Image source: Makani

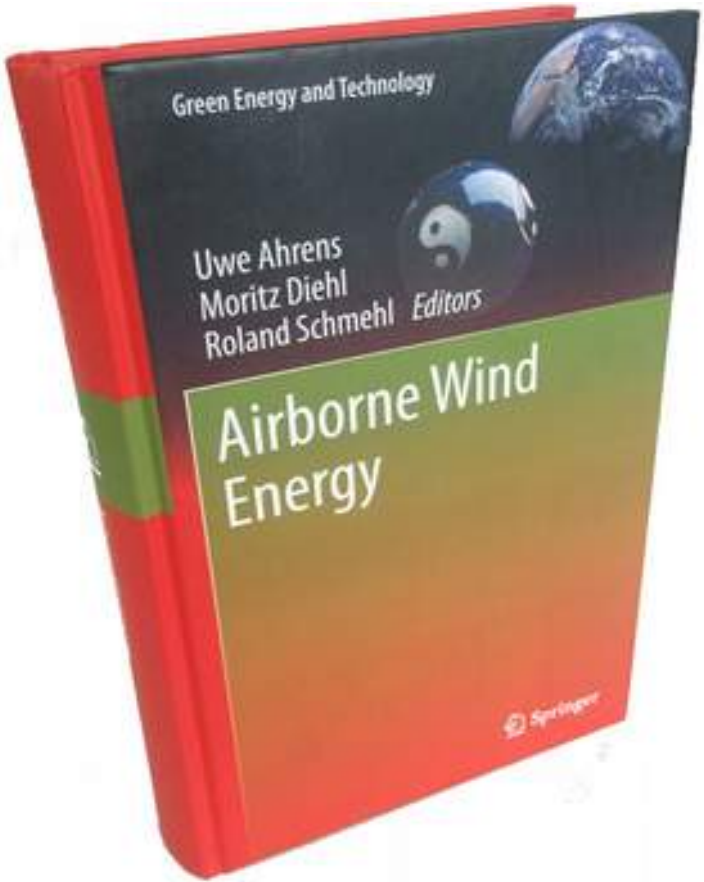
Airborne Wind Energy

R&D status & outstanding challenges

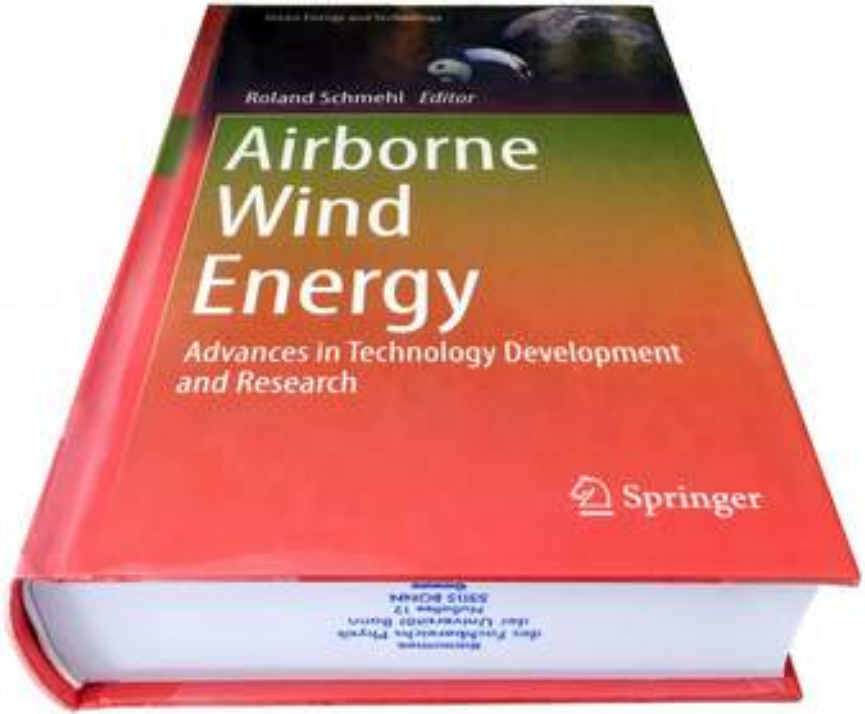
Roland Schmehl, TU Delft

Presenter

- Associate Professor at Delft University of Technology
- Co-founder of Kitepower BV
- Coordinator of 2 H2020 projects (AWESCO & REACH)
- AWE-responsible PI in Dutch NWO project NEON
- Co-organizer of AWEC 2015, 2017 and 2019
- Co-editor and editor of 2 Springer textbooks on AWE


Green Energy and Technology
Uwe Ahrens
Moritz Diehl
Roland Schmehl Editors
Airborne Wind Energy
Springer

2013


Roland Schmehl Editor
Airborne Wind Energy
Advances in Technology Development and Research
Springer

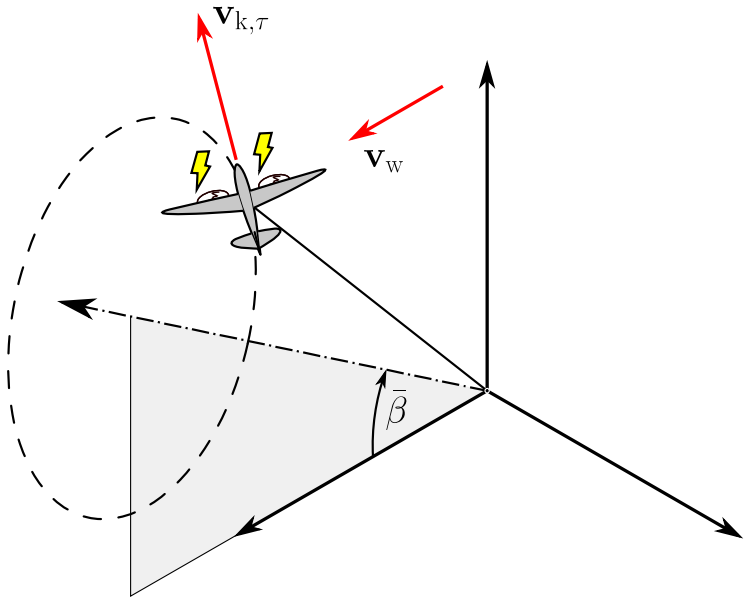
2018

Outline

- Fundamental working principles
- Classification of concepts
- Implemented technology demonstrators
- Development challenges
- Research challenges
- Development of the sector

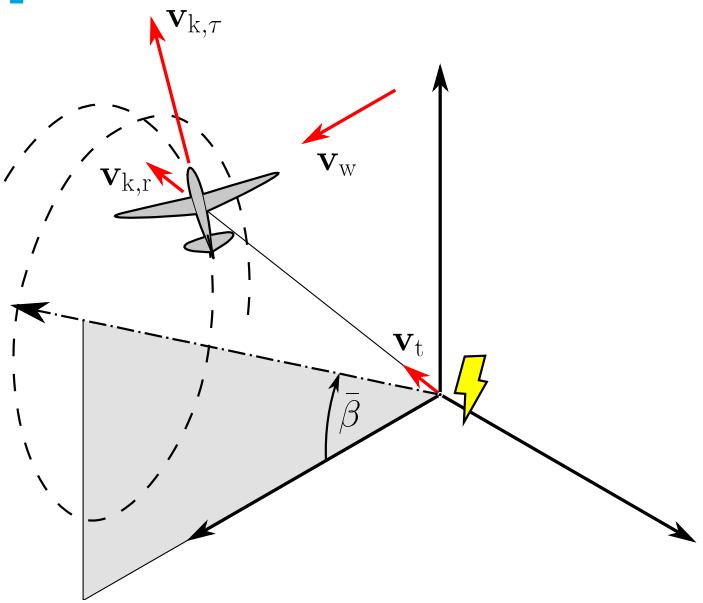
Fundamental concepts

Miles L. Loyd (1980)



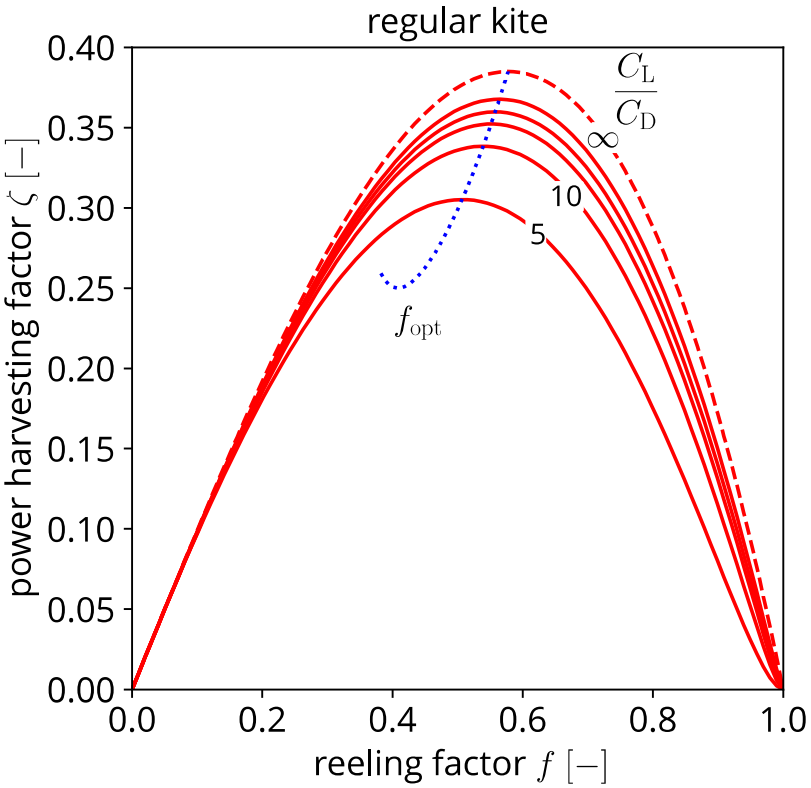
Drag power:

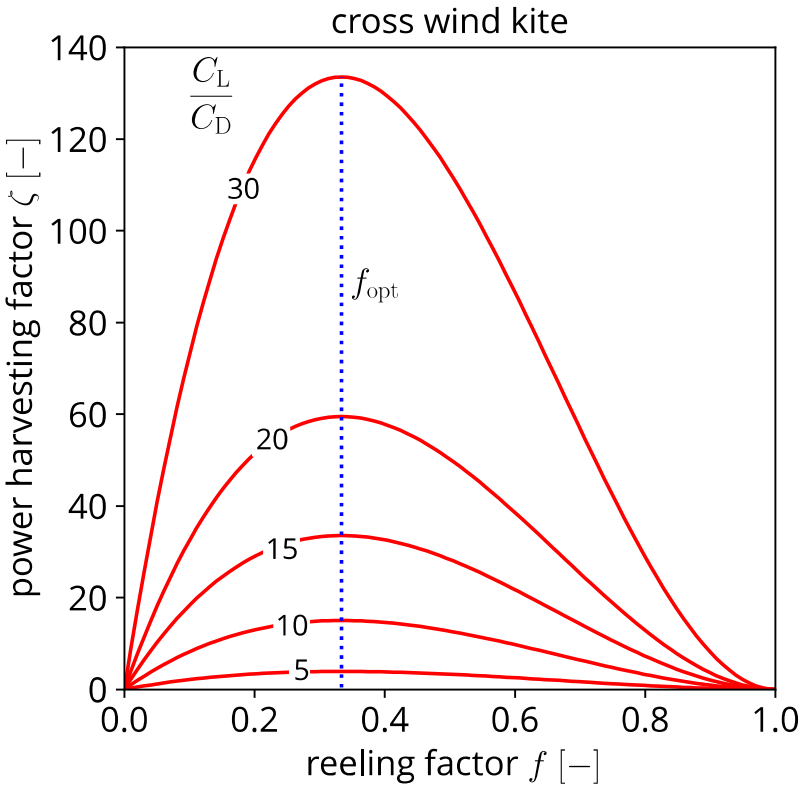
- Flying wing ⇝ shaft power
- Shaft power ⇝ electricity (ω ↑)
- Electricity ⇝ conductive tether



Lift power:

- Flying wing ⇝ traction force
- Traction force ⇝ shaft power (ω ↓)
- Shaft power ⇝ electricity





power harvesting factor $\zeta = \frac{P}{P_w S}$, wind power density $P_w = \frac{1}{2}\rho v_w^2$, reeling factor $f = \frac{v_t}{v_w}$,

mechanical power P, wing surface area S

Key aspects

- Consumes significantly less material
- Highly adjustable to wind resource
- Access to high altitude wind
- Increased mobility

