable potential significantly exceeds the current world electricity generation. Under IRENA's 1.5°C Scenario, wind will be one of the largest generation sources by 2030, supplying 24% of total electricity needs. The installed capacity of onshore wind will quadruple by 2030, after which it will grow even faster towards 2050 which involves 225 GW of annual additions. In addition, offshore wind capacity will need to grow 11-fold by 2030.

Airborne wind energy has the potential to play a key driver on wind power development, as it is a flexible and mobile technology that can be easily set up. Airborne wind energy systems are being researched on an international level and are attracting the attention of different countries and organisations, with European countries leading airborne wind energy demonstration projects [2].

References:

[1] IRENA (2022), World Energy Transitions Outlook 2022: 1.5°C Pathway, International Renewable Energy Agency, Abu Dhabi.

[2] IRENA (2021), Offshore renewables: An action agenda for deployment, International Renewable Energy Agency, Abu Dhabi.

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Kernel-based Identification of Periodically Parameter-Varying Models of Power Kites

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In airborne wind energy (AWE) systems, model mismatch may in practice lead to severe performance deterioration. It is thus desired to assess closed-loop performance from experimental trajectory data with a closed-loop model, to analyze the performance of existing flight systems and design additional control loops.

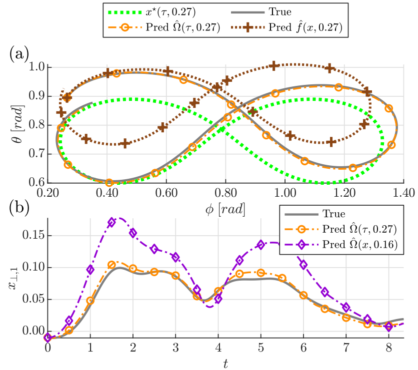
Therefore, we are interested in identifying power kite dynamics moving along a periodic orbit, which can be modeled as a periodic system parametrized with the location on the orbit. Concerning performance close to the orbit, the periodic system can linearized locally. This work proposes an approach to identifying the local dynamics with a linear periodically parameter-varying model from experiment trajectory data.

The approach decomposes the dynamics into two parts: one along the orbit, and one on a transversal hyperplane of the orbit [1]. Let the state of the kite be x, and the nominal periodic trajectory be $\{x^\star(\tau) \mid \tau \in [0, T)\}$. Define $S(\tau)$ as a hyperplane transversal to the orbit. The state can be decomposed as $(\tau, x_\perp)$, with dynamics modeled as

$$\begin{cases} \dot{x}_\perp &= A(\tau)x_\perp + O(|x_\perp|^2), \\ \dot{\tau} &= 1 + g(\tau)x_\perp + O(|x_\perp|^2). \end{cases}$$

The proposed identification method identifies $A(\tau)$ and $g(\tau)$ as smooth functions of τ. Measured data are first decomposed into transverse coordinates. The problem is then recast as a function learning problem, where the kernel method is applied to learn the model. This approach also handles additional operating parameters (e.g., radius, nominal speed), noisy measurements, and exogenous inputs (e.g., wind gusts, additional actuation).

The identification algorithm is tested on simulation data generated by a simulation model of tethered kites with a multi-loop control design. Results show that the proposed approach is able to obtain reliable predictions of closed-loop trajectories under various scenarios.



Predicted trajectories with additional parameter $v_{\theta\phi}/r$. Orange: proposed method, brown: black-box nonlinear identification, purple: without $v_{\theta\phi}/r$ modeling.

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Safety-Critical Hybrid Control of Airborne Wind Energy Systems

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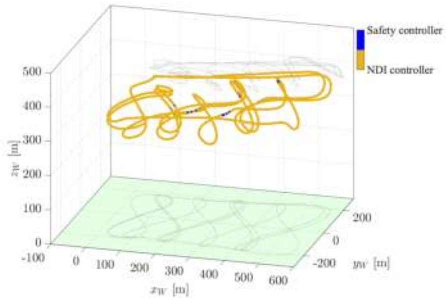
[2]Paderborn University

In order to move Airborne Wind Energy (AWE) into the future, a fundamental concern is being able to guarantee that safety requirements placed on the systems are met. Due to the high dimensional complexity of AWE systems, however, strict mathematical robustness guarantees become difficult to compute.

We draw on research from Hamilton-Jacobi (HJ) reachability analysis with state constraints [1] to compute the optimal trajectory for tracking a figure-eight flight path during the pumping cycle, while enforcing safety constraints on the system, such as those placed on the tether force. In addition to providing the optimal control policy, the subzero level-set of the computed value function inherent in HJ reachability analysis indicates the backward reachable set (BRS), the set of states from which it is possible to safely drive the system into a target set within a given time without entering undesirable states, defined by an avoid set.

Furthermore, we derive a switching law, such that the safety controller can be used in conjunction with arbitrary least restrictive controllers, e.g. NDI or MPC, to provide a safe hybrid control law. In such a setup, the safety controller is only needed when the system approaches the boundary of its maneuverability envelope. Such a hybrid control law is a notable improvement over existing robust control approaches that assume the worst-case environmental and system behavior at all times, leading to potentially sub-optimal control laws.



Multiple pumping cycles using the hybrid control law. A controller using Nonlinear Dynamic Inversion (NDI) [2] is used as a baseline controller and the safety controller is only engaged when a tether rupture is predicted to occur. While the safety controller is only activated rarely, its effect is quite significant.

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[2] Rapp, S., Schmehl, R., Oland, E., and Haas, T., "Cascaded pumping cycle control for rigid wing airborne wind energy systems," Journal of Guidance, Control, and Dynamics, Vol. 42, No. 11, 2019, pp. 2456–2473

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Estimation of Unknown Aerodynamic Forces of an AWE System

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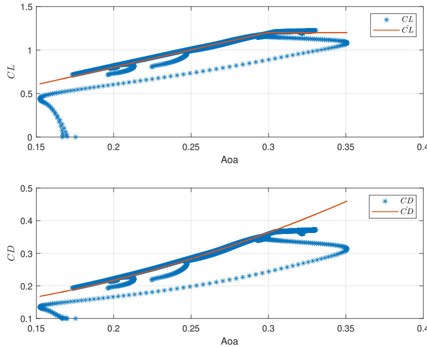
Airborne Wind Energy systems (AWE) represent a promising solution to environmental challenges that has revolutionized research in the wind industry.

The studied AWE system in this work is equipped with a multicopter drone in order to perform take-off and landing maneuvers. An estimation strategy based on an Extended Kalman Filter (EKF) is proposed to obtain precise information regarding the state vector of the system, the unknown forces that acting on it and its aerodynamic coefficients.

The proposed method is implemented and tested in a numerical and experimental environments. The obtained results show the effectiveness of the introduced method, numerically and experimentally, at estimating the unknown forces that are acting on the system despite the presence of several sources of uncertainties (neglected nonlinearities, poorly known parameters, physical constraints of the actuators, etc.). Moreover, if a reliable model of the aerodynamic coefficients is available the proposed algorithm is capable to estimate the wind velocity.

Integrating the estimation results in the control design step has also improved the performance of the nonlinear controller previously introduced in [1] where the lift and drag forces were only considered as disturbances and not as control inputs. In addition, the knowledge of these aerodynamic forces allows one to improve the robustness of the studied AWE system during the critical take-off and landing phases.



The evolution of the aerodynamic coefficients C_L and C_D computed from the estimated data and those given by the system's model.

References:

[1] A. Schanen, J. Dumon, N. Meslem, A. Hably, A. Negre, A. Sarazin, Tethered drone-based airborne wind energy system launching and retrieving, Journal of Guidance, Control, and Dynamics (2021) .

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Iterative Learning-Based Kite Path Optimization for Maximum Energy Harvesting

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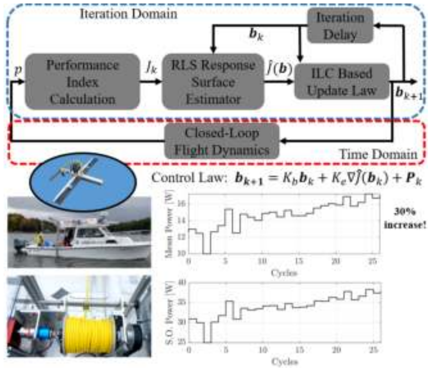
In this work, we have adapted and validated an iterative learning-based basis parameter optimization that optimizes the parameters of a flight path or orientation trajectory for an *airborne wind energy* or *marine hydrokinetic kite system*. This algorithm, first seen in [1] and further developed in [2], was adapted to accommodate parameters that describe target roll and yaw trajectories.

The algorithm consists of two steps that take place after each spool-out/spool-in ("pumping") cycle of the kite. In the first step, a meta-model is updated using a recursive least squares estimate to characterize an economic performance index as a function of a set of basis parameters ($\mathbf{b}_k$) that describe either a spatial path or orientation (roll and yaw) trajectory. The second part is an iterative learning update, which uses information from past cycles to update basis parameters at future cycles using a gradient ascent formulation with an added perturbation ($\mathbf{P}_k$) to push the controller out of local maxima.

While this algorithm can be applied to either airborne or underwater kites, it was experimentally validated on a $1/12^{th}$ scale experimental prototype underwater kite system towed behind a test vessel in Lake Norman, North Carolina. On top of the iterative learning update, a state machine was used for transitioning from figure-8 cross-current flight when spooling tether out to wings-level flight on spool-in. Furthermore, lower-level controllers were used to track setpoints generated based on the parameters updated by the iterative learning algorithm. Using our experimental system and algorithm, we were able to increase cycle-averaged power by 30 percent, relative to an initial baseline controller.



System diagram, control law, experimental apparatus, and results for an iterative learning-based optimization applied to a kite system. ***Diagram****: $\mathbf{b}_k$, are the basis parameters, p are the plant variables, J_k is the performance metric, and $\hat{\mathbf{J}}(\mathbf{b})$ is the estimated response surface.* ***Control law****: K_b and K_e are controller gains and $\nabla\hat{\mathbf{J}}(\mathbf{b}_k)$ is the estimated gradient of the response surface.* ***Results****: Cycle- and spool-out-averaged power are greatly increased.*

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[2] M. Cobb, J. Reed, J. Daniels, A. Siddiqui, M. Wu, H. Fathy, K. Barton, and C. Vermillion, "Iterative learning-based path optimization with application to marine hydrokinetic energy systems," IEEE Transactions on Control Systems Technology, 2021.

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Fault-tolerant Control of Airborne Wind Energy Systems with Quadrotor/Fixed-Wing UAV Configuration

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Safety, robustness and reliability are crucial aspects of any power generation technology, and airborne wind energy developers have been focusing on them since several years now. Since automatic control plays a key role in AWES, approaches to guarantee continuous operation of the control system shall be adopted. This work considers the AWE configuration Quadrotor/Fixed-Wing hybrid unmanned aerial vehicle (UAV), referring in particular to a prototype from Kitemill AS.

The presentation discusses ongoing research activities to apply Fault-tolerant control (FTC) for AWE tethered flight and to study how it can improve the system reliability and safety. First, a control structure dedicated to Quadrotor/Fixed-Wing hybrid UAV is introduced. The suggested scheme uses daisy chain control allocation [1],[2], which can react instantly in the event of actuator saturation; this is highly demanded in AWE for robust continuous autonomous operation. Then, the mentioned structure is upgraded to Active Fault-Tolerant Control (AFCT) by introducing a quantitative model-based Fault Detection and Isolation (FDI) approach and introducing a new parameter that links the commanded control signals to the system states. This parameter is used to assist residual generation in order to identify the faulty actuator and avoid false alarms, overall improving fault-tolerance measures for the AWE system.

Kitemill's 5kW system considered in this study

References:

[1] Dale E. at al., Dynamic inversion: an evolving methodology for flight control design. International Journal of Control, Volume 59, pp. 71-91, 1994.

[2] T. Mohammed and L. Fagiano, Dynamic inversion: an evolving methodology for flight control design. IEEE Conference on Control Technology and Applications (CCTA), Trieste, Italy, August 2022.

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Airborne Wind Energy Development Database

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[3]Airborne Wind Europe

Airborne wind energy (AWE) systems have reached a technology readiness level (TRL) at which a number of companies are deploying prototype systems with rated powers of up to several hundred kilowatts. As a consequence, topics such as reliability and safety [1], regulation and permitting [2], as well as environmental impact [3] and social perception of the new technology [4] are becoming increasingly important. Although regulations and social perception typically vary per country, a well-coordinated, networked approach to address these interlinked challenges will be indispensible for the commercial success of the technology. This requires a central and systematic collection and maintenance of relevant information.

The aim of this project is to compile an as-complete-as-possible database with information about

- the institutions involved in R&D of AWE systems,
- the physical prototypes that are currently tested,
- the deployment sites of these prototypes, and
- any other information on the R&D or deployment.

To facilitate the maintenance of this database, it is implemented in a way that its content can be displayed in various ways, depending on the specific use cases:

Research & development: Display a regional or world map showing where AWE systems are developed and where they are tested.

Permitting: List the types of permit that are used at the different test locations. Include the permitted modes of operation, such as flight during day only, or also during night, etc. Environmental impact of AWE How does a current and planned deployment impact the natural environment of the sites? How are these sites embedded in the environment?

Social perception: Information about the social perception of the new technology and analyze possible interaction with natural preserves.

During its development, the database will first be closed to the public but made open access when reaching its final stage. Following the first release, stakeholders and the general public can upload information that will be taken into account to improve the database for future use.

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[1] V. Salma, F. Friedl, R. Schmehl: Improving Reliability and Safety of Airborne Wind Energy Systems. Wind Energy, Vol. 23, No. 2, pp. 340-356, 2019.

[2] V. Salma, R. Ruiterkamp, M. Kruijff, M.M. van Paassen, R. Schmehl: Current and Expected Airspace Regulations for Airborne Wind Energy Systems. In: R. Schmehl (ed.) "Airborne Wind Energy - Advances in Technology Development and Research", Springer Nature, Singapore, pp. 703-725, 2018.

[3] L. van Hagen: Life Cycle Assessment of Multi-Megawatt Airborne Wind Energy. MSc Thesis, TU Delft, July 2021.

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Rapidly Deployable Airborne Wind Energy Systems for Defense and Disaster Response

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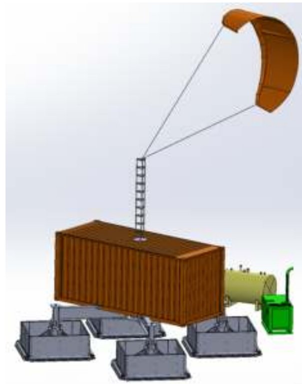
Airborne wind energy can have significant advantages over conventional towered wind turbines in remote and rapidly deployed applications. The total logistical burden (total volume or mass of material to be deployed) of an airborne wind energy system is much less than a conventional wind turbine of the same nameplate power rating. Furthermore, the energy production can be higher due to higher winds aloft. This paper compares conventional wind turbines on a ballasted tower to airborne wind energy systems supported by a ballasted foundation. This paper also serves as a summary of a full report[1] which presents the best currently available design guidance for deployable wind turbines, and the of the airborne wind aspects of a full report[2] comparing logistic burden for solar, traditional wind, and airborne wind.

Access to on-site electrical energy is critical to ensuring a successful military or humanitarian response to conflicts and disasters. These missions typically rely on access to liquid fuel that can be vulnerable to disruption or attack during transport. Generating power on location with wind technology—whether at a contingency base or disaster response coordination point—can reduce this risk and enhance mission reach by diversifying energy sources. Common characteristics of these missions are short planning and execution time horizons and a global scope of potential locations. Compared to conventional turbine applications, defense and disaster response applications place a premium on rapid shipping and installation, short-duration operation (days to months), and quick teardown upon mission completion. These design drivers depart from features found in conventional distributed wind turbines, thus necessitating unique design guidance.



Rapidly Deployable Ballasted Foundation AWES.

References:

[1]Naughton B., Jimenez T., Preus R., Summerville B., Whipple B., Reen D., Gentle J., and Lang E.. Design Guidelines for Deployable Wind Turbines for Military Operational Energy Applications. Sandia National Laboratories. (2021) SAND2021-14581R-1

[2]Naughton B, Deployable Wind-Hybrid Power Systems for Defense and Disaster Response Applications. Sandia National Laboratories. (2021) SAND2021-14967

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Lessons Learned in Maturing Novel Renewables

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RWE Renewables and its predecessors have endeavoured for decades to mature novel technologies to a state where they can become a part of the energy mix.

In wave and tidal energy, floating wind, concentrated solar, and Airborne Wind Energy RWE has been at the forefront; challenging and supporting these technologies, hoping to can one day operate them. Through this experience, we have built up a wealth of experience of what works well, as well as what has brought about near inevitable failure.

In this paper, a review of lessons learned is presented, with an emphasis on the parallel maturation of both a technology, and the company developing it. Processes, quality control, and above all safety practices must be proportionate to the risks at a given stage of development. From the intrepid inventor working in their garage, to the equipment manufacturer supplying Gigawatts of generation, understanding these requirements is vital for success.

Example novel renewables concepts from which RWE's experience has been gained.

WP1

RESOURCE POTENTIAL AND MARKETS

AEP prediction for selected sites & toolchain documentation

Global high-altitude wind resource atlas

Recommendation on AWE entry-markets

AEP prediction toolchain

Economic metrics

WP2

REFERENCE MODELS, TOOLS AND METRICS

Common definition of metrics and KPIs

Joint reference model(s)

Centralized design tool

Simulation vs. test flights comparison

Definitions

Centralized design tool database

WP3

SAFETY AND REGULATION

Concept of operations and risk assessment

Airspace integration concept

Benchmarking concepts for safe automatic operation

Whitepaper on AWES safety

WP4

PUBLIC ACCEPTABILITY

Life-Cycle Analysis

Repository of survey and studies

Guidelines for site selection, sound measurement and impact mitigation

Circular Economy

LCA of AWE

Repository of surveys & studies

WP5

AWES ARCHITECTURES

Design space representation

Market specific deployment recommendations

AWES R&D state, trends and needs

Portal for AWES engagement and development potential

Guidelines

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Fostering International Collaboration Within IEA Wind TCP Task 48

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The International Energy Agency's (IEA) Wind Technology Collaboration Programme (TCP) is an international co-operation that shares information and research to advance wind energy research, development and deployment in member countries. Companies and organisations from these countries work together in the so-called IEA Wind tasks.

In 2021, the IEA Wind Task 48 on airborne wind energy (AWE) was established [1]. Task 48 provides a platform for the open exchange of ideas, experience, and techniques of AWE systems and aims to build a strong community that works together to identify and mitigate the barriers to the development and deployment of this emerging technology.

The objective is to jointly tackle the remaining challenges, also including stakeholders who are not primarily AWE developers, i.e., policy makers, authorities, regulators as well as other wind energy and technology experts. A key benefit of the new task will be that it opens the scope of collaboration to the whole world; it will thus foster a truly international exchange of expertise, produce and gather new data and information, allow for joint learning as well as accelerate the development of AWE technology and thus its impact on the international energy sector.

Five different work packages (WPs) were defined to structure the collaboration and to match research activities with the needs for the further development of the Airborne Wind Energy sector. The WPs aim to answer the following questions:

- Where to deploy AWE? → WP1 "Resource potential and markets"
- How to deploy AWE efficiently and how to assess power production? → WP2 "Reference models, tools and metrics"
- How to deploy AWE safely? → WP3 "Safety and Regulation"
- What are AWE benefits for society and environment? → WP4 "Public Acceptance"
- Which technological potential do different AWE concepts have? → WP5 "AWES architectures"

Task 48 on AWE makes use of the IEA Wind network by collaborating with other tasks, e.g. Task 28 on Social Acceptance, Task 41 on Distributed Wind, or Task 51 on forecasting. The task is managed by the secretariat of Airborne Wind Europe who acts as Operating Agent. As of 2022, participating countries are Belgium, Denmark, Germany, Ireland, Italy, Spain, Switzerland, The Netherlands, United Kingdom, and USA. Interested organisations and other countries are welcome to join.

References:

[1] https://iea-wind.org/task48/

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Shapewave: True 3D HD Webbing Inflatable Structures

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Shapewave presents a unique new way of building medium pressure inflatable bodies with shapes hardly hindered by being an inflatable.

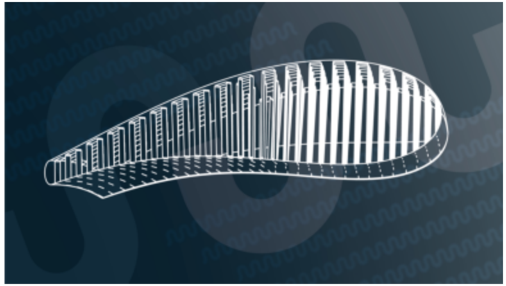
It's probably on a page in every air-foil designers sketch-book: hundreds or even thousands closely pitched threads or webbing, each with an individual length, accurately and reliably bonded between two opposing membranes. Through the years, some have even achieved building such inflatable bodies.

The patented shapewave technology [1] aims at streamlining design, evaluation, calculation and build in an integrated process. After a design is made with the appropriate mix of materials and webbing population, prepared membranes are fed into a shapewave machine, where a bonding robot feeds and bonds a tape between them.

Key starting point for the shapewave project are:

- do not pierce membrane material that is perfectly air-tight to begin with
- link elements continuous from reel
- "pre-glued"
- processed by robot: Rapid Manufacturing

While the technology may look exotic, shapewave is set out to work with proven, low cost materials and existing technologies.



Section of a single chamber inflatable wing showing continuous, internally bonded tapes.

Shapewave parts can be used for hydro- and aero applications like hulls, nacelles, wings, sails, rotor blades and kites, and are, due to the relatively low cost, within reach for recreational and consumer applications.

References:

[1] Enserink, A.R. Process for Manufacturing of Free Form Inflatable Bodies. Patent WO2021190789 (2020)

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Comparison of Two Data-driven Airborne Wind Energy Oriented Long-term Weather Forecast Methods

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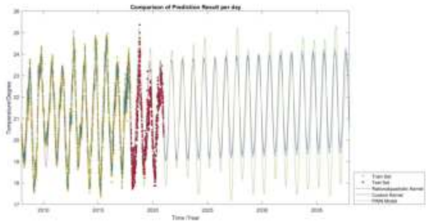
Recently there has been a rising interest in airborne wind energy (AWE) oriented weather forecast research. Especially, it is crucial for energy production prediction, health prognosis of critical components and maintenance scheduling. However, to the best of the authors' knowledge, the current research on AWE oriented long-term weather forecast is limited. To fill this gap, we developed and benchmarked two data-driven long-term weather forecast methods oriented for AWE. In the first method, we implemented a rational quadratic kernel and a custom kernel function based Gaussian Process (GP) model. In the second method, a Physics-Informed Neural Networks(PINNs) model [1] with modified loss function is used. To demonstrate the performance of the proposed methods, we implemented a case study using ten years' publicly available data (2008-2017) as the training set and three years' data(2018-2020) as testing set [2]. The performance of the two methods is analyzed by comparing their Mean Absolute Error (MAE) and Root Mean Square Error (RMSE). The comparison of the prediction results and historical weather data is presented in Fig.1. On the one hand, the GP based method shows an advantage on daily prediction accuracy. On the other, the PINNs based prediction method also shows great potential to consider the influence of geographical location and altitude.



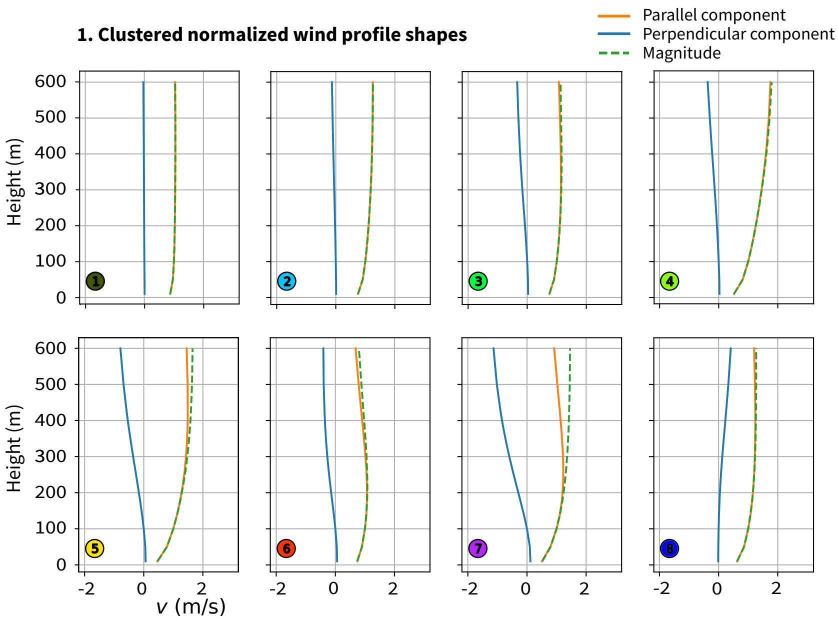
Comparison of the real time data and the results derived by the two proposed method.

References:

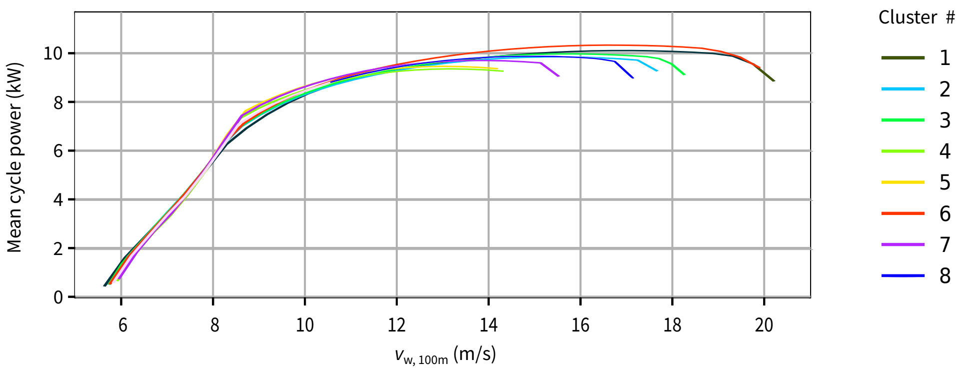
[1] G.-J. Both, S. Choudhury, P. Sens, and R. Kusters, "DeepMoD: Deep learning for model discovery in noisy data," Journal of Computational Physics, vol. 428, p. 109985, Mar. 2021, doi:10.1016/j.jcp.2020.109985.

[2] National Centers For Environmental Prediction/National Weather Service/NOAA/U.S. Department Of Commerce, "NCEP FNL Operational Model Global Tropospheric Analyses, continuing from July 1999." UCAR/NCAR - Research Data Archive, p. 524.792 Gbytes, 2000. doi:10.5065/D6M043C6.

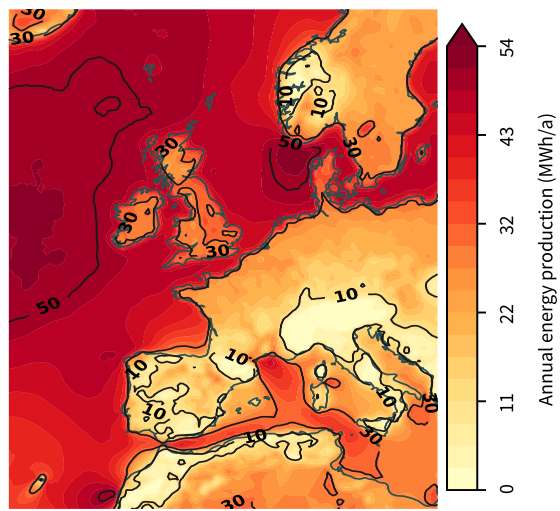
1. Clustered normalized wind profile shapes



2. Power curves for each wind profile



3. Annual energy production



1. The clustering process uses vertical profiles of normalised horizontal wind speed components. The generated cluster profiles thus represent only the shape of the profiles, and are normalised to 1m/s at reference height of 100 m. Fully denormalising to match back to an original wind data sample at a specific time and location is represented by the cluster 100m wind speed ($v_{w, 100m}$).

2. The power is therefore determined for each cluster profile when scaled to a range of $v_{w, 100m}$, yielding a power curve.

3. Knowing the cluster and $v_{w, 100m}$ of a sample, the estimated power is taken from the respective power curve.

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The Airborne Wind Energy Resource Analysis Tool AWERA

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The open-source tool AWERA [1] was developed for assessing the potential of airborne wind energy systems (AWES) on large geographical and temporal scales. AWERA can be used for spatial and temporal studies of the wind resource and power production potentials, and means for comparing different types of AWESs. It can also be used for uncertainty quantification of the computed power production for all simulation components, from wind resource to system dynamics.

AWES are characterised by a more complex power generation than conventional wind turbines. Flight operation and harvesting depend not only on the wind speed at hub height but on an extended vertical wind profile and its temporal variation. The wind resource and associated wind power density at optimal harvesting height was described in [2], indicating a high production potential for AWES accessing higher altitude winds.

Accounting for the specific harvesting process leads to a substantially improved performance estimation. There are different models describing the full flight and system dynamics or using a sequence of simplified quasi-steady force equilibrium states [3] to estimate the power output for a given vertical wind profile. The latter model was used in [4] to predict the harvested power of a prototype kite system for eight representative absolute wind profiles. These profiles are determined using a principal component analysis paired with a clustering algorithm on an ensemble of measured vertical wind profiles.

The harvesting characteristics are determined for the absolute clustering wind profiles, which then are used to obtain the spatial distribution of the annual energy production for Europe, significantly reducing the computing time compared to processing all samples individually. For validation, harvesting characteristics resulting for either approach are compared for various clustering representations. AWERA holds the opportunity to add different AWES types and power production estimation models.

The resulting hourly power is used to compute the annual energy production and capacity factor and to evaluate characteristics such as the down-time, which can be used to assess the potential for providing base load capacity. It is also possible to extract hourly timelines of measures, such as power timelines for site assessment.

Our aim was to provide a performance assessment tool and parametrisation of wind data. We invite all AWE stakeholders to add public versions of systems parametrisations and to use the tool for evaluating the power production at any location, which is an important input for broad-scope energy system evaluations.

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Towards Flow-Field Characterization for AWES

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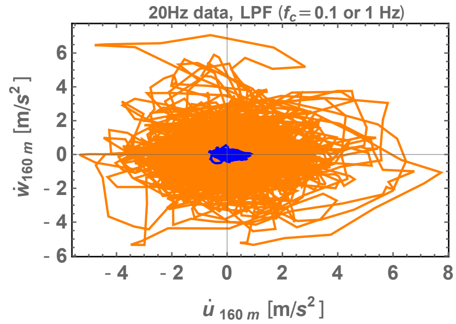
Characterizing the flow field encountered by airborne wind energy systems (AWES) is crucial for both their design and operation. In addition to affecting potential wind resources, the highly variable and complex turbulent flow at heights above the atmospheric surface layer (z>100m) also impacts the control system and flight paths which are optimal for a given AWES design. The interplay between flow field, flight paths, control system, and design ultimately affects the loads and reliability of AWES.

10-minute statistics commonly used in wind energy lack information about the events and flow at temporal and physical scales relevant for AWES. Re-analysis, mesoscale, and lidar data also fail to capture primary flow features which affect AWES operation and design. Finer resolution data is needed to cover the response times and physical dimensions of AWES; these can reach 1s and 1–10m, respectively (or shorter). Stationary horizontal axis wind turbines (HAWTs) have scales of 100m and longer response times, acting to average the inflow and its inhomogeneities. E.g., accelerations encountered in a 10-minute period are shown in the Figure, filtered separately for typical AWES and HAWT scales. Significant accelerations in multiple directions occur for AWES, whereas for HAWTs these are much smaller and mostly streamwise.

After recent parallel analysis for HAWTs [1], we investigate flow statistics at AWES scales and operational heights, showing where they cannot (or can) be expressed using conventional 10-minute statistics. Following analogous statistical characterization [2], we also give flow metrics for AWES design, operation, and resource assessment; this includes conditional vector velocity and acceleration statistics missing from typical 10-minute data.



10-minute streamwise/vertical acceleration space: Høvsøre offshore sector, 160m height, sampled at 20Hz. Filtered (O2 Butterworth) for characteristic response times of 10s (blue) and 1s (orange).

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BLUEWISE MARINE

Practicalities of Site Selection for an Offshore AWE Demonstration: A Case Study for Ireland

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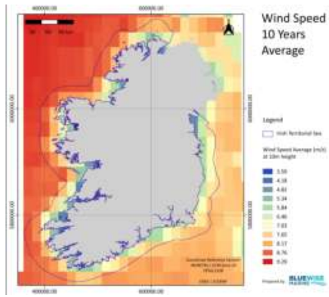
Airborne wind energy systems (AWES) open promising solutions to the developing renewable energy industry. The offshore deployment of those systems sees challenges and features that cannot (necessarily) be generalized within floating wind turbine studies. Therefore, it is necessary to adopt suitable methodologies to carry out appropriate site selection studies both for pilot testing and further operations.

Identification of suitable sites involves integration and interpretation of multi-faceted geospatial factors and a full understanding of technical, socio-economic, environmental and political elements. Finding and collecting reliable, up to date, and high resolution data can be challenging for some variables and some of the data sources present gaps in information. Defining the technical criteria (e.g., required wind speed, water depths, accessibility, aviation restrictions, etc.) is also key for successful site selection and it is highly dependent on the objectives and characteristics of the project and the technology that will be used.

Irish waters present an advantageous environment for the development of offshore AWES, given the resource and the test facilities, already established on the territory.

In the present work, an integrated process is adopted to identify the viable areas for deployment of the AWES designed by Ampyx Power, in Irish waters. The method employs Geographic Information System (GIS) tools and multi-criteria decision procedures, as well as the use of numerous siting criteria offered by the national legal framework, international literature and resources, and technology providers knowledge [1]. The same methodology can be applied for future initiatives in other regions, and it can be easily adapted to other AWE technologies.



Average Wind Speed in 10 years (2010-2020)

References:

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Social Acceptance of Airborne Wind Energy

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Airborne wind energy (AWE) has recently been called a potential game changer for the energy transition [1]. Yet, the success of AWE is determined not only by its technical and economic feasibility but also by its acceptability. Strong negative reactions of the public have slowed down the deployment of other renewable energies in the past [2,3].

Our recent review showed that the existing literature mainly paints an optimistic picture of the social acceptance of AWE but lacks empirical evidence for this assessment [4]. Social science studies, as done in this PhD, will help achieve a more accurate understanding of how different stakeholders, including hosting communities, perceive and respond to the technology. For the long-term success of the industry, it is important to identify critical acceptability issues at an early stage of technology development and to engage relevant stakeholders in the development and deployment of AWE.

In this talk, I will present preliminary outcomes from systematic interviews that I am conducting with stakeholders. Examples of these stakeholders are residents, developers, policymakers, regulators, NGOs and interest groups. I will discuss stakeholders' experiences, concerns, and expectations regarding the technology.

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Kite Path–following with L0 and L1 Controllers Tested on a Small–scale Prototype

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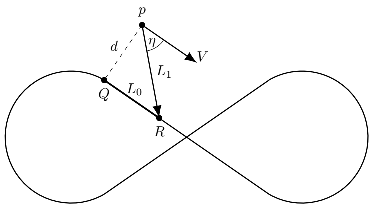
We address the problem of controlling an aircraft of an airborne wind energy system (AWES) to follow a prescribed geometric path. We consider two path-following guidance methods, the L1 and the L0 controllers, adapt them to AWES, implement them in *Ardupilot*, analyse their behaviour, and compare their performance.

The L1 controller is based on an well–known guidance logic reported in [1], while the L0 controller is a modification of the previous controller, described in [2,3], which removes the need to switch control laws when operating far from the reference path. The L1 controller considers the current kite position p and a predetermined design parameter L_1, representing the distance from the kite to a reference target point R in the desired path. This defines the location of R as well as the heading of the vector L_1, thereby defining its angle η with the kite velocity vector V. The lateral acceleration a_s needed for the kite to join the path at R can be computed by $a_s = 2\frac{V^2}{L_1}sin(\eta)$.



Path to be followed and signals involved.

In the L0 controller, the design parameter is now L_0, representing the distance from the closest point Q in the path to the reference target point R. These variables also determine the location of the point R, as well as the quantities L_1 and η, allowing a_s to be computed using the same formula as before.

We have implemented the techniques in *Ardupilot* and carried out software-in-the-loop simulations with the help of JSBsim. The simulations allowed the performance comparison of both controllers under fast changing wind conditions, such as wind gusts. The L0 controller exhibited a better performance when measured in terms of the average cross–track error [3]. The L_0, L_1 parameters can be adjusted accordingly to the flight characteristics of the aircraft to achieve the desired behavior converging to the path.