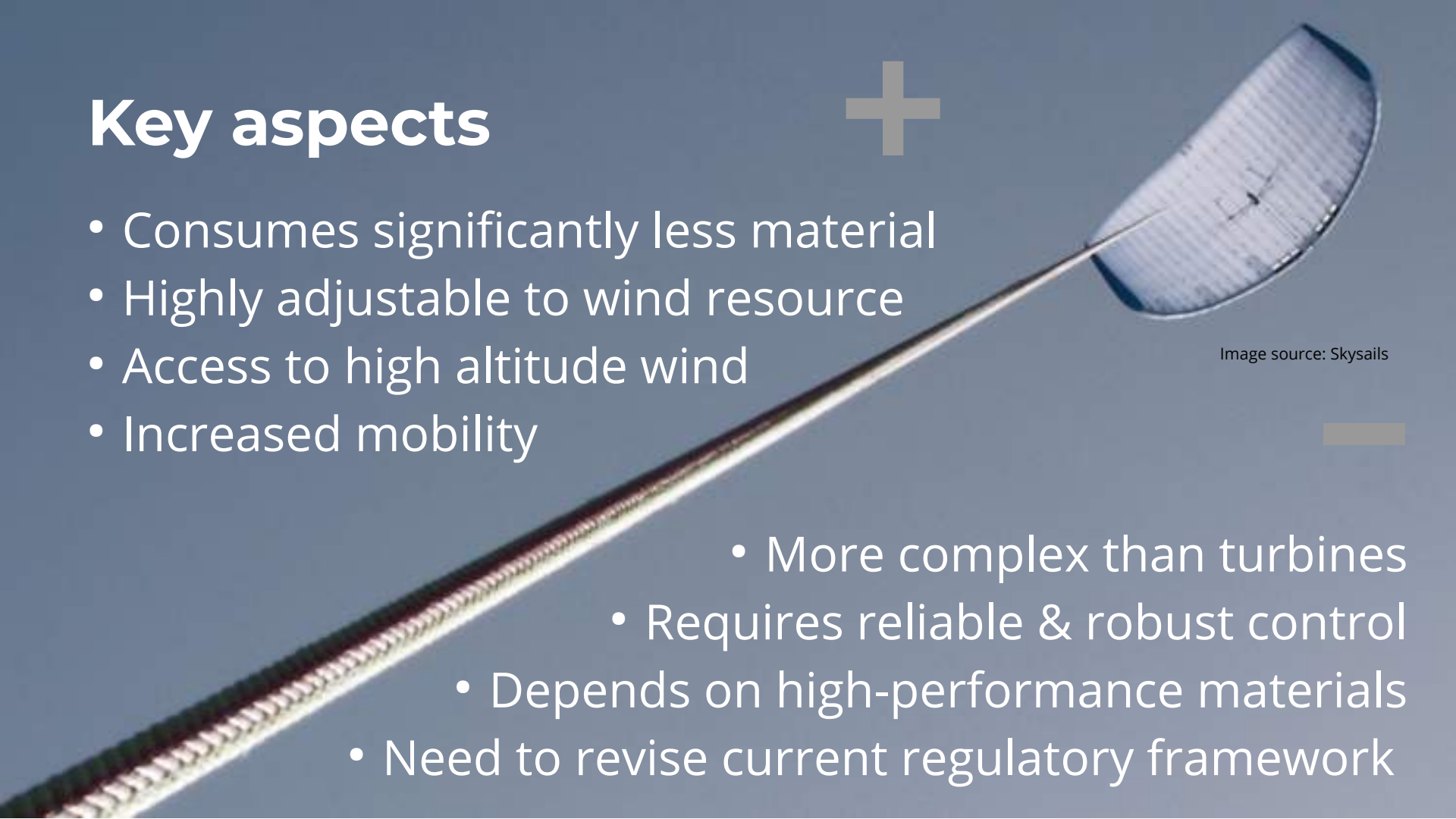
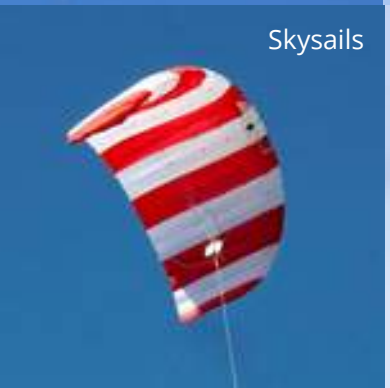
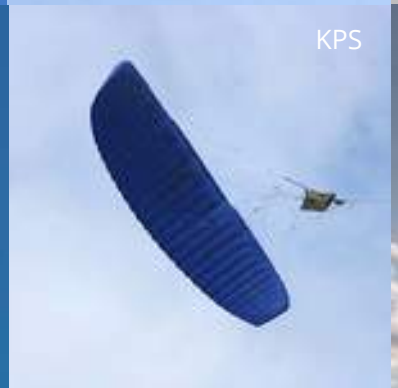


Image source: Skysails

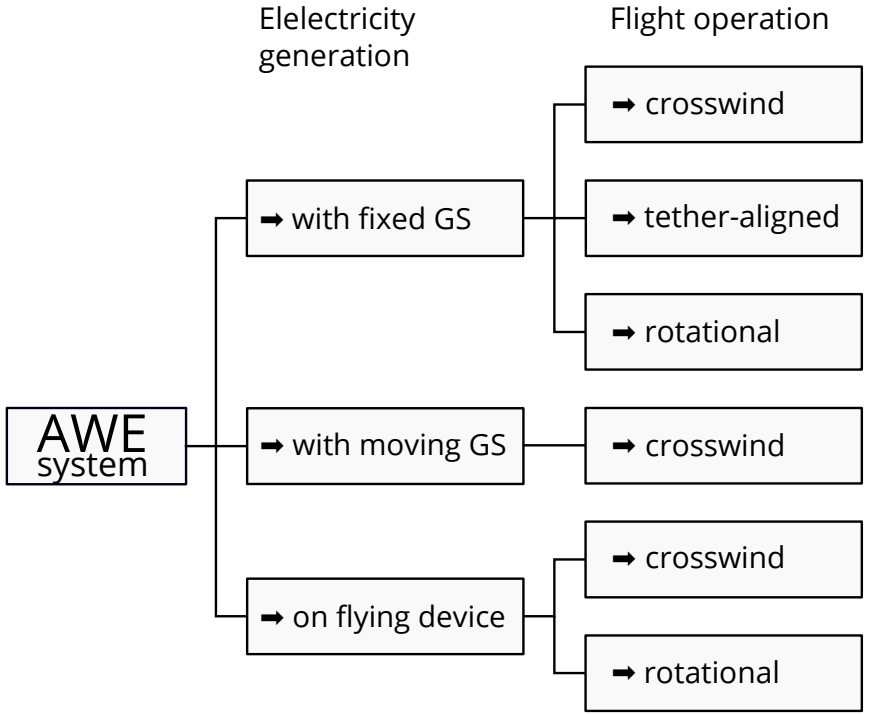
- More complex than turbines
- Requires reliable & robust control
- Depends on high-performance materials
- Need to revise current regulatory framework

Technology demonstrators





AWES classification

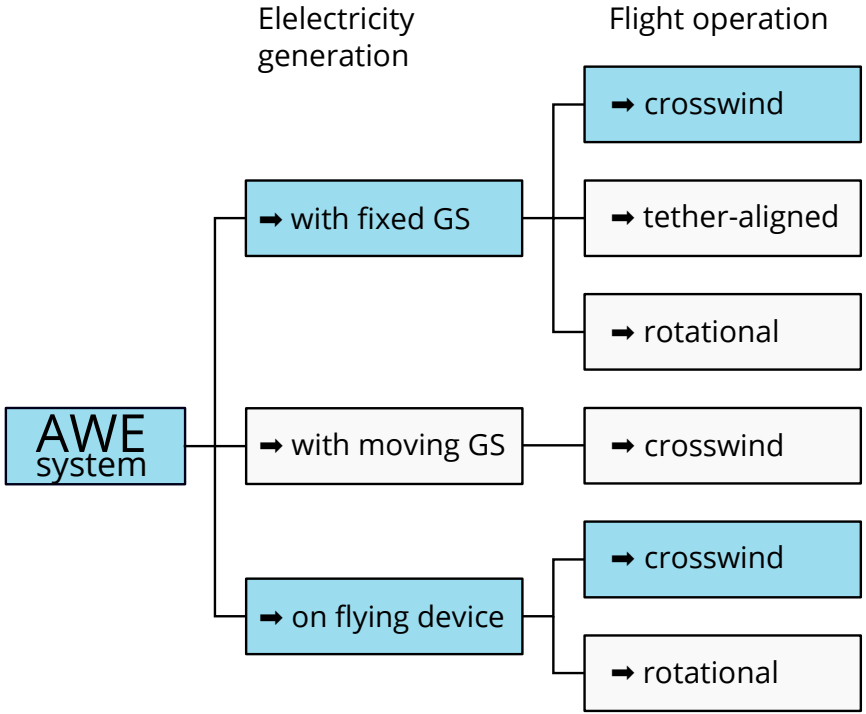


- Kitemill
- Skypull
- TwingTec
- E-Kite
- EnerKíte
- Ampyx
- KPS
- Kiteswarms
- Kitepower
- Kitenergy
- eWind Solutions
- KiteGen stem
- SkySails Power
- Omnidea
- Laddermill
- Guangdong HAWP
- Windswept
- someAWE
- Kitewinder
- X-Wind loop track
- KiteGen carousel
- Makani
- KiteKraft
- Windlift
- KiteX
- Altaeros
- Magenn
- Bladetips
- Brainwhere
- Sky WindPower

- Vertical take-off and landing (VTOL)
- Horizontal take-off and landing (HTOL)
- Multi-drone concepts
- Ligther-than-air concepts
- Flexible wing concepts

Adapted from: Watson et al. “Future emerging technologies in the wind power sector: a European perspective”, Renewable and Sustainable Energy Reviews, 2019.

AWES classification



- Kitemill
- Skypull
- TwingTec
- E-Kite
- EnerKíte
- Ampyx
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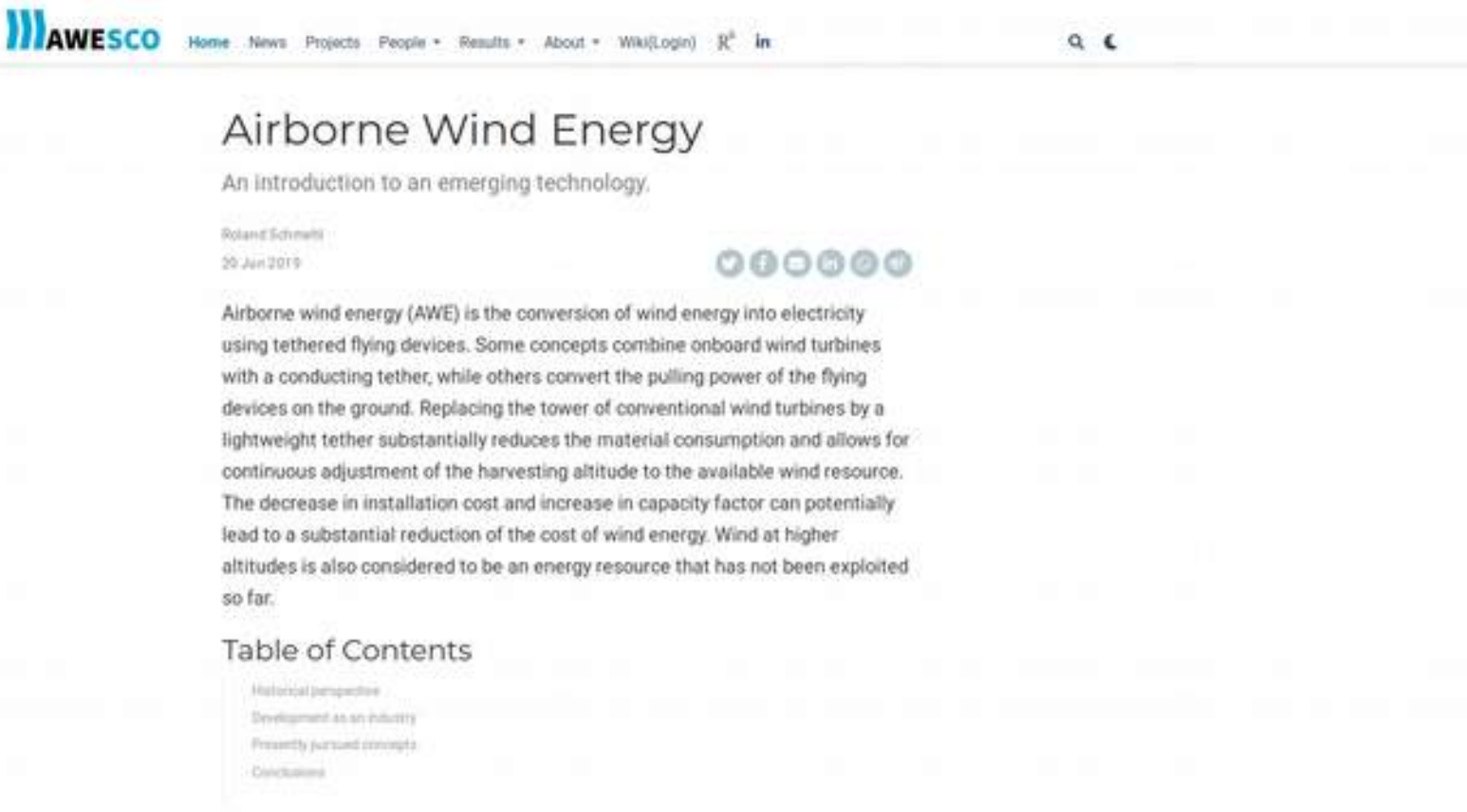
Further reading: awesco.eu/awe-explained



Technology demonstrators

- Makani
- Ampyx (→ presentation Jaap Bosch)
- Enerkite
- Twingtec
- Kitemill (→ presentation Lode Carnel)
- Kitepower

Wing7 (30 kW)

MAKANI

California 2013

M600 (600 kW)

MAKANI

California 2017


MAKANI
Hawaii 2018


MAKANI
Norway 2019


Karmøy, Norway
August 2019

AP-2 (50 kW)

Noordoostpolder 2013

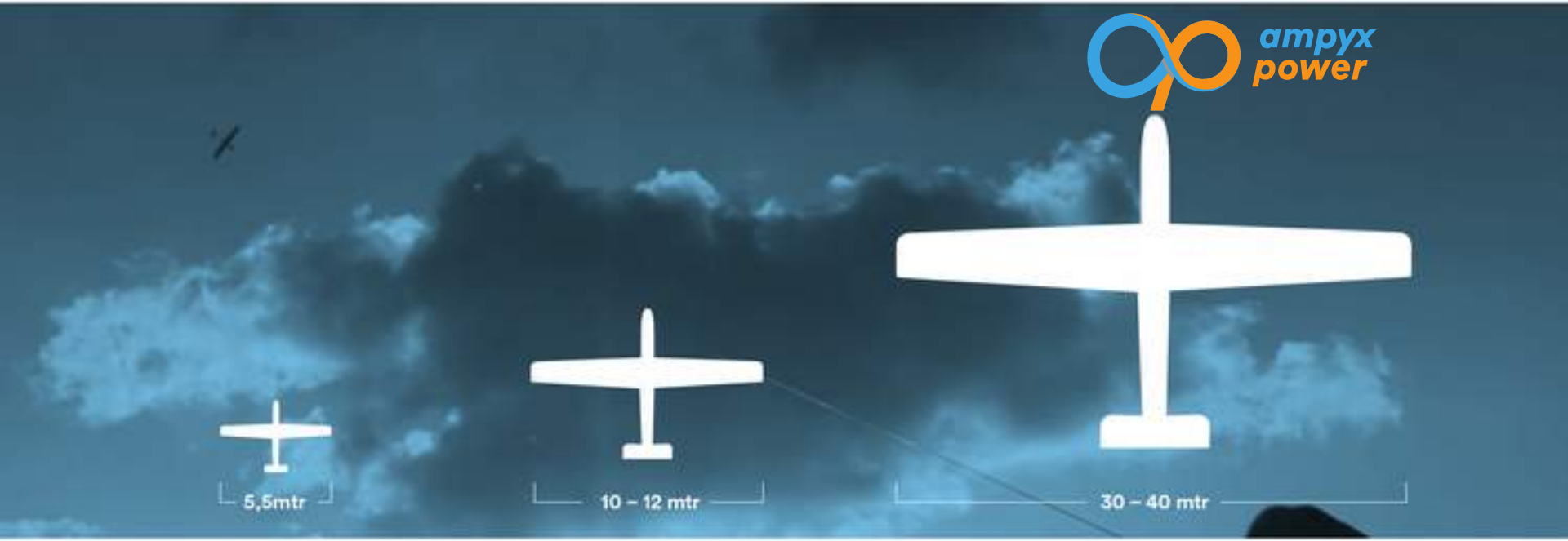
AP-3 (250 kW)

ampyx power

Marin 2018


SCHELLING

= ±250 households*



50kW

Prototype AP2
30 households

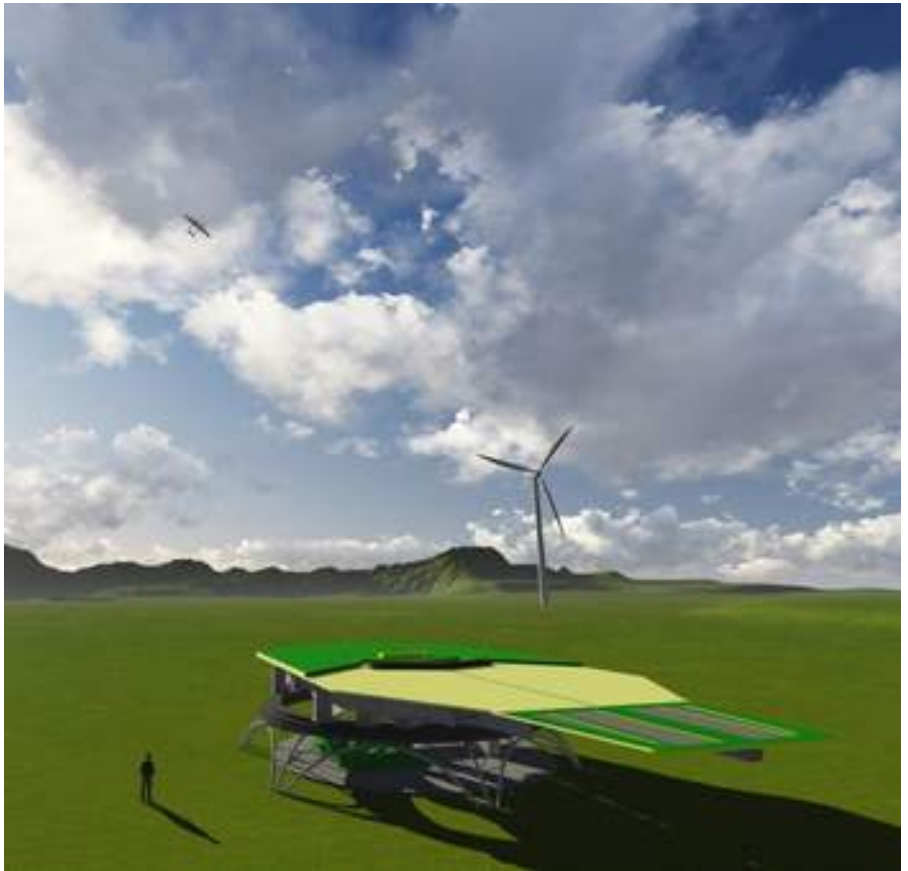
250 kW

Demo AP3 full functionality, certifiable,
restricted type certification 150 households