Field tests were carried out on a small-scale aircraft prototype to extract real flight data. The data confirms the conclusions obtained in the simulations regarding the ability to follow closely the reference path.

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Model Predictive Path–Following Control of Airborne Wind Energy Systems with Guaranteed Stability

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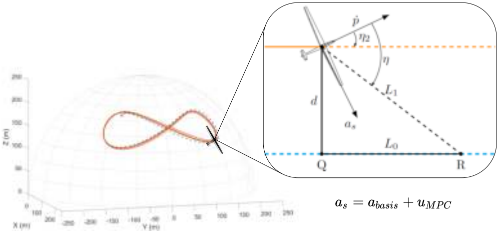
In AWES concepts in which the power generation is done with a kite flying crosswind, a pre–specified, optimized, cyclic path should be followed closely. Here we address the problem of devising a controller for a kite to follow the pre–specified path.

We propose a Model Predictive Control (MPC) scheme that is added to an existing basis path–following controller. The MPC scheme aims to improve the performance of the original controller, while maintaining its stabilizing properties. We start with a basis path–following guidance law, named L0 guidance logic, that was demonstrated to have a large domain of attraction and global asymptotic stability [1], and add a MPC control law on top of it. The usage of this combined controller has been shown to offer several benefits:

1. the stability of the resulting system is guaranteed by means of an adequate selection of the MPC design parameters [2];
2. the combined controller can only improve the performance of the basis controller;
3. the MPC numerical optimization can be efficiently solved, since the basis controller offers an already feasible initial solution to start with;
4. the method is robust to an optimization failure, since the initial solution is already an adequate one.

We present simulation results gathered using Matlab in order to evaluate the MPC Path–Following controller applied to a crosswind flying kite. The simulation results confirm the expected performance increase of the combined controller.



MPC Path-Following Controller descriptive image.

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Quantifying AWE Optimal Control Problem Tractability with Simple Vortex Models

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[3]Norwegian University of Science and Technology

One of the methods for predicting how an AWE system will perform uses the offline solution of a trajectory optimization problem [1]. The present work considers such a an optimal control problem (OCP) for a two-kite AWE system, as formulated by the software package `awebox` [2].

Many AWE subsystems or physical effects in the OCP can be described by various models of differing fidelity. The modeling of the aerodynamic induction effect on the AWE system is one such effect whose model must be selected. One can readily find information that describes the expected trade-offs of various induction models from the perspective of physical realism [3], however, information is less easily available when considering the perspective of OCP tractability.

When this optimization problem is solved using an exact Newton method, its tractability depends on the linear system being solved within each Newton iteration. This suggests, that the tractability of the problem might be described quantitatively by a number of indicators:

A1. the size of the matrix in the linear system,
A2. the condition number of that matrix,
A3. the sparsity of that matrix, and
A4. a quantitative indicator of that sparsity's structure.

Specifically, one might expect that the values of these indicators at a reasonable initial guess and at the problem's converged solution, might describe the problem's relative tractability, assessed using:

B1. the number of Newton iterations,
B2. the total wall-time, and
B3. the maximum memory usage during solution.

The hypothesis of this work, then, is that the indicators (A) can meaningfully describe the observations (B), when selecting between different vortex models. Since the proposed indicators might arguably be predicted prior to OCP solution, such a relationship might be generally used for model selection when formulating AWE OCPs.

The specific focus in this work is on the quantitative tractability indicators, rather than the induction models. Therefore, the considered models are highly-simplified vortex filament and cylinder super-positions. If promising, the approach might be used for more complex models - whether for induction or for other physical effects.

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ICM-autoKite Project: Control Approaches for an Automated Kite Propulsion System for the KITE GAS/FUEL SHIP

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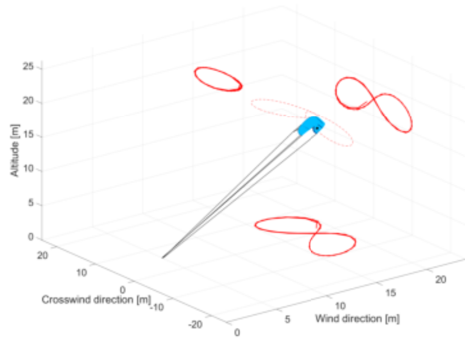
Tethered kites have become a popular option for generating green energy in so-called Airborne Wind Energy (AWE) systems. The kite can be used to unwind a rope from a spool and use it to power a generator or directly to pull a vehicle or ship in a certain direction. For the operation of such a plant, the automatic control system is of great importance. It ensures energy optimal trajectories and keeps the kite aloft in the first place. Additionally, it can be used to steer the kite in a certain direction if the kite is used in towing mode. There are different ways to develop such a control algorithm ranging from classical PID controller [1] to model predictive control (MPC) [2].

The automated control strategy for the operation of the kite, which will be the main propulsion system of the KITE GAS/FUEL SHIP, constitutes the centrepiece of the ICM-autoKite project. The prime objective is to track the kite on a figure-eight, that was found to be an energy optimal trajectory [4]. A nonlinear dynamic inversion guidance law with a basic proportional controller can precisely track the kite on such a figure-eight trajectory, as can be seen in the figure on the right. However, the basic controller is tuned for a certain trajectory given a certain wind speed. Varying conditions would need an adjustment of the control gains. Therefore, a reinforcement learning (RL) approach, valid for different trajectories and wind speeds, is proposed to potentially replace a classical basic controller for AWE applications.



Kite flight of a figure-eight trajectory using a nonlinear guidance law with a proportional controller [5].

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Automated Power Cycles in Daylong Operation at SkySails Test Site

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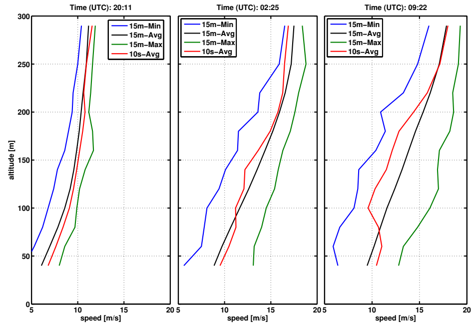
Automation of tethered flight is a key challenge for AWE Systems, which needs to be mastered in order to enable successful commercial deployment of such systems.
In the past SkySails has demonstrated extended periods of automated flight on systems featuring tether tensions of 20kN [1],[2],[3],[4].

In this talk, flight data from the SkySails 60kN power prototype, installed at a test site in Northern Germany, will be presented. Recent improvements in power cycle automation have enabled automatic operation during daylong flights. During these tests flight altitudes varied between 150 m and 350 m. Significant changes in wind speed and wind direction are expected in this altitude region, due to the layering of the atmosphere.

Lidar measurements of these important quantities at the flight test site will be presented and allow the characterization of vertical wind shear. Typical vertical wind shear transitions occurring during daylong operation and its effect on flight operation will be discussed.
Flight results indicate the robustness of the implemented target point control [4] against these systematic disturbances and that adaptation at the guidance level is sufficient to address the key aspects of wind shear.

The talk will conclude with an outlook on how further adaptation to changing vertical wind shear conditions can help to improve the overall system performance.



Lidar measurements of vertical wind shear conditions during daylong operation of the SkySails 60kN power prototype. Notable are significant changes in average wind speed and wind shear situation over time. During night (at 20:11 and 2:25) temporal variation (range min - max) is decreasing with altitude.

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Loading Kitepower's mobile AWE system at Eemshaven, the Netherlands (September 2021).

Kitepower Falcon 100 kW AWES flying next to the wind farm Vader Piet on Aruba (October 2021).

Close-up of Kitepower 60 m^2 kite with portrait of late wind energy pioneer Henk Hutting (October 2021).

Kitepower Falcon 100 kW AWES harvesting electricity on Aruba (October 2021).

Kitepower 60 m^2 kite flying above the shoreline of Aruba (October 2021).

Kitepower 60 m^2 kite flying above the shoreline of Aruba (October 2021).

Close-up of Kitepower's Falcon 100 kW AWES and Greener smart battery during operation on Aruba (October 2021).

Photographic visualization of a figure-of-eight flight maneuver during night operation by tracing a marker light on the kite from the ground station using long-term exposure (Aruba, October 2021).

Kitepower Falcon 100 kW AWES on the wind farm Vader Piet on Aruba (October 2021).

Kitepower Falcon 100 kW AWES during operation at sunset in Aruba (October 2021).

Kitepower team on Aruba (October 2022).

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First Airborne Wind Energy Operation on a Tropical Island

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Kitepower BV

In the last quarter of 2021, Kitepower operated the 100 kW Falcon system on the Caribbean island of Aruba as part of a collaboration between Kitepower and the Dutch Ministry of Defence (MoD). The system was shipped to the Caribbean on a commercial vessel and deployed Dutch Defence's training area near the Vader Piet wind park. After delivery to the site the system was operational in a couple of days. It was part of a local minigrid, including battery, loadbank, generator and users. The system was operated for a total 2 of weeks and was then shipped back to the Netherlands, leaving no trace at the site. Due to low wind conditions during this period of the year, it was not possible to fly continuous. Longest flight was close to 22 hours. The flights were fully automatic from launch till land decision with minimal tuning for changing local wind conditions. During part of the operation the system was supervised remotely from the Netherlands. The system functioned well under the hot conditions. This project demonstrated the maturity and mobility of the Kitepower system.

Airborne wind energy systems work extremely well on islands due to high coastal winds ensuring strong steady power generation. Islands offer fundamental challenges for any energy supply, as the cost of running a power line or even supplying fuel to local generators are often several times what the same would cost on the mainland. For this reason, energy tends to be supplied by generators running on diesel imported at very high costs. Kitepower offers an excellent solution to reducing the fuel consumption, cost and environmental footprint of these generators. The presentation will give an overview of the project and indicate the lessons learned.

The journey to Aruba (October 2021): https://thekitepower.com/kitepower-in-aruba/

WINDSLED pulled by a kite in Antarctica Eastern Plateau (December 2018).

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Polar Wind Highways

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The existence of Katabatic winds in the coastal areas of Greenland and Antarctica has been known for a long time. Human activity in the shores of these two major masses of permanent ice on Earth has been conditioned by the violent pieces of air that precipitate down the slopes of their respective high plateaus.

In the upper part of these enormous "islands", the layer of air close to the surface cools down, radiating all its heat away, and therefore gets denser and denser, increasing the pressure, until it flows down to the coast, accelerating in the steeper and more channelized relief as it approaches the coast.

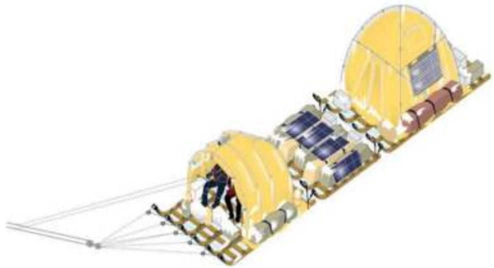
Theoretically, in its way, like any other fluid, the wind follows the maximum slope and it is, in some degree, deviated by Coriolis force, which is associated with the turning of the planet.

This process is quite regular and intense in stable conditions. Any disturbance created at continental/regional level and the presence of the sun can modify the velocity and the direction of the main pattern.

Due to obvious reasons, the validation of this behaviour with reliable data collected in meteorological stations is a significant challenge, above all in the vast and inhospitable interior of Antarctica.

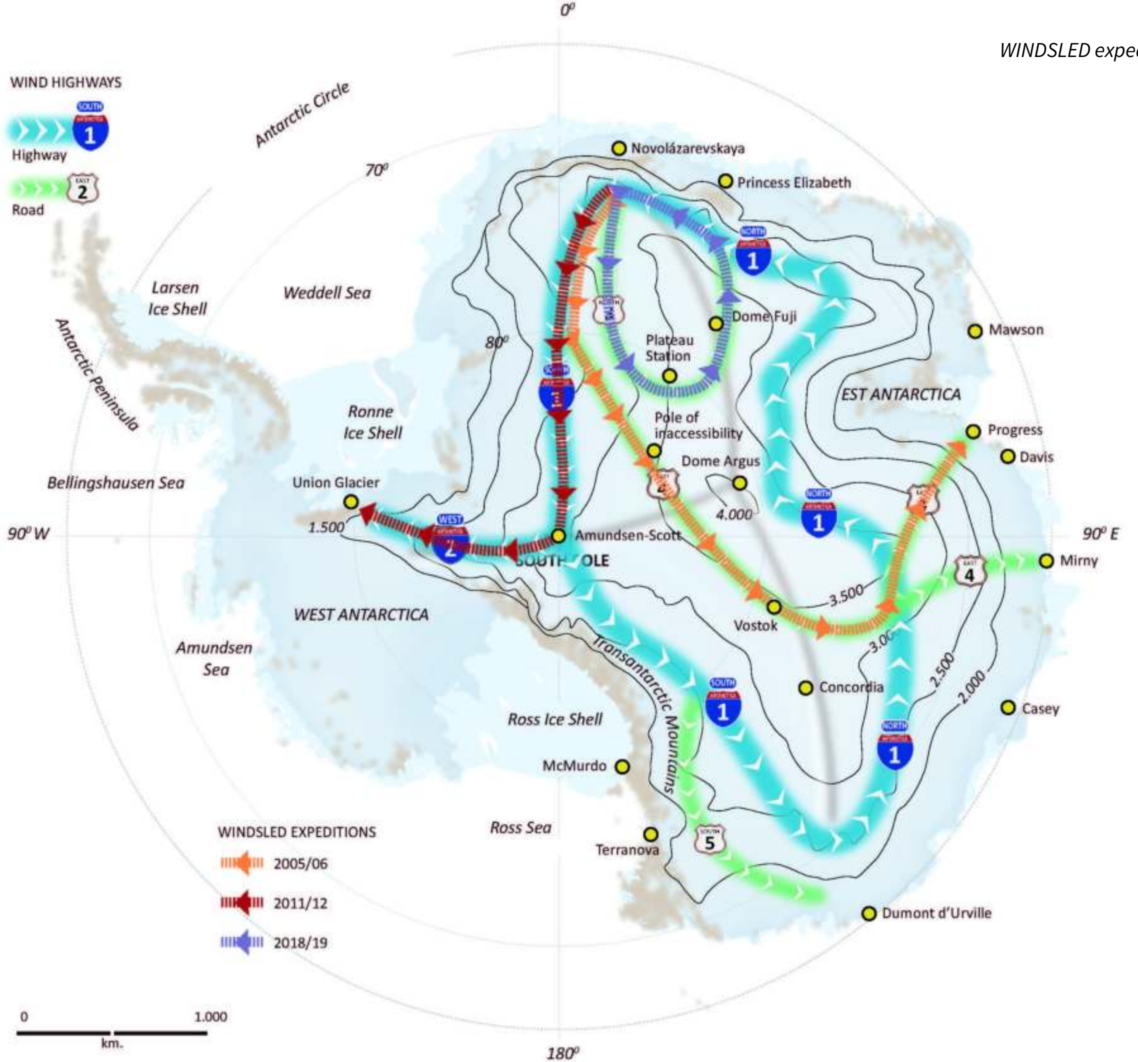
From year 2020, WINDSLED PROJECT, started its own empiric validation. After more than 25.000Km flowing with these winds, studying their local behaviour, interpreting the consequences in the shape of the frozen surfaces, WINDSLED has stablish proven "Wind Highways", and "Secondary wind roads", that allow the transportation of persons and goods across the most pristine and unexplored areas of the world.

Today, WINDSLED is able to communicate main scientific and logistic bases using Airborne Wind energy as unique fuel. Current developments/plans of WNDSLED include the direct pulling with kites, kite reel in/out electricity generation systems, and Polar proof autonomous electric vehicle with auto transportable renewable energy generator.



In 2022 a new journey is scheduled in Greenland. Later, in 2023, WINDSLED will become the first sustainable mobile International Scientific Base in Antarctica, hopefully under the auspices of the Spanish Polar Committee.

WINDSLED expeditions 2005–2018.



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Rotary Kite Turbine Development

Roderick Read
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Rudimentary Kite Turbine systems were first analysed in [1]. Kite Turbines extract wind energy using one or more autogyro rotors connected through a Tensile Rotary Power Transmission (TRPT) to a ground-based generator. The study [1] characterised the torsional rigidity of TRPT and basic Kite Turbine operation.

Windswept and Interesting recently attracted project funding from Shell GameChanger, HIE & SIC to develop and test a 10kW Kite Turbine System. The project will assess Kite Turbine automation, scaled performances, operational factors, manufacturing options, market potential, offshore options, and scalability.

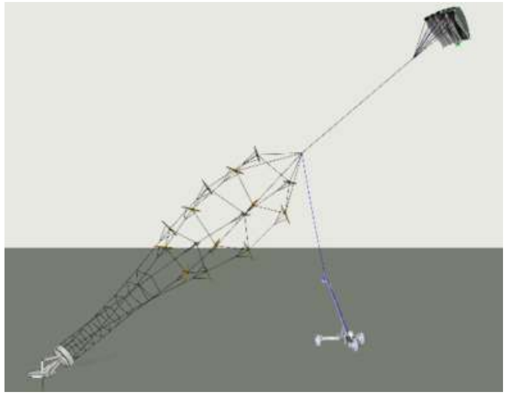
An extended failure mode and effects analysis of previous Kite Turbine prototypes as seen in [2] and company risk analysis identified autonomy as a key need for our systems development.

Autonomous systems are being developed for:

- Coordinating the operations of Lift-Kite, Back-line and Ground-Station devices, with condition monitoring, weather services and operator input.
- Safer deployment of both Lift-Kite and Kite Turbine, via a backline handling field robot.
- Ground station axial alignment tracking.
- Turbine steering via Lift-Kite steering and Back-line and ground anchor handling.
- Generation control based on sensing TRPT rotational lag, turbine compression and more.

Our test & specification validation schedule is designed to increase reliability in scaled systems and to collect detailed techno-economic performance data.

We will present our design reasoning, our plans for high resolution data collection, control methods and our Kite Turbine performance validation plans.



Concept sketch for a 10kW automated Kite Turbine System with a back-line handling device.

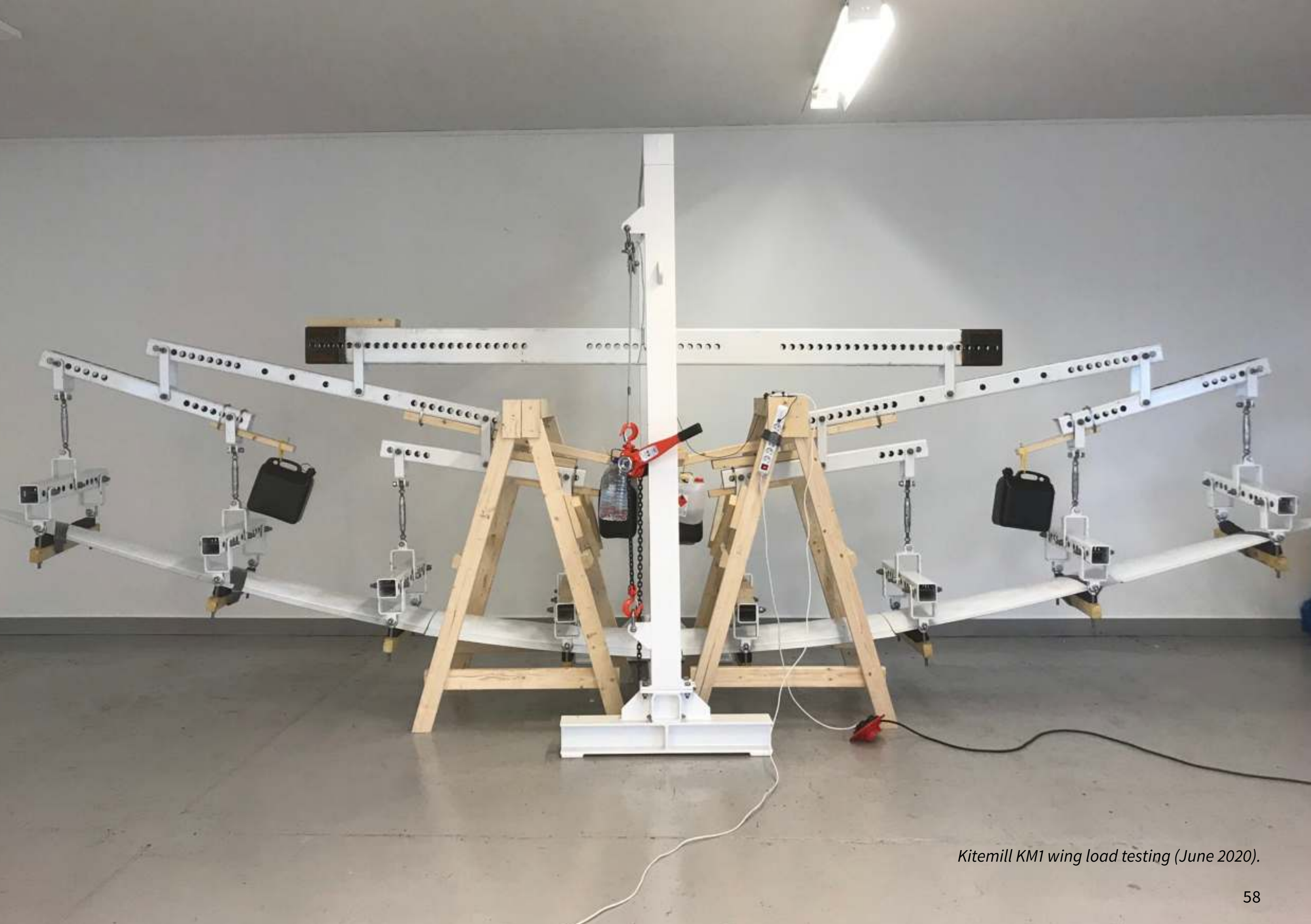
References:

[1]Tulloch, T: Modelling and analysis of rotary airborne wind energy systems : a tensile rotary power transmission design University of Strathclyde (2021) [Available online]

[2] Read, R: Kite Networks for Harvesting Wind Energy, Ch21, in Schmehl, R: Airborne Wind Energy Advances in Technology Development and Research

Kitemill crew placing the KM1 prototype on the launch pad (March 2020).

Close-up of Kitemill KM1 VTOL unit (March 2021).



Kitemill KM1 wing load testing (June 2020).

Bottom view of Kitemill KM1 prototype during hovering (May 2021).

Kitemill KM1 prototype hovering above Lista airfield (May 2021).

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Technical Progress in Kitemill

Espen Oland, Alfred van der Brink
Kitemill AS

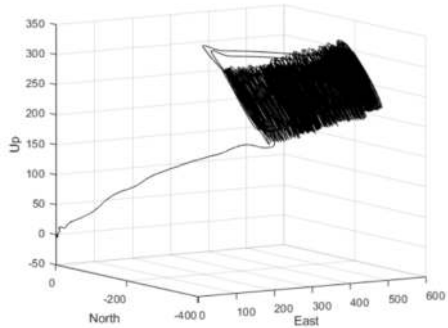
Kitemill develops airborne wind energy systems comprising rigid kites using lift-based power generation. At AWEC 2019, Kitemill presented latest results with initial VTOL flights with the KM1 system (7.4m wingspan; 20kW), 2 hours autonomous flight with the KM0 system (3.7m wingspan; 5kW) and many other results [1,2]. Since 2019, Kitemill has performed autonomous landing, autonomous take-off and autonomous power production with the KM1 system. In 2021, the team was able to achieve 30kW peak power with an average power production of about 10kW during looping with a net positive power production. Through optimization the KM1 system is expected to perform equal to its rated power. In addition to the KM1 system, Kitemill is also developing the KM2 system, which will be rated to 100kW, where the first prototype is planned to fly within 2023. This presentation will present the technical results in Kitemill since 2019, as well as the future plans for the company in terms of technical development.

References:

[1] Carnel, L., E. Oland, S. Smidt, J. Grini, C. Svenkerud, T. Tveide and T. Hårklau. Kitemill: From minutes to hours of autonomous operations 2017. Airborne Wind Energy Conference 2019, Book of Abstracts, editors R. Schmehl and O. Tulloch.

[2] E. Oland, C. Svenkerud, T. Tveide, J. Grini, S. Smidt, L. Carnel and T. Hårklau. Kitemill's vertical take-off and landing system for the KM1 model. Airborne Wind Energy Conference 2019, Book of Abstracts, editors R. Schmehl and O. Tulloch.

Autonomous take-off with the KM1.



Production cycles with the KM1.

Skypull prototype during testing (October 2020).

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Save Japan from a Future Social Crisis! "Mothership" Project Current Development Progress

Eiji Itakura
Toyota Motor Corporation

"Mothership" Project has been started since 2018 with very futuristic and noble vision for solving social issues such as energy security and/or government financial difficulties due to less emerging industry for many developed countries using high altitude westerly jet streams strong wind [1].

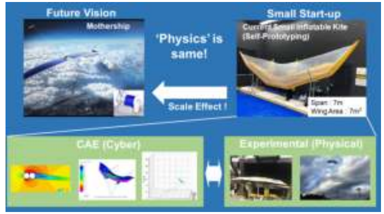
Inflatable structure kite configuration is adopted with potentials to realize both large wind area and less weight. The structure can be deformed with wind and tether force, so its dynamics and control are important technology issues for our project.

We started to design and fabricate small inflatable kites from fabric in order to learn many significant technologies like fabric choices, joining methods, CAE, and dynamics control methods etc. from many predecessors in this AWE participants.

Our kite usages are not only for power generation but aerial platform for observation, communication and aerial mobility etc. Therefore, the first milestone was set to reach 1000m AGL with stable flight.

By virtue of engineering struggling developments for two years we achieved the milestone on May 27 in 2020 [2]. We have learned inflatable kite design, fabrication and evaluation technologies through the process.

The next milestone is a 24-hours long-term continuous flight at mountain region with very turbulent high speed wind. We had to introduce more rigid kite configuration design and appropriate attitude control system to be stable flight. Our development progress is getting faster and faster.



Pattern diagram of Mothership Project 'Small Start-up'

First milestone achievement

References:

[1] Itakura, E.: Save from Future Japan Social Crises! 'Mothership' Project, Airborne Wind Energy Conf. p.71 2019

[2] Toyota Official Website https://www.toyota-global.com/innovation/partner_robot/news/202201_01.html

Kitemill team with the KM1 prototype (September 2021).

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Flying a Rigid Kite With a Single Tether Attachment Point

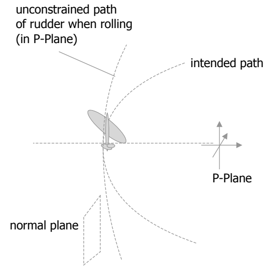
Tallak Tveide
Kitemill AS

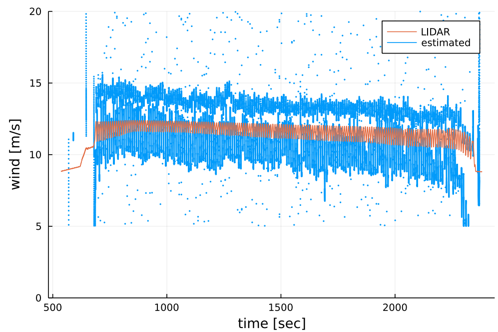
Kitemill uses a rigid kite with a single tether attachment point close to the centre of gravity.

Full production loops are performed using only the elevator to control lift and the rudder to control the curvature of the circular looping path [in the P-Plane, where the P-Plane is the plane of the looping path with zero reel-out]. The dihedral effect is instrumental to make this happen. We discuss the notion of constrained and unconstrained flight, and how this relates to either an attitude or curvature of the flight path.

When we consider gravity, tether force and required centripetal forces, the kite must roll relative to the P-Plane. As the rudder is no longer aligned perpendicular to the P-Plane, the deflection angle may have to increase to maintain the flight path curvature. Likewise, the elevator deflection angle should change to account for flying in a curve if constant angle of attack of the main wing is to be achieved.

We may go further in a system where the attitude and speed of the kite is well known due to precise navigation systems. We may estimate the wind during normal operation and without other sensors. We present how this may be done, along with experimental results of an implementation of such an algorithm.





Experimentally gathered wind speed during a normal production flight with only navigation sensor as input, compared to LIDAR measurements in red.

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GHENT UNIVERSITY

High Fidelity Fluid-Structure Interaction Simulation of a Multi-Megawatt Airborne Wind Energy Reference System

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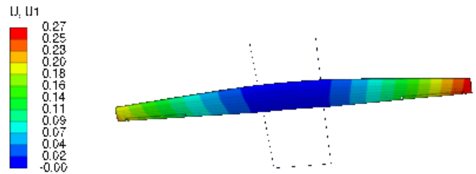
Department of Electromechanical, Systems and Metal Engineering, Ghent University

Airborne wind energy (AWE) is an emerging technology for the conversion of wind energy into electricity by flying crosswind patterns with a tethered aircraft. Having a proper understanding of the unsteady interaction of the air with the flexible and dynamic system during operation is key to developing viable AWE systems [1]. High fidelity simulation tools are needed to correctly predict these interactions, which will provide insights for the design and operation of advanced and efficient AWE systems.

This research examines the multi-MW AWE reference system presented in [2], which has a wing span of 42.7m. The high fidelity FSI of the wing of this system is determined by means of a partitioned and explicit approach, using the open-source coupling tool CoCoNuT. This method couples an existing finite element method (FEM) model of the wing structure with a newly developed computational fluid dynamics (CFD) model of the wing aerodynamics. Moreover, a prescribed flight path of the AWE system is enforced and realized by overlaying the moving body-fitted mesh attached to the AWE aircraft's wing over a background mesh. By means of the chimera technique both meshes are connected, interpolating the solution at the overset boundary.

The FSI model predicts a lift coefficient of 0.86, for the conditions displayed in the figure, which is 42% lower than predicted in [2]. This can be explained by the inability of the lower fidelity model used in [2] to predict flow separation, which occurs at low angles of attack due to the high thickness and camber of the wing profile. Furthermore, the FSI model predicts 3.2% less lift compared to the undeformed structure for the highest loading. This can be explained by the negative wing twist predicted by the FSI model. These discrepancies emphasize the need for both FSI and high-fidelity tools.



Wing deflection in m (scaled by factor 5) in direction perpendicular to flight for 80 m/s, a vertical circular path with radius 265.5 m and 0° AOA.

Ongoing research is directed towards coupling our high fidelity FSI model with the body dynamics model presented in [2] in pursuit of physically feasible flight prediction and the simulation of power production.

References:

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[2] Eijkelhof., D., Rapp, S., Fasel, U., Gaunaa, M. and Schmehl, R.: Reference Design and Simulation Framework of a Multi-Megawatt Airborne Wind Energy System. Journal of Physics Conference Series (2020)

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Improving Lifting-Line/Vortex-Step Methods for Kite Applications Using 2D Unsteady Thin Airfoil Theory Results

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

Fast and efficient aerodynamic models are needed in AWES to optimize the aircraft design and optimize the control and operation. Lifting line models are attractive due to the balance between fidelity and computation efficiency. However, care is needed since a flawed implementation, used in optimization, can lead to the algorithms exploiting numerical errors to make solutions that in reality give poor performance. Recent work for wind turbines employs lifting line methods to expand the existing engineering modelling complex with great success to include properly the effects of blade sweep and dihedral [1-3]. During this work it has proven crucial to revisit first-principles theory to "get the implementation details right". Specifically, key information has been extracted from careful analysis of unsteady 2D thin airfoil theory. This is a suitable basis for the "inner" 2D model of lifting line models.

The present work revisits the unsteady 2D thin airfoil theory framework [4] in the context of lifting line/vortex step methods for use in power-kites. The results show that this approach yields a lifting line model very similar to the aerodynamic model of Rannenberg [5]. The evaluation of the local lift is analogous, but the added benefit of the present approach is that the consistent treatment of the drag removes the need for Trefftz-plane analysis. For a straight flying wing the results from the present method are identical to those resulting from a Trefftz-plane analysis. The added benefits of the present method is that the local value of the drag along the span can be obtained as well as a consistent calculation of the drag during general unsteady motion (e.g. roll motion) of the kite. This is not possible using a Trefftz-plane analysis.

The present work show results from different implementations of Lifting Line methods found in literature compared to the present one, as well as a higher fidelity Vortex Lattice Method. Comparisons include different aspect ratios, wing dihedral and sweep.

References:

[1] Li et.al. The influence of the bound vortex on the aerodynamics of curved wind turbine blades. Journal of Physics: Conference Series, 1618:052038, 2020.

[2] Li et.al A computationally effcient engineering aerodynamic model for swept wind turbine blades. Wind Energy Science Discussions, 2021:1 49, 2021

[3] Li et.al. How should the lift and drag forces be calculated from 2-D airfoil data for dihedral or coned wind turbine blades? Submitted to Torque 2022.

[4] Gaunaa. Unsteady two-dimensional potential-flow model for thin variable geometry airfoils, Wind Energy, 13, 167–192, 2010.

[5] Rannenberg. Direct Wing Design and Inverse Airfoil Identification with the Nonlinear Weissinger Method. arXiv:1501.04983 [physics.flu-dyn].

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Combined Experimental and Numerical Aerodynamic Optimisation of High-Performance Rigid-Wing AWE Systems

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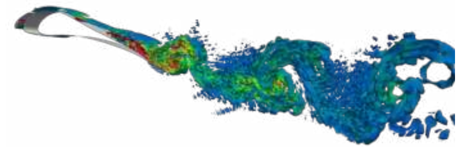
When designing and optimising high-performance rigid-wing AWE systems, unique aerodynamic requirements have to be met. Airfoils with favourable power factors and high lift are crucial, as is the ability to reliably predict the aerodynamic properties of a 3D wing in a very early design stage. The work at TU Berlin focuses on experimental and numerical methods to approach those challenges.

The task of increasing performance at high Reynolds-numbers and gen-erating favourable aerodynamic behaviour in the retraction phase, while still maintaining the simplicity of a wing without moving parts, led to the integrated design of airfoils with a fixed slat. The geometry of airfoil and slat is optimised simul-taneously using steady-state RANS simulations. Promising candidates are investigated in the wind tunnel, using additive manufacturing for rapid model generation. The influ-ence of 3D effects is minimized by a custom test setup, allowing for high aspect ratios and employing force and pressure measurements. For in-depth investigations, high-fidelity simulations using DDES methods are conducted.

For inexpensive early prediction of aerodynamic properties of a 3D wing, a simulation tool based on the non-linear lifting line free vortex wake method [1] is developed and subsequently validated. This ap-proach was also chosen to allow for a more precise simulation of transient aerodynamic effects at moving wings at a later stage. Initial validations using generic geome-tries were promising, therefore more realistic wings were investi-gated. This included full 3D CFD simulations, as well as wind tunnel experiments using half-models at high Reynolds-numbers.

The combined experimental and numerical approach proves to be very successful for thorough aerodynamic analysis. An overview of the work conducted so far will be presented.



DDES simulation of an optimised airfoil-slat combination.

References:

[1] van Garrel, A.: Development of a Wind Turbine Aerodynamics Simulation Module, ECN,C-03-079 (2003)

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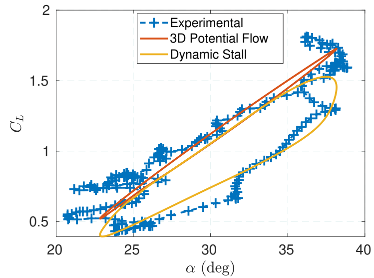
A Semi-Empirical Aerodynamic Model Based on Dynamic Stall for Rigid-Framed Delta Kites during Figure-of-Eight Maneuvers

Iván Castro-Fernández[1], Rauno Cavallaro[1], Roland Schmehl[2], Gonzalo Sánchez-Arriaga[1]
[1]Universidad Carlos III de Madrid
[2]Delft University of Technology

Effectively developing airborne wind energy systems requires reliable aerodynamic models. The figure shows recent experiments with a two-line rigid-framed delta (RFD) kite, revealing hysteresis in the lift and drag coefficients versus angle of attack during figure-of-eight maneuvers [1]. This might be caused by dynamic stall (DS), which is normally experienced by wings undergoing periodic pitching motions, which are naturally induced during the figure-of-eight maneuvers. This interesting phenomenon mostly affects the longitudinal aerodynamic coefficients (lift, drag and pitching moment). Pure potential flow theory captures the average value for the lift coefficient, but cannot reproduce the hysteresis [2]. This work presents a semi-empirical aerodynamic model for the RFD kite by combining unsteady potential flow theory with a dynamic stall phenomenological model. The goal is to find a model with a low computational cost to be coupled with dynamic simulators.

The study is based on a modification of the semi-empirical DS model by Leishman and Beddoes [3], involving four building blocks: i) attached flow model, ii) leading edge separation model, iii) trailing edge separation model, and iv) leading edge vortex model. For block (i) we use an in-house 3D potential flow model [4], while blocks (ii-iv) are governed by a set of dynamic equations which take as inputs longitudinal kinematics variables (angle of attack and pitching rate) and the 3D unsteady potential flow outputs from block (i). Static and dynamic viscous parameters, obtained from the literature [3] and the flight test campaign [1], respectively, are used to feed the empirical part of the model.



Experimental and numerical (potential flow and semi-empirical DS) lift coefficient during a figure-of-eight maneuver.

References:

[1] Borobia-Moreno, R., et al.: Identification of kite aerodynamic characteristics using the estimation before modeling technique. Wind Energy 24 (6), 596-608 (2021)

[2] Castro-Fernández, et al.: Three-Dimensional Unsteady Aerodynamic Analysis of a Rigid-Framed Delta Kite Applied to Airborne Wind Energy. Energies 14 (23), (2021)

[3] Boutet, J., et al.: A modified Leishman-Beddoes model for airfoil sections undergoing dynamic stall at low Reynolds numbers. JFS 93, 102852 (2019)

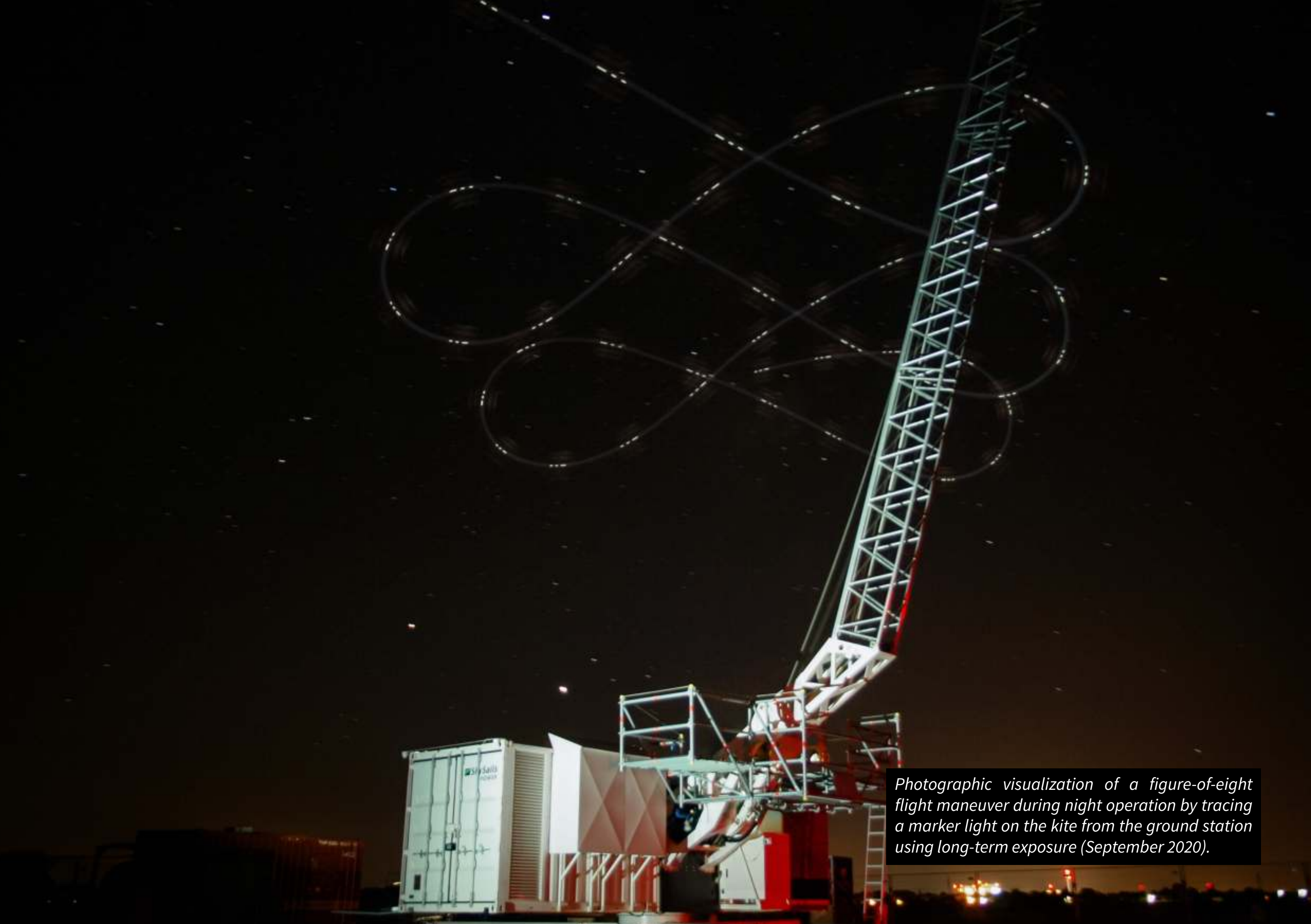
[4] Cavallaro, R., et al.: Amphibious Prandtl Plane: Preliminary Design Aspects Including Propellers Integration and Ground Effect. 56th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference (2015)

SkySails Power production in Germany (April 2021).

SkySails Power PN-14 system with reefed kite and retracted mast.

SkySails Power PN-14 system with inflated kite connected to mast.

SkySails Power PN-14 system during take-off.



Photographic visualization of a figure-of-eight flight maneuver during night operation by tracing a marker light on the kite from the ground station using long-term exposure (September 2020).

SkySails Power pilot site in Klixbuell, Northern Germany (March 2020).

SkySails Power unit on Mauritius (December 2021).

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Making AWE a Reality

Stephan Wrage
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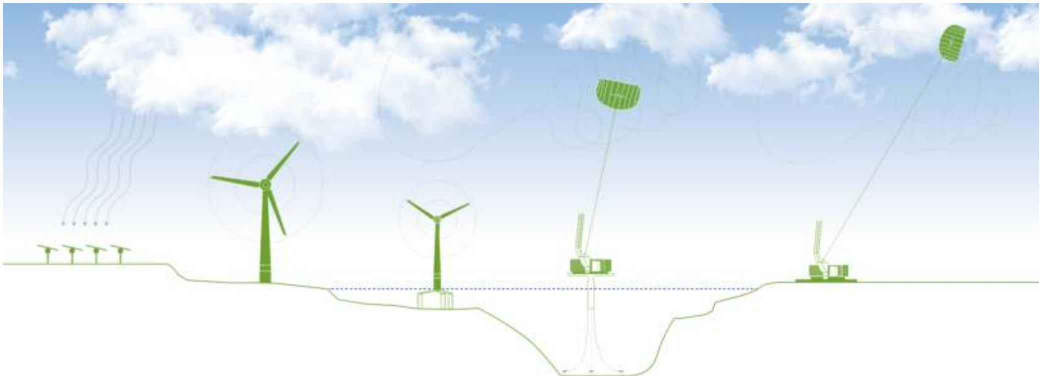
Global warming and ongoing political crises require an urgent shift to renewable energy generation. All available renewable energy sources must be accessed to make this transition possible.

In this context, AWE has a crucial role to play: High-altitude wind is the largest yet untapped source of energy. AWE systems can harvest this powerful and reliable source with low material requirements and are therefore a key technology for the shift to 100% renewables.

SkySails has proven that airborne wind technology works: Since 2019 we conduct prototype operation at our site in Klixbuell, Northern Germany. The commissioning of our first customer system in the Republic of Mauritius is currently ongoing.

However, implementing a new energy source is a challenge – from a technical, financial, industrial but also social perspective. Based on the results of our pilot installation we re-designed some core components and procedures to optimize energy yield. We are in permanent exchange with policymakers and administration to create an environment that allows AWE to be integrated in the existing energy mix. Like any other innovation we are facing hurdles and have to work step-by-step. The constant improvement of our AWE system finally leads to a commercially viable product, ready to complete the mix of proven renewable energy sources like conventional wind energy, PV or biogas.

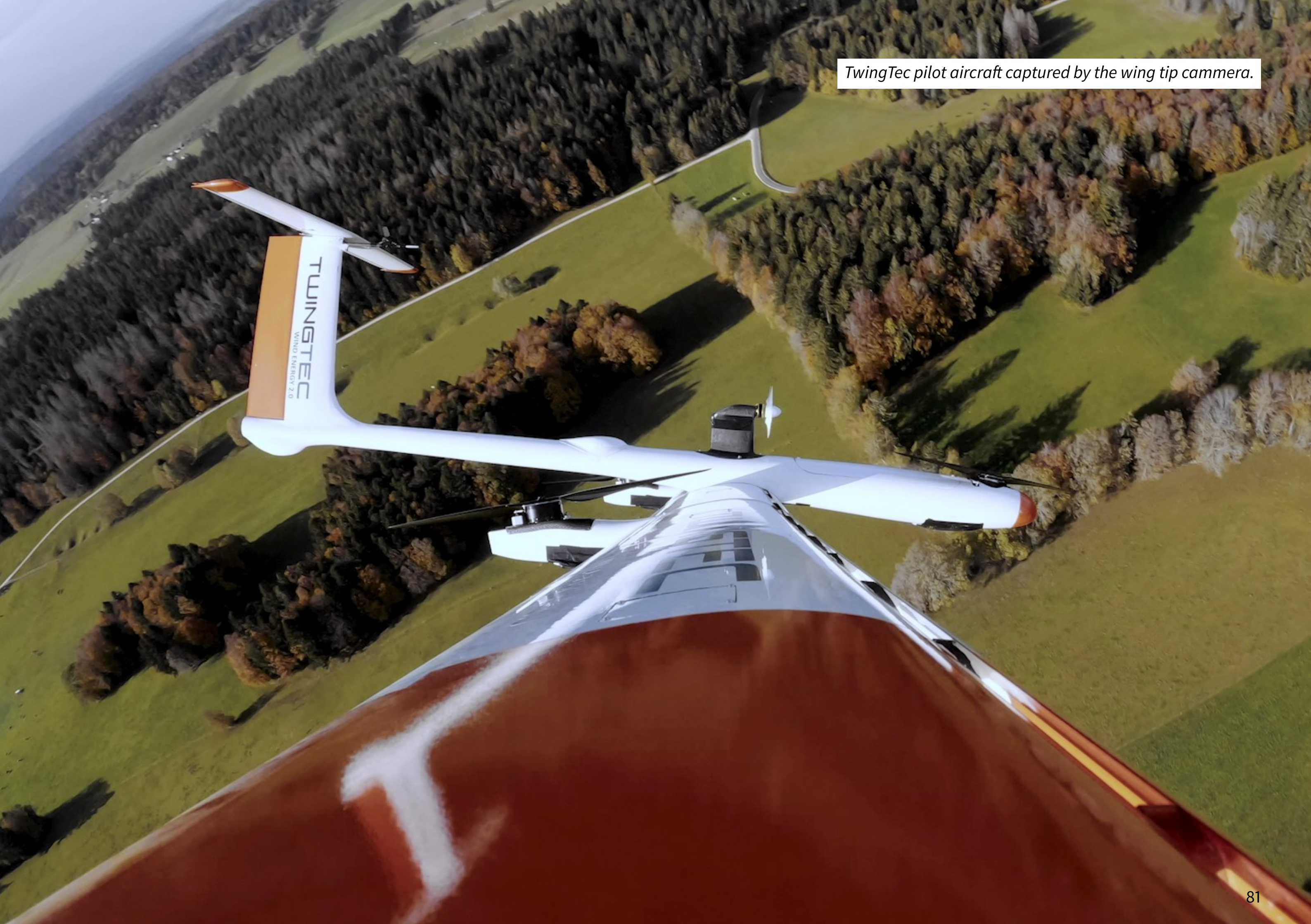
We at SkySails are committed to tackle those challenges and develop AWE to become a main pillar of renewable energy generation.



TwingTec pilot system in VTOL mode.

TwingTec pilot system lifting off from its launch platform.

TwingTec pilot system in dawn.



TwingTec pilot aircraft captured by the wing tip cammera.

Rendering of large-scale TwingTec systems deployed offshore.

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TwingTec's Path to Commercialisation

Rolf H. Luchsinger, Florian Bezard, Dino Costa, Cédric Galliot, Flavio Gohl, George Hanna, Corey Houle
TwingTec AG

While the net zero target for 2050 has been confirmed during COP26, elaborated predictions indicate that we are not on track to reach this goal [1]. As a matter of fact, what can be achieved in this decade will be decisive. The energy transition will be driven by the deployment of terawatts of solar and wind power. However, the main technologies PV and wind turbines, although today fully commercialized and cost effective, have their limitations. The key to reach the climate target is a mix of different power technologies, each deployed where it makes most sense. AWE is in many aspects complementary both to PV and wind turbines. It can unlock vast resources of renewable energy where the incumbents are not economical. The mobility of AWE is a key differentiator, which is of particular interest for off-grid and remote power users. Decentralized power is an interesting market but in order to have a significant contribution to the energy transition AWE needs to operate at the utility scale with MW sized units. However, it might be very difficult to attract the significant investments needed to scale up the technology to be competitive in the utility market if smaller units are not first successfully commercialized in the decentralized power market. The challenge for the AWE OEM's is to develop a first product in short time which is at the same time very attractive for the decentralized power market and the stepping stone for a fast entry of the utility market. Working with strategic customers active in the decentralized market, TwingTec has performed a number of product-market-fit studies which have shaped our commercialization roadmap. A key learning from these studies was that the cost of energy of AWE has to be significantly lower than for diesel power in order to obtain the market penetration needed to justify the investments for the product development as well as the production volumes to become cost competitive. As a result products below 100 kW might only reach a marginal market share while larger units will be significantly more attractive and will reduce the step to the high volume high impact utility market.

TwingTec's small scale pilot system.

References:

[1] DNV Energy Transition Outlook 2021 - A global and regional forecast. DNV, 2021.

Kitekraft founding team (August 2020).

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Kitekraft: Building Flying Wind Turbines

Florian Bauer, Maximilian Isensee, André Frirdich, Christoph Drexler
kiteKRAFT GmbH

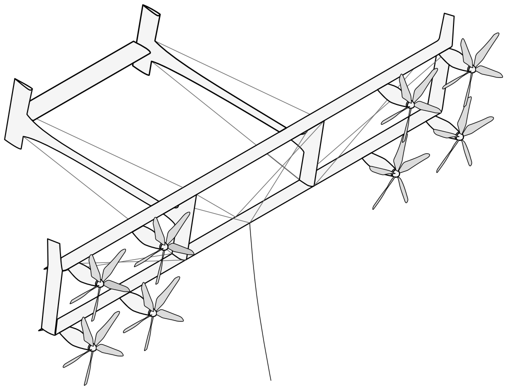
Kitekraft was founded in 2019 with the mission to enable the world's transition to 100% clean energy with 10x more efficient wind turbines. Although the company is relatively young compared to other players in the AWE sector, it is deeply rooted in the academic and entrepreneurial ecosystem of the Technical University of Munich. We came together when Christoph and André were writing their master's theses in the scope of a project Florian had initiated for his PhD research: Kitekraft. Max had just moved to Munich and contributed his experience in the startup world and business development.

Designing airborne wind energy systems and bringing them to market was the perfect match for our ambitions to fight climate change. And the timing was right: technology components had advanced to be powerful and lightweight enough to meet the challenging requirements of airborne wind energy conversion. The market demands innovative solutions to generate energy more efficiently and at a lower cost. And people and governments around the world realize that the climate crisis is already in progress and cannot be ignored any longer.

Building on our many years of academic research and development, we opted for a concept where the electricity is generated onboard the kite, with small wind turbines, using the tether also as an electrical conductor. The boxplane structure with a truss-like airframe maximizes the rigidity while minimizing the weight. Both factors increase the achievable power density, allowing economic viability even at small system sizes. The non-tapered wings can be produced by a cost-effective and highly scalable aluminium extrusion process.

Eight onboard electrical machines are used as motors during take-off and landing. The same machines are used as generators during crosswind flight. The single-point attachment of the tether ensures full roll-control freedom of the kite for optimum power harvesting efficiency and stability. The conducting tether consists of a Kevlar core to transfer tensile forces and electrical cables spiralling around the core.

We verify design changes as quickly as possible with real-world tests, whose results feed our simulation models, our digital twins.



Kitekraft boxwing design with onboard wind turbines.

WindFisher’s dual cylinder Magnus effect kite resting on launch stand prior to flight.

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Magnus Effect Kites: Optimal Reel-Out Speeds for Cross-Wind Power Production Including Simulation and Test Results

Garrett Smith, Armand Tardella, Yacine Boucheriguene
Wind Fisher SAS

Optimal power production using cross-wind kites occurs at a reel-out speed of 1/3 the wind speed, as established by Miles Loyd [1].

The authors show that this orthodoxy does not apply to kites that use the Magnus effect due to the power needed to rotate the cylinder. For this type of kite, the traction power in the reel-out phase can be determined by subtracting rotational power from cross-wind kite static power

$$P = P_\mathrm{w} A \left[\underbrace{C_\mathrm{L} E^2 f (1-f)^2}_{\text{Crosswind Production}} - \underbrace{k_{\omega^3} E^3 (1-f)^3 X^3}_{\text{Rotational Consumption}} \right],$$

where P_w denotes the wind power density, A the cross section area of the kite, C_L the aerodynamic lift coefficient, $E = L/D$ the lift-to-drag ratio and $f = v_\mathrm{t}/v_\mathrm{w}$ the reeling factor defined as ratio of tether reeling speed v_t and wind speed v_w. The aerodynamic coefficients are dependent on wing design and spin ratio. This equation leads to a new optimum based on line speed and spin ratio X.

Using empirical test data from the Madaras Rotor Power Plant concept [2] it can be shown that the optimal reel-out speed is approximately 1/2 the wind speed.

Power curves are proposed using static assumptions for a pumping cycle as demonstrated in [3]. A numerical simulation of a point mass model using variable tether length provides further insight. A comparison with test data will be presented.

First flight of WindFisher's developmental prototype.

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[1] Loyd, M. L.: Crosswind Kite Power. Journal of Energy 4(3), 106-111, 1980. doi:10.2514/3.48021

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Modeling and Control of Airborne Wind Energy Systems Using Lifting Line/Surface Aerodynamics

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Compared to wind turbines, airborne wind energy systems (AWES) are not rigidly supported by a tower and therefore need to stabilize themselves in turbulent wind fields and along various trajectories. The study of their behavior in their environment, and the development of models, is therefore of primary importance. Much research was already achieved in the field, and various models were already developed. However many models used for control applications are based on much simplified aerodynamics, such as empirical lift coefficient laws.

In this work, we investigate the use of more advanced models, such as lifting line (LL) and lifting surface (LS). They allow to better take into account the aerodynamics for the establishment of AWEs models in order to study their performance and control them. The LL and LS methods are cheap computationally, yet they already provide a fair representation for wing and kite aerodynamics in quasi-steady situations (i.e., with a time scale moderate relatively to b/U_∞). A steady solution is computed at each time step using the current inflow condition, and a shed vortex sheet model accounts for the influence of the wake. This study mainly focuses on kite modeling, thus considering curved lines/surfaces. Kite section polars were first generated using 2D RANS simulations, so to have an evaluation of the lift and drag coefficients along the span. The results obtained with the curved lifting line and lifting surface methods will be compared and discussed. Simulations for different configurations will be performed, also to better understand the steering mechanism. It will be used subsequently, together with a reference frame suited for AWEs [1], to investigate the behavior and control of modelled AWEs in different flow conditions. Various perturbed inflows are targeted such as the encounter with a system of contra-rotating vortices (as when crossing the wake of another wing or kite), with wind gusts, or being subjected to the whole spectrum of turbulent scales in atmospheric turbulent wind fields or wind turbine wakes, and generated using Large Eddy Simulation (LES).

The simple LL and LS models constitute a first step; yet they already allow to get insight about the dynamics of AWEs at low computational costs, and to investigate control strategies in various scenarios. The next level of modeling will use the actuator line model as implemented in our LES code (and which also allows for fast variations) for fixed wing concepts, and also a new flexible actuator curve model [2] for kite configurations. The model has already been used for aeroelastic simulations of large wind turbine blades in turbulent winds. Such LES will be useful to study AWEs with fast and complex dynamics, and their turbulent wakes; which is not possible with the LL and LS models.

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Using the Lidar-Validated Hindcast Model NORA3 for Resource Estimates of Airborne Wind Energy Systems

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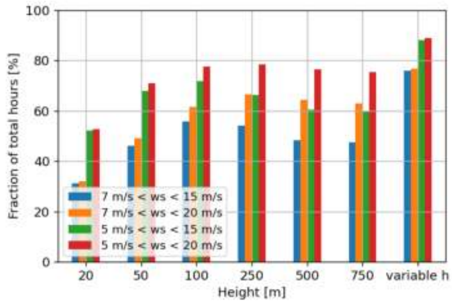
The amount of time Airborne Wind Energy Systems (AWES) can stay in the air and their annual power production depend on the meteorological conditions at the site with the wind profile being the most important condition. We analyze these meteorological conditions using the NORA3 hindcast model that is a downscaling of the ERA5 reanalysis model. The altitude of operation of AWES is higher than conventional wind turbines. For these higher heights, there have been no validation studies so in a first step, we are validating NORA3 and ERA5 with tall wind profiles from one year of Lidar measurements (100 m vertical spacing).

The next step is to create a resource estimate for AWES based on the meteorological conditions taken from the NORA3 model (a hindcast model with 3 km resolution). To accomplish this, we introduce a new method for wind resource assessments, which evaluates the influence of several meteorological conditions on the maximum operation time of AWES. These conditions include profiles of the wind speed, whereby the operation of the system is limited by a minimum (cut-in) wind speed and a maximum (cut-out) wind speed. Also, extreme precipitation and the danger of lightning strikes limits the total flight hours. This method applied to the limits from unfavorable wind conditions is shown in the figure for Farsund Airport in Southern Norway. This site was chosen because it is a test site for AWES run by Kitemill AS.

The annual power production can then be estimated for specific AWES based on the specific design parameters. By using this type of parameter study we provide an insight into how much annual power production can be gained by extending the flying conditions to a wider range of wind speeds and by continuing operation during more difficult meteorological conditions. Thus, these results can also be used for designing kites by for example quantifying how important it is to be able to fly in strong rain conditions or low visibility conditions.



Fraction of time where conditions are suitable for AWES operation at several heights at the AWES test site Farsund Airport (Norway). There is an upper and lower limit to the windspeed "ws" shown by the different colors. "variable h" includes the ability of the system to adjust its height of operation to the optimal meteorological conditions.

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Modelling Aeroelastic Deformation of Inflatable Membrane Kites

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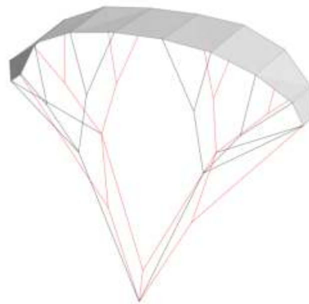
A fast design tool that allows shape optimization can increase aerodynamic performance and hence the energy production of airborne wind energy systems. Most membrane kite design tools are too computationally expensive or not accurate enough. Deformations occur at large and are relevant because they substantially change the aerodynamic characteristics [1]. Asymmetric actuation twists the kite, which contributes to its ability to turn. Symmetric actuation bends the wing in spanwise direction, thereby changing the generated aerodynamic force.

The tubular frame of the V3 kite of TU Delft is fully bridled on both the leading and trailing edges [1]. Therefore, the deformation is regarded as caused by the changing geometric layout of the bridle line system. The line attachment points form a wireframe representation of the wing, consisting of nine plates. Each plate has three edges of constant length, each being a rigid representation of a tube segment. The plate models have varying trailing edge lengths when including the effect of canopy billowing. A photogrammetry analysis provided kite width change for different symmetrical actuation settings and empirical relations, used to model canopy billowing.

We developed a particle system model (PSM), in which each bridle line connection is represented by a point mass. The particles at the plate corner points are subject to a discrete aerodynamic force, which is scaled based on the respective plate width and local angle of attack. The aerodynamic force is balanced by the spring and damper forces of the bridle line system, plate edges and plate diagonals. For asymmetric actuation, the orientation-based aerodynamic force scaling leads to the required dynamic stabilization.

The PSM can predict the change in width due to symmetrical actuation within, on average, 1% of the experimentally obtained width. Due to its accuracy, relatively low-computational cost and ability to predict both main deformation modes, the PSM is considered an excellent building block towards the development of next-generation design models.



The PSM for a fully powered kite. Red lines are bridles attached to the trailing edge and black to the leading edge.

References:

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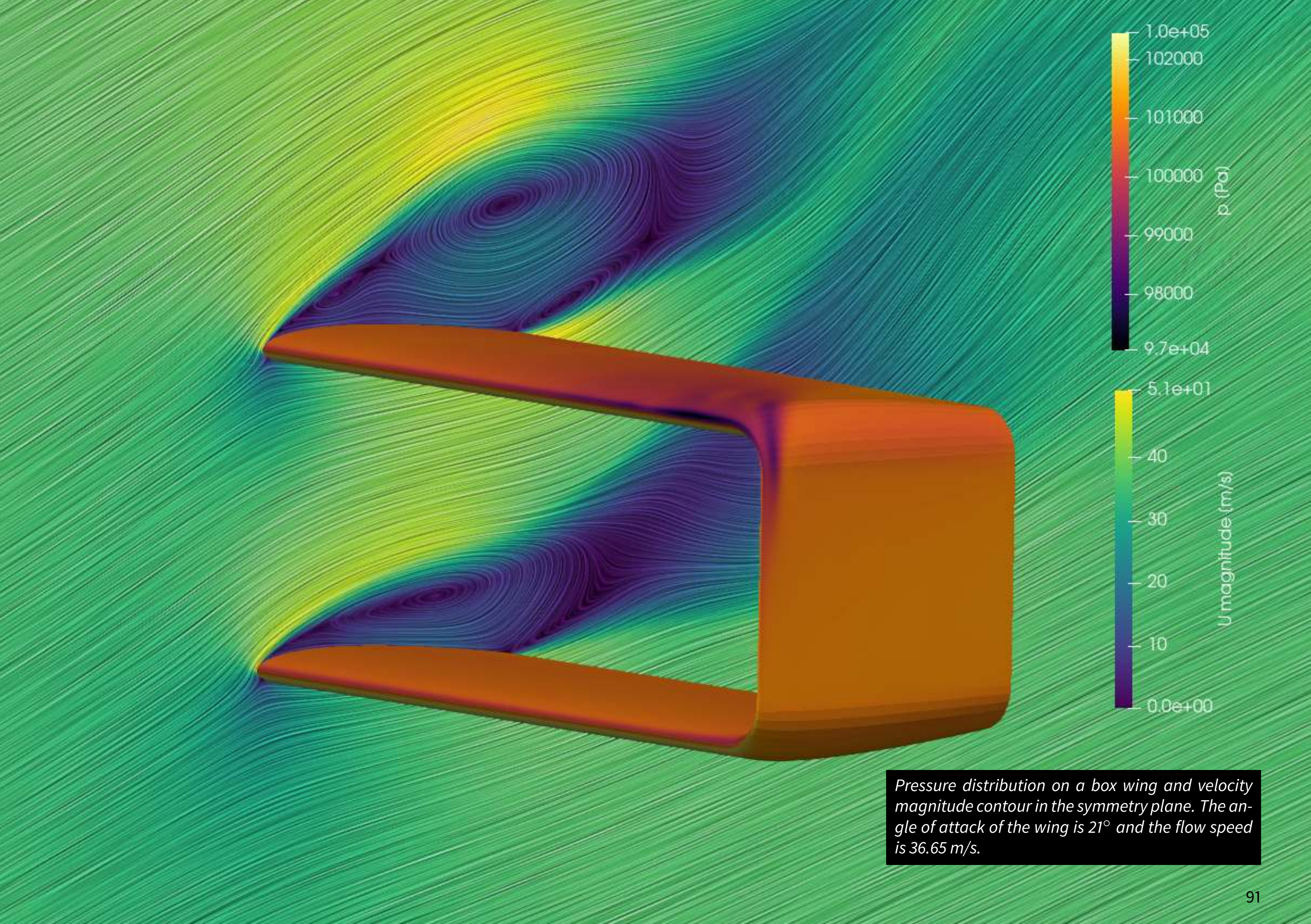
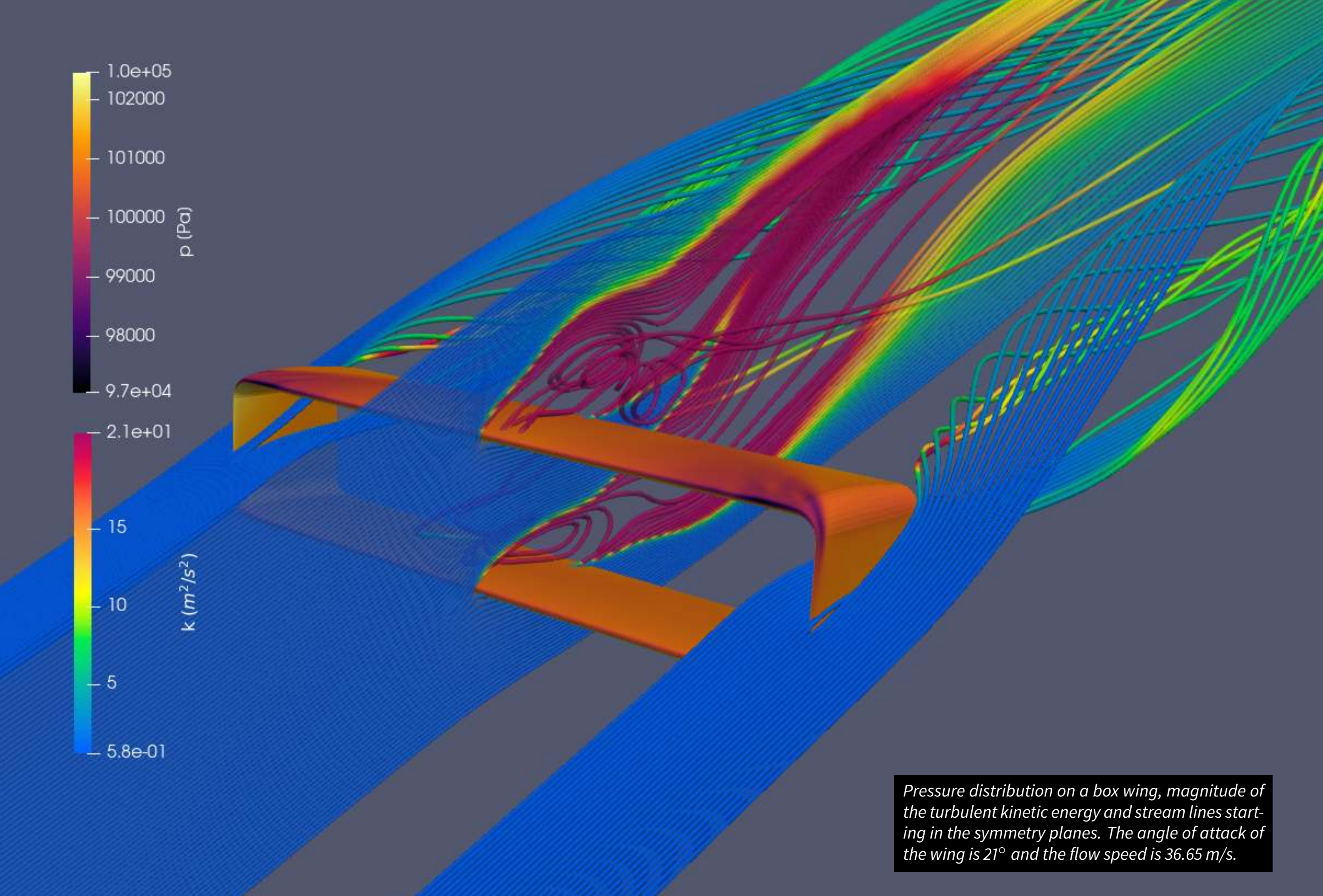


Pressure distribution on a box wing and velocity magnitude contour in the symmetry plane. The angle of attack of the wing is 21° and the flow speed is 36.65 m/s.



Pressure distribution on a box wing, magnitude of the turbulent kinetic energy and stream lines starting in the symmetry planes. The angle of attack of the wing is 21° and the flow speed is 36.65 m/s.

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Low and High Fidelity Aerodynamic Simulations for Airborne Wind Energy Box-Wings

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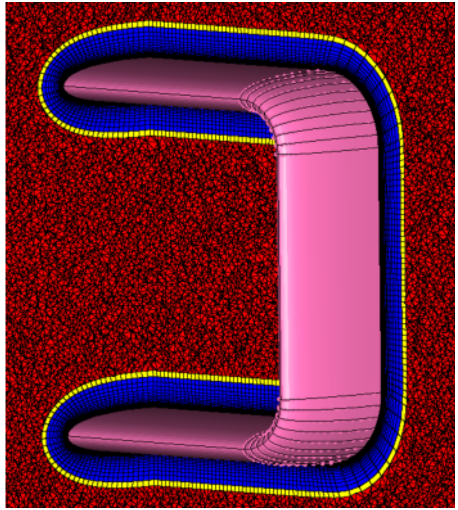
Airborne wind energy systems convert the kinetic energy of wind into usable power. In general terms, this power is proportional to the ratio C_L^3/C_D^2 of aerodynamic coefficients [1]. From a structural perspective, the thickness-to-chord ratio of conventional AWE wings needs to be high to withstand the high aerodynamic loads. The box-wing concept opens the possibility of exploring a broader range of airfoils since structural loads can be re-distributed with reinforcements between the two wings. Based on theory and measurements, Prandtl concluded that the wing system giving the maximum aerodynamic efficiency (L/D) was the box-wing configuration [2].

This study aims to develop an automatic process for constructing a finite volume CFD mesh from a parametrized box-wing geometry, which is generally the most time-demanding part of CFD analysis. A further comparison of its aerodynamic performance with an equivalent conventional wing design is presented.

The aerodynamic tools used for this study are a steady panel method (APAME) and Reynolds Averaged Navier-Stokes simulations using a k-ω SST turbulence model (OpenFOAM). Both tools are validated using the results of Gall & Smith [3].

The work provides an accurate estimate of the viscous drag of box-wings. In addition, the computational framework is ultimately suitable for aero-structural optimization of a box-wing because of the high degree of automation and the reduced number of design parameters.



Example of box-wing meshing with cut planes in x and y.

References:

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Modelling and Sizing of a Hybrid Power Plant using Airborne Wind Energy Systems

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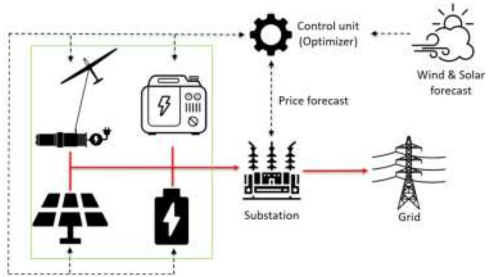
Currently, in remote off-grid locations, electricity is primarily generated using diesel generators, which is expensive and has significant carbon emissions. Alternatively, these remote locations have a huge potential for utilizing renewable energy sources. In such locations, airborne wind energy (AWE) systems could have an advantage over conventional wind turbines. Since, the AWE systems operate at higher altitudes, stronger and more consistent wind energy can be harnessed. Moreover, they are more compact and have higher mobility, which can reduce installation, operation, and maintenance costs. A possible architecture of a hybrid power plant (HPP) using AWE systems is shown in Figure 1. The centralized controller of the HPP optimizes the energy sources' dispatch based on the resource and demand forecasts.

Due to the anti-correlation between the wind and solar resources, electricity can be generated more constantly on a daily and seasonal scale [1]. The batteries can be smaller, and diesel generators rarely need to be used. The stronger the anti-correlation between the wind and solar resources, the better the HPP performs.

The model of the HPP uses wind, solar, and load data as inputs. The hourly energy production is calculated, and combined with the load data, the battery capacity is determined. To find the optimal number of kites, modules, battery capacity, different combinations of kites and modules are put in the model. The Levelized Cost of Electricity (LCoE) is evaluated for each configuration. The model's output is the minimal LCoE with the corresponding capacity of the different components.

The model is used to evaluate multiple case studies, which resulted in the following key findings. HPPs have a stronger case in off-grid markets than utility-scale grid-connected markets. The cost reduction by sharing the infrastructure is minimal. The security of the power supply is better maximized at lower costs than standalone installations. The LCoE has become so competitive that the use of diesel can almost wholly be replaced in suitable locations, which results in a significant reduction in carbon emissions.



Possible architecture of a Hybrid Power Plant using Airborne Wind Energy, Solar PV, batteries, and diesel generators.