2 MW

Commercial product AP4 certified,
minimal cost of energy 1000 households

Ampyx Power AP4: 2 MW




EnerKíte
Germany 2012

EnerKíte

Germany 2014

EnerKíte

Germany 2019

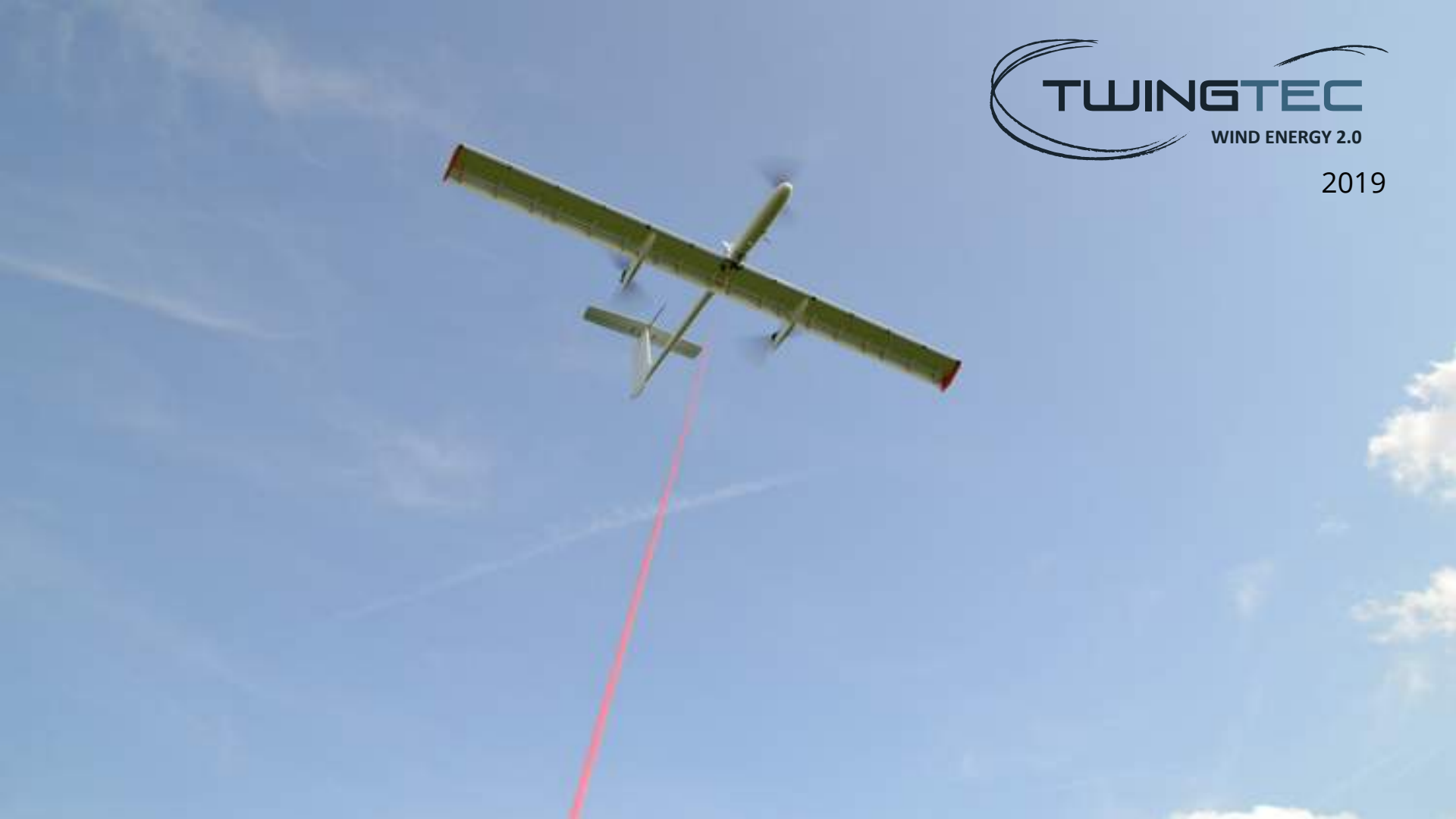

EnerKite
ENERKITE
AMK


EnerKite
AMK

TWINGTEC

WIND ENERGY 2.0

2012


TWINGTEC
WIND ENERGY 2.0
2019


TWINSTEC

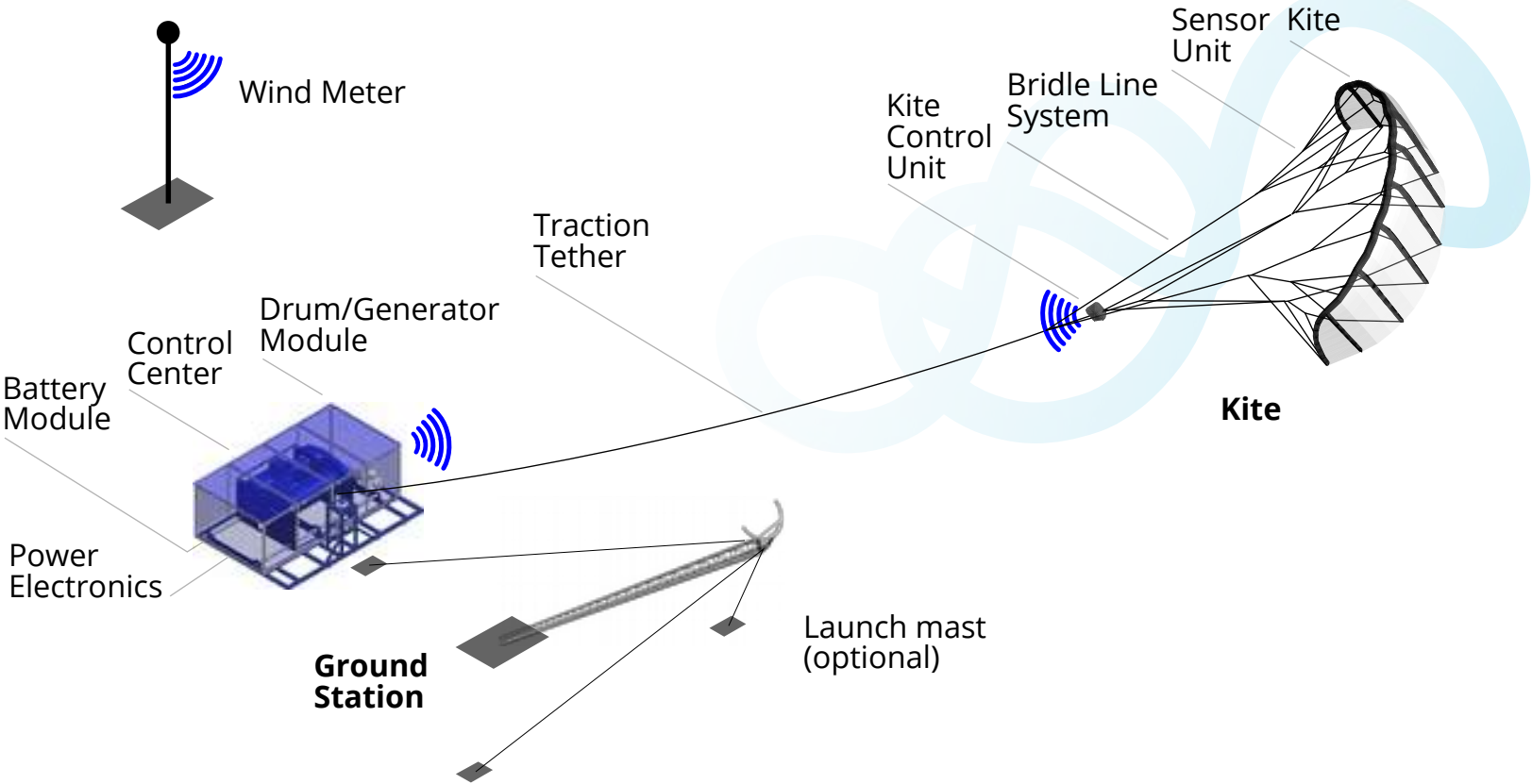

TwingTec pilot next to turbine with same power

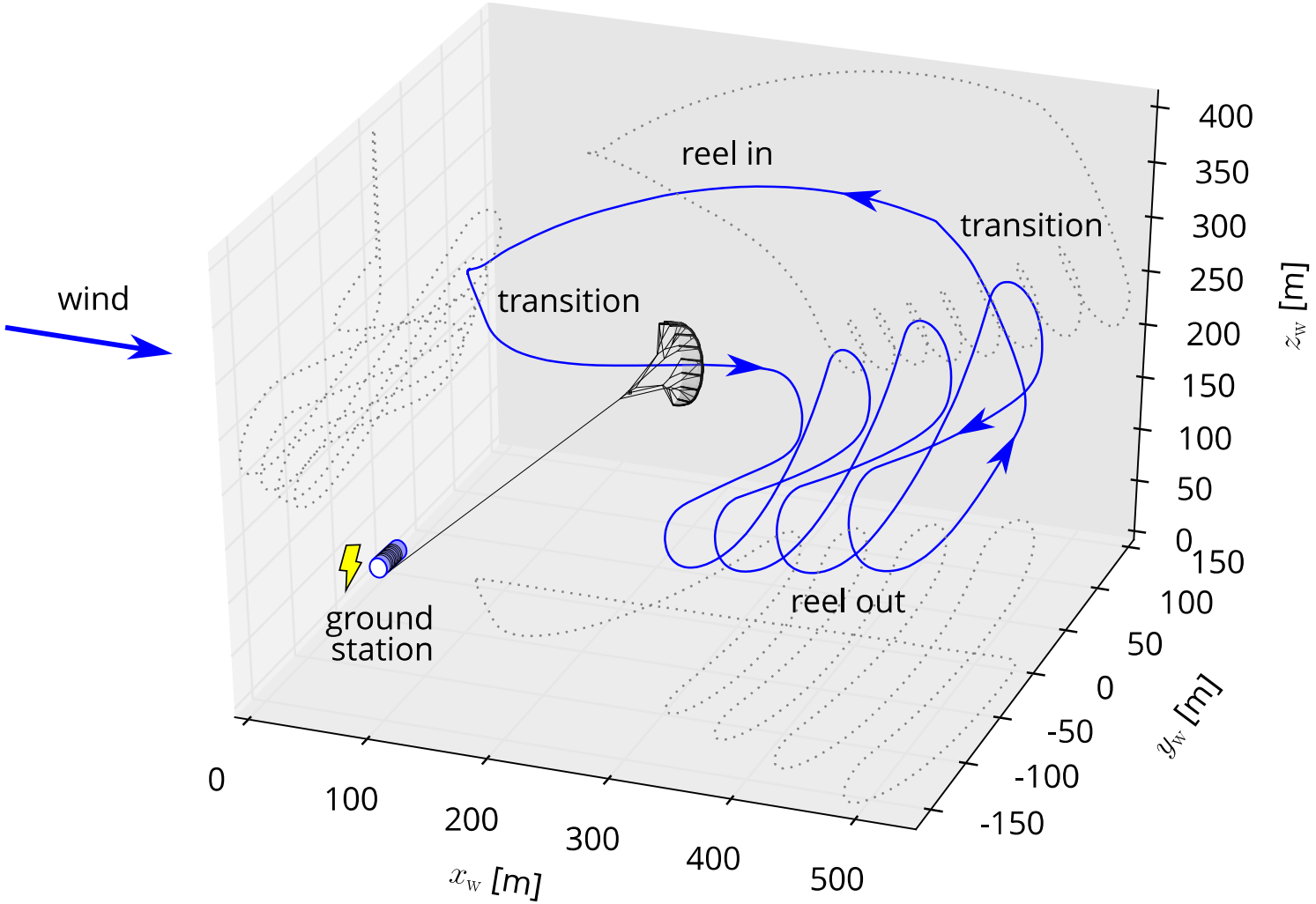
25 kW kite power system

TU Delft

2012

System components



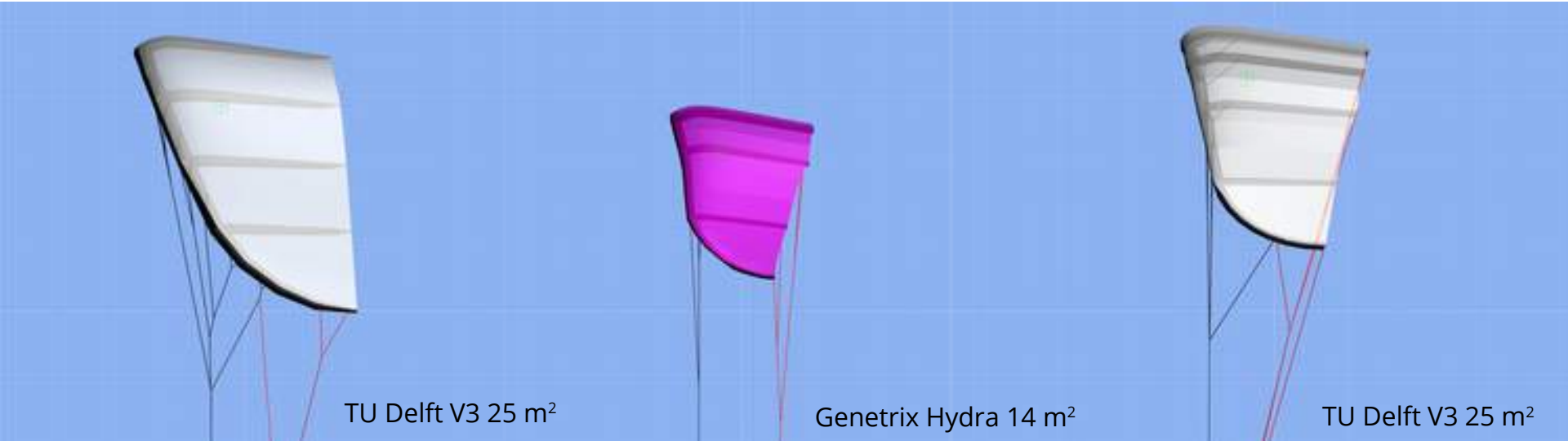

wind
reel in
transition
transition
reel out
ground
station
0
100
200
300
400
500
x_W [m]
-150
-100
-50
0
50
100
150
y_W [m]
0
50
100
150
200
250
300
350
400
z_W [m]


TU Delft V3 25 m²


Genetrix Hydra 14 m²


TU Delft V3 25 m²

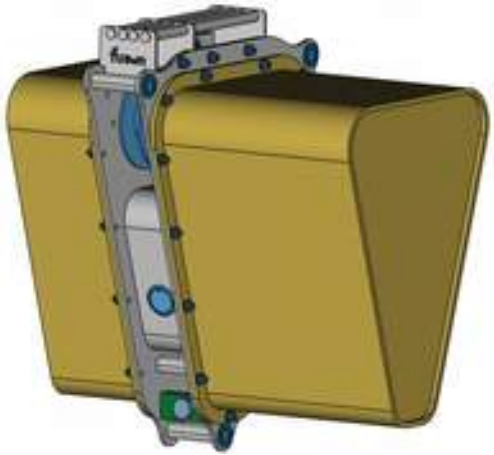

TUDelft
smi

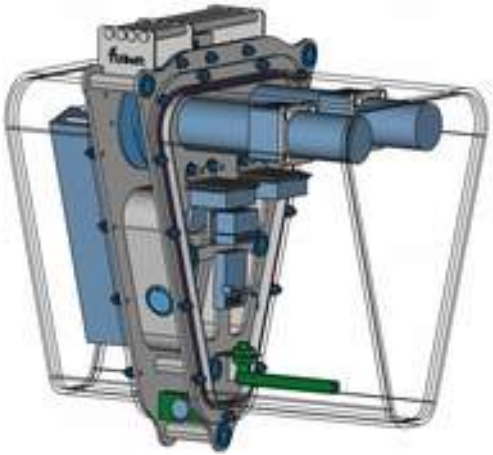


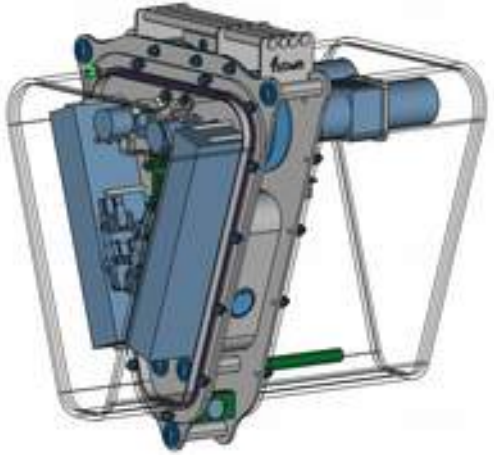
TU Delft V3 25 m^2

Genetrix Hydra 14 m^2

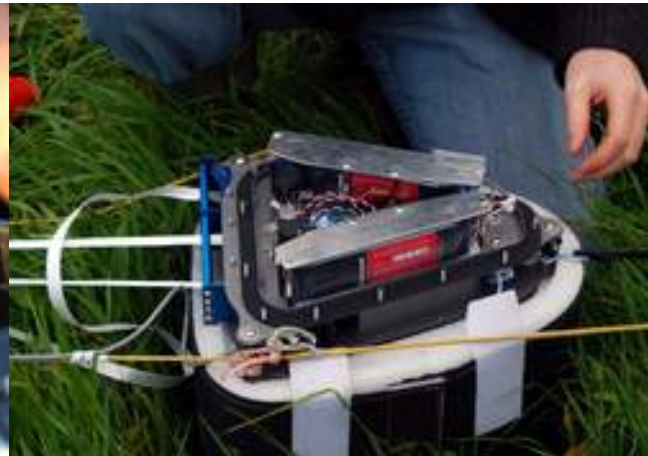
TU Delft V3 25 m^2

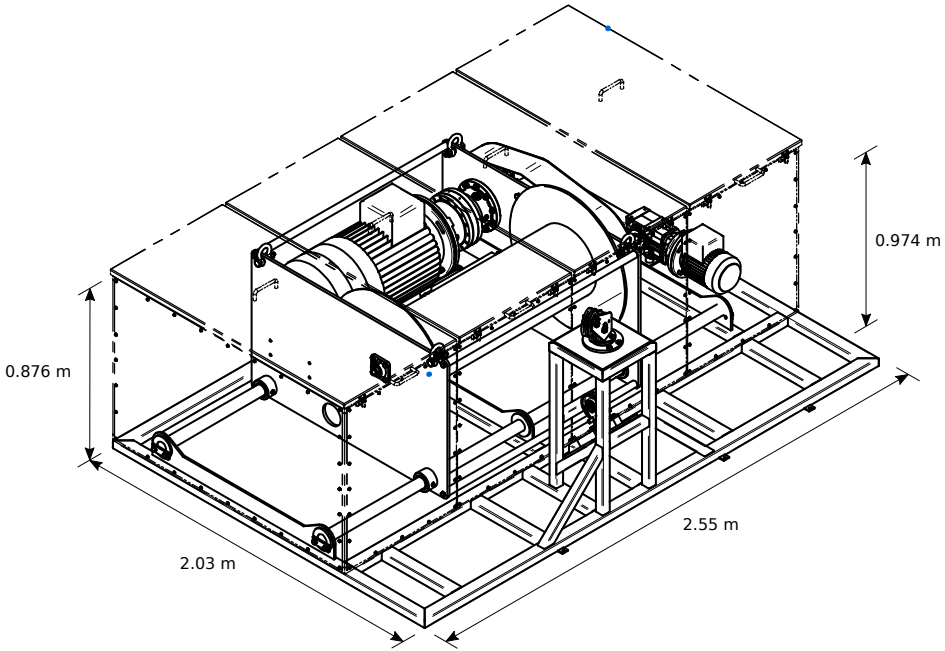


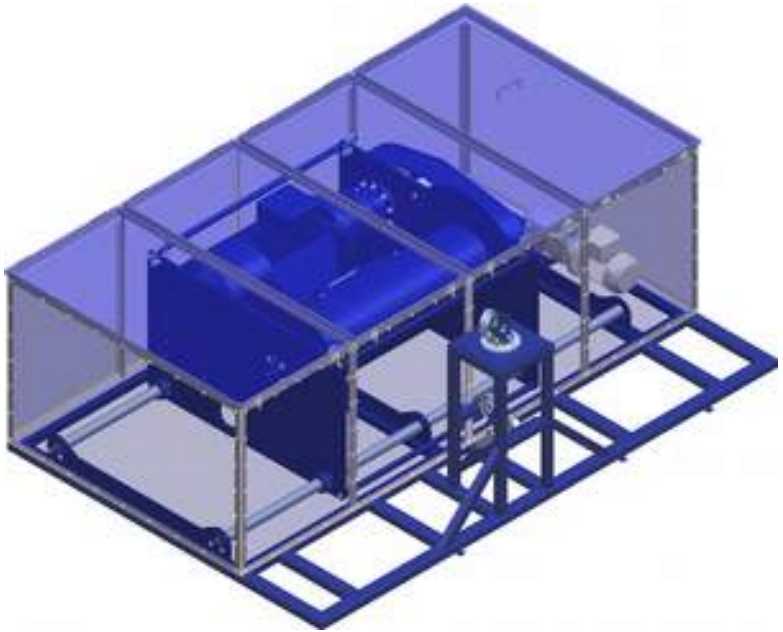


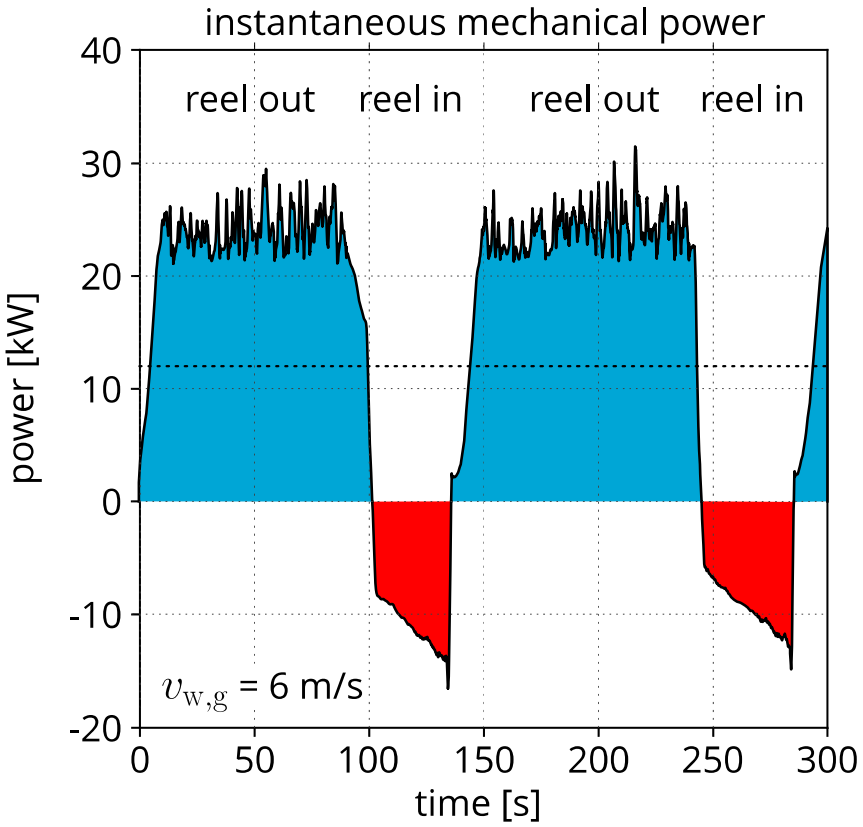


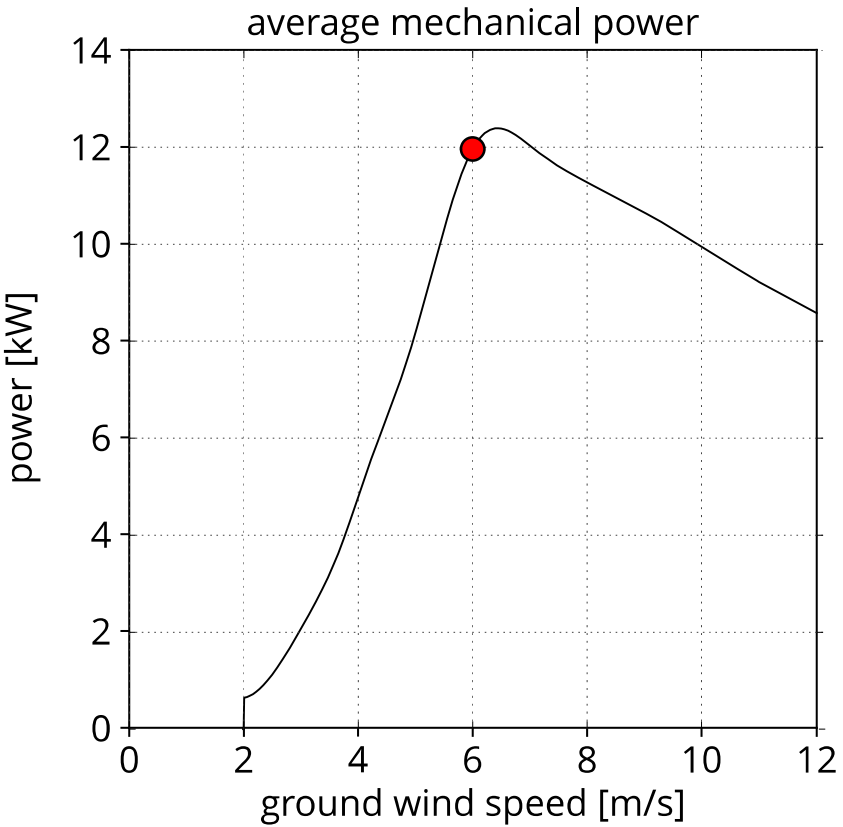

TUDelft




0.974 m
0.876 m
2.03 m
2.55 m




instantaneous mechanical power
reel out
reel in
reel out
reel in
power [kW]
time [s]
$v_{w,g}$ = 6 m/s
40
30
20
10
0
-10
-20
0
50
100
150
200
250
300


average mechanical power
power [kW]
ground wind speed [m/s]
14
12
10
8
6
4
2
0
0
2
4
6
8
10
12


TU Delft
2012
Automatic pumping cycles at Maasvlakte II of Rotterdam Harbor

Kite Power 2.0 (2014-15)

40 m² kite

airborne wind energy
KITEPOWER
2017

100 kW ground station


airborne wind energy
KITEPOWER


airborne wind energy
KITEPOWER


KITEPOWER ™

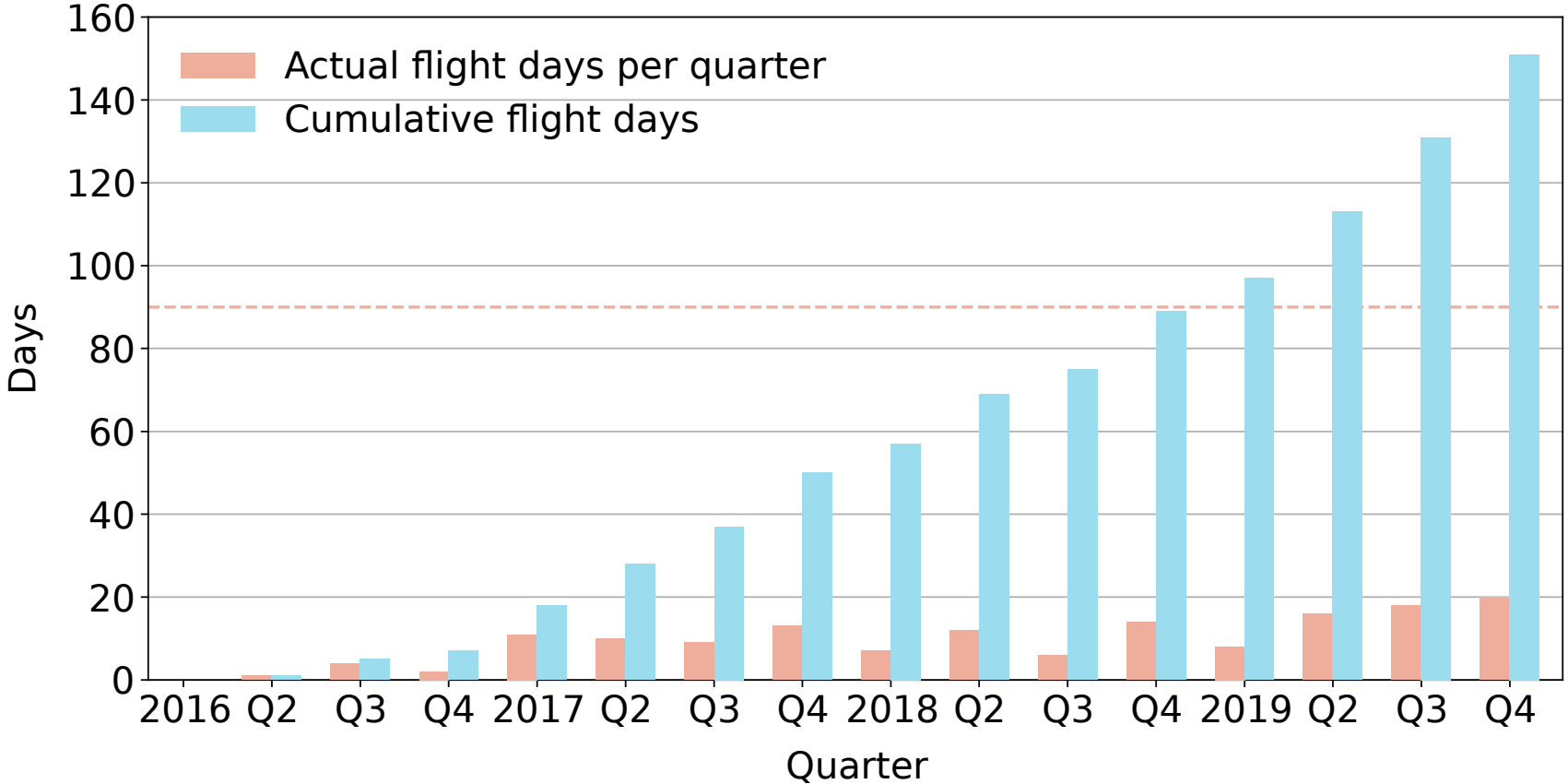

KITEPOWER™

Kite development: 25 – 40 – 60 m²

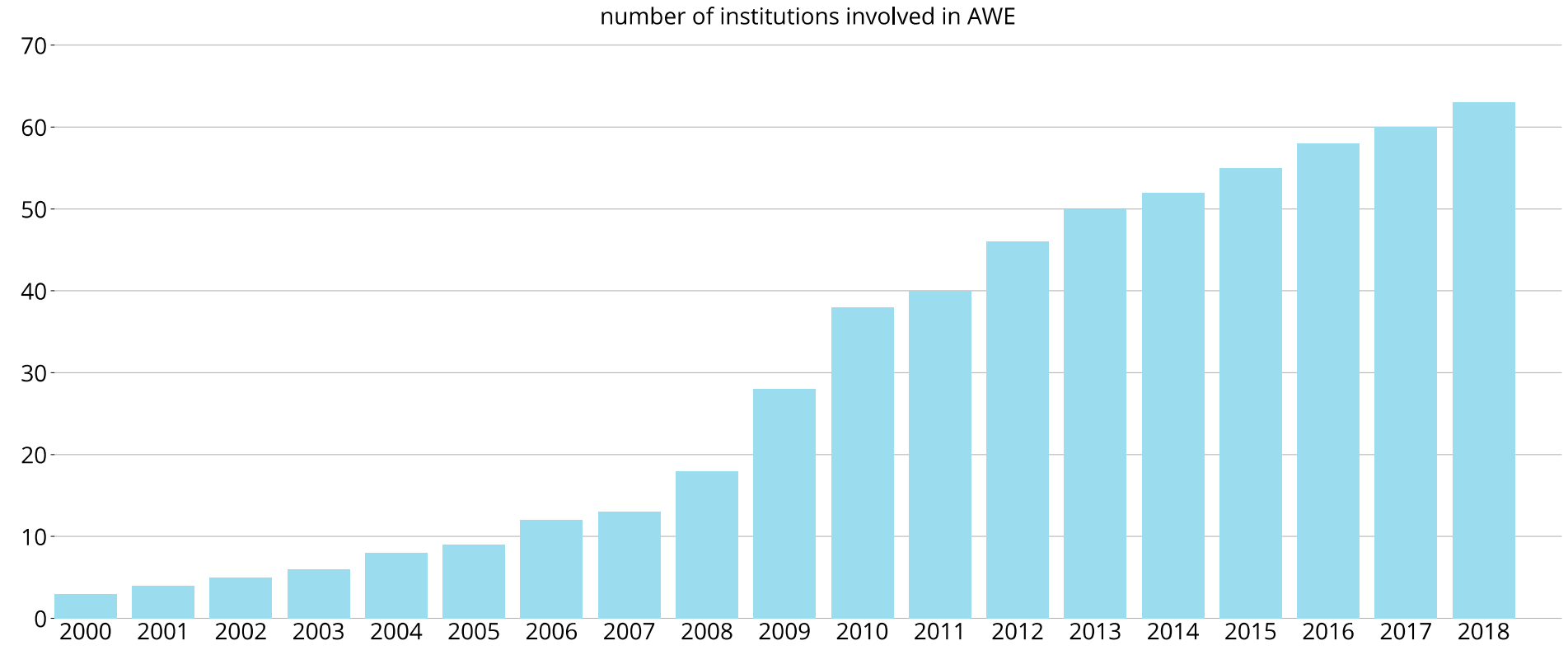
Kite development: 100 m²


airborne wind energy
KITEPOWER

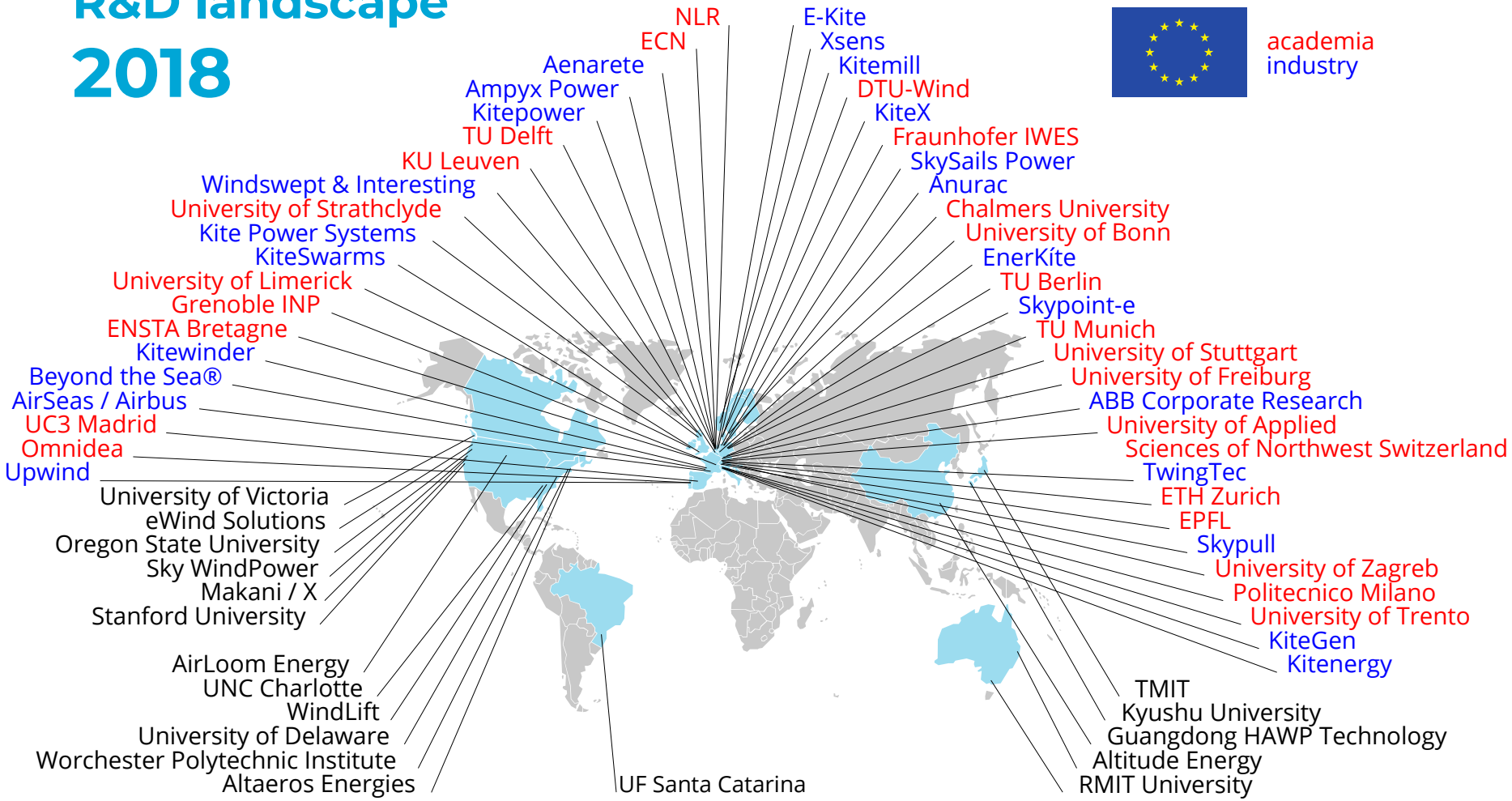
Flight days


Actual flight days per quarter
Cumulative flight days
Days
Quarter
0
20
40
60
80
100
120
140
160
2016 Q2
Q3
Q4
2017 Q2
Q3
Q4
2018 Q2
Q3
Q4
2019 Q2
Q3
Q4