References:

[1] Bett, P. and Thornton, H. (2016). The climatological relationships between wind and solar energy supply in Britain. Renewable Energy, 87(1), 96–110. doi:10.1016/j.renene.2015.10.006

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Fatigue Life Optimized Electromechanical Tether Design for Multimegawatt AWE

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The tether is one of the most critical key element in airborne wind energy (AWE), connecting the kite to the ground station. Optimized to minimal weight, the applied materials are exposed to loads exceeding requirements of standard fibre ropes and electromechanical cables by far. A fatigue resistant and scalable tether for multimegawatt AWE is currently a missing key element.

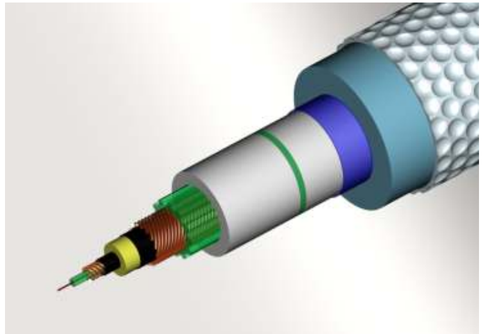
Whereas systems with electric generation on ground (ground-gen) expose the fibre rope to several hundred bending cycles per day and spooling velocities of several meters per second. At systems with electric generation on the kite (fly-gen) only a few bending cycles with low spooling velocity are necessary to adapt to the wind jet core height changing over a day.

However, up to now fly-gen systems were limited to operate with fixed tether length due to the lack of protection of the electric system from deformation at winding operations. Furthermore, the allowed maximal strain of < 0.1

For electric power transfer up to the multimegawatt range, a new fatigue life optimized, scalable and ultralight tether design, windable under full work load, is proposed [1]. It consists of:

- central optic fibres,
- an elastic conductor design [2],
- a high voltage insulation system with
- a radially stiff protection element, and
- an outer axial strain member.

The radially stiff element protects the electric system from deformation. Cyclic axial elongation of the tether is transformed into fatigue life-controlled bending of the electric conductor [2]. Detailed numerical case studies showed e.g. a tether weight below 4 kg/m for a 5 MW system with 5 years fatigue life. Contacts to industry and investors are ongoing for prototyping and testing.



Scalable, fatigue life optimized, windable, multimegawatt electromechanical tether design for fly-gen AWE systems

References:

[1] Neuhold, S. M.: Electric Energy Transmission Tether for an Airborne Wind Power Station. Patent, WO2016062735 (A1) — (2016)

[2] Neuhold, S. M.: A Hyper Elastic Conductor for Bulk Energy Transfer in the Wall of Spoolable Tubes for Electric Deep Drilling. PHD thesis, ETH Zurich, (2007)

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An Efficient Optimal Control Method for Airborne Wind Energy Systems with a Large Number of Slowly Changing Subcycles

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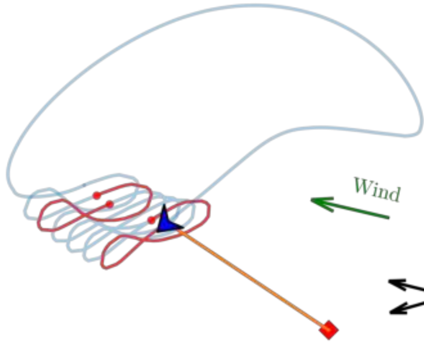
We present a simulation method to efficiently solve highly oscillatory optimal control problems and discuss in detail its application to the optimization of pumping airborne wind energy systems with a long reel-out phase duration.

In the context of AWE systems, the reel-out trajectory of a kite can be considered highly oscillatory since it is 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 cycles in the reel-out phase, the optimal control problem (OCP) of finding power-optimal trajectories becomes increasingly more computationally expensive to solve.

Instead of exactly simulating all cycles of an oscillating trajectory, we only simulate a few of them to gather information about the slow change that occurs over the time horizon. We numerically approximate the slow change using a semi-explicit differential-algebraic equation (DAE), that can then be integrated with large integration steps. For the use in optimal control problems, we provide a way to parametrize the controls.

We utilize this method to find the optimal trajectory of a simple AWE kite system model by [1]. We solve the DAE OCP with 20 cycles in the reel-out phase. Since we assume that the cycles are very similar to each other, we also have to restrict the control scheme for a single cycle to only vary slowly over the horizon. Compared to a 'full' OCP, where we simulate the whole trajectory, the DAE OCP slightly overestimates the power that the AWE system can generate by less than one percent. Due to the smaller problem size, we solve the DAE OCP about six times more efficiently.



Example trajectory of an AWE kite system. The two subcycles used to approximate the slow reel-out dynamics are marked in red.

References:

[1] M. Erhard, G. Horn, and M. Diehl, "A quaternion-based model for optimal control of the skysails airborne wind energy system," ZAMM Journal of applied mathematics and mechanics: Zeitschrift für angewandte Mathematik und Mechanik, vol. 97, 08 2015

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Production Cycle Optimization for Pumping Airborne Wind Energy

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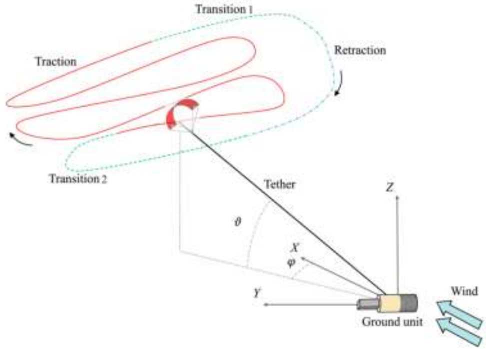
Politecnico di Milano

The work aims at increasing the efficiency of an airborne wind energy (AWE) system with soft wing flying in cross-wind motion while avoiding that the force on the tether and on the sail increases during the transition phase.

In this AWE systems, power generation occurs in cycles, each consisting of a traction phase where the cable is unwound and a phase called retraction where the cable is rewound. Transition phases are required to go from the traction phase to the retraction phase (Transition 1) and vice versa (Transition 2).

The simulation model adopted follows the approach presented in [1]. The implementation of a control strategy for the Transition 1 phase ensuring the desired tether force behaviour is a crucial aspect affecting the component's lifetime and the system safety. Two different control strategy were developed. The first one exploits the measure of the wind and ensures that the winch controller follows the desired reeling speed profile. The second implementation does not rely on wind measurements, which are often unreliable and not suitable for real world applications.

Once a solution to this problem was found, an optimization routine was run in order to determine the optimal trajectory for the kite during the transition phase and the optimal reeling-in and reeling-out speeds. Simulations results show an increase on the average cycle power of 3-5%. The optimization was performed considering varying the wind speed in given range and the results show that a sub-optimal trajectory can be found independently from the wind speed without losing efficiency on average cycle power.



Production cycle phases of a pumping AWE system equipped with a soft kite. Adapted from [2].

References:

[1] Fagiano Lorenzo Mario. Control of Tethered Airfoils for High-Altitude Wind Energy Generation. PhD thesis, Politecnico di Torino, 2009.

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Multi-Element Airfoil Design for an AWE Rigid Kite

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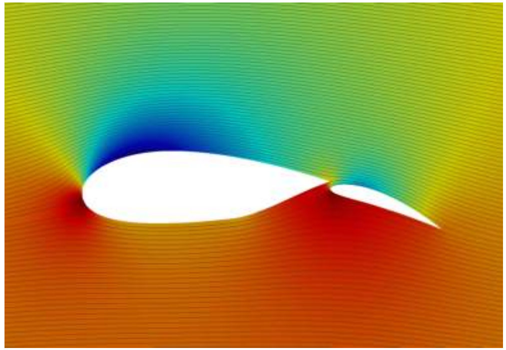
Airfoil design is crucial for the aerodynamic performance of an airborne wind energy (AWE) kite and thus also the achievable power output. Next to the aerodynamic performance, we must also consider the structural constraints.

In this study, we maximised the net power output of a high lift airfoil configuration for a 100 kW kite system operated in a pumping cycle. This optimisation requires accounting for the entire pumping cycle, consisting of reel-out (energy generation) and reel-in (energy consumption) phases with both significantly different requirements.

The parametrization of the airfoil emphasises the flap integration through a parametrised modification on the main element trailing edge. Furthermore, we identified the optimal position of the rotation pivot point of the rear element.

Our tool of choice for the airfoil design optimisation was a multi objective genetic algorithm (MOGA) because of its robustness in finding global optima in a highly non-linear design space as well as its capability of finding the pareto front, which is significant for a multi objective problem.

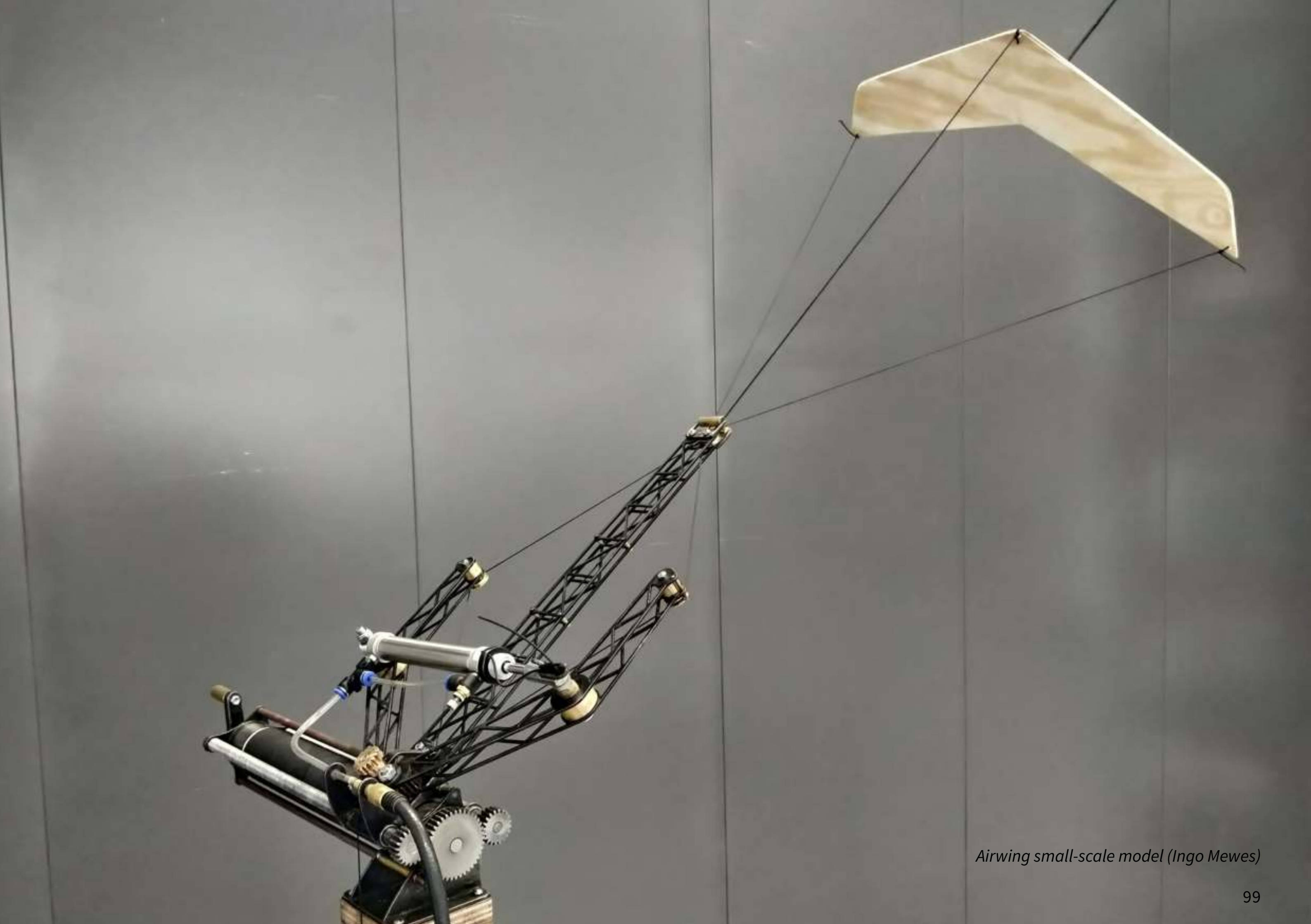
For analysing the airfoil aerodynamics we used MSES, which is a 2D airfoil design and analysis tool aimed at multi-element airfoils [1]. MSES solves the Euler equations using a finite volume discretization, while modelling viscous phenomena in the boundary layer and wake. For design iterations such a tool is preferred over CFD simulations because of the short computation times. The resulting optimised airfoil is verified through CFD, this method harnesses the accuracy of CFD analysis and combines it with the celerity of a lower-fidelity solver.



Pressure plot with streamlines of the multi-element airfoil.

References:

[1] https://web.mit.edu/drela/Public/web/mses/



Airwing small-scale model (Ingo Mewes)

Airwing steering mechanism (Ingo Mewes)

Ingo Mewes

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AirWing, a Self-Regulating Control System for Kites

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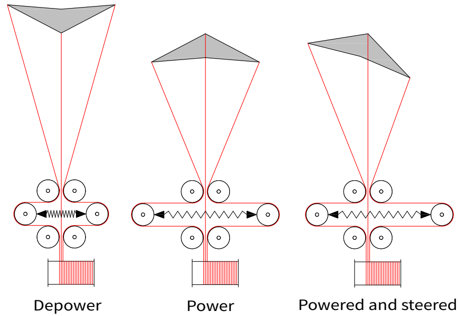
Hochschule für Schauspielkunst Ernst Busch

One of the major challenges for reliable and safe operation of kites is flight control. In my study I present an innovative control concept, suitable for marine propulsion and power generation. Compared to existing control systems, my development differs in three main points: simple and robust mechanical design (the basic functionality can be ensured even without electricity); for take-off, landing and cyclic power generation only one common winch for all lines is needed; a flying control unit is not required.

As shown in the figure, AirWing is a part of the ground station. It consists essentially of six pulleys, four fixed and two mounted on a movable air spring element. The force, the damping and the stroke of this spring can be adjusted individually. This makes it possible to adapt the system to different kites and flying conditions. All control commands and load-dependent self-regulation are thus performed from the ground. The fact, that the kite is always connected to the ground station by three lines increases operational safety. The central main tether connects the kite directly to the winch, while the less stressed control lines are routed around the spring element. By spreading the control lines, and moving the spring element horizontally, the kite can be trimmed and steered. The preset spring force limits the maximum tension of the control tethers; in case of higher pulling forces on the control tethers, they are automatically lengthened. This leads to an immediate depowering of the kite at the event of temporary overload.

The entire system is thus self-regulating, and can be safely operated at the power limit even in gusty winds, which can improve efficiency. Despite the simple mechanical design, the system can also be operated with a digital autopilot. So the system I will present can help to operate airborne wind energy systems in a safe, cost-effective and reliable manner.



AirWing concept

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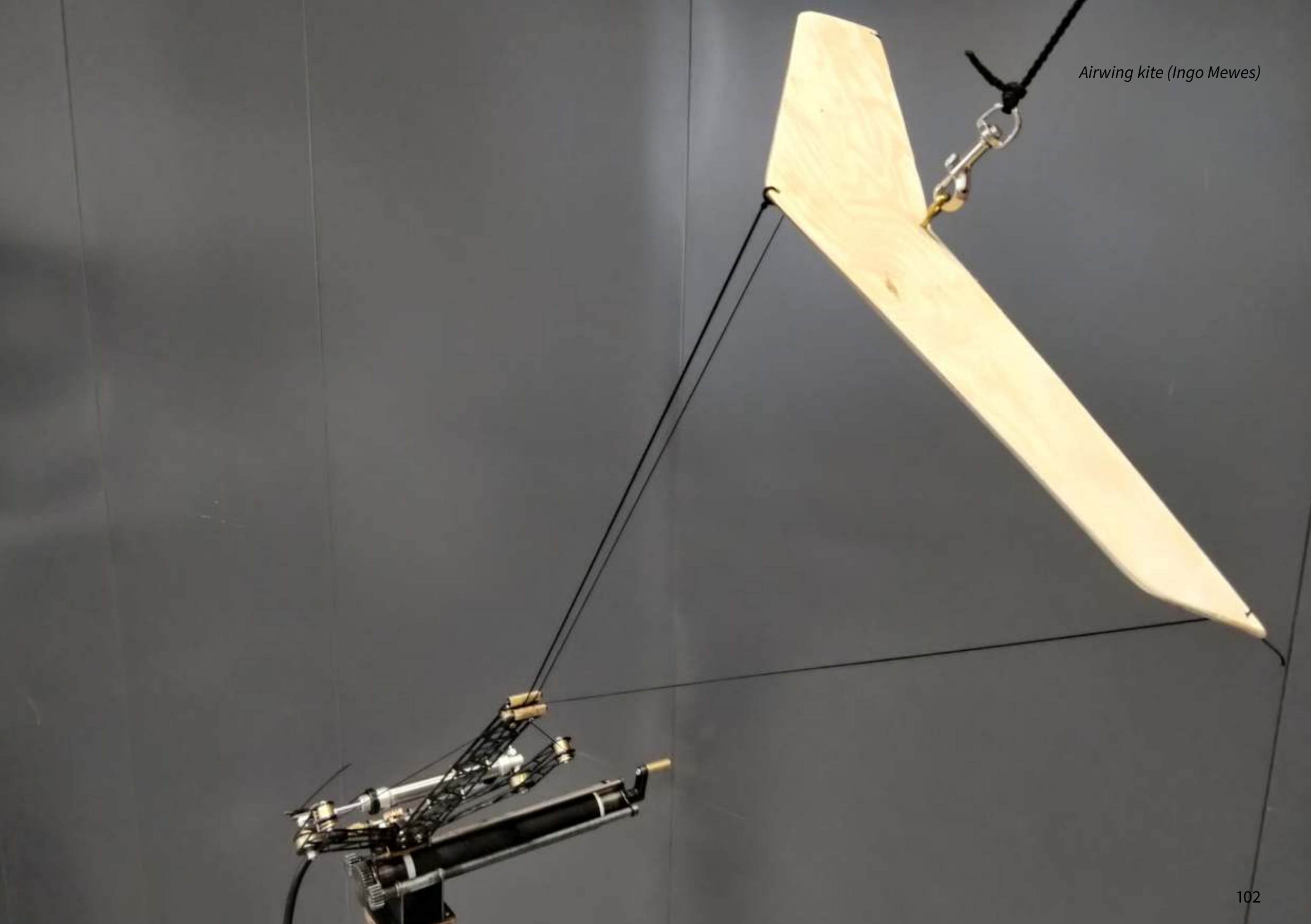

Airwing kite (Ingo Mewes)

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Economic Potential of Applying Circular Economy to AWE

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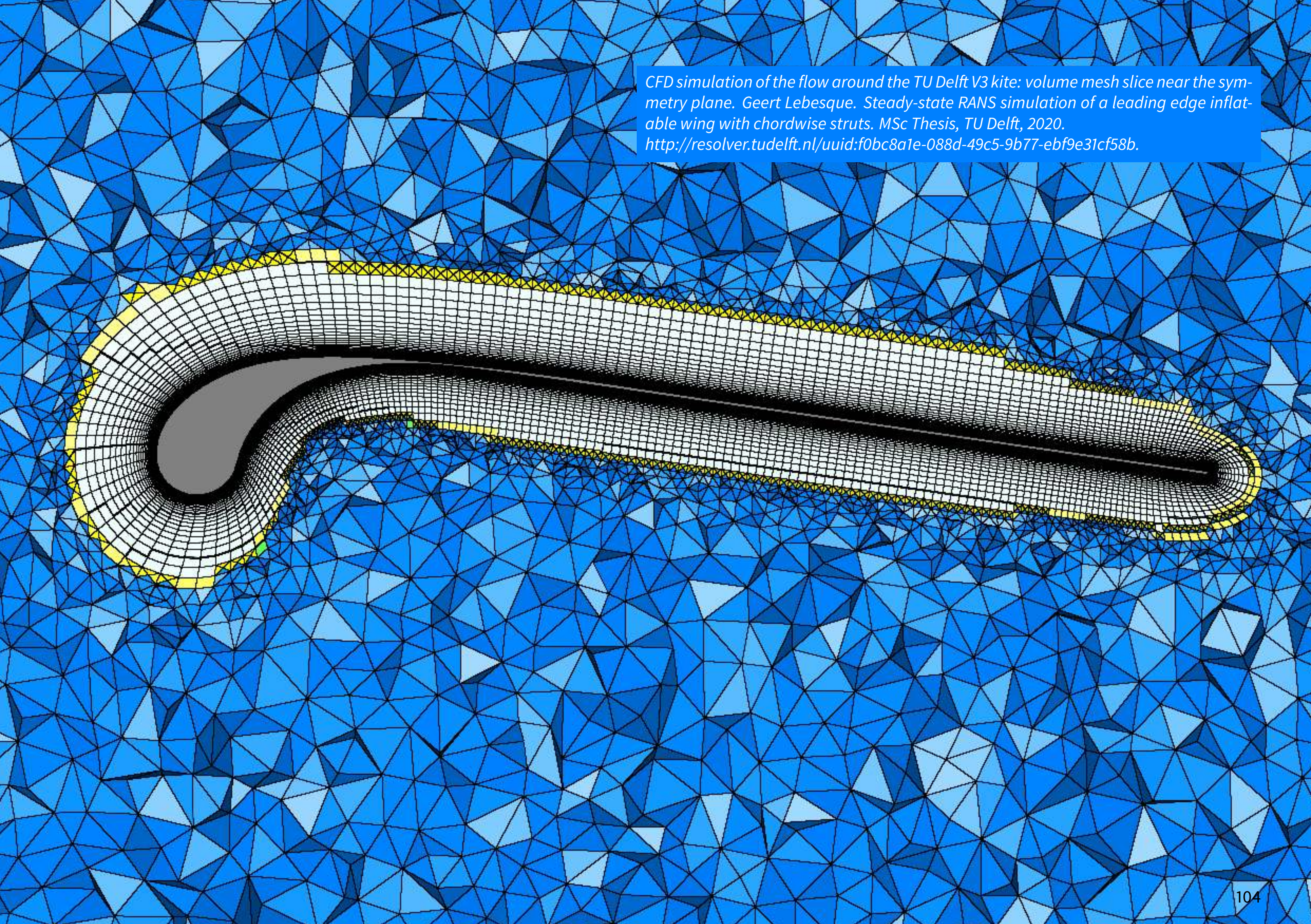
AWE companies has made tremendous technical progress in recent years. The next challenges will be the scale-up and the commercial expansion. Assuming the industry succeed in the future and become an important asset to the global energy transition, the Life Cycle Assessment of its components needs to be kept on sight. This is an obvious lesson learned from the 15.000 wind turbine blade material reaching the end of life in 2022. In a nutshell, circular economy concepts are Prevention, Reusing, Repurposing, Recycling, Recovering and Disposal. The higher in the "circular ladder", the more desirable. In general, Prevention is achieved today in AWE technology by using relatively compact equipment. The state-of-the art technologies of the AWE companies rely on the flying kites, tethers and the control systems. In all this equipment, it will be hard to reuse existing materials upstream or downstream in the supply chain. Recycling approach needs to be kept in mind from early design phases. For the ground stations, specifically the generators, the repurposing approach needs to be analysed. Specifically, the possibility of using second-hand generators from other industries. The most obvious places to source old generators would be the old wind farms, currently under decommission after reaching their lifespan. The possibility of reusing their nacelles (generators), needs to be explored, with the prospect to provide transmissions to the different land based AWE systems. Turbines operating from the year 2000 are approximately 200kW-800kW, very close to current AWEC's technical power. Each AWE company would need to analyse if the specifications of power and its mechanical and electrical properties would fit their technology. As a reference, second hand turbines available in the market are E30, V27, V39, V47, N29, N50 and B44. Original suppliers of these second-hand generators are the Utility companies, the exact same clients that AWE companies need to contact in their sale processes. They are paying large sums to recycle and dispose their complete wind turbines, so both parties would gain dramatically from this exchange. In some cases, there could also be commercial opportunities to install temporary AWE systems, during the replacement of old turbines for new ones (Repowering). It is paramount that during early stages, AWE companies adopt circular economy concepts in order to bring benefits to all stakeholders in the industry and to reduce the environmental impact of power generation.



CFD simulation of the flow around the TU Delft V3 kite: volume mesh slice near the symmetry plane. Geert Lebesque. Steady-state RANS simulation of a leading edge inflatable wing with chordwise struts. MSc Thesis, TU Delft, 2020. http://resolver.tudelft.nl/uuid:f0bc8a1e-088d-49c5-9b77-ebf9e31cf58b.

Development of an Aeroelastic Simulation Framework for Leading Edge Inflatable Kites

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Leading edge inflatable (LEI) kites pose a strongly coupled fluid-structure interaction problem due to the formidable flexibility of the wing's structure. Whilst pure aerodynamic analyses (in which the membrane wing is assumed to be a rigid body) do provide insight into the flow field around the kite [1,2], the omission of structural deformations is an approximation that neglects substantial aeroelastic effects.

As such, a more accurate representation of the flow field would account for load and design shape changes due to fluid-structure interactions. Building upon an aeroelastic model developed for ram-air kites [3], the purpose of this project is to establish a computational simulation framework that accurately reproduces the aeroelastic deformation phenomena endured by LEI wing profiles in airborne wind energy (AWE) operations.

The aeroelastic simulation framework follows a partitioned coupling approach that conducts parallel communications between dedicated aerodynamic and structural solvers. The Reynolds-averaged Navier-Stokes (RANS) equations, closed by the $k-\omega$ shear stress transport (SST) turbulence model, simulate the flow field around the wing using the open-source computational fluid dynamics (CFD) software OpenFOAM. The in-house finite element solver mem4py, developed solely for flexible membrane wings [3], models the structural deformations. The two-way coupling between the aerodynamic and structural solvers is handled by preCICE, a software library for fluid-structure interaction coupling [3].

The modelling framework has been developed according to this method in the interest of building upon the existing body of knowledge regarding flexible membrane wing aeroelasticity. The feasibility of this strategy ultimately depends on the trade-off between computational cost and accuracy.

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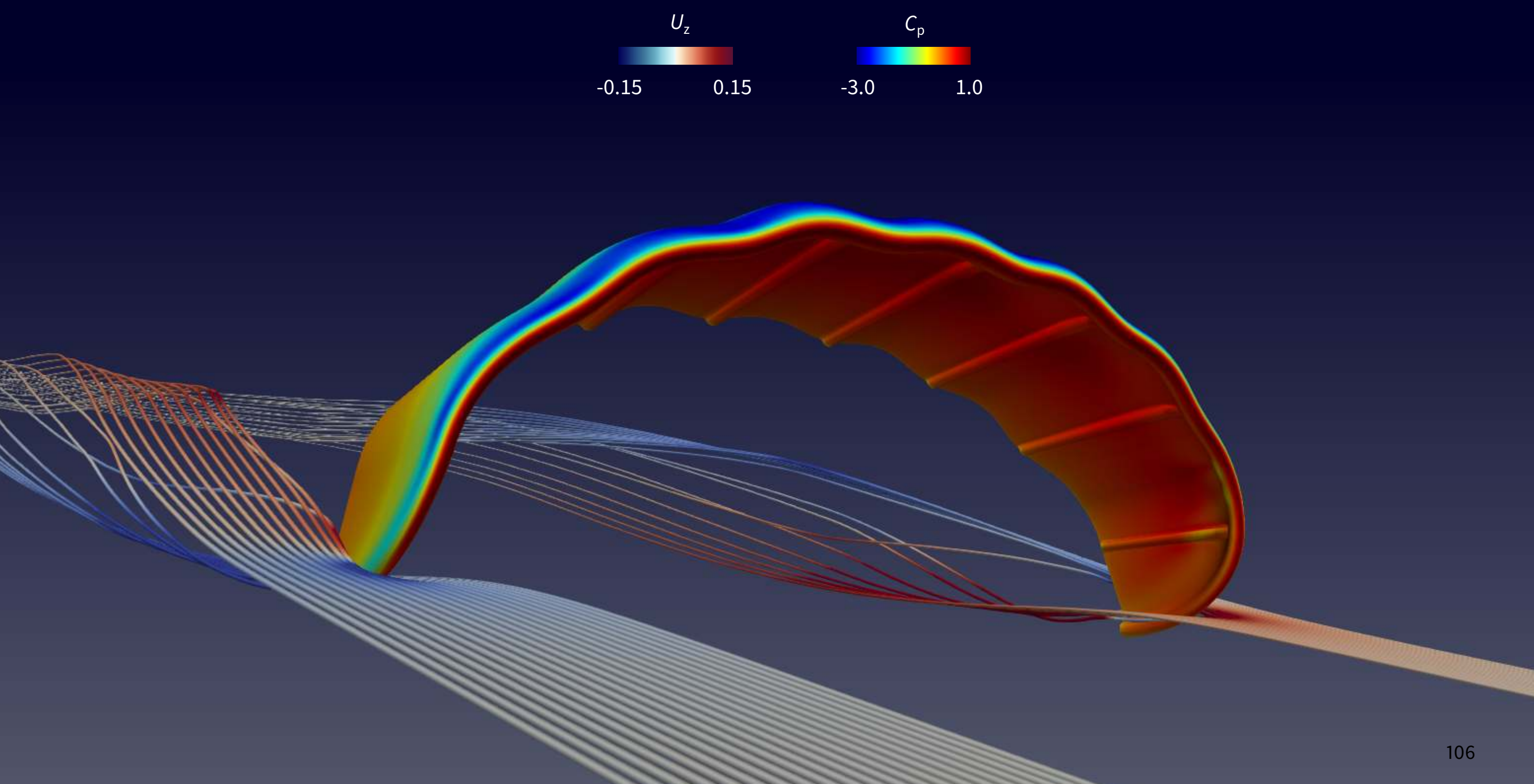
TU Delft

CFD simulation of the flow around the TU Delft V3 kite: streamlines colored by the downstream velocity component U_z and pressure coefficient C_p on the wing surface, at α = 12°, β = 0 and Re = 3×10^6. *Geert Lebesque. Steady-state RANS simulation of a leading edge inflatable wing with chordwise struts. MSc Thesis, TU Delft, 2020. Postprocessing result by John Watchorn. http://resolver.tudelft.nl/uuid:f0bc8a1e-088d-49c5-9b77-ebf9e31cf58b.*



Power Smoothing in Utility-Scale Airborne Wind Energy Trajectory Optimization

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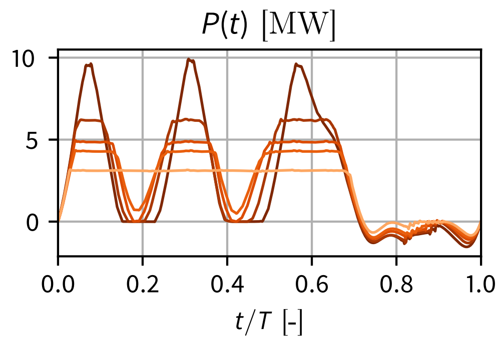
The prevailing vision for upscaling airborne wind energy systems boils down to increasing the aircraft aerodynamic surface until the desired power output is attained. One side-effect of this strategy is the increased influence of the aircraft mass on the power-optimal flight trajectories and associated high peak-to-average power ratios (PAPR). The gravity-induced power peaks would then lead to disproportionally expensive components in the electrical machinery.

It is however possible, both for lift- and drag-mode systems, to smoothen out the power peaks for heavy AWE systems by adapting the flight trajectory accordingly – at the cost of a lower average power output.

In this work, we propose a variation of the standard optimal control problem formulation which allows us to investigate this trade-off in a straightforward fashion. To illustrate the capability of the proposed formulation, we compute the Pareto efficiency front for a utility-scale single-aircraft pumping system and we discuss how the control strategy is altered to achieve the PAPR reduction. These steps are repeated for a triple-aircraft system of equal power output and the Pareto fronts are compared.

The simulations show that in this case study, the PAPR of a 55 m wing span (2.5 MW) single-aircraft system can be reduced from 4 to 2 by a loss of 10% of the average power output compared to a PAPR reduction from 2.6 to 2 combined with a power loss of 2% for a system with three aircraft of 30 m wing span each.



Possible mechanical power output profiles of a utility-scale pumping single-aircraft system on the Pareto efficiency front of average power vs. PAPR.

The proposed problem formulation has been implemented in the open-source AWE optimization toolbox AWEbox [1] and the simulation code will be made publicly availabe.

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POLITECNICO
MILANO 1863

Power Losses Analysis of AWES Via a Novel Quasi-Analytical Dynamic Model

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Although several models for the power production of AWES are present in the literature, some major physical aspects related to power losses have yet to be definitively understood. In addition to the usual cosine losses associated with elevation, what are its consequences on kite motion? How can the influence of gravity on system performance be assessed? And given a certain trajectory shape, what are the optimal values that parameterize it and how do they change under different conditions?
For this purpose, the work introduces a quasi-analytical dynamic model that provides a more physical insight than a low-fidelity one but is far much simpler than a high-fidelity one. The model informs about the behaviour of significant quantities varying design parameters. Moreover, the system dynamics along the trajectory can be assessed. The main difference from the existing flight path studies is the choice of a cylindrical reference system. It allows a deep comprehension of the physical causes of power losses. In addition, simplicity and suitability for both Fly and Ground-Gen systems with any kite type (rigid or soft) and trajectory shape are peculiarities of the model.

In the model, the flight path shape is prescribed independently before solving the equation of motion [1]. The main assumptions are the point mass representation of the kite, the perpendicularity between the span-wise direction and the relative wind speed, the perfect control (constant C_L and C_D) and the high system glide ratio. In the work, the model is used to analyse the power losses of a Fly-Gen AWES in a circular path shape. Figure 1 shows the efficiency flying the optimal circumference for each different condition which is expressed by the non-dimensional parameters M (from [2]) and G_r (from [1]). The first represents the ratio between centrifugal and lift force. The second expresses the ratio between gravity and centrifugal force and is a function of the wind speed.

The deep understanding of how power losses due to gravity and elevation affect each other, system performance and kite motion as a function of M and G_r is the main outcome of the analysis.

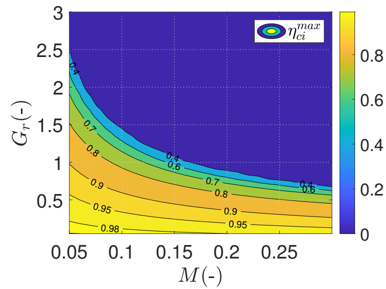

Figure 1: efficiency of a Fly-Gen AWES with the optimal circular flight path (η_{ci}^{max}) for each condition expressed by M and G_r. The blue region represents the conditions for which the kite cannot fly.

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POLITECNICO
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Multidisciplinary Design, Analysis and Optimization of Fixed-Wing AWES

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To enter the market successfully, AWES need to prove reliability and robust operations over long time frames, on top of being competitive in the energy market. To consider these requirements at the design stage, a new multidisciplinary design and optimization framework *T-GliDe* (*Tethered Gliding system Design*) [1] is being developed. In *T-GliDe*, the AWES is designed based on market metrics, while ensuring good flight mechanics characteristics which may enhance reliability by relieving the control system. This approach differs from optimization approaches based on low-fidelity models, which typically do not include flight dynamics, and from approaches which find power output and loads by running time simulations, which include active control.

The architecture of *T-GliDe* is showed in Figure 1: it features an optimization module and a uncertainty quantification module, allowing for a number of algorithm-based design techniques. The physical model is based on *LT-GliDe* (*Linearized Tethered Gliding system Dynamics*) [2], which is used to find loads and power production. *LT-GliDe* assumes the dynamic problem to be axial-symmetric by considering the fluctuating terms over the circular loop as disturbances. In this way, the AWES states over the trajectory can be described with a unique steady state, which is considered representative of the dynamics over the loop. The dynamics of the system is then linearized about the steady state, thought the use of analytical aerodynamics theories. *T-GliDe* is then ensuring good dynamic characteristics by constraining the eigenvalues of the linearized problem.

Even though the framework is not restricted to any crosswind generation type (Fly-Gen or Ground-Gen), the features of the proposed approach will be presented through the analysis of a Ground-Gen AWES.

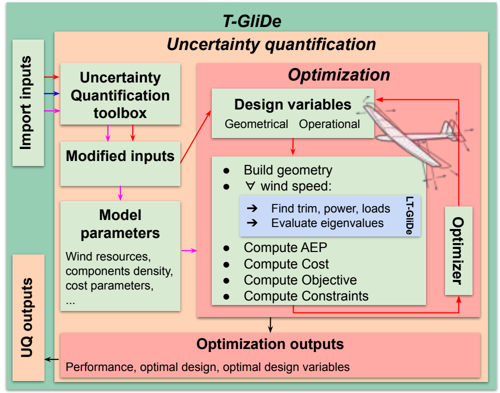

Figure 1: T-GliDe (Tethered Gliding system Design) architecture.

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Circular AWE Farms With High Surface Power Density

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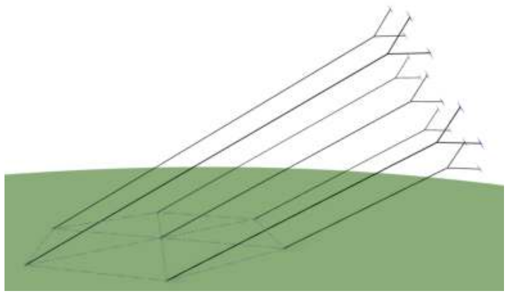
The power density (PD) per ground surface area of existing wind power farms is estimated to be around $p_{PD} = 2$ MW/km^2 [1]. For solar PV farms we have a PD of around 10 MW/km^2. Despite the fact that wind and solar power would - even with these low PD - need only a tiny fraction of the earth's surface area in order to generate all of humanity's energy needs, the PD still matters because many of the infrastructure costs of renewable energy farms such as grid connection and installation logistics scale proportionally with the farm area.

The PD of any wind harvesting system is limited by Betz' law and by the reachable altitude of the installation. One distinct advantage of airborne wind energy systems with small tether drag - such as dual-kite systems - is the possibility to locate them at arbitrarily high locations above the ground and harvest wind power at distinct locations on the sky.

This work proposes and simulates circular AWE farms with high PD. These farms consists of many independently ground located dual-kite AWE systems that are all flying at the same tether inclination angle $\alpha = 30°$ but with different tether lengths, depending on the wind direction, such that all wings fly in a large planar elliptical area that is vertical to the tethers. The individual systems are assigned non-overlapping "operation cones" that depend on the wind direction. Otherwise, the individual systems are completely independent and can e.g. be started and landed independently.

Detailed calculations that take into account Betz' limit show that the effective wind harvesting area is proportional to the ground area of the farm for this concept, but reduced by several factors: first the circle packing loss factor $\eta_{circ} = 0.7$, second the cosine and area reduction loss factor $\eta_{geo} = \cos(\alpha)^2 \sin(\alpha) = 0.375$, third the Betz factor $\eta_{Betz} = 16/27$. Together, they lead to an effective area reduction factor $\eta_{total} = \eta_{circ}\ \eta_{geo}\ \eta_{Betz} = 0.15$. Assuming a cubically averaged wind speed of $v = 7$ m/s, the yearly average wind power density in the air would be given by $p_{air} = 1/2 \rho_{air} v^3 = 206$ W/m^2, such that the PD of the AWE farm would be given by $p_{PD} = \eta_{total} p_{air} = 32$ MW/km^2, which is more than 15 times the PD for conventional wind and 3 times the PD of solar PV. This assessment is supported by more detailed simulation studies of a wind farm consisting of many moderately sized dual-kite systems.



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POLITECNICO MILANO 1863

Optimal Reeling Control for Pumping Airborne Wind Energy Systems Without Wind Speed Feedback

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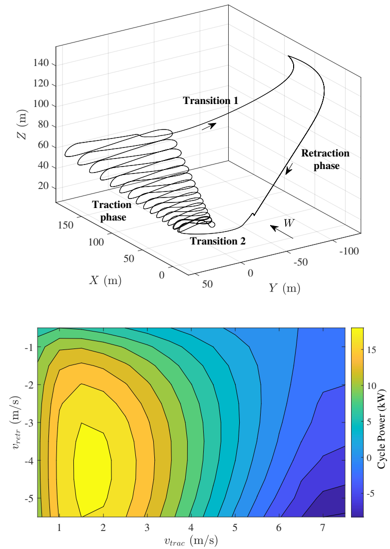
To obtain the highest conversion efficiency in pumping AWE, cycle power shall be maximized during operation (subject to constraints such as maximum tether force and tether speed limits), however this is not trivial to obtain. One reason is that the optimal reeling speed depends on the wind speed encountered by the kite, which is generally time- and space-varying and is not accurately measured. We propose a systematic approach to design feedback reeling controllers for both phases, that overcomes this problem. We employ a model of the system to estimate the response surface of power cycle as a function of reel-in and -out speeds, for different wind speed values. Then, using such a response surface we compute the manifold of optimal reeling speeds and corresponding optimal traction force values as parametrized by the wind speed. Finally, we derive a feedback law where the reference reeling speed is computed based on the measured tether force, such that these two variables converge to the found manifold. Therefore, the resulting control strategy employs tether force and speed as feedback variables, which are readily available. Simulation tests with a widely used AWE model show that the proposed approach achieves optimal performance, i.e. the same that would be obtained with an optimal reeling speed allocation assuming exact knowledge of the wind speed. After introducing the problem formulation and employed system model, the presentation will describe the various steps of the proposed approach and showcase its application in a numerical example. For more details, the interesed reader is referred to [1].



Top: example of kite path during one pumping cycle obtained with the simulation tools employed in this study. Bottom: level curves of the cycle power response surface computed with 9 m/s wind speed.

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NREL Airborne Wind Energy Workshop and Technical Report 2021

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In response to a request in The Energy Act of 2020, the U.S. Department of Energy's (DOE's) Wind Energy Technologies Office (WETO) provided a Report to Congress on the Challenges and Opportunities for Airborne Wind Energy in the United States [1]. This effort was supported by the National Renewable Energy Laboratory (NREL) through outreach to the airborne wind energy industry and research community and through internal research and analysis. Supported by WETO, NREL hosted a technical workshop on U.S. Airborne Wind Energy in March 2021 which was attended by over 100 domain experts and relevant stakeholders, predominately based in the United States [2]. Further detailed insight, separate from the workshop, was gained though stakeholder meetings with over 50 domain related experts including 14 different technology development entities (4 from the United States and 10 from the European Union [EU]). Following a broad literature study the NREL team conducted internal studies covering research and analysis across 6 topics: a) Technology assessment and upscaling, b) Techno-economic analysis and markets, c) Resource potential and energy output, d) Technical potential, social and environmental impacts, and permitting, e) Research, development, demonstration, and commercialization needs. The findings were published in an NREL technical report [3] assessing the potential for, and technical viability of airborne wind energy in the United States including research, development, demonstration, and commercialization recommendations, outlined in a conceptual 10-year program, to further examine and validate the technical and economic viability of AWE technologies.

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NREL
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Airborne Wind Energy for Sea Water Desalination: A Techno-Economic Study

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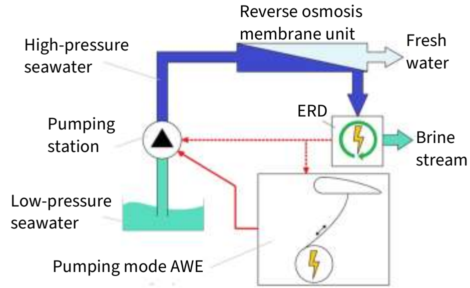
Vicinity to consumer and zero-carbon emission have made renewable energies ideal for desalination applications. Solar, wind, wave, and geothermal have been considered in several desalination projects for industrial, agricultural, and domestic uses [1]. Advances in airborne wind energy (AWE) toward commercialisation have paved the way for the utilisation of AWE technology in new applications. SkySails has recently introduced the first commercial AWE product, SKS PN-14, a 200 kW pumping-mode AWE system ideal for remote areas and off-grid applications [2]. Several other AWE developers are also close to offering their commercial products.

This work focuses on utilising pumping-mode AWEs in reverse-osmosis (RO) desalination technology. RO is a semi-permeable membrane process to remove salts and contaminants from the water. RO process benefits in low energy consumption and cost-effectivity [1]. In addition to fresh water, RO systems produce a high-pressure rejected saltwater stream that can be used for power generation. So far, different energy recovery devices have been developed for RO systems [3]. The recovered energy can be used at the pumping station to improve the system's specific energy consumption (SEC).

The figure illustrates the proposed system. An AWE device generates electricity to run the RO's pumping station, and an energy recovery device (ERD) is used to generate power from the high-pressure outlet brine. A part of the recovered energy is used for the AWE's recovery phase, and the rest is transmitted to RO's pumping station.

This talk will analyse the feasibility of utilising AWE technology for RO systems. The technical practicality of the system will be discussed, and the estimated cost of the generated power and freshwater will be compared with the other sorts of renewable energy-based RO systems. Also, the system's performance with several ERDs and RO operating strategies will be investigated.



AWE-based RO desalination system.

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Airborne Wind Europe

Life-Cycle Analysis of an Airborne Wind Energy System

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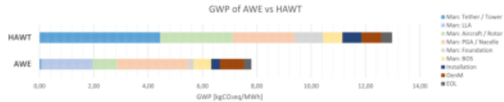
One of the key advantages of AWE is the low material use which should lead to a further reduced carbon footprint of renewable electricity, and also when compared to Horizontal Axis Wind Turbines (HAWT).

The goal of this research was to assess the environmental performance of a future multi-megawatt Airborne Wind Energy (AWE) system by quantifying its Global Warming Potential (GWP) and material intensity, and by comparing it with the impacts of a HAWT system. The study is based on an MSc thesis carried out at TU Delft and which had been commissioned under the Interreg NWE MegaAWE project. The LCA study compares two hypothetical onshore wind farms of ten units totalling 50 MW with the same farm layout, one consisting of hypothetical commercial fixed-wing 5MW AWE systems and the other of recently optimised 5 MW NREL reference HAWT. The AWE system is based on the Ampyx technology which uses a catapult to launch the fixed-wing aircraft.

The analysis found that AWE requires 70The actual mass reduction of AWE vs. HAWT will strongly depend on the AWE type and further developments. Therefore, it is also important to further investigate how materials can be reused or recycled. Notwithstanding the lack of detailed design data and assumptions, this LCA concluded that AWE systems have an even lower environmental impact in terms of GWP than HAWT – which already have very low impacts among electricity generating technologies. AWE applies consequently the “reduce” rule which is one of the most valuable Circular Economy options. Offering a significant mass reduction for energy generation from wind, AWE represents a step-change and fundamental re-design of wind energy technology. Applying the LCA method provides most benefits to OEMs at early stages of development. It also serves to make policy makers and other stakeholders aware of the large potential of AWE to further improve the carbon footprint of renewable energy technologies.



Global warming potential of AWE vs. HAWT

References:

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A Reference Economic Model for Airborne Wind Energy Systems

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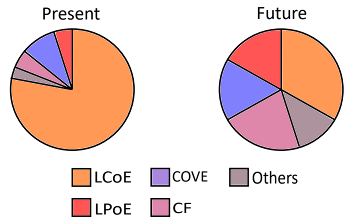
The IEA Wind Task 48 [1] about airborne wind energy (AWE) has been kicked off in 2022, aiming at building a strong community that can identify and mitigate the barriers to the development and deployment of AWE systems. Among the planned research activities, WP-1 focuses on determining economic metrics which will be relevant for the deployment of systems in potential markets, considering different penetration scenarios. On the other hand, WP-2 involves, among other activities, the development of reference models and metrics.

The present work aims at developing a reference open-source economic model, which researchers and companies can use to asses the performances of their AWE concepts. On top of describing the cost of systems, this work aims at introducing reference business cases and value-based market driven performance metrics for the future systems. Few of these metrics are levelized cost of energy (LCoE), cost of valued energy (COVE), levelized profit of energy (LPoE), capacity factor (CF) etc. This is by taking inspiration from the conventional wind industry which is moving towards beyond LCoE metrics [4].

The model shall be as general and comprehensive as possible, so that different concepts can be analyzed. Moreover, the model aims to provide cost functions capturing the main trends, so that it can be used for analysis [2] but also in design and optimization frameworks [3].

A report is being produced and will constantly be updated. In parallel, a code in one or more programming languages is being developed and will also be constantly updated with the new models proposed in the report. Even if the first version of the model is produced by the authors, the updates can be carried out by anyone who wants to contribute to the development, upon fulfillment of prescribed guidelines regarding documentation and publication.



Representation of the performance metrics of the AWE systems

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Energy Mix and Security Benefits of Airborne Wind Energy for Net Zero

Will Kennedy Scott
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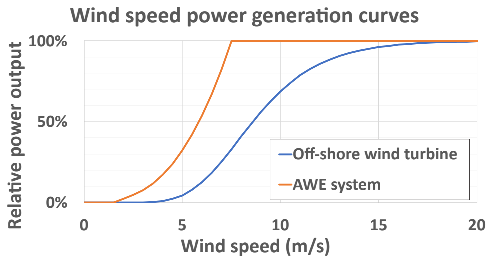
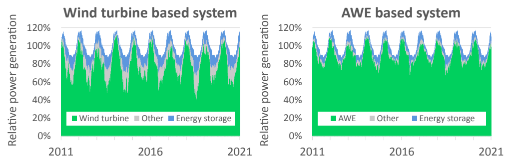
Achieving net zero requires large growth of renewable energy generation, with wind energy a key contributor in many economies. However, the output power from wind energy is subject to weather fluctuations and this is exacerbated by the low efficiencies of wind turbines at low wind speeds. An economy requires assured power generation, and therefore one that predominately uses wind energy will require substantial power generation 'over' capacity, therefore significantly increasing the total costs of its power generation system. We show that utility scale airborne wind energy (AWE) with its more sustained generation at lower wind speeds (and higher altitudes) substantially reduces generation fluctuations, and therefore substantially reduces the amount of 'over' capacity required whilst increasing energy security. We have created a demand and supply model for UK power generation using measured hourly wind data [1] for the period 2011 – 2020. The model assumes power demand is met from 3 sources; offshore wind power, other power and energy storage and assumes that wind will be used by preference if available. For both the wind turbine based system and the AWE based system, we optimised the mix of installed capacity of the 3 power sources to achieve assured supply over the 10-year period. We defined 'assured supply' as being where the energy storage remaining charge level never falls below 50% or 100 hours. For wind turbines we used the power generation curve for the Vestas V164-8.0 turbine and for AWE we used an in-house estimated efficiency curve (both shown below). The work shows that for equivalent net zero supply assurance the AWE based system requires significantly less total installed wind capacity and requires only half of the total capacity of other power and energy storage compared to the wind turbine based energy system.



Power curves for wind turbines and AWE used.



Comparison of the contribution to total power demand from wind, other and energy storage. Due to the more sustained power generation at lower wind speeds airborne wind energy requires much less contribution from other power generation sources.

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Status of UC3M Testbed for the Aerodynamic Characterization of Kites Applied to Airborne Wind Energy Systems

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Due to its importance for research and industrial applications, several testbeds have been developed aimed at the dynamic and aerodynamic characterization of airborne wind energy systems [1,2,3,4]. The incorporation of sensors to measure the flow characteristics in-situ and the implementation of robust closed-loop control to acquire abundant and high-quality data are identified as their major drivers. The first version of the UC3M testbed had a manual control of the kite and it incorporated sensors for measuring the kite position, velocity, attitude, and angular velocity, the full aerodynamic velocity vector by using a multi-hole pitot tube, the tether tensions and the wind velocity vector. An Extended Kalman Filter was fed with the measurements from this first flight campaign to estimate the full state, including the aerodynamic coefficients, of the kite used [4].

This work presents the last improvements implemented on the UC3M testbed. Firstly, a robust mechanical system with high-performance actuators has been incorporated. Secondly, the former GPS sensor was substituted by a high-quality differential GPS system which communicates via telemetry to the ground station. A triple-camera computer stereo vision system based on machine learning algorithms was also added. These sensors provide an accurate and redundant measurement of the relative position of the kite, essential for developing a robust closed-loop algorithm. The actuator of the control system can be commanded manually (open-loop) or by the ground station (close-loop). Experimental results proving its control capabilities are shown and related to recent aerodynamic simulations [5].

UC3M Testbed.

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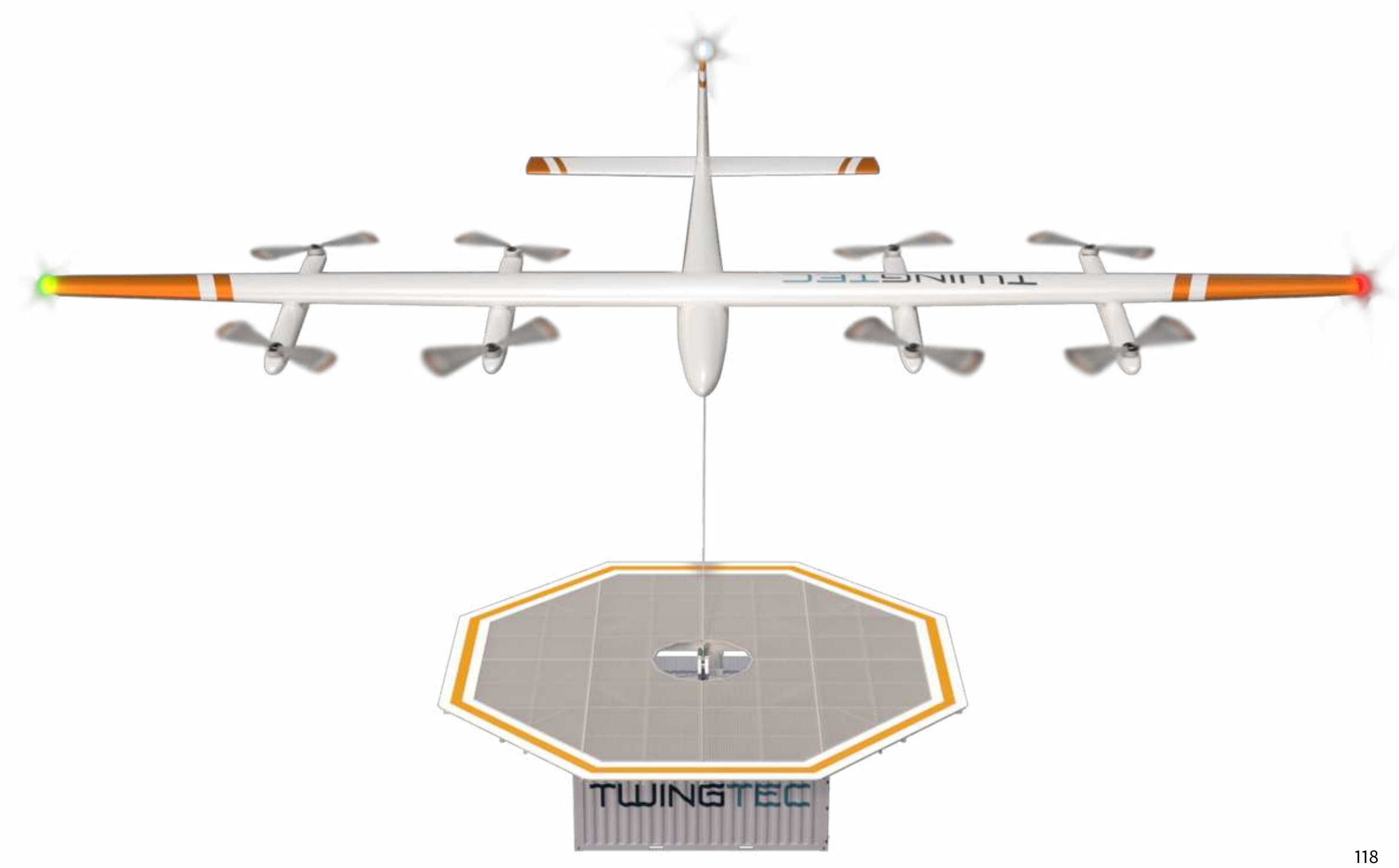
Twingtec's envisioned MW-scale energy drone.



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Maximizing Visibility of AWE Systems for Airspace Users

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TwingTec AG

Airborne Wind Energy systems pose a potential hazard to airspace users (private aircraft, helicopters, gliders,...) which must be adequately de-risked in order to gain widespread acceptance in the marketplace. Over the past years TwingTec has operated a series of prototypes in Switzerland under operational approvals from the Swiss Federal Office of Civil Aviation (FOCA). Since 2019, these approvals have been issued under the 'Specific' category for operation of Unmanned Aerial Vehicles (UAVs) through the Specific Operational Risk Assessment (SORA) process. In order to de-risk the operations for other airspace users and gain an approval, a number of strategic and tactical air-risk mitigations have been developed in cooperation with the Swiss FOCA. These include:

- Appropriate marking and lighting of the airborne part
- Use of a FLARM based transponder system
- Publication of a Danger Zone via Notice to Airmen [1]
- Visual line of sight (VLOS) operations with pilot and observer on site [1]

During 2020 a series of flight tests were conducted in which these measures were implemented. Using the results from these tests as well as a literature study, an estimate of the distance at which TwingTec's pilot system will become visible to incoming aircraft has been made. This estimate can also be extended to larger, commercial scale airborne wind energy systems based on a simple model taken from literature[2]. Combining this with aircraft cruise speeds and estimated minimum reaction distances needed for pilots to see and avoid obstacles, also taken from literature[3], the concept of a "minimum avoidable wingspan" has been developed. Upcoming challenges concerning the integration of the tether into the airspace, as well as U-space integration will also be explored (see https://www.bazl.admin.ch/bazl/en/home/good-to-know/drohnen/wichtigsten-regeln/usp for more information.). These activities have been supported by the Swiss Federal Office of Energy as part of the project: Demonstration of Energetic Potential, Safety and regulatory compliance of Airborne Wind Energy Systems in Switzerland on a pilot scale, 2019-2021.

Aerial view of TwingTec pilot system in operation [4].

References:

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Enerkíte EK30 development platform during a rotational launch (May 2021)

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EnerKíte

Rotational Launch and Landing: Flight Tests at EnerKíte

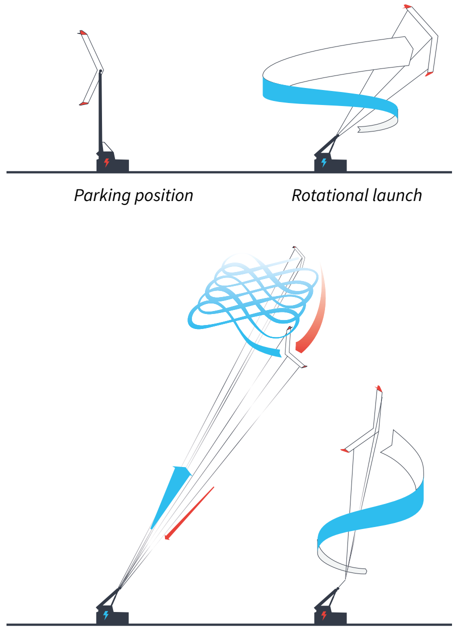
Christian Gebhardt
EnerKíte GmbH

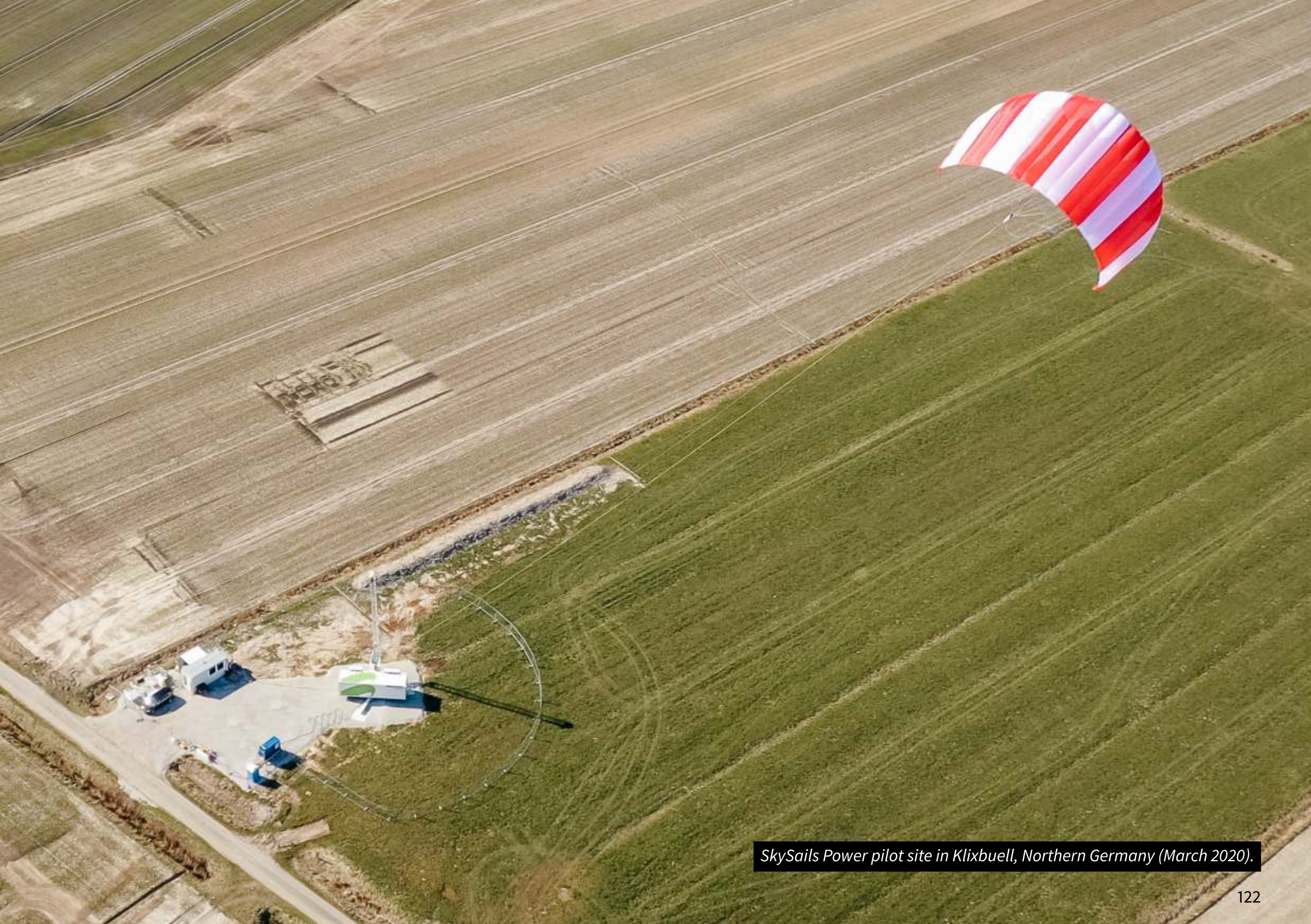
In the broad spectrum of airborne wind energy system designs, EnerKíte has come up with its very own system concept. Controlling the wing via three lines and the use of a rotating mast, no actuators for control or drives for launching are needed in the wing. In combination with light and efficient rigid wings, high availability can thus be achieved even at comparatively low wind speeds.

However, the concept poses particular challenges in terms of mechanical engineering, flight control and wing design. Important development steps at EnerKíte were always accompanied by intensive flight testing, and important decisions were thus supported by practical experience. The respective questions were dealt with using a flight setup and testing methods that were tailored to the possibilities and requirements in each case. Over the years, for example, a wide variety of wing systems have been used, ranging from typical ram-air-kites to rigid carbon fibre constructions.

The author gives an overview of flight testing at EnerKíte from its beginnings until today.

Deeper insights are given into the special challenges of rotational take-off in “real” wind and weather conditions and the practical experiences with the different wing systems.





SkySails Power pilot site in Klixbuell, Northern Germany (March 2020).

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SkyPower100 - Realization of a Fully Automatic AWES (100 kW)

Patrick Junge
SkySails Power GmbH

In 2019, SkySails Power took its first AWES into operation that provides all the functions of a future series-production system. For the first time worldwide, hundreds of flight hours could be collected with an AWES in the >100 kW size class. This pilot plant in northern Germany is a door-opener in talks with stakeholders (authorities, politicians, investors, customers) and has kicked off the market entry of SkySails Power.

The project was launched with the aim of conducting fundamental research into the utilization of high-altitude wind potential by fully automated AWES [1]. The aim was to lay the foundations for later continuous operation, as well as scaled operation of the same or similar systems. The main research topics were operational safety, automatization as well as the creation of international licensing requirements, but also basic research regarding the strength and durability of different materials.

The talk will report on the experience gained by the joint partners during the project. The University of Hanover has investigated several drive concepts and developed the first drive train that is precisely tailored to the requirements on an AWES deployment. Omexom Offshore (formerly EWE OSS) was responsible for the grid connection of the pilot plant as well as the approval process. EnBW researched the international licensing requirements [2].

References:

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SkySails POWER

Enerkíte EK30 development platform during a rotational launch (May 2021)

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EnerKíte

Concepts for Obstruction Marking and Demand-Oriented Obstruction Avoidance to Ensure a Safe Operation of AWE Systems

Nicole Allgaier, Hauke Herschel
EnerKíte GmbH

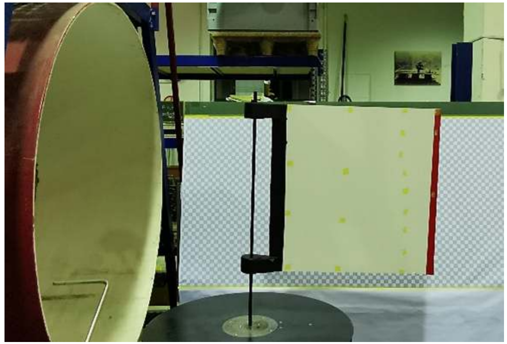
Airborne Wind Energy Systems (AWES) operate at altitudes where collisions with other aircraft systems can occur. The application of the existing legal basis for marking of aviation obstructions for collision avoidance is contrary to typical kite operation for an efficient electricity production.

For this reason, dialogue is currently taking place between approval authorities and AWES manufacturers, in order to find a safe and economical solution. Several possible solutions emerge both from the legal situation and from the current state-of-the-art in the field of conventional wind power [1].

In this work, the current European and German legal basis is briefly covered, and several alternative concepts are investigated. The concepts can be reviewed and ranked regarding their technical and approval feasibility as well as their impact on the LCOE. Furthermore, changes to the current legislature are assessed to obtain permits for operation of each variant.

One such solution category is based on demand-oriented obstruction avoidance by aviation surveillance systems, such as radar or transponder systems. The differences between those systems, advantages, and disadvantages and the implementation in AWES are presented [1].

Another category contains obstruction marking and lighting of the tether and the kite. Tether marking solutions based on ball markers and flags are investigated. To identify the optimal flag material and elasticity several wind-tunnel tests have been conducted. Furthermore, a mount for attaching markers to tether is presented. In the case of pumping operation the markers need to be removed before the tether is guided over the winch. Therefore, the mount is designed so that it can be easily attached and removed [1].



Wind-tunnel test to identify the flow resistance of various tether markers including mount.

References:

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Commercial AWE Systems – a White Paper for the AWE Sector

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[1]Airborne Wind Europe
[2]BVG Associates

A major milestone in the commercialization of Airborne Wind Energy (AWE) has been achieved in 2021 when the first commercial systems in the 80 to 200 kW range have become available [1]. At least one other company is likely to sell its system by 2023, whereas several others are planning to go to market by 2024.

While most critical technical challenges have been mastered (such as automatic energy harvesting, reliable sensors), remaining challenges are systematically increased reliability and especially policy and regulatory aspects. This White Paper – commissioned by Airborne Wind Europe and carried out by BVG Associates – will inform about the status of AWE industry and explain the commercially available AWE systems in more detail regarding costs and performance. Furthermore, current and future markets and existing barriers for upscaling will be analysed. At this stage, AWE companies mainly target remote and island off-grid markets where AWE can already today compete with diesel generated electricity. To successfully enter the highly competitive and regulated European and other electricity markets, this paper will analyse actual and possible policy support schemes and resources in different countries and regions, and discuss recommendations to reach AWE's full potential like other renewable energy technologies in the past. The paper will be based on a review of the latest developments in the AWE sector, combined with interviews with leading OEMs and experts, and include quantitative and qualitative elements regarding costs and performance. Recently published papers and reports on the topic will be clustered and summarized (e.g. NREL 2021)2. Commercialization-relevant findings of on-going activities in projects like Interreg MegaAWE or the work packages within the IEA Task 48 on AWE3 will be supplemented with insights from real-life business cases. The paper addresses suppliers in the wind and aeronautics sector who can help the further development of AWE systems by supporting AWE OEMs in improving their system performance, reliability and upscaling. Furthermore, the paper will help increase awareness of wind project developers to include AWE in their portfolios, looking for adequate sites and business opportunities, e.g. for self-consumption or repowering. Finally, the paper addresses policy makers on how to facilitate AWE deployment, e.g. by including AWE in regulation, defining adequate support schemes and providing R&D finance.

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Building "Institutionalised Trust": Towards Completing the Open AWE Tool Chain

Philip Bechtle
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The expected success of Airborne Wind Energy (AWE) by now is long in the making – maybe for too long when compared with other areas in the "tech" world, and given the financing and public funding opportunities available [1]. At the time of this conference, the world is rapidly changing, and many regions, including Europe and the Americas, are finally increasing the incentives and decreasing the hurdles towards a fully renewable energy system. Yet, AWE is struggling in an environment where the expected development path of the proven technology of batteries, power-to-X, solar PV and wind turbines are technologically well laid out, and where the existing technology is "good enough" both economically and technologically for increasing the renewable energy share substantially.

If AWE wishes to attract the significant investment necessary to build on-grid systems in such a situation, it is required to build "institutionalised trust" into the claims of its operational feasibility, its realistic harvesting potential and its economic viability. A way to build this trust can be provided by open science, with an open tool chain of high-altitude wind data, reference models, simulations of various complexity, power harvesting characteristics parametrisations and a rigorous and open cross-validation of all steps in this tool chain between academia and industry, between real flight data and simulation, and between economic estimates of potential customers and OEMs [2]. Within Task 48 of the International Energy Agengy's Wind Technology Collaboration Programme (IEA Wind TCP), such steps are already being prepared [3].

This talk aims to focus on the available status and on candidates of missing links in this toolchain, mainly concerning the cross-validation between open tools and flight data of prototypes (and hopefully soon of the first small commercial systems under operation), and concerning the potential methodological pitfalls of such comparisons in the light of the necessary simplifications within such a toolchain – be it the parametrisation of the short-term variability of the wind, wake effects between AWES or the challenges of the validation of simulations against prototypes with e.g. unknown optimisation of control algorithms. Filling these and many more missing links can still build enough institutionalised trust in AWE – the challenges of finally making the developed economies sustainable are enormous and imminent, and every bit of renewable energy with the potential of complementarity to other sources could help.

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Experimental Validation on Using Drones for the Take-off and Landing Phases of an AWE System

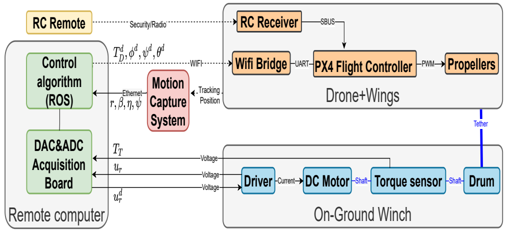
Audrey Schanen, Zakeye Azaki, Jonathan Dumon, Ahmad Hably, Nacim Meslem
Gipsa-lab, Grenoble INP

Recent research results are gradually assessing and eliminating feasibility risks and improving the understanding of Airborne Wind Energy systems (AWE). One direction is to reduce their costs required for each generation unit compared to traditional wind turbines. AWE systems have also to cope with partially unpredictable wind to remain airborne and need to land when wind conditions are poor. Landing and take-off are hard to automate and they increase risk of catastrophic failure.

In the present work, the former theoretical solution based on drones for the take-off and landing phases of an on-ground power generation AWE System [1] is extended and validated experimentally on a benchmark of Gipsa-lab. This benchmark is composed of wing attached to a drone and linked with a tether to an on-ground winch. A motion capture system tracks the drone position and sends it to an on-ground computer that controls the winch and the drone.

The novelties of this work can be summed up in the following three points:

- A 3D space control law is proposed to steer the AWE system.
- All the subsystems involved in the global control loops are introduced and a discussion on their tuning parameters is presented.
- Several experiments are performed to show the efficiency of the proposed control method.



Global architecture of the benchmark.

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Trajectory Tracking Controller Design and Simulation of a Tethered Aircraft

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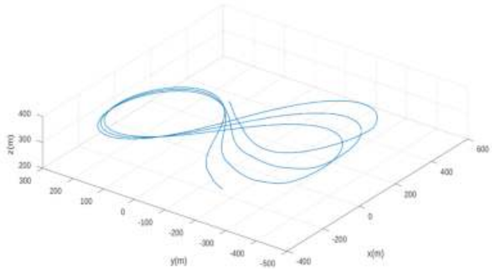
Control problem of an airborne wind energy aircraft, generating power on the ground is addressed. The proposed control tracks a pre-defined trajectory in the power generation phase. The reference attitude information is computed by the trajectory tracking controller such that the aircraft carries out a coordinated turn as well as maintains a proper pitch attitude to generate the necessary lift. A novel quaternion based nonlinear attitude controller is designed, utilizing the attitude commands generated by the tracking controller. These commands are in terms of to-go quaternions to utilize a similar nonlinear attitude controller previously developed for quadrotor flight control as well as solar sail attitude control [1]. However, the approach is extended to the fixed wing airborne wind energy aircraft with aerodynamic nonlinearities. The six degrees of freedom mathematical model of the aircraft includes aerodynamic, gravitational, and environmental sub-models combined with nonlinear equations of motion. The aerodynamic model includes the variation of aerodynamic forces and moments with respect to the angles of attack and sideslip, as well as control surface deflections. The aerodynamic damping terms due to body angular rates are also included. The drag contribution of the tether is computed in the aerodynamic model of the nonlinear simulation. In addition, the winch which is also an important part of the energy generation system on the ground is modelled. It is assumed that the tension in the tether is kept constant with the feedback controller of the winch.