Development as an industry

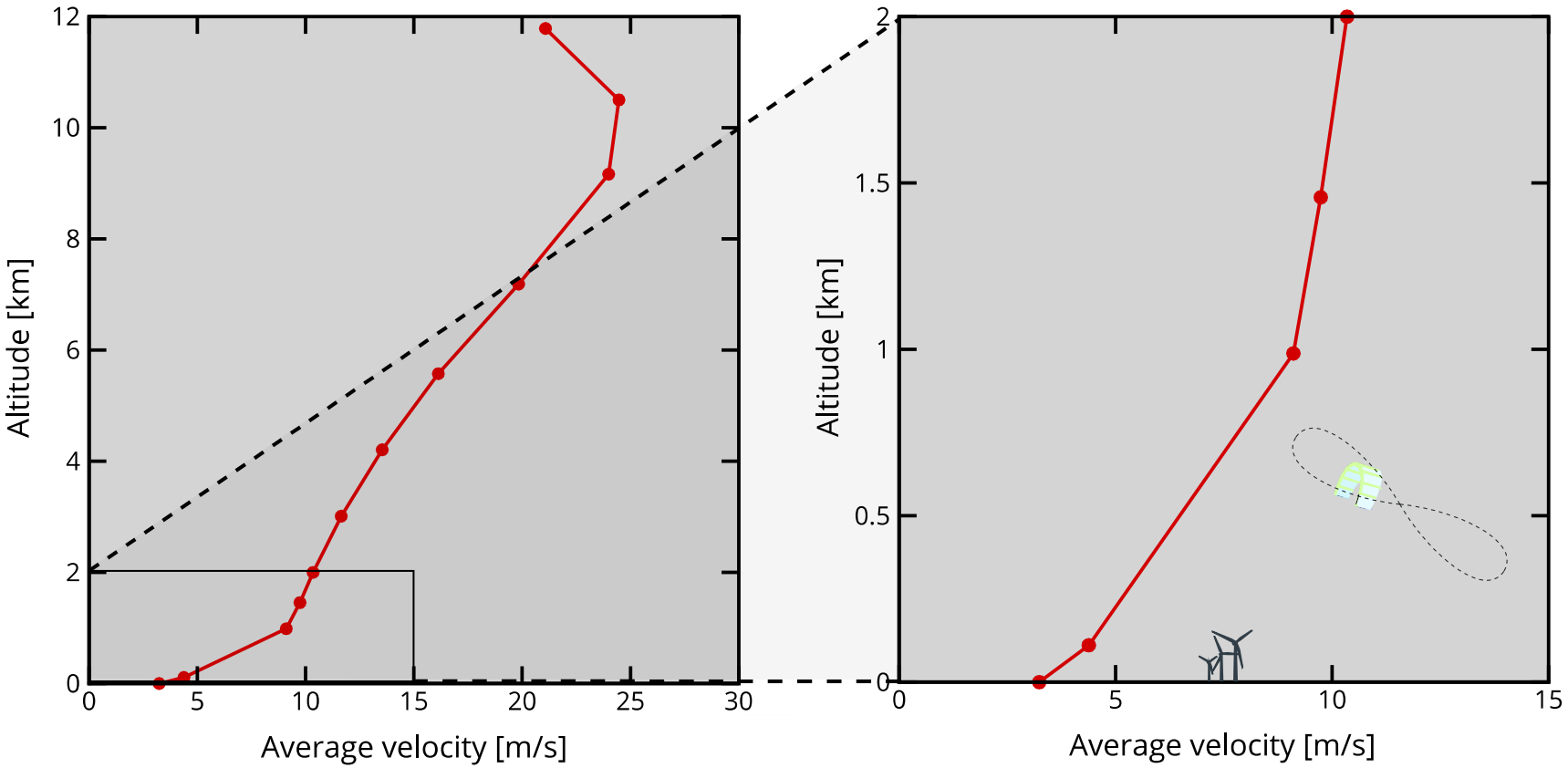


R&D landscape 2018



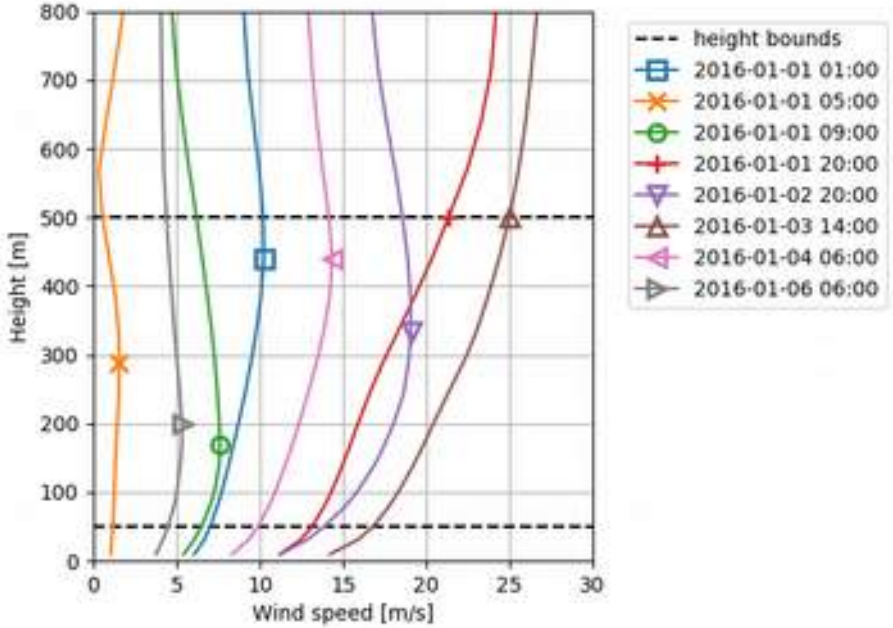
Challenges

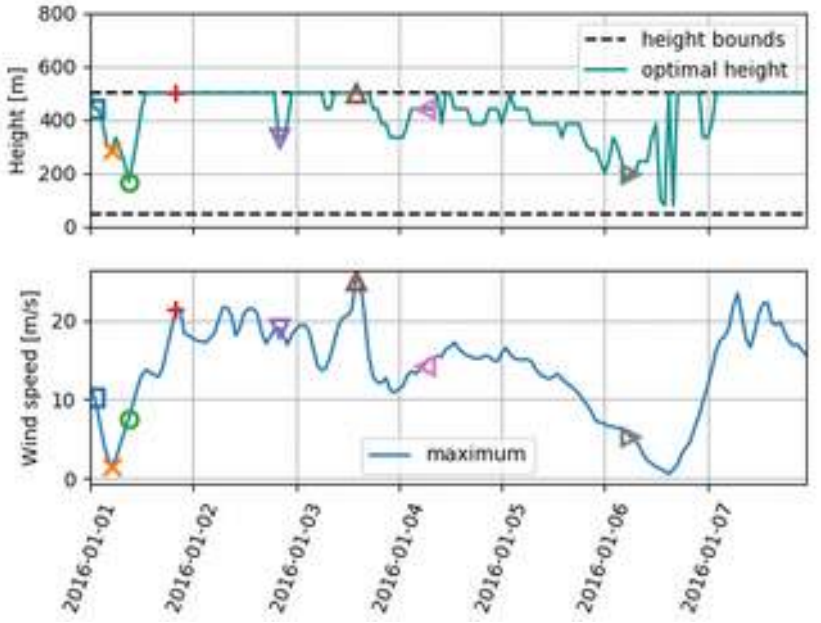
- Reliability & Safety
  - None of the projects has proven more than a few days of operation
  - Operation in kite parks
- Durability of materials
  - Tether and kite are critical components
- Regulations
  - Interference with air traffic and ground use



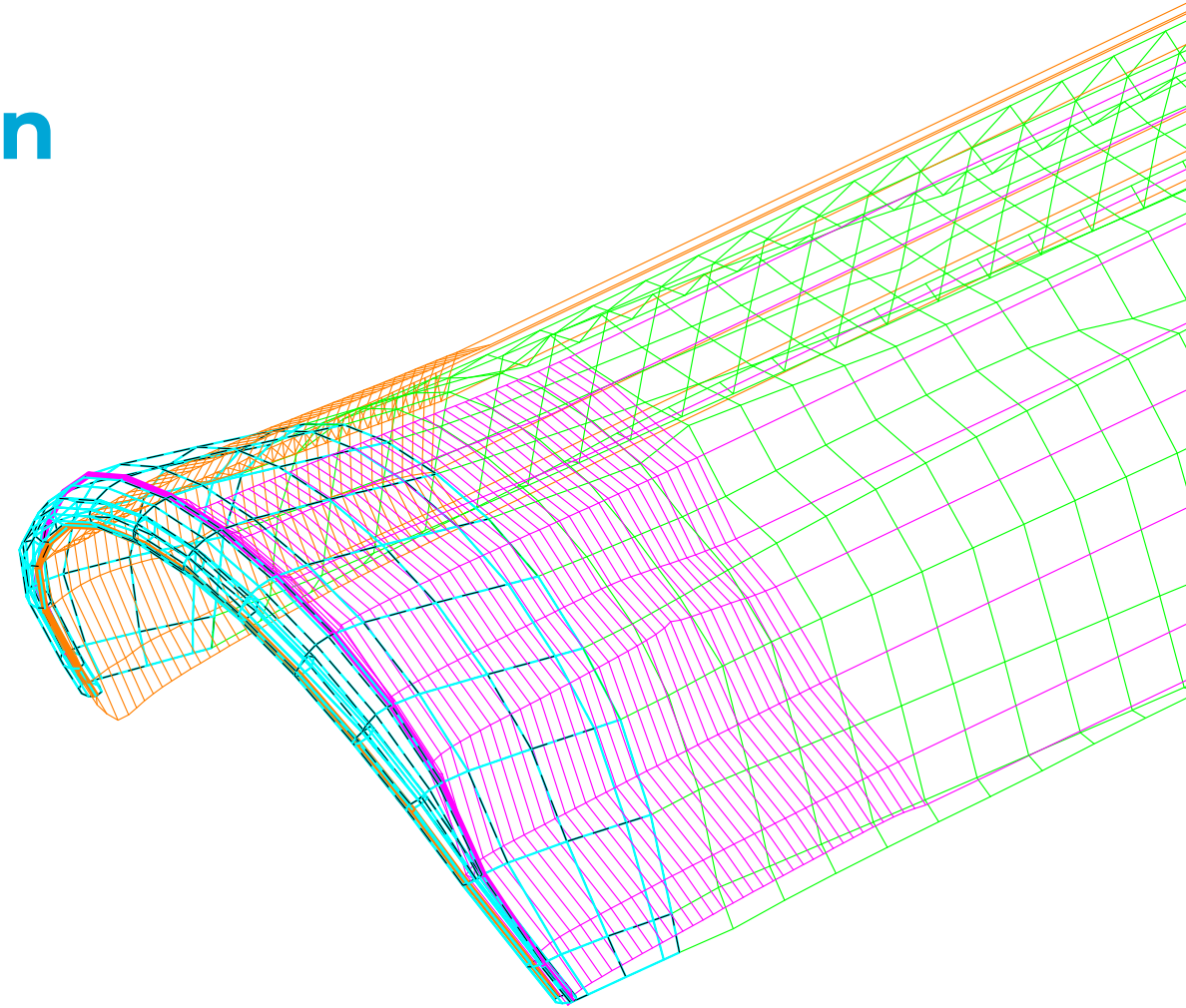
KNMI 20 year average wind data for De Bilt, the Netherlands.