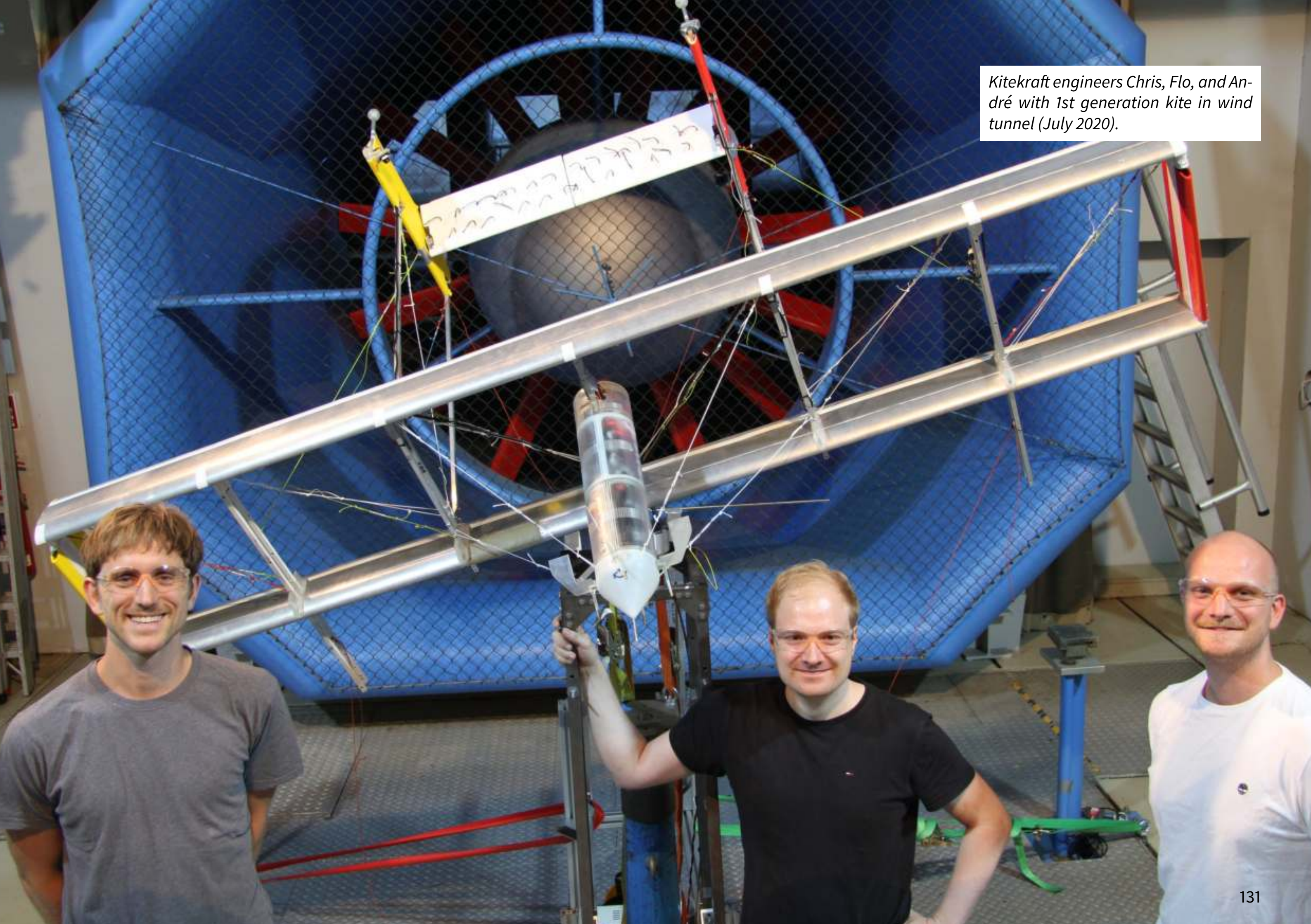


Flight trajectory

References:

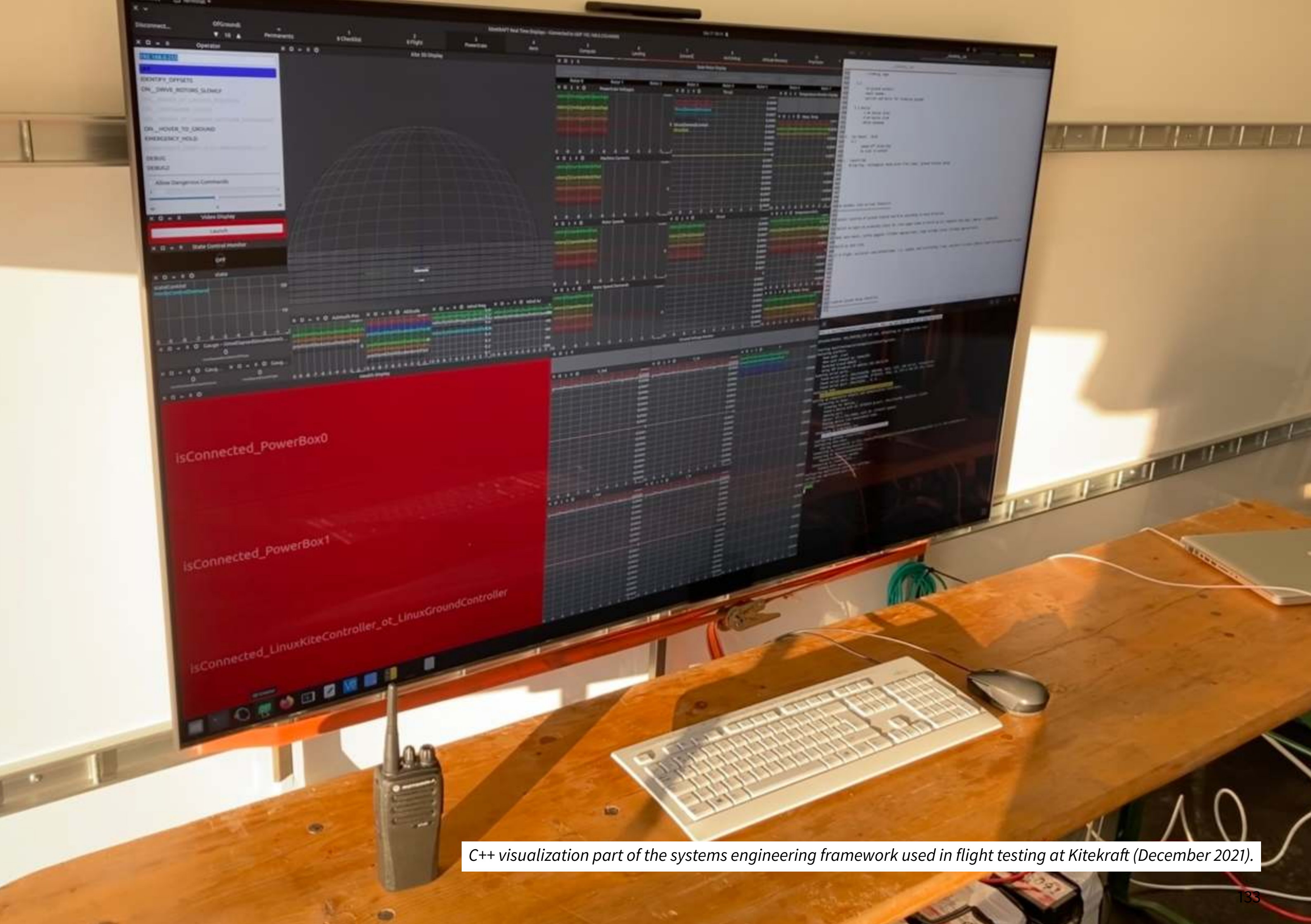
[1] Ariyibi, S., Tekinalp, O.: Quaternion-based nonlinear attitude control of quadrotor formations carrying a slung load. Journal of Aerospace Science and Technology, 105,105995 (2020)

Preparing the 1st generation kite for launch (February 2020).



Kitekraft engineers Chris, Flo, and André with 1st generation kite in wind tunnel (July 2020).

Kitekraft engineer Chris at 2nd generation kite during checklist drill prior test flight (August 2021).



C++ visualization part of the systems engineering framework used in flight testing at Kitekraft (December 2021).

Kitekraft kite launching into figure-eight flight mode (January 2022).
Full video available from https://youtu.be/gZ06BumGPAU.

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KITE//KRAFT

C++ Based Systems Engineering Framework as a Key Approach Towards Efficient, Reliable, and Autonomous Flying Wind Turbine Products

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[2]Technical University of Munich

An airborne wind energy system (a.k.a. flying wind turbine) is a challenging product development: Unlike toy- or camera drones, it must operate for 20+ years in harsh and uncertain conditions. Unlike classical wind turbines, mass constraints apply and a versatile sensor suite is required. The design space is vast, and it is hard to grasp all pros and cons of design choices. The simulation and control software is by far the most important engineering tool and subsystem of the technology, which has to be versatile, yet requires a high-level abstraction, and fast execution capabilities. While much of the academic research tries to solve specific questions on simulation and control, a holistic approach was proposed in [1], in which, e.g., the entire power plant is modelled by a suite of domain sub-models (Systems Engineering Model). While MATLAB allows a quick start, it was already suggested that it may not be the best choice for the complexity of continued development due to numerous restrictions.

Those works were extended at kiteKRAFT, numerical simulation and control algorithms have been implemented in C++ and have been validated with a flight demonstrator. It not only offers to be easily extensible with increasingly complex algorithms, e.g., flight trajectory predictions and nonlinear vortex lattice aerodynamics models [2], but quick switches between parameter sets or execution cases (e.g., software/hardware/plant-in-the-loop), and real-time execution and -visualization. The high-level abstrac-tion character of C++, e.g., using the Eigen library [3], not only allows MATLAB-like syntax, but also a highly extensible, concise, yet intuitive source code, including, e.g., definition and communication of thousands of variables of interest. For example, introducing a new variable (e.g., for a new angle of attack sensor) can be as little as two lines, 1. define variable, 2. define communication path, which is enough for it be available to any control sub-algorithm code, and to show up in flight logs and in the real-time graphical user interface, instead of connecting many arrows in MATLAB Simulink. The ASCII text of C++ source code allows using efficient collaboration tools like git. This systems engineering framework approach has proven to be an excellent choice to maximize overall development speed and reliability. It is in part inspired by the approach taken by SpaceX [4]. In this talk we will give details of its features, testing results, and solutions to C++ challenges. The Figure shows a photograph of the C++ visualization (left) and a launching kite (right) taken during flight testing.

References:

[1] Florian Bauer, Multidisciplinary Optimization of Drag Power Kites. Dissertation. Technical University of Munich (2021).

[2] Florian Bauer, Tech-Deep-Dive: How Kitekraft Solves Aerodynamics. Blog (7 Nov 2021). https://medium.com/kitekraft/

[3] Guennebaud Gael, Jacob Benoit and others. "Eigen v3" (2022). http://eigen.tuxfamily.org

[4] SpaceX AMA (Ask Me Anything) on Reddit (2020). [Available online]

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Julia Kite Power Tools

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Julia Kite Power Tools are a set of open source packages for the simulation and visualization of kite power systems, written in the Julia programming language [1]. They consist of the following packages:

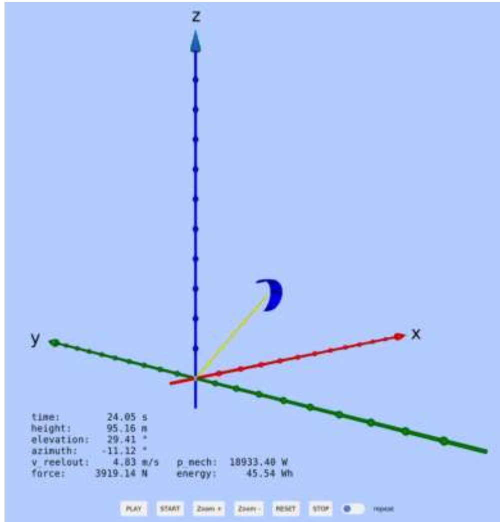
- KiteUtils
- KitePodModels, KiteModels [2]
- WinchModels, AtmosphericModels
- KiteControllers, KiteViewers

Each package [3] can easily be installed on Windows, Linux and Mac computers. Continuous integration is used for quality ensurance. Without modifying the original code the packages can be extended by implementing abstract types.

A detailed documentation with a growing set of examples is available und should be suitable for self-study of MSc and Phd students.

The code was originally written in Python/ Numba. The conversion to Julia makes the code much more readable and maintainable. Finally the performance increased by a factor of 10 to 20 on a single core machine. When multi-threading is used, an increase by a factor of 100 can easily be achieved. This gives completely new opportunities for optimization and robustness studies.

Feedback and contributions of the community are very welcome!



3D Kite Viewer replaying the results of a Simulation.

References:

[1] Bezanson, Jeff and Edelman, Alan and Karpinski, Stefan and Shah, Julia: A fresh approach to numerical computing. SIAM Review ***59****(1), 65-98 (2017)*

[2] Fechner, U., Vlugt, R. V. D., Schreuder, E. & Schmehl, R. (2015). Dynamic Model of a Pumping Kite Power System. Renewable Energy, 83, 705–716. doi:10.1016/j.renene.2015.04.028

[3] Source: https://github.com/ufechner7/KiteModels.jl

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EnerKíte

Some Modelling and Control Aspects of Rotational Starting and Landing

Maximilian Ranneberg, Bernhard Kämpf
EnerKíte GmbH

Airborne wind energy hinges on the ability of the system to autonomously launch and land the power generating wing from some safe state on the ground into high altitudes. The approach of EnerKite is the rotational start, where a rotating lever supplies the wing with airspeed. It was first mentioned in [1] and subsequently analysed as an example for model predictive control[2] and realised in small prototype variants[3]. EnerKite presented a realised system in the scale of a 30kW machine and a comparison of launching and landing mechanisms during the AWEC2017[4].

This presentation follows the development of control strategies at EnerKite through different modelling depths. We start at simple formulas estimating the sizing rules and aerodynamic quantities and advance to optimal control formulations and point mass model simulations for strategies at different wind conditions and the effect of inertias on system behaviour and we show how the models compare to the test data acquired with the EK30 development platform. We arrive at a full 6DoF model, specifically formulated in a rotating frame and in aerodynamic coordinates, which allows for steady-state analysis and linearization of a rotating kite controlled via three lines from the ground in rotation.

In each step more aspects of the system are added to the analysis, and the rationale of adding them is discussed – as well as the rationale of leaving them out before.

EnerKite EK30 development platform during a rotational launch.

References:

[1] Diehl, M., Houska, B. Windenergienutzung mit schnell fliegenden Flugdrachen: eine Herausforderung für die Optimierung und Regelung. at-automatisierungstechnik 57.10, pp. 525–533 (2009)

[2] Zanon, M., Gros, S., Diehl, M. Rotational start-up of tethered airplanes based on nonlinear MPC and MHE. In: 2013 European Control Conference (ECC), pp. 1023–1028 (2013)

[3] Geebelen, K., et al. An experimental test set-up for launch/recovery of an Airborne Wind Energy (AWE) system. In: 2012 American Control Conference (ACC), (2012).

[4] Rieck, B., Ranneberg, M., Candade, A., Bormann, A. Comparison of launching & landing approaches. Airborne Wind Energy Conference 2017, Freiburg, 2017.

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Optimal Flight Path for Fly-Gen Airborne Wind Energy Systems

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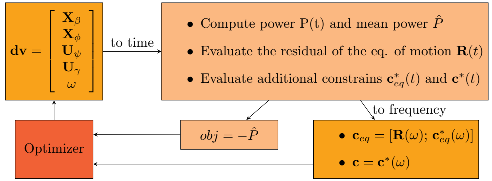
The computation of optimal trajectories for power production of Airborne Wind Energy Systems (AWES) is an active research field, where different optimization problems often lead to different trajectories [1]. Optimal trajectories are evaluated offline or during operation and the computed paths are typically used as guidance inputs to the control system. Optimization problems can be characterized by low-fidelity models, where strong assumptions are taken, or higher fidelity, which can better describe the physics. Low-fidelity dynamic models are suitable for trajectory optimization problems since they allow to obtain insightful physical understanding of the systems. The present work introduces an optimization problem for flight paths of Fly-Gen AWES which is based on the model in [2], adapted for Fly-Gen AWES.

The dynamics of the system is stated in the frequency domain through a harmonic balance formulation due to its inherent periodic character. This allows to reduce the problem size by solving only for the main harmonics. Indeed, the time evolution of trajectory is described by the Fourier coefficients of elevation and azimuth ($\mathbf{X}_\beta$ and $\mathbf{X}_\phi$), which are included as optimization variables in the optimization problem. Moreover, the Fourier coefficients of the time evolution of the on-board wind turbines thrust and of the AWES roll angle, which are the two control inputs, ($\mathbf{U}_\gamma$ and $\mathbf{U}_\psi$) are included as optimization variables as well. The optimizer then maximizes the mean power production ($\hat{\mathbf{P}}$) while respecting the dynamics, which is treated as a set of nonlinear equality constraints thanks to the frequency-domain formulation ($\mathbf{R}(\omega)$). Additional nonlinear constraints (e.g. minimum elevation angle) are expressed in frequency and included in the optimization.

To conclude, the present work aims at giving a detailed physical understanding of optimal paths, by highlighting their characteristics. Optimal trajectories will be analyzed as function of non-dimensional parameters to generalize results.



Optimization framework for the optimal flight path evaluations.

References:

[1] Vermillion C., Cobb M., Fagiano L., Leuthold R., Diehl M., Smith R.S., Wood T.A., Rapp S., Schmehl R., Olinger D. and Demetriou M.: Electricity in the air: Insights from two decades of advanced control research and experimental flight testing of airborne wind energy systems. Annual Reviews in Control, 52:330–357, 2021.

[2] Fernandes, M.C., Paiva, L.T. and Fontes, F.A.: Optimal Path and Path-Following Control in Airborne Wind Energy Systems. Advances in Evolutionary and Deterministic Methods for Design, Optimization and Control in Engineering and Sciences (pp. 409-421). Springer, Cham, 2021.

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Rotation Compensator Based Cyclic Pitch Control for Rotary Airborne Wind Energy Systems

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Rotary airborne wind energy systems (RAWES) that use rotors similar to conventional wind turbines and ground based generators combine some of the known benefits of Loyd [1] based crosswind kite power systems with potential additional benefits such as continuous energy generation and no tether drag from crosswind flight. Current RAWES [2] work without an active control system for the rotor using a pilot kite for passive control and lift. A cyclic pitch system in the rotor could remove the need for a pilot kite by making the rotor steerable. Combined with collective pitch it would also allow for reel in/out RAWES. Swash plates – as used in helicopters to generate the cyclic pitch - need to be connected to a rotary stable airframe. An airframe and tail rotor less alternative design is to build active rotation compensation into the swash plate. Such an active rotation compensator [3] has been suggested for RAWES to avoid twisting of the primary tether and for providing a rotationally stable attachment point for position sensors (e.g. GPS). The result of these considerations is a rotation compensator based cyclic pitch control for RAWES in which the position of a swash plate is maintained by a small motor that spins the plate against the rotation of the rotor maintaining its position relative to the ground.

This talk discusses the mechanics, the control system and the practical implementation and testing of the system. The best part? The entire system is free and open source so you can use it in your own RAWES.

Stationary white swash plate inside rotating red control pod

References:

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

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

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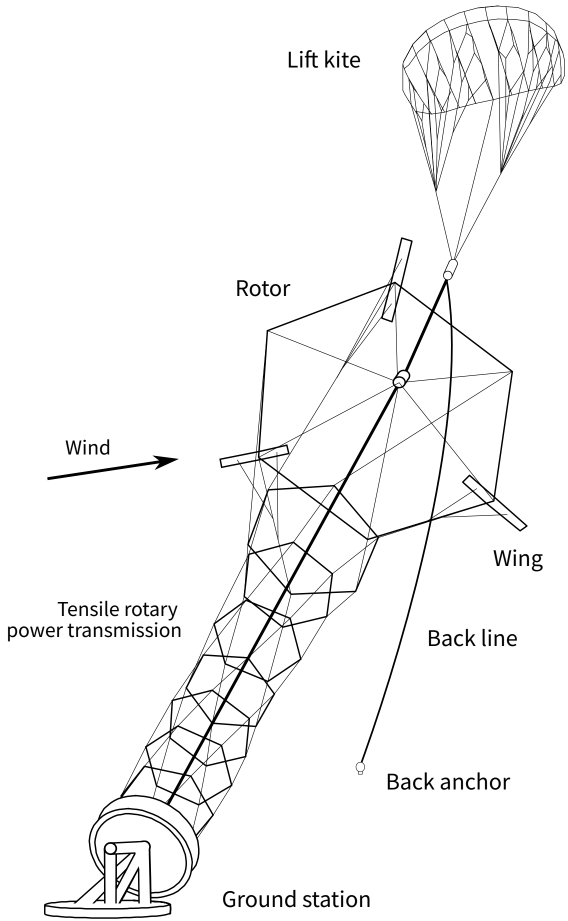
Daisy Kite AWES with labelled main components. Oliver Tulloch. Modelling and Analysis of Rotary Airborne Wind Energy Systems - a Tensile Rotary Power Transmission Design. PhD Thesis, University of Strathclyde, 2021. https://doi.org/10.48730/pm13-at49



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Design Analysis of a Rotary Airborne Wind Energy System

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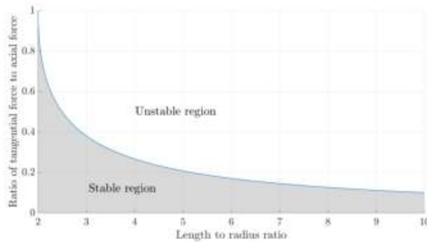
The rotary kite airborne wind energy system (AWES) under study incorporates a unique design of tensile rotary power transmission (TRPT) from the airborne components to the ground. Recent model development and experimental campaign have demonstrated promising features of this prototype such as stable lifting structure, less line drag and easier to automate for larger deployments [1,2]. The aim of this study is to investigate impacts of design parameters on system performance. Model-based steady state analysis has been undertaken considering key factors in the TRPT design, the rotor design, and the tether drag.

The amount of torsion that a single TRPT section can transmit is dependent on the TRPT's geometry, the axial force applied to it and the torsional deformation of the section. The static torque is calculated against selected design parameters individually. The critical value of the torsional deformation angle, δ_{crit}, can be identified for a given geometry. The operational limits are then analyzed to determine the maximum force ratio that can be achieved. The simulation figure shows the stable and unstable regions with a constant ring radius, the dividing line in between the two regions is formed by the values of δ_{crit} under each geometry and operating setting.

The rotor is a crucial component for any rotary AWES, which is responsible for extracting the power from the wind. The need to fly the rotor on the top end of a tether, avoiding ground strikes and reaching higher altitudes, means that the flying rotor must be tilted into the wind. The influences of the rotor elevation angle, the wing pitch angle, the blade length and the rotor solidity on the maximum power coefficient are studied, based on which an optimized rotor design is suggested.

The tether drag is assed using a simple tether drag model and an improved one. The torque loss and the TRPT efficiency are evaluated against key TRPT parameters. The full range of the tip-speed ratio is analyzed for the tether drag's impact on steady operating conditions.

The above model-based analysis provides useful insights that will help to achieve the optimized design, operation and scaling.



Force ratio against the length to radius ratio of a TRPT section.

References:

[1] Tulloch, O.: Modelling and Analysis of Rotary Airborne Wind Energy Systems – a Tensile Rotary Power Transmission Design. PhD Thesis, University of Strathclyde (2021).

[2] https://windswept-and-interesting.co.uk/

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Non-Intrusive Modeling of an AWE Generator's Bidirectional DC/DC Converter

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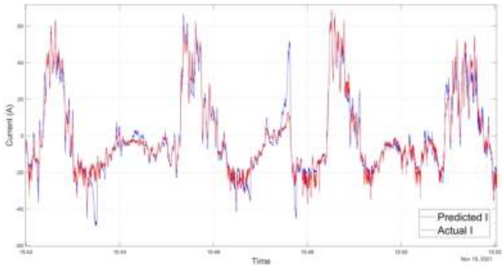
This work presents a non-intrusive black-box modelling approach applied to a bidirectional DC/DC converter used to link the 600V DC bus to the battery and supercap storage systems in Kitenergy's AWE generator. Since manufacturers do not disclose enough information about the converters topologies and internal parameters, it is not trivial to define an accurate electrical model of the converters to design and simulate new control strategies.

Long Short Term Memory LSTM Neural Network (NN) based modeling technique is used to model the converters. The training of the model is performed off-line and is able to predict long time behaviours. The NN is trained through a dataset of current and voltage measurements, logged in a field-testing campaign of KE60. Depending on the simulation in which the model should be used, different measurements can be set as input and output states. The proposed NN architecture has four layers: sequence input layer, long-short term memory layer, fully connected layer, and regression output layer. The NN can learn the long term dependencies between the variables by assigning heavy weights to them, while forgetting or assigning a lower weight to uncommon dynamics of the electrical signals.

The dataset is formed by a set of flights obtained at different operational conditions. The training dataset included a total of 163 minutes of logged electrical signals while KE60 MkII was in operation at different wind conditions. The models were trained for 500 epochs, the hyperparameters were tuned using a Bayesian optimization algorithm. The models were tested and validated with data from flights not included in the training dataset. The model has been used in support of the design of a novel DC bus control strategy for KE60 MkII DC bus management.



Measured current and predicted current for a flight not included in the training dataset.

References:

[1] J. Naranjo, "Long-Time Predictive LSTM-NN based model of a bidirectional DC-DC converter used in Airborne Wind Energy generator" M.S. Thesis, Sch. of Industrial engineering and informatics., Politecnico di Milano, 2022.

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Drivetrain Concepts for Pumping Airborne Wind Energy Systems

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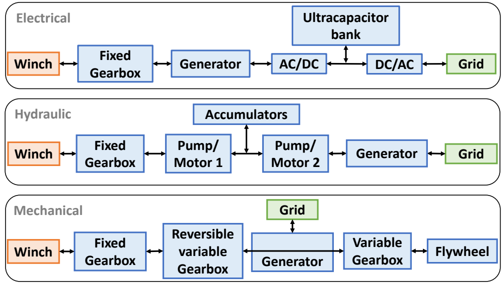
[2]Ampyx Power BV

Airborne wind energy (AWE) systems with crosswind flight operation and ground based electricity generation have alternating reel-out and reel-in phases, which are also known as the pumping cycles due to their cyclical nature. These cycles lead to an oscillating power profile which needs to be smoothened out before it can be supplied to the electricity grid.

Power smoothing essentially means providing a constant power output to the grid irrespective of the fluctuations in one full cycle operation. This can be done by maintaining the net cycle average to the grid at all times. The intermediate energy storage for power smoothing must be capable of delivering high number of charge-discharge cycles with a fast response time. Conventional electrical energy storage batteries are not suitable for such heavy operation.

This work proposes three drivetrain concepts which can fulfil this purpose. The three concepts are based on three different types of storage technologies: ultracapacitors, hydro-pneumatic accumulators and flywheels. Techno-economic models of these drivetrains have been developed and a case-study on sizing and costing of the three drivetrain concepts for a MW scale AWE system is evaluated. The results indicate that it is essential to capture the effect of the drivetrain in the scaling and system sizing studies of AWE.

Since most of the AWE companies are now entering the commercialization phase, it is necessary for them to include drivetrain in their design process. The objective of this study is to provide guidance to the AWE developers for choosing a suitable drivetrain concept for their systems. Detailed analysis can be found in [1].



Architectures of the three potential drivetrain concepts for pumping AWE systems

References:

[1] Joshi, R., Schmehl, R., Kruijff, M., Von Terzi, D. Techno-economic analysis of power smoothing solutions for pumping airborne wind energy systems. Journal of Physics: Conference Series ***2265****, 042069, 2022. doi:10.1088/1742-6596/2265/4/042069*

The ICM-autoKite Project: Developing an Automated Kite Propulsion System for the KITE GAS/FUEL SHIP and Economic Green Hydrogen Production

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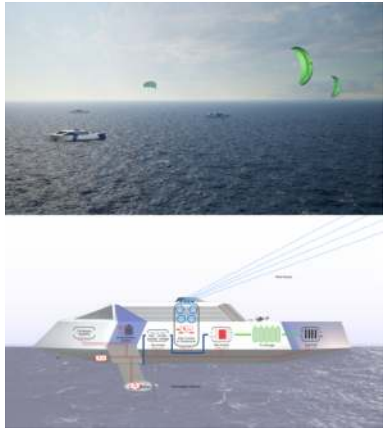
Reducing humanity's impact on climate change is a core challenge for our time. To achieve the goal of zero net greenhouse gas emissions in the EU by 2050, significant adjustments are necessary for each CO2-emitting sector [1]. One effective method for decarbonisation is the use of green hydrogen as an energy source [2]. It can directly be utilized as a green energy source or refined to higher grade E-Fuels [3].

A ship capable of exploiting the high wind power densities and capacity factors of high-altitude winds on the open ocean could provide green electricity for the electrolysis of water to hydrogen [4]. The KITE GAS/FUEL SHIP [5] is such a concept using an automated kite system as propulsion. Due to the large available area on the ocean, this technology is highly scalable and does not compete with the green energy production of the grid.

The ICM-autoKite project studies and provides the required scientific background for the development of the technology and the automated operation of the kite based propulsion system for the KITE GAS/FUEL SHIP. Both the KITE GAS/FUEL SHIP and the ICM-autoKite project along with the corresponding research topics methodology for preliminary kite design and scaling, aerodynamic modelling and experimental characterisation of highly flexible tethered wings, controller design and system technology for automatic operation, visual rope monitoring and lifecycle of fibre ropes, as well as system simulation and optimisation of the energy yield are shortly introduced.



The KITE/GAS FUEL SHIP [5]

References:

[1] European Commission: European Green Deal. (2019) https://bit.ly/3qnTnuG

[2] Hydrogen Council. Hydrogen scaling up. A sustainable pathway for the global energy transition. (2017) https://bit.ly/3FjCtSt

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[4] Platzer, M. F. Sarigul-Klijn, N. The Green Energy Ship Concept. Springer International Publishing, Cham. (2021)

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The Pyramid, a TRPT Rethink

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[2]Kitemill AS

Reimagining the TRPT [Tensile Rotary Power Transfer] concept, we combine a tensile rotary shaft with three rigid steerable kites all with a single tether attachment point. The design promises: Continuous power output, a plausible launch and land mechanism and unparalleled scaling due to not being affected much by gravity slow-down.

We look at the building blocks of the design; a soft shaft, a motorized triangular bridle between the kites, an algorithm to control average vertical and horizontal force and provide constant tension on each tether, and more.

We introduce the Λ factor describing the soft shaft's ability to transfer power. This scale independent factor is used to show that the shaft's power transferring ability scales equal to the power generating ability of the kites.

We see that the three tethers without further shaft expansion support provides sufficient power transferring capabilities at practical elevation angle and altitude. We look at how tether drag limits the length of the shaft. The shaft needs a high glide ratio, but longer tethers defeat this requirement.

We present a detailed simulation providing a power curve.

Open source simulator and further documentation may be found at https://github.com/tallakt/TRPTSim

The Pyramid Illustration

High-Fidelity Tether Models for Airborne Wind Energy

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research-sections/sys

High fidelity simulation is important for airborne wind energy systems (AWES) to help reduce the reliance on time-consuming and expensive prototype testing. Unlike conventional wind energy or aerospace, tether dynamics play an important role in AWES dynamics. This work looks to compare different tether models at a range of fidelities.

This work starts by considering three models. The first is a quasi-static lumped mass model by Paul Williams [1] developed specifically for AWES. The model is built around the assumption that the weight, aerodynamic drag and centrifugal forces dominate, while any vibrations are quickly damped. With these assumptions, the shape and tension of the cable can be estimated simply by solving the static equilibrium equations.

The second model considered in this study is the nonlinear beam model in an Absolute Nodal Coordinate Formulation (ANCF) [2]. This model has considerably higher fidelity by considering all the dynamics and internal strain, including bending. The ANCF is based on nodal coordinates in the absolute reference frame, determining the strain based on the tangent and curvature of the shape functions. The advantage of this approach over other nonlinear beam formulations is that the mass matrix does not need to be rotated with the element orientation, yielding faster results for dynamic calculations.

Finally, the third and highest-fidelity model is the nonlinear Geometrically Exact Beam Theory (GEBT) [3]. This is another finite element approach that additionally considers the orientation of the cross-sections to determine the internal strain. It is unlikely that this will offer significant advantages for this application. However, since it is the most comprehensive, it can stand as the reference case for comparison purposes.

The comparison will be based on simulating an airborne wind energy system with onboard generation (i.e. only constant length tether) on a fixed circular path, with prescribed tether top forces. Using the Mann turbulence model, the tether will be subjected to both a steady and turbulent wind [4]. The tether will be based on Dyneema material. Material damping will be based on Rayleigh damping tuned to achieve a damping ratio of 5%. Viscoelastic effects are beyond the scope of this research. The models will be compared based on the shape, internal forces and vibrations that arise. Each model will be simulated with a wide range of elements (4-200) to assess both the convergence rate and the computational cost of all three models.

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Analytical Wake Models for Crosswind Kites

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This paper reports on two novel analytical wake models for crosswind kite power systems. The two models were developed to calculate the annular wake radii and the average flow velocity in the wake of a crosswind kite. These models were derived from Refs. [1,2] andare widely used for conventional wind turbines. The new wake models provide a first step in the understanding of the effects of kite-to-kite aerodynamic interactions in prospective wind energy kite farms.

If a number of crosswind kites were to be arranged together on kite farms or parks, as standard modern-day wind turbines are, it would be important to know how one kite affects the other to ensure optimal energy extraction. On this front, some progress has been made; however, the studies have been on mainly mechanical (or physical) interactions; see, e.g., Ref. [3]. Despite this success, it is not known yet whether avoiding only the mechanical interference between kites and staggering them spatially, as considered above, will be sufficient for optimal layout design of kite farms. When designing and optimizing a farm of conventional wind turbines, wake flow from individual turbines and the aerodynamic interference between them are the primary factors to be considered. Thus, examining the aerodynamic features of individual kites, such as their wake flow, as well as the aerodynamic interference between neighboring kites seems essential. Good-quality wake models inform us on the proper distances by which to place one kite from the other.

We develop expressions for the dimensionless wake flow velocity and wake radii by adopting similar assumptions as those made in [1,2]. In particular, self-similarity of the flow velocity and linear wake expansions are assumed. Also, for simplicity, it is assumed that the kite remains on a plane that is normal to the incoming wind, and the wind is uniform in space and time. The results from the two analytical models, which are called Continuity Wake (CW) and Continuity-Momentum Wake (CMW) models, are compared with each other and are verified considering computational fluid dynamic results presented in [4,5]. Bearing several assumptions, these models are meant to simply offer a preliminary insight that will hopefully see many improvements with added complexity in the near future.

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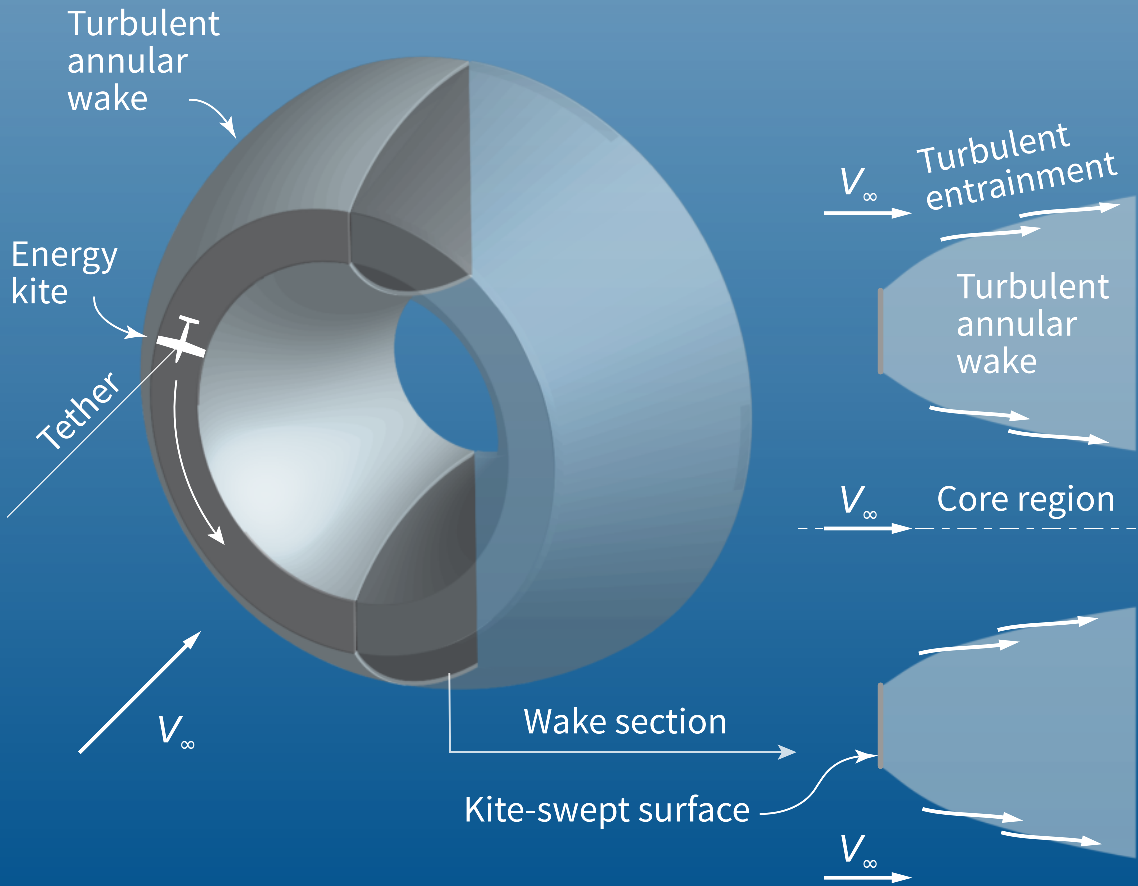
Turbulent
annular
wake
Energy
kite
Tether
V_∞
Wake section
Kite-swept surface
V_∞
Turbulent
entrainment
Turbulent
annular
wake
V_∞
Core region
V_∞

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An Entrainment-Based Model for Annular Wakes, with Applications to Airborne Wind Energy

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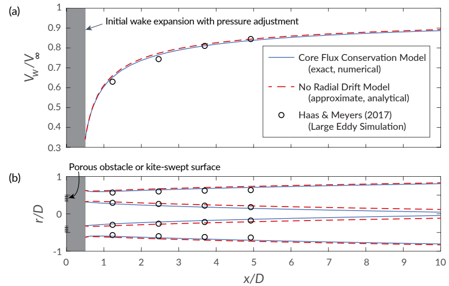
Several novel wind energy systems produce wakes with annular cross-sections (as illustrated the figure on the opposite page), which are qualitatively different from the wakes with circular cross-sections commonly generated by conventional horizontal-axis wind turbines and by compact obstacles. Since wind farms use arrays of tens or hundreds of turbines, good analytical wake models are essential for efficient wind farm planning. Several models already exist for circular wakes; however, none have previously been published for annular wakes, making it impossible to quickly estimate their array performance across a variety of configurations.

To address this challenge, we use the turbulent entrainment hypothesis to develop a reduced-order model for the shape and flow velocity of an annular wake behind a generic annular obstacle. Our model consists of a set of three ordinary differential equations, which we solve numerically. In addition, by assuming that the annular wake does not drift radially, we further reduce the problem to a model comprising only two differential equations, which we solve analytically. Both of our models are in good agreement with previously published large eddy simulation results, as shown in the following figure.



Comparison of our entrainment wake models with the simulation of Haas & Meyers [1] for the laminar inflow case. Similar agreement is found for turbulent inflow [2]. (a) Wake velocity. (b) Wake cross section.

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Aero-Structural Design Tailoring of Composite AWE Wings

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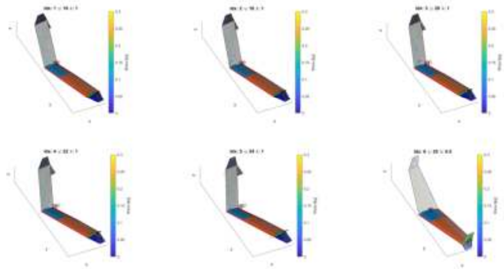
Composite wings employed in so-called "rigid" and "semi-rigid" Airborne Wind Energy Systems commonly undergo load-deflections coupling that arise from anisotropic materials typically utilised in their structures. These coupling effects need consideration already in the initial design phase, wherein certain aerodynamic and structural designs along with subjected load cases result in undesirable aeroelastic phenomenon. At EnerKíte, slender carbon composite wing skeletons are utilised together with a membrane covering to achieve extremely light airborne mass, while maintaining the required strength and stiffness criteria. The aeroelastic response depends on the wing planform and resulting aerodynamics, and is further influenced by the bridle component that distributes the tether forces into the wing structure.

This work focuses on the initial design stage and uses a computationally fast 2+1D Fine Element (FE) structural solver, along with a 3D nonlinear vortex step method to compute the aerodynamic response [1,2]. Subsequently, the aero-structural equilibrium state of the kite and bridle system is solved by using a steady state coupled solver [3]. This toolchain allows for the efficient probing of the initial design space. In this work, designs for different wing topologies, bride configurations and site-specific conditions are explored and analysed for typical operational scenarios.



Wing design configuration and topology exploration.

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The Daedalus Project: AWE Tether Engineering Method Substantiated

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The goal of the Daedalus project [1] at Ampyx Power is to be able to optimize the interaction between tether design and aircraft design of a megawatt pumping AWE system (AP4) towards lowest levelized cost of energy. For this purpose a full-scale tether test machine is designed and built capable of simulating relevant AWE flight conditions. The machine is now available for testing and first results are evaluated.

The Daedalus test set-up is such that long lengths of tethers can be tested covering the full stroke of a power pumping cycle. This is facilitated by a winch with a big drum where the tether runs off the drum at the top towards a remote sheave (about 20 m further) and back onto the drum at the bottom. The load is applied to the remote sheave by a tension winch. The maximum operational load is 40 tons. Several test scenarios are available to the machine. Simple Bending Over Sheave (CBOS+) at constant load, CBOS High Speed and Cyclic Operational Wear over Sheave (COWS). The sizes of the sheave can be varied between sheave to rope diameter (D/d) ratios of 20 and 40. The sheave can be blocked to evaluate abrasion as a result of possible inertia effects. Current tether samples are Dyneema® DM20 based ropes in 2 constructions, a 12 strand circular braid as well as a 5 strand flat braid with (equivalent) diameters of 21 and 40 mm. The breaking strength range of these ropes is between 40 and 160 tons. A special tether lifetime tracking (TLT) system has been developed to track the damage induced by means of bending and creep at every meter of the rope sample. Ropes are tested to failure as well as damaged to a level that is varying over the full length of the stroke, with a wear distribution over the stroke that is representative of an actual tether of a pumping AWE system. A residual break test will give a correlation between test settings, damage attribution by the TLT and the residual breaking strength, to validate the safe-life models developed. In the end the results will lead to an engineering method for tether design being optimized towards local weather conditions, plane behaviour and desired operational lifetime. First test results will be shared and next steps described.

Daedalus tether test machine.

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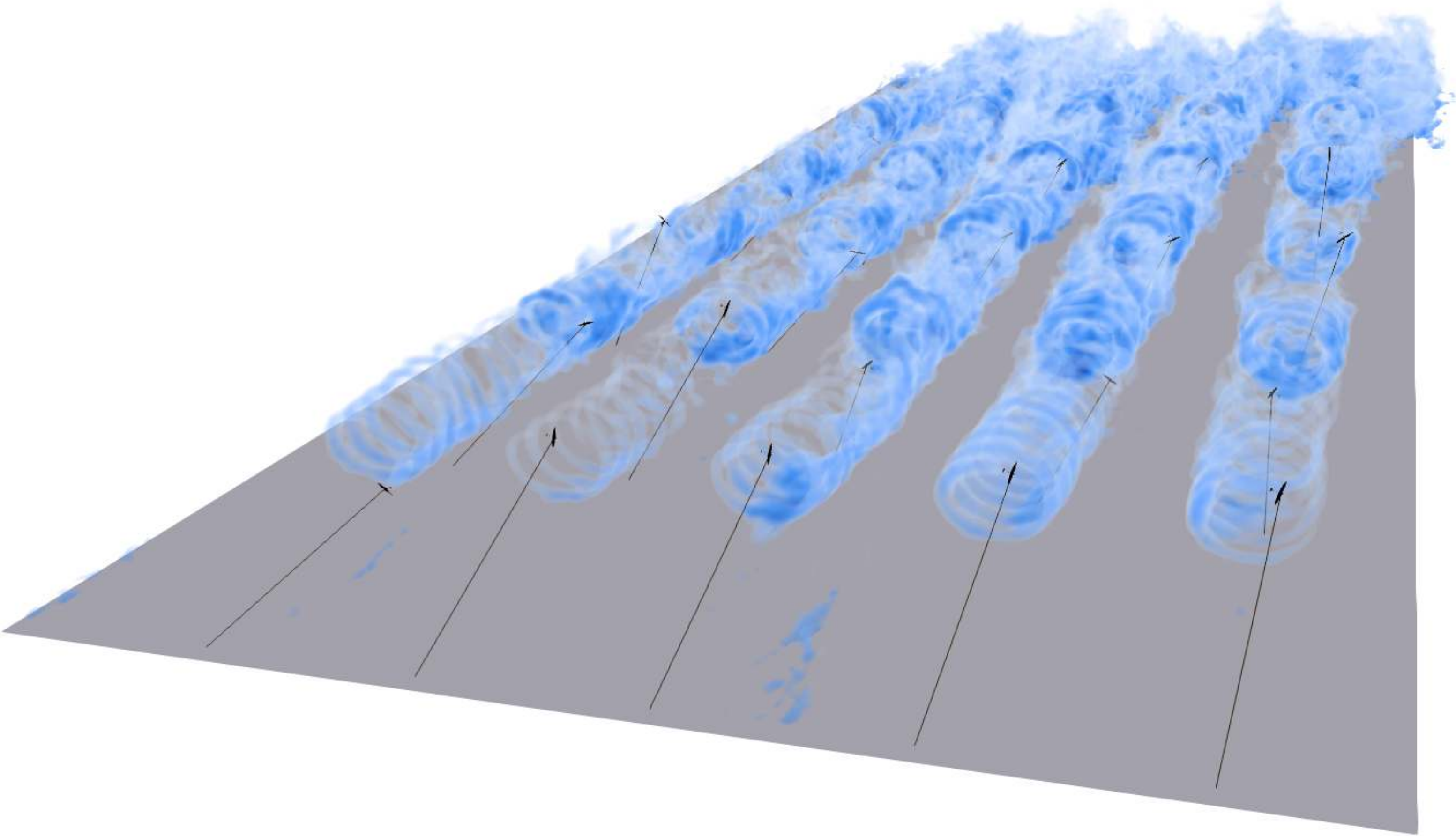
Visualisation of flow structures in the wake of on-board power generation AWE systems (D1) by means of iso-volumes of the wake velocity deficit coloured by axial wind speed component (PhD dissertation Thomas Haas, KU Leuven, 2022).



Performance Investigation of Utility-Scale Airborne Wind Energy Farms using Large-Eddy Simulations

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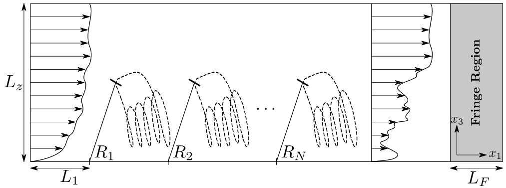
The utility-scale deployment of airborne wind energy (AWE) requires the development of large-scale AWE systems in the multi-megawatt range targeting farm operation [1]. We propose a virtual AWE farm simulator combining large-eddy simulations and optimal control techniques to investigate the performance of AWE farm configurations [2]. The wind field in which the AWE farms operate is an unsteady three-dimensional turbulent boundary layer and the tracking of individual flight path in the presence of these turbulent fluctuations is tackled using a nonlinear model predictive controller (NMPC). The complex dynamics of wind and AWE systems are subsequently coupled using an actuator sector method. The considered AWE systems operate in both on-board and ground-based pumping generation modes (drag and lift modes) and are scaled to harvest up to 5 MW of power at a rated wind speed of 12 m/s. We investigate three farm configurations comprising of 25 systems arranged in 5 columns and 5 rows using two different farm layouts: Two drag-mode AWE farms with moderate and high system densities of respectively 10 MW/km2 and 28 MW/km2 (D1 and D2) and one lift-mode AWE farm with the identical moderate system density (L1) are considered.

The AWE farms operate in below-rated wind conditions with a mean background flow speed of 10 m/s measured at 100 m. During operation, the individual systems adapt their flight path to the encountered large-scale boundary layer wind speed variations and local wake effects. The wake effects significantly impact the power performance of downstream rows, resulting in power losses of up to 17% (L1), 25% (D1), and 45% (D2) relative to the front row of the farm configurations. Although the employed NMPC successfully accomplishes flight path tracking, for lift-mode systems however, it fails to adequately track the power profiles. Hence, over one hour of operation, the combined wake and tracking losses result in farm efficiencies of 82.5% (L1), 89.2% (D1), and 75.6% (D2).



Side view of the computational domain used for co-simulation of turbulent boundary layers and AWE parks. The dimensions in streamwise, spanwise and vertical directions are L_x = 10 km, L_y = 4 km, and L_z = 1 km, respectively. The downstream position of the first row of AWES systems is L_1 = 1 km [3].

References:

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Harnessing the Power of Model-Based Control to Further the Performance and Robustness of Airborne Wind Energy Systems

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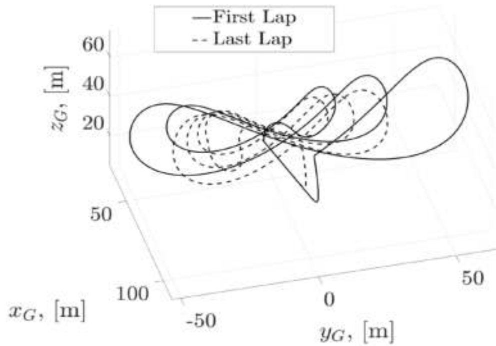
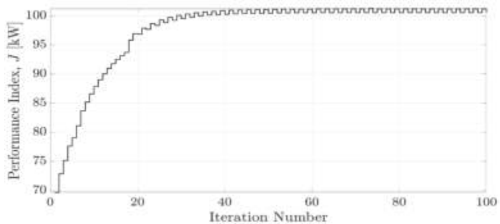
The past two decades have been pivotal for the field of airborne wind energy (AWE) systems, with concepts moving from paper to practice, and experimental demonstrations moving from short-duration demonstrations of basic crosswind flight to long-duration demonstrations and pilot projects. Embedded within this success story of airborne wind energy is the story of how model-based control tools, often glossed over in other application domains in favor of "black box" techniques, have played a pivotal role in realizing the levels of performance and robustness seen in AWE systems today. Underlying the development of these model-based control strategies has been a suite of experimentally validated dynamic models, ranging in complexity from point mass models to six degree-of-freedom kite models with multi-element tethers. These models have been used to develop an arsenal of control tools for AWE systems, including nonlinear model predictive control (NMPC), Smith predictors for delay compensation, and iterative learning control (ILC) for flight path adaptation. Even when data-driven modeling has been leveraged for control, the underlying controllers have been consistently verified against physics-based models that allow for the certification of system performance and robustness. This talk will highlight a number of model-based control success stories within the AWE field, focusing on the modeling approaches employed and the mechanisms used to ensure that the underlying control approaches could in fact be realized in the field. In presenting these case examples, the talk will showcase how our community can indeed serve as a guide for the successful application of model-based control to a complex, high-order system.



Example illustrating the use of ILC for figure-8 flight path adaptation.



Example performance improvement resulting from the use of ILC for figure-8 flight path adaptation.

On Control of Phase Transitions in Airborne Wind Energy Systems

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To operate efficiently and reliably, AWES are supported by active control systems in all phases, such as take-off, landing and power generation, possibly composed of further sub-phases [1,2,3]. Employing modern control theory, state-of-the-art controllers are able to obtain rather repetitive operation in each phase.

In non-repetitive phases like vertical take-off and landing (VTOL) pumping systems the aircraft is lifted with an hovering controller, then its forward speed and pitch angle are increased until switching to an "airplane" controller when the airspeed is large enough, and possibly to a "tethered airplane" controller to enter crosswind mode, when its attitude lies in a chosen set. These solutions have the advantage of being simple to conceive and implement, however they may yield virtually no guarantee of robustness against wind uncertainty, which is indeed an important performance metric in AWES operation and the jumps in the control signal are undesirable.

On the other hand, novel control strategies for ride-through between operational phases promise rigorous theoretical guarantees as well as increased efficiency for phase transitions[4]. Moreover, these tools can also be useful to analyze the robustness properties of existing solutions. The aim of this research is to provide a two degree of freedom controller synthesis method for provably robust transitions between modes of operation, with application to AWES. We adopt a sequence of switching linear state-feedback controllers designed by linearization at chosen points along the trajectory. Robustness is guaranteed by formulating a bound on the maximum deviation from the reference trajectory and applying a simultaneous Lyapunov stability result on the set of possible linearized models under feedback control. The computed piece-wise affine control law can be stored with little memory and thus implemented in embedded systems with a high sampling rate. Furthermore, we allow a smooth transition to given control laws from the beginning and to the end. Thus, the approach can be easily integrated with existing control strategies employed in the starting and ending phases.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 953348

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Predictive Control of a Morphing Airborne Wind Energy System

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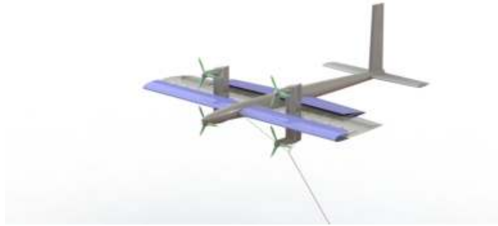
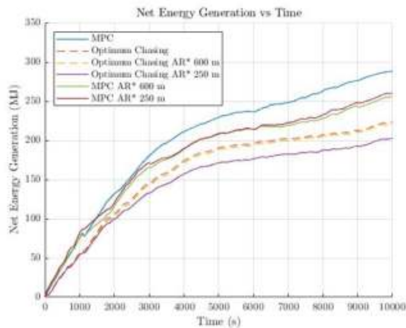
In this work, we have assessed a predictive control approach for an energy-harvesting kite capable of adjusting its geometric parameters in real time. The variable nature of the wind shear profile motivates control strategies that allow for variable-altitude operation, which in turn requires a variable tether length for a given elevation angle. As the tether length increases, however, the contribution of kite drag to the total drag decreases. When tether drag dominates, it is beneficial to deploy a kite with maximal wing area, irrespective of efficiency; however, when the tether length and drag are minimal, wing efficiency is key. This coupling between tether length and the optimal lift-drag characteristics motivates the development of control strategies for real-time wing morphing.

In this work, aspect ratio was considered as a controllable, reconfigurable plant parameter with a fixed-span wing. A two-layer model predictive controller was developed, where the first layer determines the tether length, elevation angle, and aspect ratio setpoints that maximize energy generation assuming an infinite time horizon with spatially omniscient knowledge of the flow field. The second layer finds the rates that will maximize energy generation and bring the kite to these setpoints over the horizon. Preliminary simulations using a simplified plant modeled from fundamental equations in [1] has shown upwards of an 11% increase in energy generation, as compared to a fixed-wing kite following the same control strategy. Furthermore, the MPC formulation showed a 25% increase in energy generation when benchmarked against a naive "optimum chasing" controller that adjusts the reconfigurable parameters without regard to the time or energy costs associated with doing so.





Top: *CAD model of morphing kite. Telescoping flaps and slats deploy along the leading and trailing edge to augment the wing area.* ***Bottom:*** *Projected energy generation for morphing kites with MPC and naive "optimum chasing" controllers benchmarked with fixed aspect ratio kites optimized for 250m and 600m operation.*

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Airborne Wind Energy Farm Layout and Optimization

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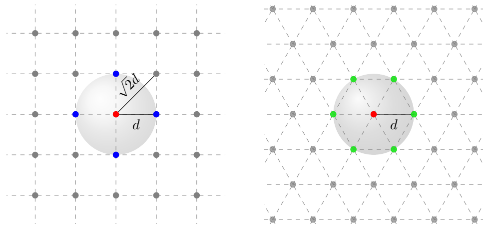
We address the design and optimization of an airborne wind energy farm. In particular, we study the problem of deciding the number, location, and flight envelope, of each AWE unit, aiming to maximize power production while avoiding collision among kites.

We consider a conic shaped flight envelope within which each kite system is allowed to fly. We parameterize this envelope by the azimuth angle span, the elevation angle span, the elevation angle offset, as well as the maximum and minimum tether lengths. While a broad flight envelope and low elevation angle permits a large power production per kite, a narrow envelope and high elevation angle allows to place more kites within a terrain area. Given a specific land area, we optimize the combination of the farm layout with the flight envelope of each kite in order to maximize the total power production.

In a first stage, the total power production of each kite is estimated by an explicit formula that takes into consideration the kite characteristics, the envelope constraints, the loss of efficiency due to the cubic cosine law as well as the loss of efficiency due to the actuation on the kite roll angle. Initial estimates for the number of kites in each of the land dimensions, the envelope parameters, and the corresponding power generated are computed by an heuristic method. We explore two possible layout patterns, a squared layout (the most standard layout) and a hexagonal/triangular layout (our proposal), since each of these might allow to place more kites within the area for different ratios between the land area dimensions and the minimum distance.

In a second stage, the obtained estimates are used as initial solutions in a population based global optimization method, a Biased Random Key Genetic Algorithm [1]. In this algorithm, several combinations of the number of kite units, location, envelope parameters are evolved, evaluated and ranked, in order to maximize the total power production of the kite wind farm [2].



Wind farm layout with squared pattern (25 kites) and hexagonal pattern (39 kites) for the same minimum distance among kites, d, and the same land area.

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CONACYT

Maestría en Ingeniería Aeroespacial
Programa del PNPC del CONACYT

Annual Wind Resource Assessment for an Airborne Wind Energy System

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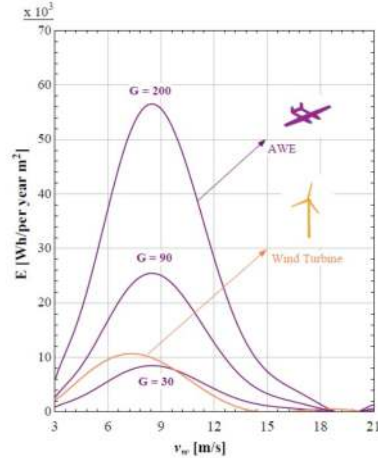
We present a methodology for assessing the wind resource available to AWE and comparing the profitability of the technology with conventional wind energy. The statistical analysis for a specific region of interest in Mexico considers the following:

- the vertical wind speed profile at 400 m above ground,
- the variation of air density with altitude,
- the influence of the flight path on the harvesting efficiency (we assume 90% to account for the misalignment of wind velocity and tether),
- the optimal reel-out speed of 1/3 of the wind velocity component along the tether,
- a pumping cycle with 80% production and 20% consumption time,
- the aerodynamic performance of the lifting device.

The diagram shows the hypothetical maximum annual energy production (AEP) per unit wing surface area for different values of the effective glide ratio. We conclude that an AWE system operated in pumping cycles can harvest more energy than a wind turbine, because it is a dynamic system that can access wind at higher altitudes. The methodology consists of the following steps:

i get hourly wind speed data from a meteorological platform or from experimental measurements,
ii cluster wind speed data in classes $v_{w,i}, \dots v_{w,k}$ with absolute frequencies $n_i \dots n_k$ for an average year,
iii get parameters and Weibull distribution velocities $P(V)$ and cumulated frequency $F(V)$,
iv get vertical wind speed and air density profiles,
v compute the max. specific AEP with Loyd's theory [1],
vi repeat process for a wind turbine at 150 m height.



Considering that the average wind speed is 2.78 m/s, we computed the maximum specific AEP of an AWE to be 0.362, 1.087, and 2.415 MWh for effective glide ratios of 30, 90, and 200. For a conventional wind turbine, we computed 0.493 MWh. Given the capacity factor of both technologies, this resource could be available at least 40% [2].

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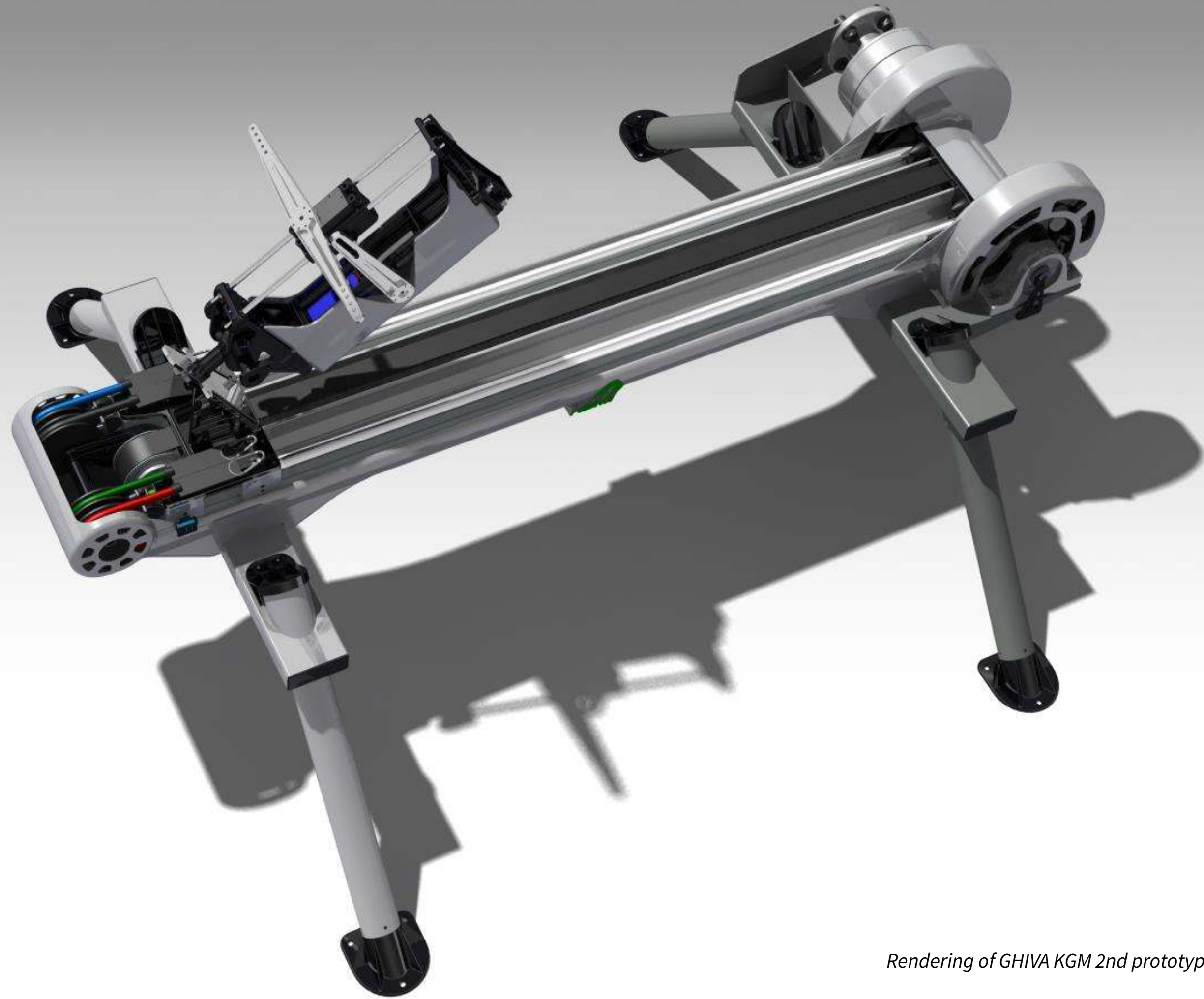
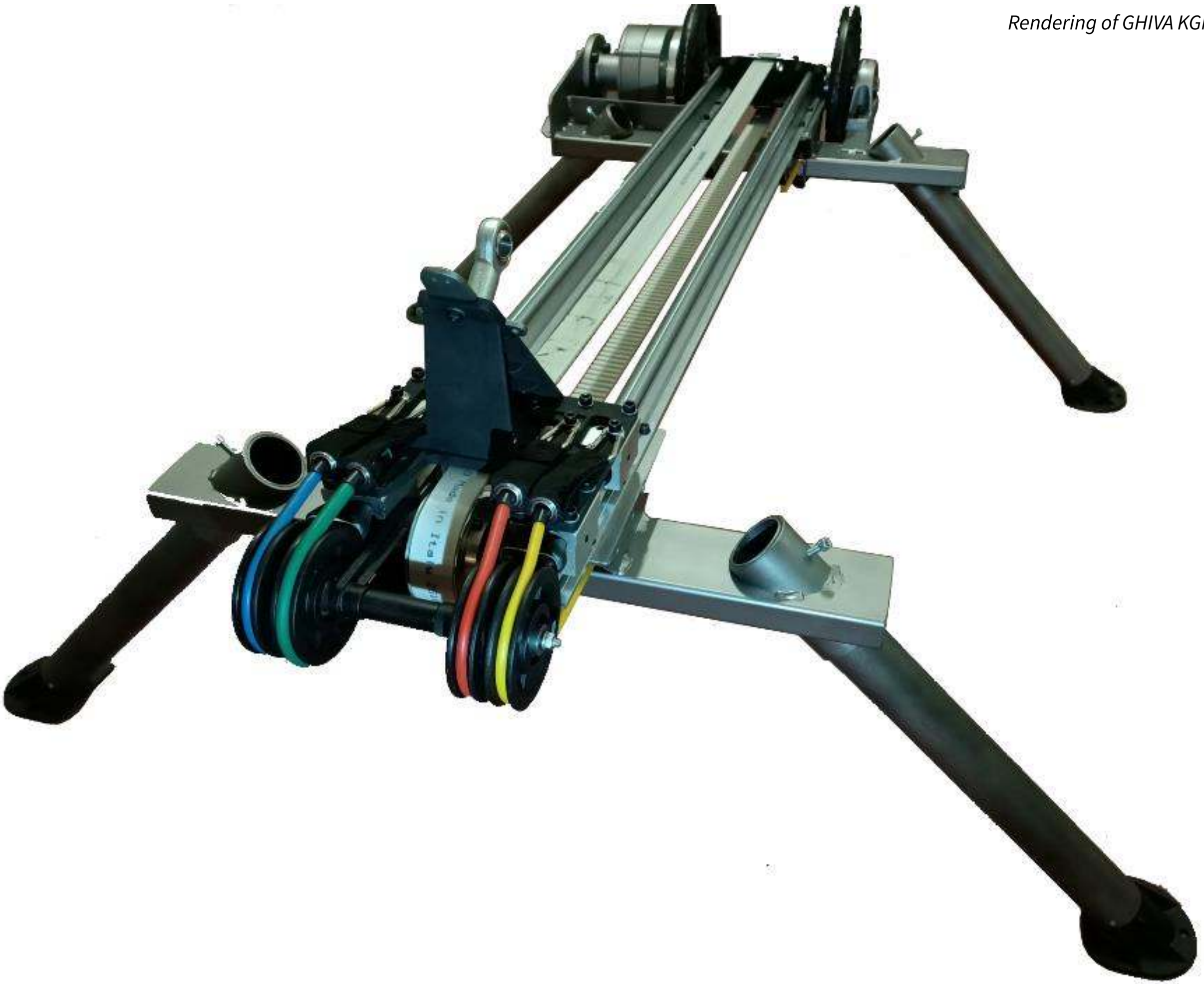


Rendering of GHIVA KGM 2nd prototype.

Rendering of GHIVA KGM 2nd prototype.



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KGM1 – A Different Approach to the Airborne Wind Energy Technology

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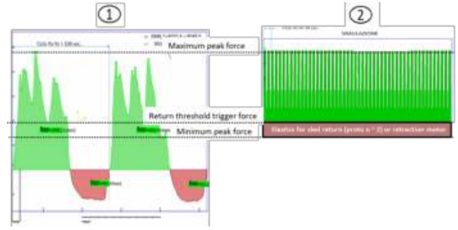
This is a research project in the sector of "Airborne Wind Energy" (AWE), belonging to the type "ground-gen" and operating through a personal type of "yo-yo" cycle. The KGM1 initiative aims to draw a new path in the AWE sector, with a first small size generator (5-20 kW, modular sizes), working off-grid, customized on the needs of "Inuit" and worldwide off-grid populations.

KGM1 have identified and patented a linear generator based on simple solutions, chasing what is called "robust design", while trying to steering clear of the "hypertechnology syndrome", which leads to frequent maintenance intervals, difficult insurability and an exponential increase of the "complexity" (represented below).

This first prototype - developed on the "Inuit" needs - is now lacking of azimuth tracking and will have a simplified flight control, now foreseen without any kind of automatic take-off. The research has originated two variants of the project (the first studied in the Master's degree thesis [1], the second actually in test) as well as a third described in the EU patent. The second prototype still features a linear motion of the KSU pulled by a kite that supplies at least one generator connected via a toothed belt. It no longer works using the "pull peaks" of the ropes, but on the "pull variations" of the ropes themselves. These variations are created by the different positions and speeds of the kite as it flies within the "flight window".

KGM1 compensates for the lower power produced through an increase in the frequency of active cycles with a super short slide stroke, synchronized on the flight path, as shown in the plots below. Moreover, it also compensates with more constant kinetic energy impressed on both the kite and the generators, as well as "low cost depower". These characteristics allow to keep dimensions and weights contained and a probable simplification of the automatic flight control SW, with consequent savings on the total cost of the generator.



Left: typical power course of a conventional AWE system. Right: simulated power course of KGM1.

References:

[1] Federico Montanari, Modeling, control and optimization of an airborne wind energy system with translating ground unit, Politecnico di Milano, MSc thesis, 2018. [Available online]

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Ground Station Control of an Airborne Wind Energy System in a Complete Operational Cycle

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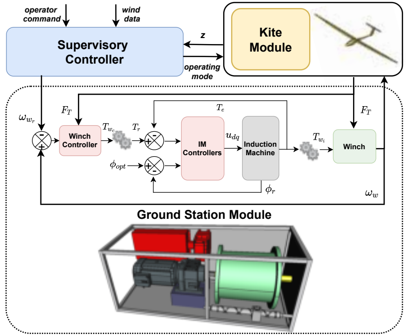
In this work, we develop and integrate a ground station controller together with a supervisory controller for an airborne wind energy system (AWES) in all its operational modes, covering a complete operational cycle. The main focus of this research is the robust control of the GSM, however, we also analyse the integration of the supervisory controller with the GSM and with an already developed kite module (KM) controller [1].
In order to obtain a reliable performance of the AWES during all the operational modes, we propose a cascade control strategy for the ground station module (GSM), which is adapted from [2]. The proposed control strategy includes two control loops. The outer loop uses sliding mode control (SMC) algorithm to maintain a desired winch velocity which serves as an input to the KM, whereas, the fast, inner control-loop is for obtaining the desired torque of the IM. A rotor flux oriented control (RFOC) technique is used, to achieve high performance control of the IM and enabling a DC machine like control of the two phase IM model. By using the RFOC technique, the torque and flux control problems are decoupled in such a way that the decentralized control of both torque and flux is possible. Moreover, back-stepping based SMC is employed for the IM controllers. The torque controller tracks the desired trajectory of the torque, which is required to obtain a desired winch speed. Simultaneously, the flux controller tracks an optimum flux trajectory, which minimizes the losses in the IM.
To evaluate the performance of the control scheme, simulations are carried out in MATLAB/Simulink. The simulation results show the desired behaviour in all operational modes.



Control architecture integrating the supervisor controller with the GSM and KM, detailing the GSM cascade controller. .

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Swinging Motion of a Flexible Membrane Kite with Suspended Control Unit During Turning Manoeuvres

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Most airborne wind energy systems use a single tether to connect the kite with the ground station. Some concepts use an additional bridle line system to distribute the force from the kite to the tether. Typically, flexible membrane kite systems use such a configuration and are steered by a control unit fixed to the bottom of the bridle. The inertia of the control unit affects the turning mechanism of the kite. Outside the reel-out phase, also tether sag affects the attitude of the kite substantially. In this study, we evaluate how well these effects are captured with two different models.