AWE resource assessment

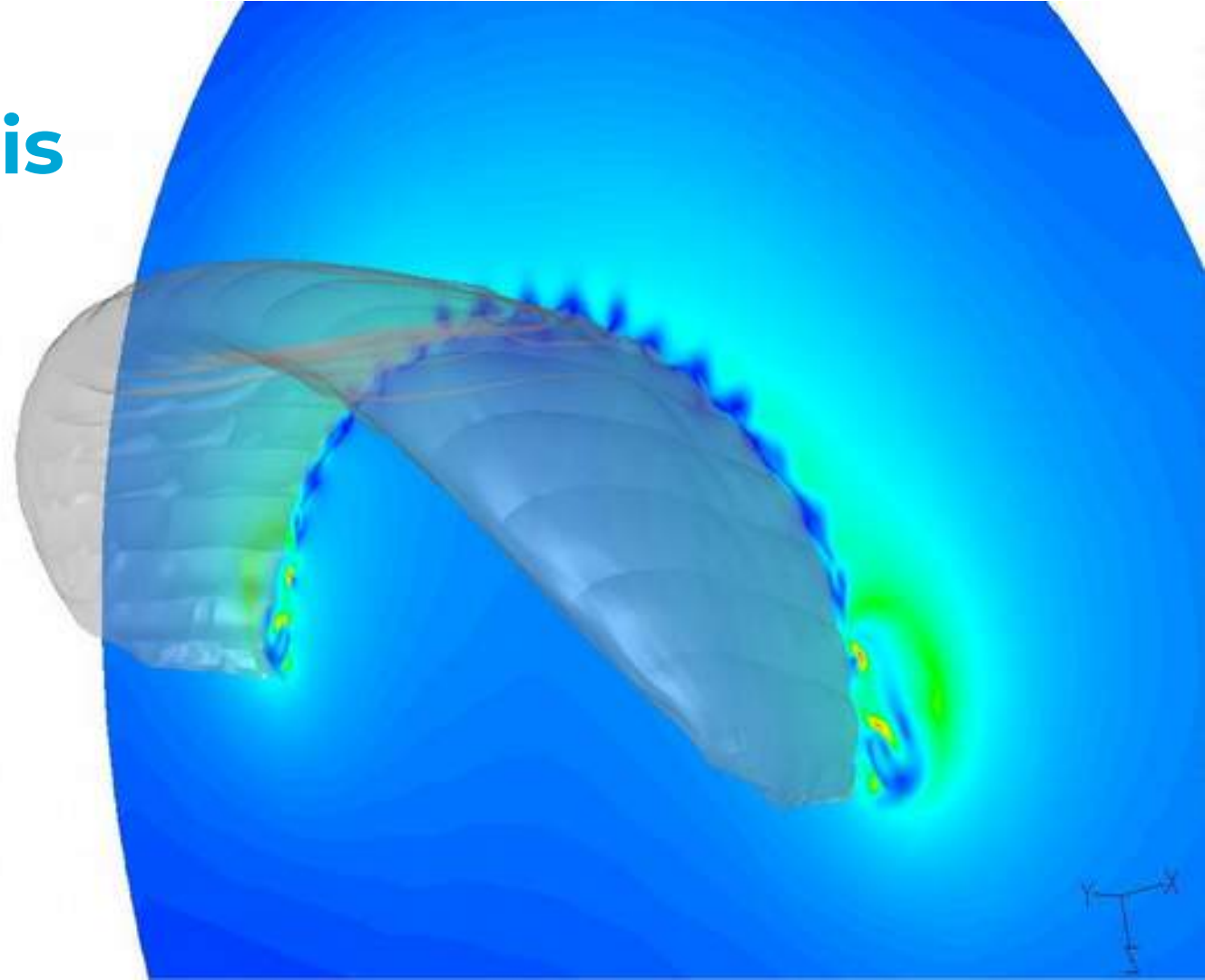


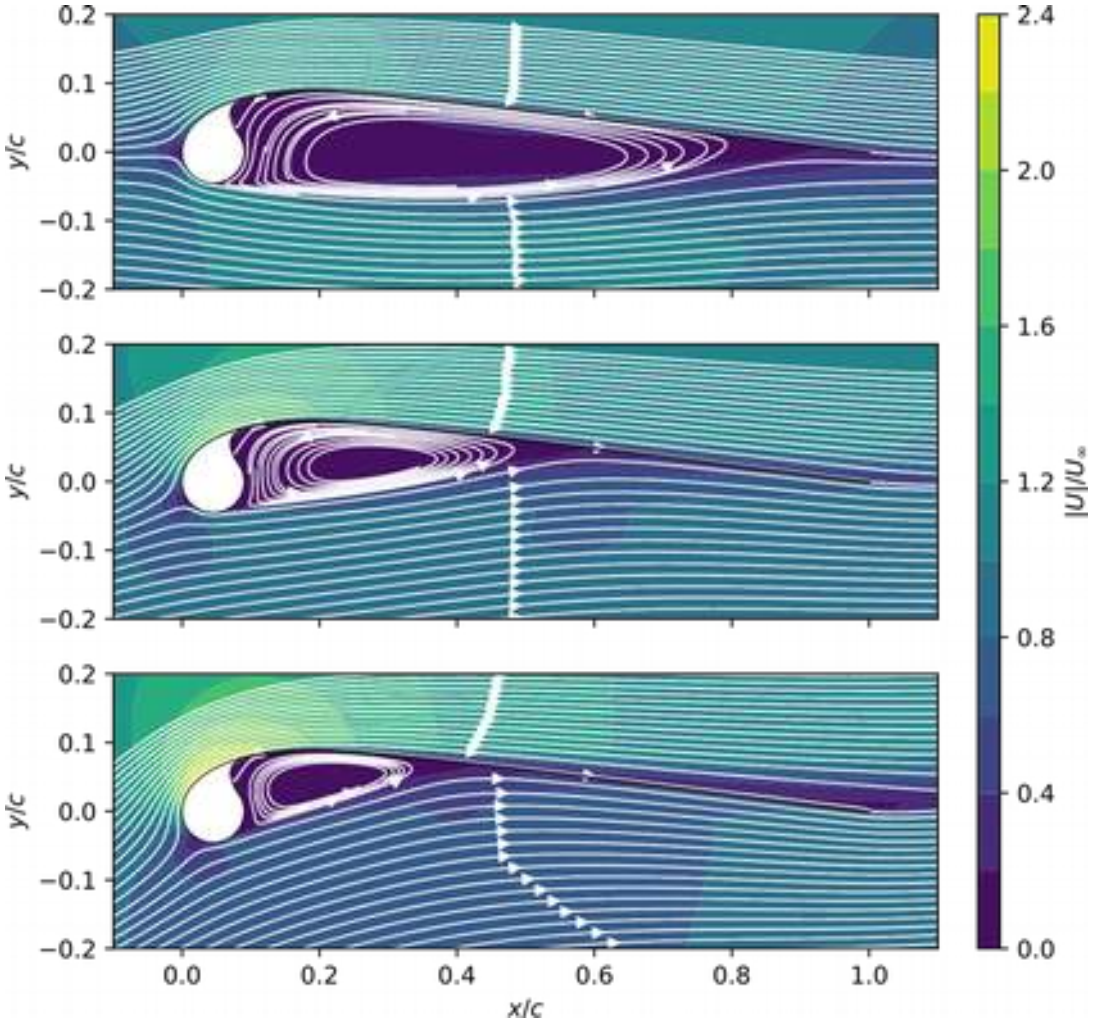


VLM simulation

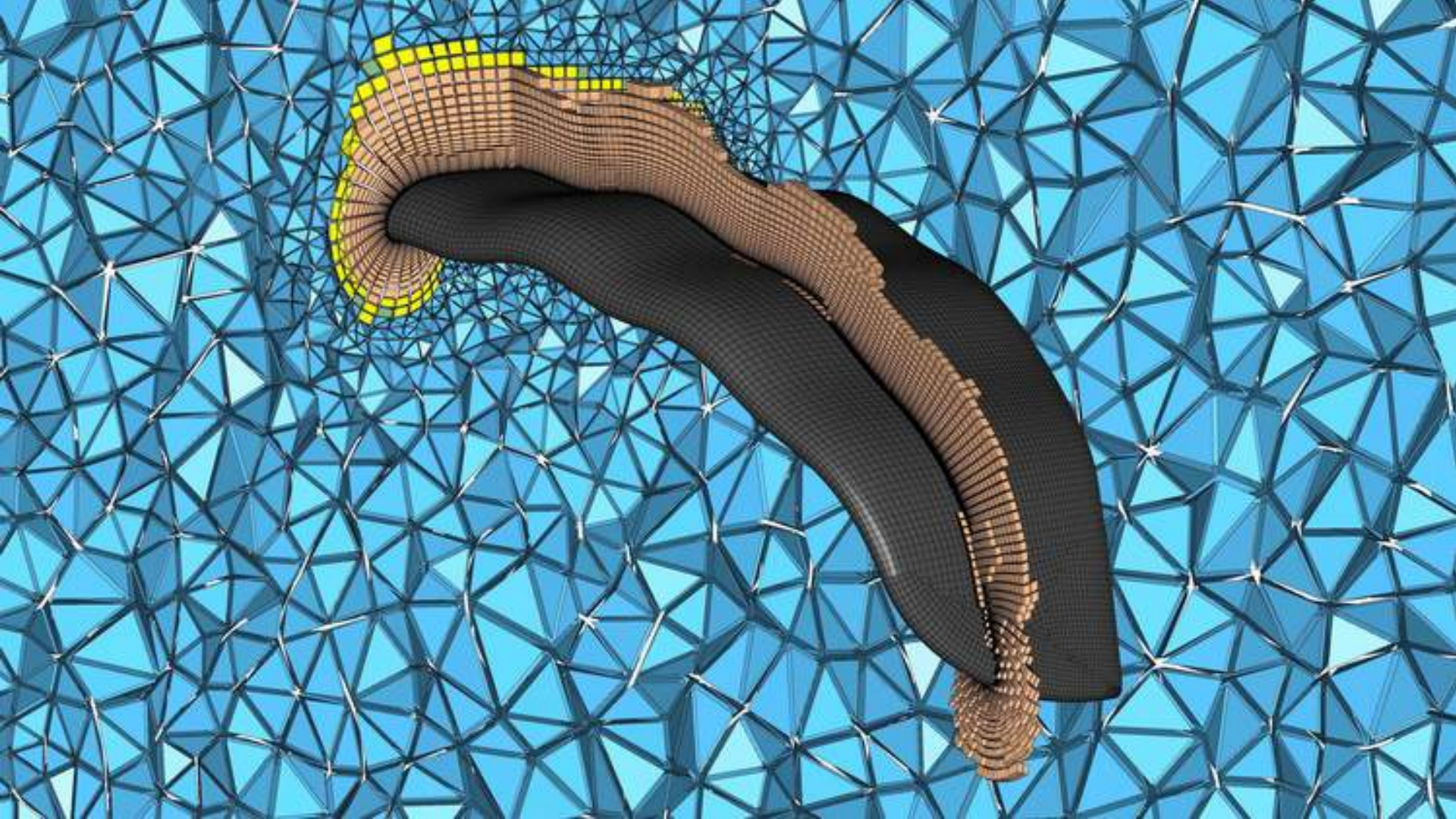


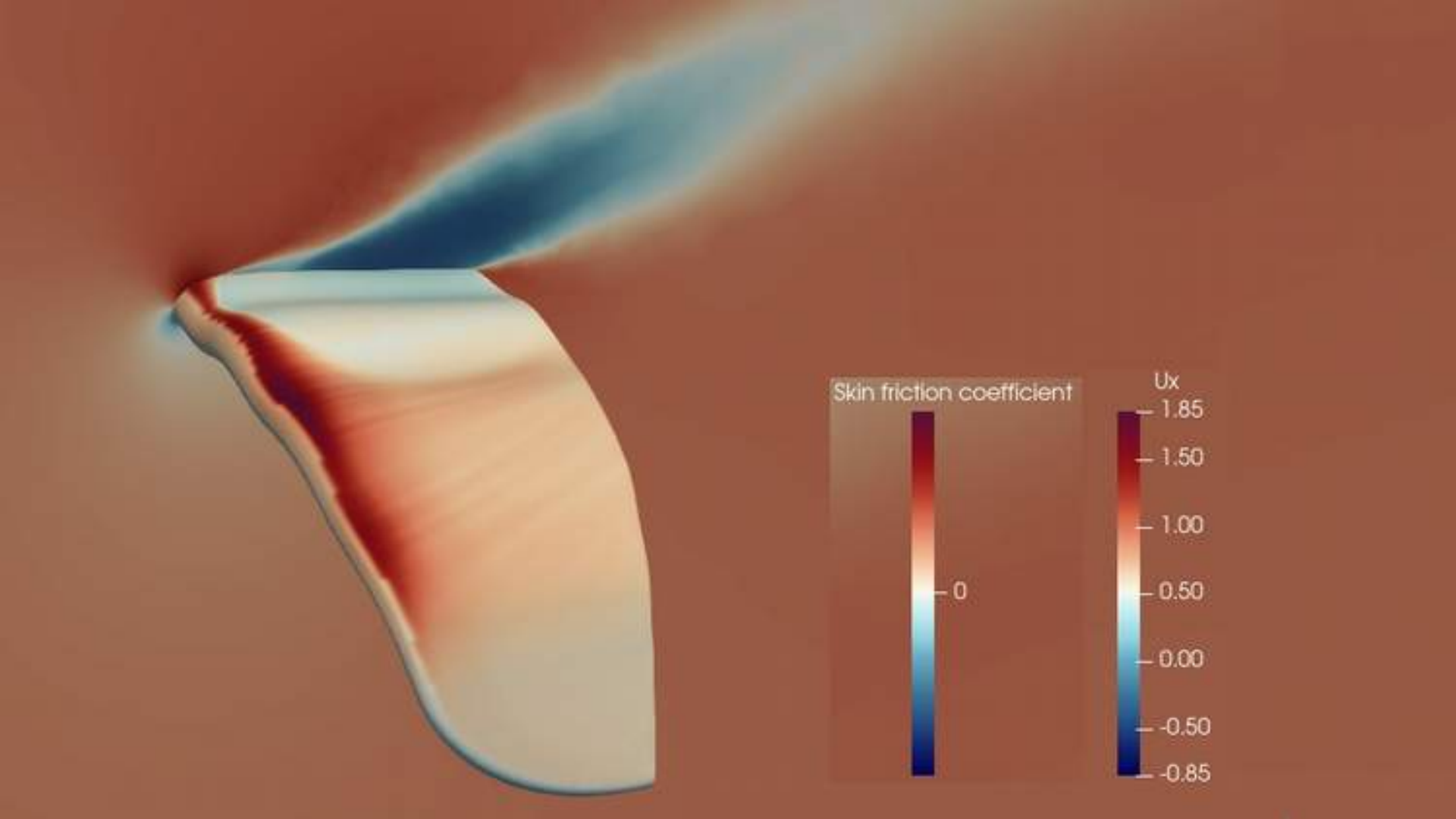
CFD analysis

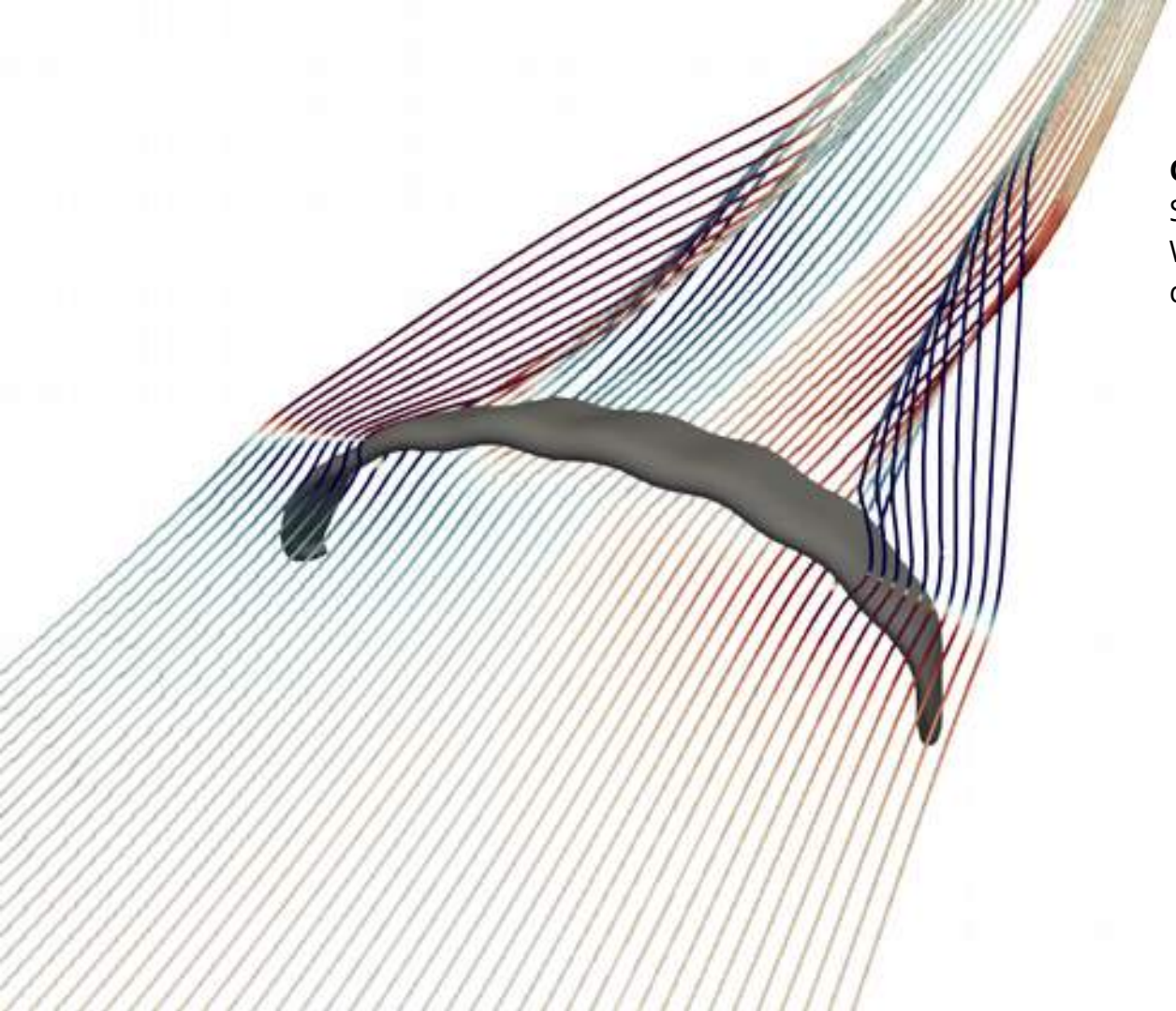




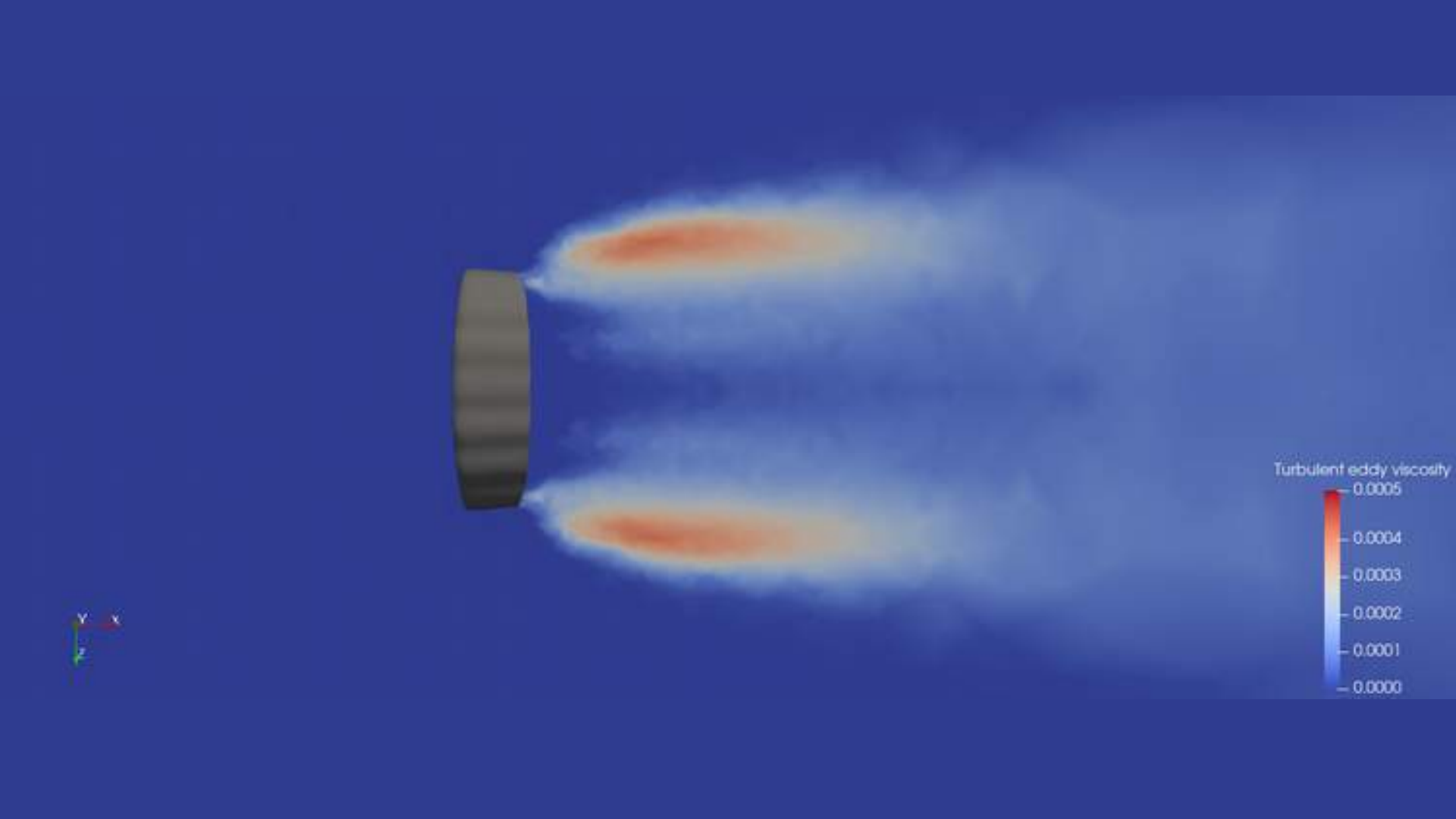
Oehler & Schmehl. "Aerodynamic characterization of a soft kite by in situ flow measurement". Wind Energy Science, 2019

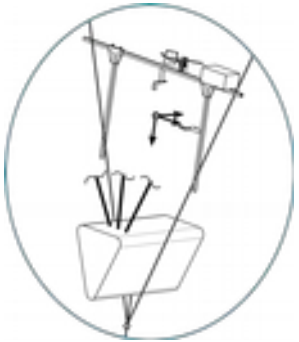



Skin friction coefficient
0
Ux
1.85
1.50
1.00
0.50
0.00
-0.50
-0.85

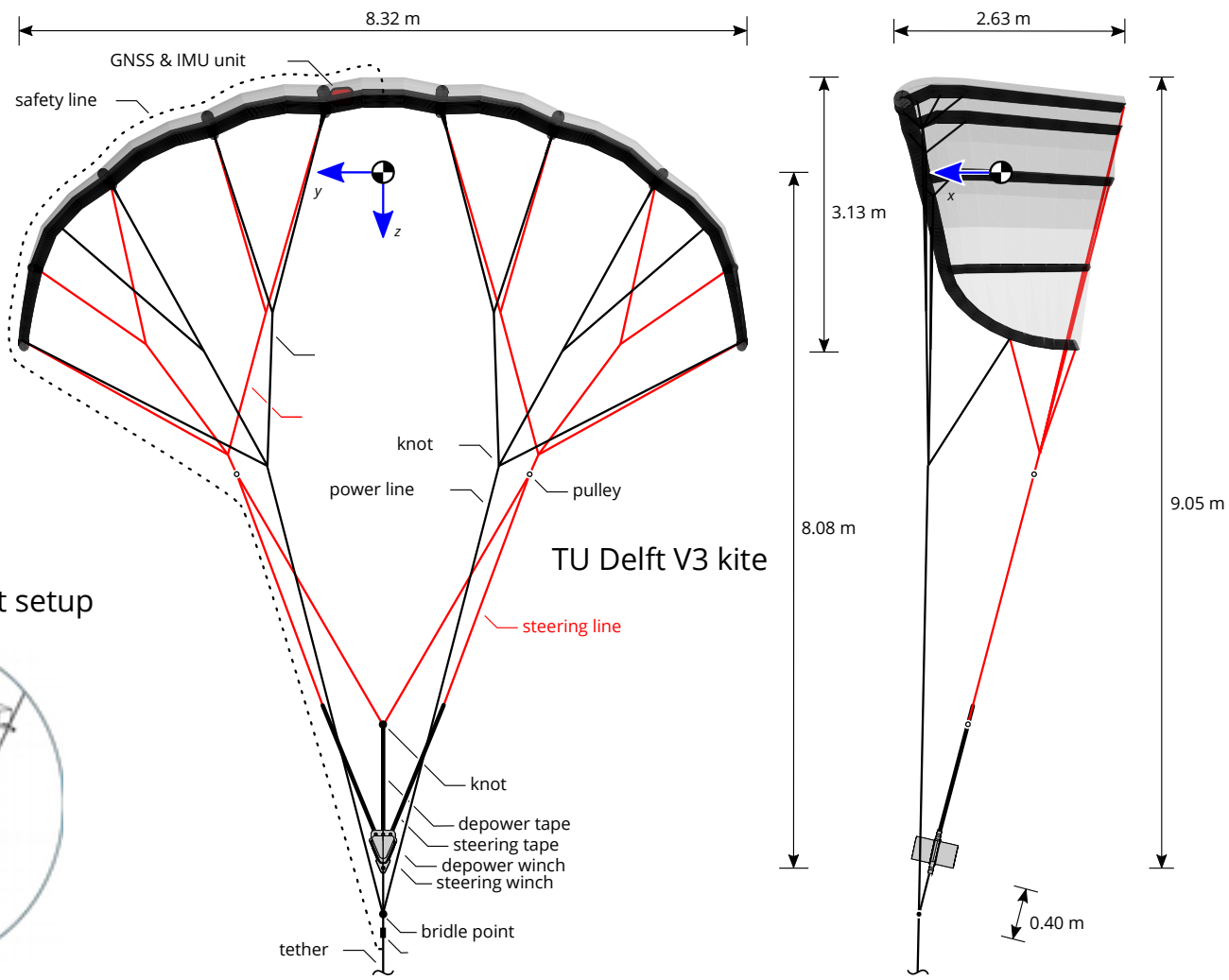