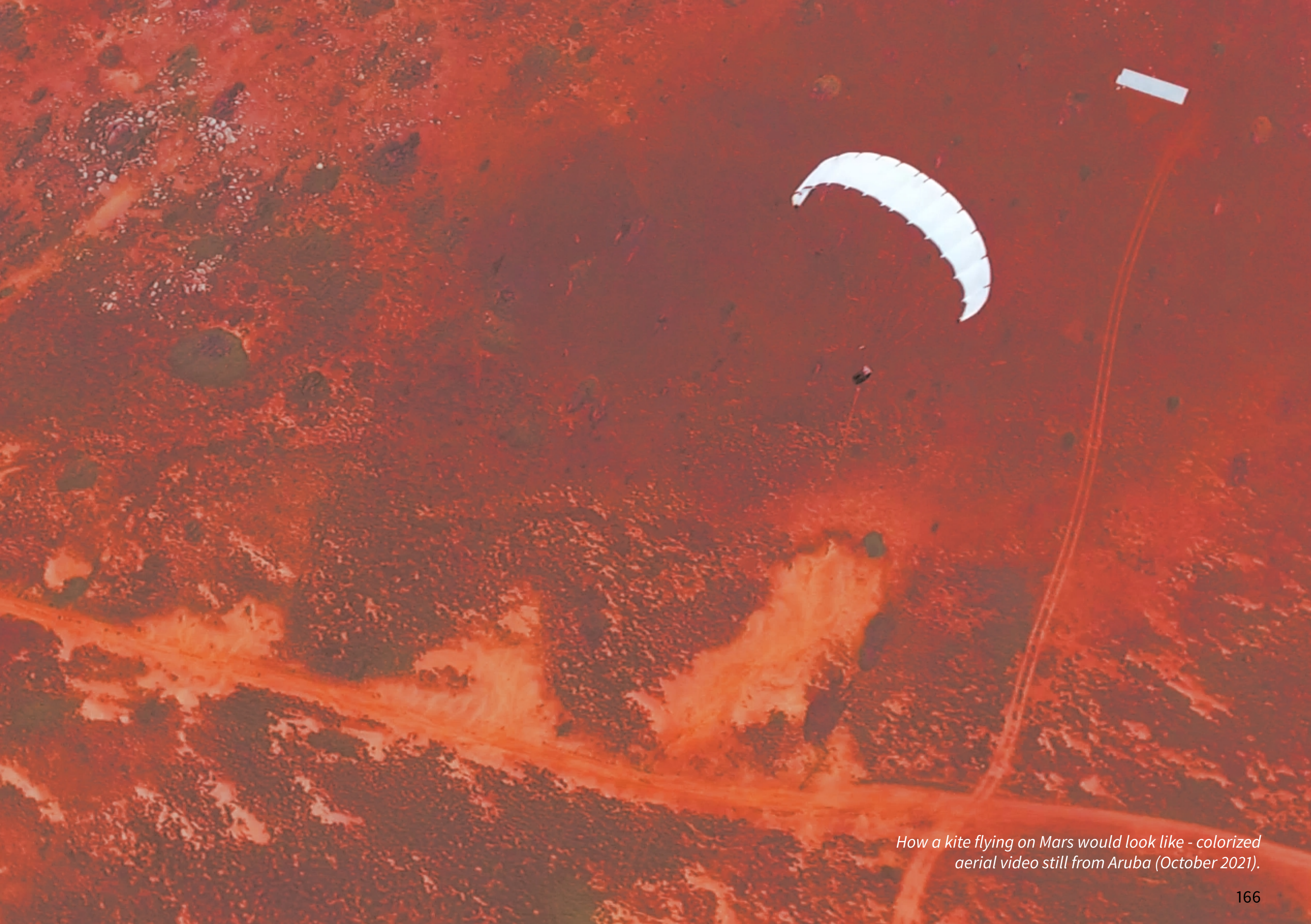
The pitch and roll of the kite are evaluated along an actual figure of eight flown by the development system of Kitepower B.V. using an extended discretized tether model. When under tension, the bridle fixes more or less the shape of the leading edge of the kite canopy. Consequently, the bridle can be modelled as an additional rigid link in a discretized tether model.

The tether-bridle shape is evaluated using two types of tether models. First, a time-invariant model is used to calculate the tether-bridle shape at individual snapshots in time. This model finds an instantaneous solution by assuming that the airborne components together rotate as a rigid body. The change over sequential snapshots illustrates the motion of the tether-bridle. Next, the full tether-bridle motion is simulated using a dynamic model by imposing the motion of the canopy inferred from the flight data.

The results of both the time-invariant models with single and 30 tether elements and the 30-element dynamic model agree well with the measured pitch and roll of the kite along the figure of eight. The roll of the aerodynamic force of the kite provides the centripetal force and thus enables the kite to turn. Most of the roll of the aerodynamic force into the turn results from the roll of the kite. Since a multi-point-mass model accurately captures the roll of the kite, the turning mechanism can be incorporated with a physical model. In contrast, a single point mass model needs to rely on empirical relationships for turning the kite.

The 30-element time-invariant model is also used to evaluate the pitch of the kite along ten pumping cycles. During the reel-in, the pitch varies substantially as the kite is flying towards the zenith. Nevertheless, the results show a good match with the measurements. Consequently, the model is compatible with an aerodynamic model of the kite with a dependency on the angle of attack, which strongly depends on the pitch.

To conclude, performance models with a dedicated point mass for the control unit are general applicable and model the state of the kite more faithfully than single-point-mass models. In the case of a two-point-mass model, the extra computational effort is small. As such, these models can be a powerful tool for the performance modelling of flexible kite systems.



How a kite flying on Mars would look like - colorized aerial video still from Aruba (October 2021).

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Design of an Airborne Wind Energy System for Mars Habitats

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Renewable energy for a Mars habitat is a technological challenge. Resources such as solar and wind are weaker than on Earth because the atmosphere is 70 times less dense, solar irradiation is roughly half and global dust storms can sometimes render photovoltaic (PV) panels useless for months. The requirements on reliability and robustness are demand- ing. Martian gravity is a third of that on Earth. It is crucial to combine resources for an effective renewable energy solution. Wind and solar resources are complimentary and result in a more consistent power supply. Batteries are used to store excess energy for periods of exceptionally low energy production. Airborne wind energy (AWE) was selected as a solution because of its low mass-to-wing-surface-area ratio, compact packing volume, and high capacity factor which enables it to endure strong dust storms in an airborne parking mode. This work investigates the feasibility of a pumping kite power system in combination with solar PV modules to power the construction as well as the subsequent use of a Mars habitat. A scaling study assesses how AWE on Mars differs from that on Earth, performing dimensional analysis.

The present study builds on an earlier design project for a 10-kW Mars habitat [1]. The Luchsinger model [2] and the higher fidelity quasi-steady model (QSM) [3] are used to simulate the performance of the AWE system located North of Arsia Mons at the Tharsis bulge. The QSM is used for validation and also allows accounting for the mass of airborne system components. Due to the lack of in situ observations of meteorological data, the Mars Climate Database (MCD) is used to retrieve wind data and Weibull probability distribution functions. The MCD is based on numerical simulations of the Martian atmosphere using a General Circulation Model and validated with available observational data. Seasonal vertical wind profiles are generated from the meteorological data. An optimiser wrapper around the QSM is used to refine the free parameters of the pumping cycle operation to maximize energy production for the determined wind profiles.

To meet the requirement of 10 kW continuous power supply to the habitat for each Martian day, throughout the year, the AWE system is combined with solar PV and battery storage. The performance model is used to size the different components. The study shows how AWE can be used in combination with solar PV to provide a stable renewable energy supply to a habitat on Mars. This is similar to remote off-grid solutions on Earth, with the additional challenge of having lower resource availability, both for wind and solar.

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Dynamics of Tethered Airborne Wind Energy Systems

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We present numerical results from ongoing research on the dynamics of tethered airborne wind energy (AWE) systems. The systems considered are a stationary autogyro and a kite power system. The on-board power generated by the autogyro is transmitted to the ground station via a tether, whereas in the case of the KPS, aerodynamic forces from the kite cyclically drive the winch-generator via a tether that can reel-in/-out to generate electricity on the ground. Unlike most tether models in the literature (e.g., Refs. [1,2]), in the present model, the equations of motion are derived within the Lagrangian framework. The continuous elastic tether is modelled as a series of inter-connected extensible links with lumped masses at the ends and negligible rotary inertia. The derivations as well as implementation were made much simpler by adopting the Cartesian coordinates of the end-points of the links as the generalized coordinates. This contrasts with the models (e.g., Ref. [3]) which adopt polar and azimuthal angles as generalized coordinates. In addition to the above novelties, the present study also introduces unsteady blade element momentum (UBEM) theory to predict the unsteady aerodynamics of autogyro based on look-up tables, unlike averaged aerodynamic performance predictions, which is common in the literature.

AWE systems have a great potential for harnessing large amounts of wind energy at lower costs when compared to conventional bottom-fixed wind turbines. However, flow-induced vibrations and tension fluctuations in the tether are potential threats to the reliability and efficiency of the system. They can reduce the fatigue life of the tether and can result in a complete failure of the airborne module and likely the base station.

The dynamics of the tether is modelled in a vertical plane, for simplicity. The axial stiffness of the tether is accounted for by linear springs, and the structural damping is modelled by viscous dampers. The reel-in/-out dynamics of the KPS is implemented by dynamically changing the length, mass, and stiffness of the links. The wind profile follows the power law. The aerodynamic forces acting on the tether are distributed on the lumped masses. They are calculated following the well-known independence principle and by obtaining the relative velocity between the wind and vibrating tether. The aerodynamic performance of the autogyro is predicted using the UBEM theory and the kite is similar to a fixed-wing. The results are obtained by solving a system of differential equations in the time domain. The results include the time history of vibrations, tether tension and the power output of the system. Future works will include (but are not limited to) a three-dimensional model incorporating the winch dynamics.

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Open-Source Parametric Finite-Element Meshing Tool for Fixed-Wing AWE Kites

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To reach a power production of multiple megawatts, AWE systems are required to grow considerably larger in size. Over 60% of the global warming potential (GWP) of a fixed-wing kite is due to carbon fibre reinforced polymers [1]. A lower GWP of materials is indispensable in scaling-up of AWE systems. Soft-wing kites have the benefit that the added volume is mostly extra air entrapped within the flexible membrane structure. However, for fixed-wing kites, increasing the dimensions leads to a substantially stronger increase in mass, which negatively affects the power output of larger AWE systems. Therefore, a higher fidelity structural model is required to better estimate and reduce the mass in the conceptional design phase of the system and study the viability of using more environmentally attractive materials.

Finite element (FE) modeling is considered a high-fidelity structural modeling approach and can potentially require many hours of design work to implement. The framework presented here is intended to be used as an open-source fixed-wing kite meshing tool, capable of creating an FE mesh from a set of common AWE system design parameters within seconds. This framework is also well suited for structural layout optimization studies. The parametric FE meshing and weight prediction capabilities are validated against the Ampyx Power AP3 remote piloted aircraft and compared to a tapered beam model, commonly used in conceptual design studies. In turn, an improved detailed reference kite progressing from MegAWES [2] can be designed. Future application of the tool will include studying the effects of design changes and the use of more environmentally attractive materials on a pre-determined set of structural failure criteria and fatigue behavior.

The tool chain couples Matlab with GMSH, an open source three-dimensional finite element mesh generator. A list of parameters is thereby converted into a FE mesh. Simcenter Nastran, a commercial structural solver from Siemens, is then called for structural analysis. The tool chain can also support other solvers, however, in this instance Simcenter Nastran was chosen due to the high degree of reliability.

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Example of a quadrilateral mesh of the wing tip section generated from the MegAWES [2] reference kite (colorized for illustrative purposes).

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Achieving Ultralight, Rigid, Durable, Low-Cost Composite AWE Kites With Efficient Design and Manufacturing

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[2]Delft University of Technology

The economic viability of AWE systems is linked to the performance, robustness, and economics of the wing. This represents a challenging field of research and development – to manufacture cost effective composite wings. At EnerKíte, the choice of ultralight, multi-tethered rigid wings prescribe unique requirements that cannot be readily achieved with conventional techniques from aircraft wings.

EnerKíte is collaborating with DLR, TU-Berlin, and INVENT GmbH within the industrial research project EnerWing, funded by the German Federal Ministry of Economics and Technology BMWi [1]. The aim of the project is to set up validated design methodologies and toolchains for rapid iteration of wing configurations and designs. This allows for optimized, use-case, and site-specific scalable wings to be effectively designed and manufactured.

In this work, we present our practical experiences from multi-generational kite development and manufacturing composites over the years.

References:

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Dbox and rib skeleton, with membrane cover of early generation prototype wing.

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Fast Aeroelastic Model of a Leading-Edge Inflatable Kite

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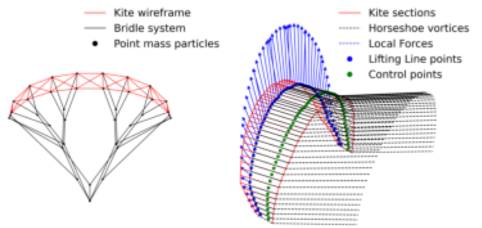
[2]Technical University of Denmark

When designing an airborne wind energy system, it is necessary to be able to estimate the traction force that the kite produces as a function of its flight trajectory. Being a flexible structure, the geometry of a soft kite depends on its aerodynamic loading, and vice versa, which forms a complex Fluid-Structure Interaction (FSI) problem. Currently, kite design is usually done on an experimental basis, since no model meets the requirements of being accurate and fast at the same time.

In this project, an FSI methodology is developed to study the steady-state aerodynamic performance of leading-edge inflatable (LEI) kites by coupling two fast and simple models.

On the structural part, the deformations are calculated with a particle system model [1], based on the assumption that the shape of the kite can be modeled using a wireframe wing model represented by the bridle line attachment points, whose coordinate changes are modeled using a bridle line system model and canopy ballooning relations.

On the aerodynamic side, the load distribution is calculated with a 3D nonlinear vortex step method [2,3], coupled with 2D polars obtained with a correlation model derived from CFD data [4], to account for viscous effects and flow separation, as well as the changes in airfoil geometry. Based on 2D thin airfoil theory, the 3/4c point is used to determine the magnitude of the forces and the 1/4c point is used to determine direction of these forces. Moreover, the model developed for LEI kites is capable of taking into account ballooning and variations in kite and airfoil geometry, while proving to be robust and inexpensive. This model has been validated with several geometries, together with a RANS analysis of the LEI kite, showing great accuracy for pre-stall angles of attack.



Particle system model representation (left), vortex step model discretization example (right).

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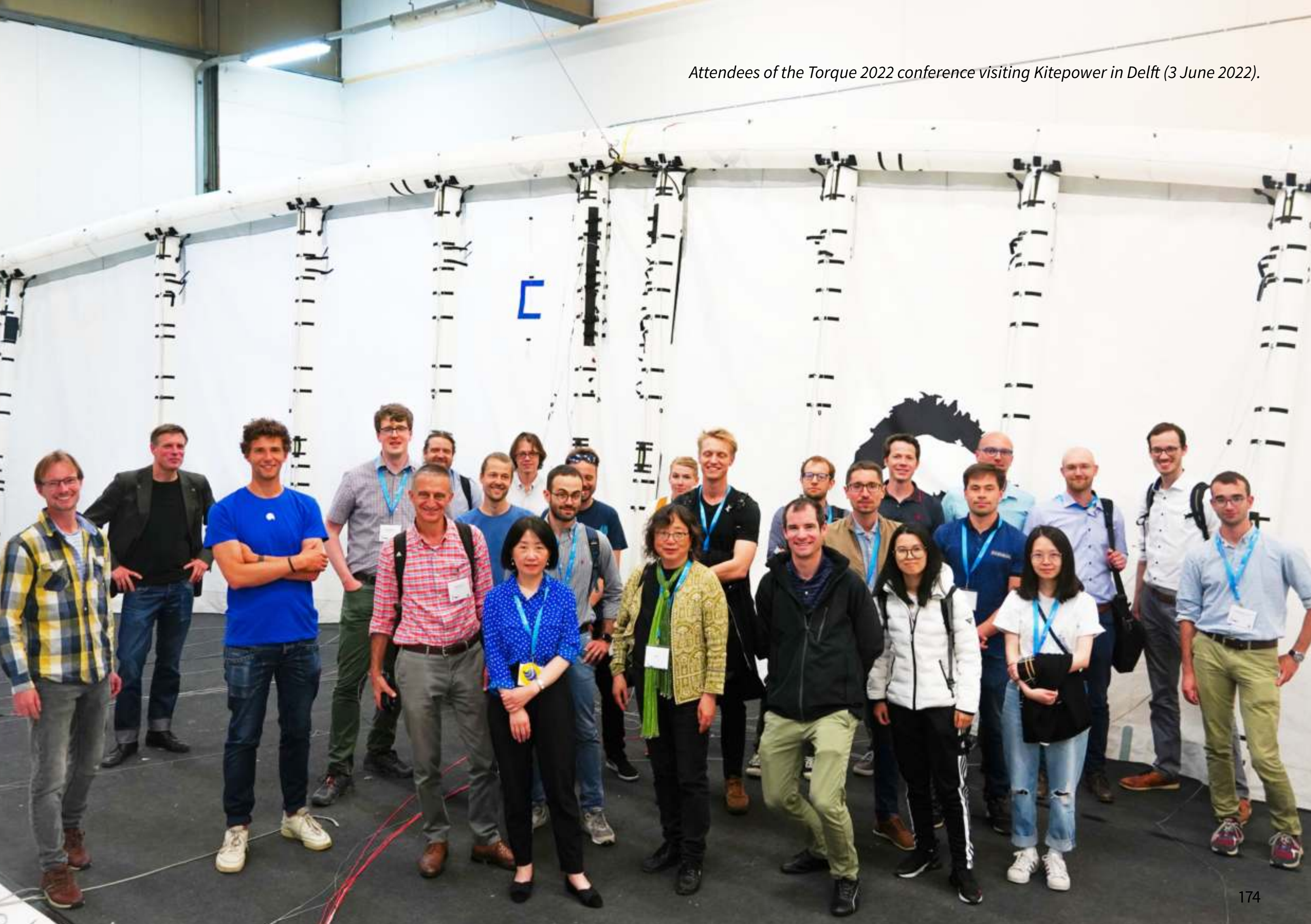
Kitepower's 60 m² kite during a system demonstration in Melissant, the Netherlands (May 2021).

Kitepower Falcon 100 kW AWES during operation a system demonstration in Melissant, the Netherlands (May 2021).



Attendees of the Torque 2022 conference visiting Kitepower in Delft (3 June 2022).

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Kitepower's Journey to the Islands and Beyond

Johannes Peschel, Joep Breuer
Kitepower BV

Kitepower has developed a unique airborne wind energy system since 2016: structurally reinforced leading-edge inflatable kites with a semi-autonomous launch and landing system and a containerized winch which is designed to produce 100kW nominal power. A simple, low-cost system that can easily be deployed at customer sites.

We know that timing and cost of electricity are major concerns for our stakeholders, including potential customers. We have identified that one of the main cost drivers of the system is an autonomous launch and landing system, both in terms of development cost and CAPEX. Permitting uncertainties, safety, environmental impact as well as performance guarantees are key challenges for customer engagement.

We have developed our containerized Kitepower system which addresses these issues. Swiftly trained operators set up within hours and guarantee safe operation. The unique depower system for the kite ensures efficient energy conversion with a small footprint. Our safety system lands the kite in a parachute mode in all unforeseen conditions. The kite can be relaunched within hours. The integrated rechargeable battery offers a standalone solution that can be deployed in places with no electrical infrastructure.

In October 2021, the system was successfully deployed and operated on the Caribbean Island of Aruba as part of a training mission which was funded by the Dutch Ministry of Defense.

We are currently accelerating the relaunching process and reduce the number of landings by lowering the minimum flyable wind speed to zero by investing energy and the maximum wind speed beyond 20m/s. This will make most of the landings obsolete as shown in the figure below. We are ready to increase our flight time, power output and to do more pilot projects.

References:

[1] https://thekitepower.com/kitepower-in-aruba/

Kitepower's 60 m^2 kite deployed in the companies workshop in Delft (June 2021).

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Kitemill – Commercial Development

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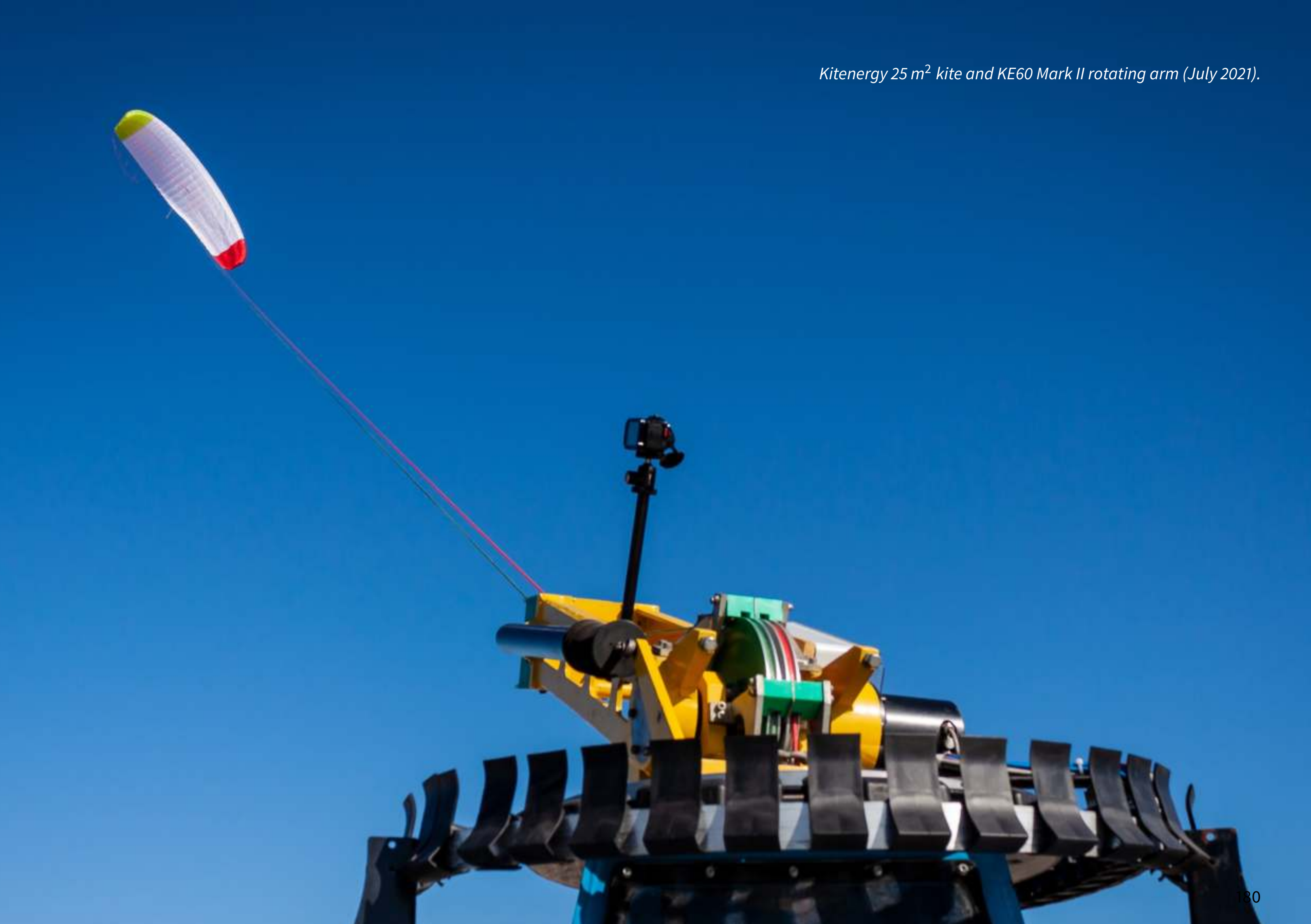
This presentation summarizes important developments for Kitemill since the AWEC 2019 in Glasgow. In 2020, Kitemill acquired the Scottish airborne wind energy company Kite Power Systems (KPS), obtaining all the intellectual properties comprising multiple patents, a market analysis that recently was made publicly available, as well as engaging KPS's former CEO David Ainsworth as an advisor and business developer in Kitemill. Said collaboration has already resulted in the approval of the Norse Airborne Wind Energy Project (NAWEP), a 7.5-million-euro project where Kitemill will operate 12 x KM2 kites rated to 100 kW from 2024 at Holtålen in Norway [1]. In 2021, Kitemill also acquired the Dutch airborne wind energy company eKite, resulting in the acquisition of additional patents and intellectual properties, such as the eKite ground station, their flying wing, and several analyses. As part of the eKite acquisition, the eKite team joined Kitemill such that Kitemill now comprises more than 20 core members who are collaborating all across Europe. This is part of Kitemill's belief in consolidation within the industry to focus investments and effort resulting in accelerated progress towards commercial operations. Kitemill sees many new opportunities for cooperation and risk sharing as the technology being industrialized and aims to continue with similar methods.

References:

[1] European Commission Innovation Fund: NAWEP: Norse Airborne Wind Energy Project (NAWEP), 2021. https://ec.europa.eu/clima/system/files/2021-12/policy_if_pf_2021_nawep_en.pdf

Kitenergy KE60 prototype being installed in Puglia region in Southern Italy.

Kitenergy KE60 Mark II at San Pancrazio airfield on the south-east coast of Italy. (July 2021).



Kitenergy 25 m^2 kite and KE60 Mark II rotating arm (July 2021).

Kitenergy 25 m^2 ram-air kite clean configuration (September 2021).

Kitenergy 25 m^2 ram-air kite with avionic payload (October 2021).

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A Multidimensional Trade-off

Gian Mauro Maneia, Stefano Sanmartino
Kitenergy Srl

More than ten years of testing with Kitenergy KE60 prototype led us to a simple conclusion: the winning architectures will be limited to a few brilliant interpretations of technical and economic constraints generating sound business cases.

The first dimension is lightness, we immediately understood that given a certain kite surface each gram makes a huge difference, increasing the minimum ground wind speed during take-off and reducing the yearly energy yield. We also learned very soon that slightly reducing the tethers diameter dramatically affect the Safety Factor.

A second dimension is flight autonomy, on board sensors require energy, on board actuators require a lot more energy. How much is compatible with 24/7 continuous operations?

The third dimension is related to climate change. In 2010 we initially built our mission profile around Mediterranean climate. During Spring 2021 test campaign, for several weeks the "African Bubble" raised temperatures in Puglia Region well over 45° C, red lights populated the cockpit and top-quality industrial grade components started protecting themselves from overheating. A few months later, we had tropical rainfalls and flooded surrounding fields. High Ingress Protection rating increases manufacturing costs, cabinet's conditioning increases energy baseload as well, which operating conditions must be considered for a twenty years mission profile?

Finally, we realized that redundancy cannot be avoided in many more areas than originally foreseen. Kitenergy's design always adopted a two tethers approach for increased safety, but time after time we discovered (and solved) many other single points of failure. If a DC-DC converter fails while operating in energy island mode, you can hardly recover the kite back to the ground, then we added a second converter and energy storage. If a node of the industrial fieldbus experiences a problem, the Integrated Safety of industrial automation devices launches the emergency stop procedure just in the middle of a beautiful flight, then we changed our bus topology. And what about the motion controller? Will any of us cross the Ocean knowing that the pilot has a single flight computer onboard?

Airborne Wind Energy is aerospace technology, isn't it?

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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 archived documentation of the following events 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

Mediasite Video Showcase, edited by Roland Schmehl, 56 presentations.
https://collegerama.tudelft.nl/mediasite/Showcase/Channel/conference-airborne-wind-energy

AWEC 2017, 5-6 October 2017, Freiburg, Germany
Book of Abstracts, edited by Moritz Diehl, Rachel Leuthold, Roland Schmehl, 188 pages.
ISBN 978-94-6186-846-6
DOI 10.4233/uuid:4c361ef1-d2d2-4d14-9868-16541f60edc7
DOI 10.6094/UNIFR/12994

University of Freiburg Media Portal, edited by Patrick Caspari, 53 presentations.
https://videoportal.uni-freiburg.de/search/tags/AWEC/

AWEC 2019, 15-16 October 2019, Glasgow, United Kingdom
Book of Abstracts, edited by Roland Schmehl, Oliver Tulloch, 164 pages.
ISBN 978-94-6366-213-0
DOI 10.4233/uuid:57fd203c-e069-11e9-9fcb-441ea15f7c9c

Video series, edited by Roland Schmehl, produced by Marco Seyer, 43 items.
https://av.tib.eu/series/973

AWEC 2021, 22-24 June 2022, Milan, Italy
Book of Abstracts, edited by Lorenzo Fagiano, Alessandro Croce, Roland Schmehl, Stefanie Thoms 188 pages.
ISBN 978-94-6384-350-8
DOI 10.4233/uuid:696eb599-ab9a-4593-aedc-738eb14a90b3

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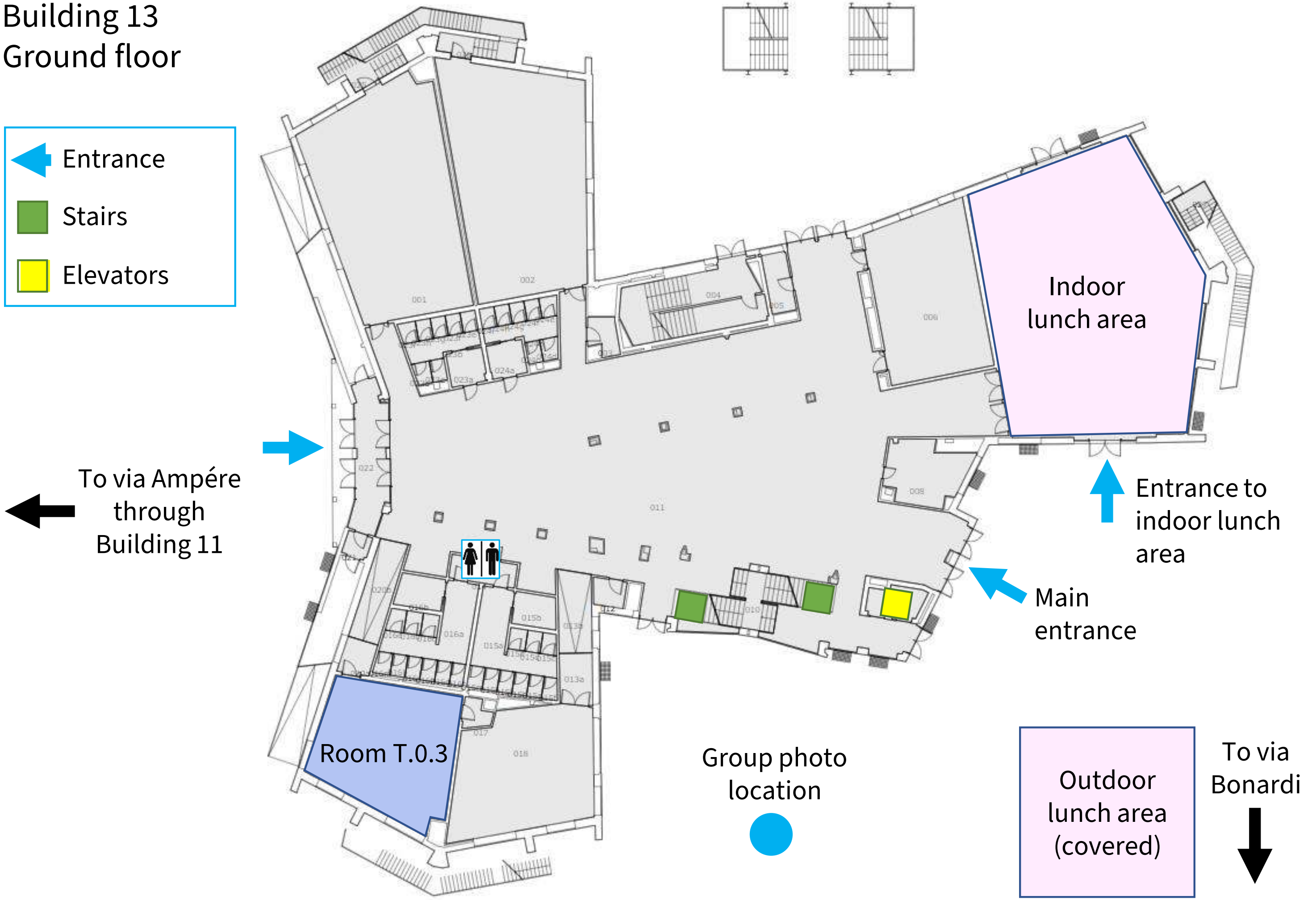
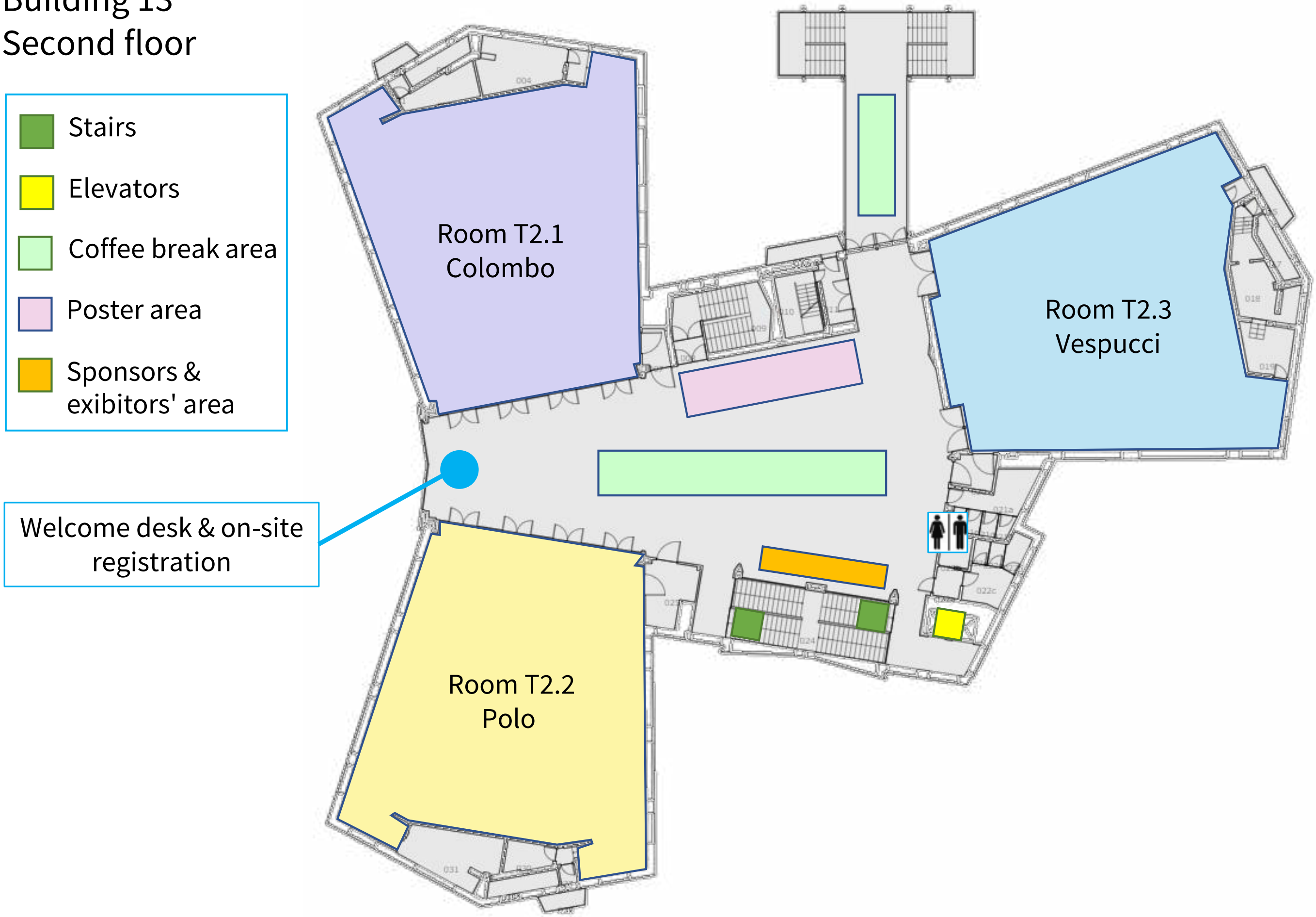
Building 13
Ground floor



Building 13
Second floor



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