CFD simulation with OpenFOAM
Streamlines around the kite colored
With the spanwise velocity component,
computed for Re=3x10^6 and 12° AoA


Turbulent eddy viscosity
0.0005
0.0004
0.0003
0.0002
0.0001
0.0000
Y
X
Z



Relative flow measurement setup

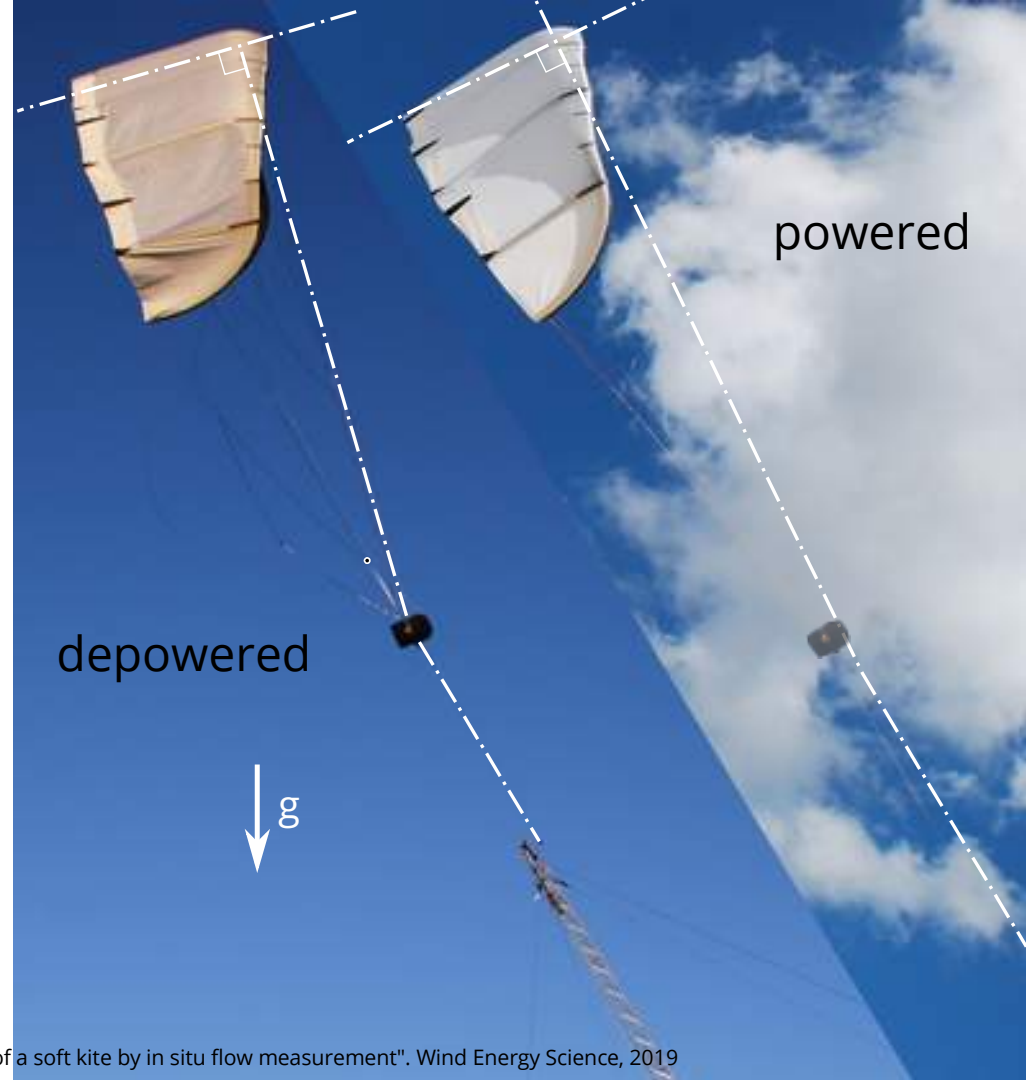


TU Delft V3 kite

Oehler & Schmehl. "Aerodynamic characterization of a soft kite by in situ flow measurement". Wind Energy Science, 2019

Effect of power

- Changes chordwise force distribution
- Powering up the wing makes wing pitch backwards

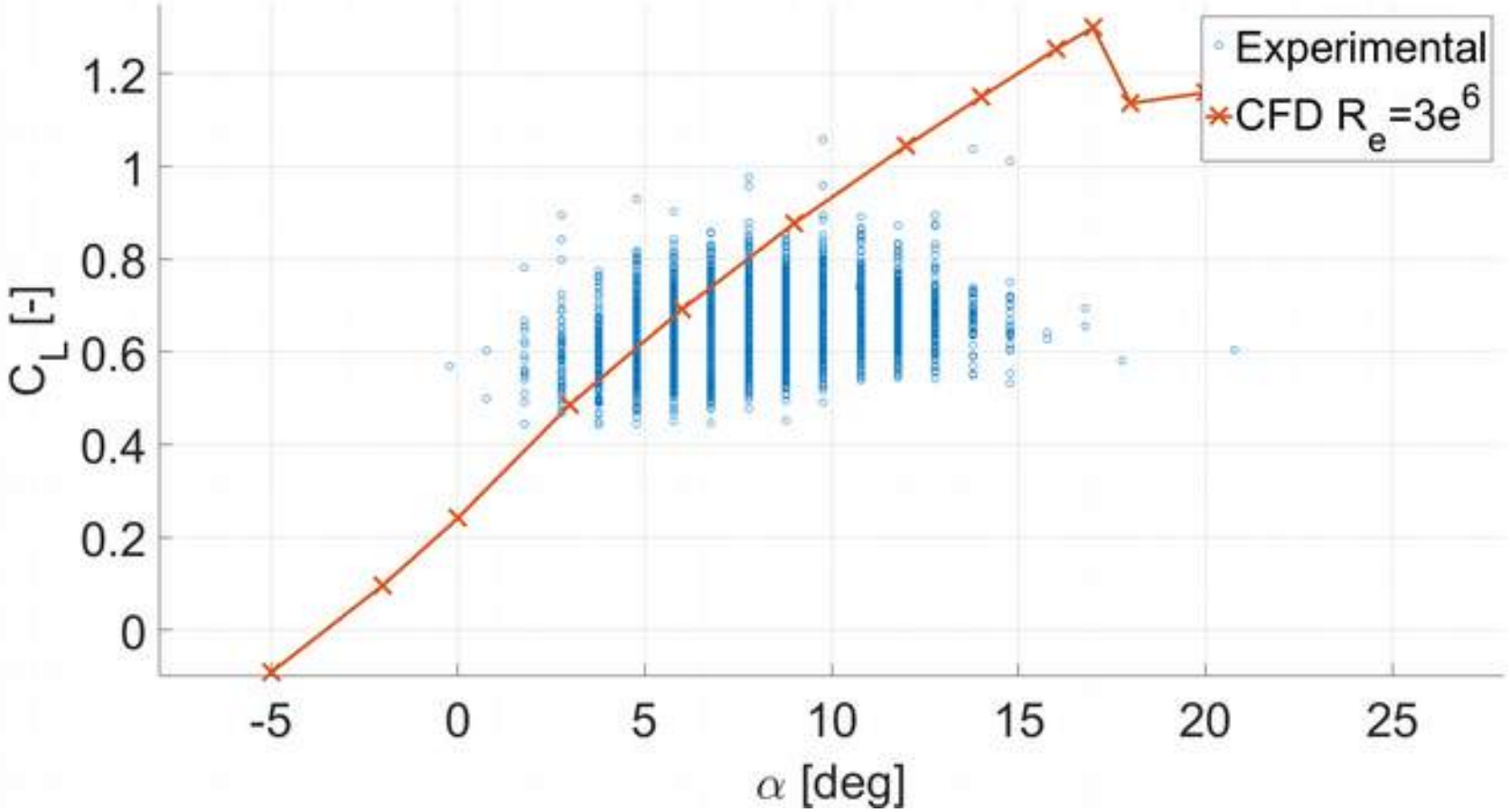


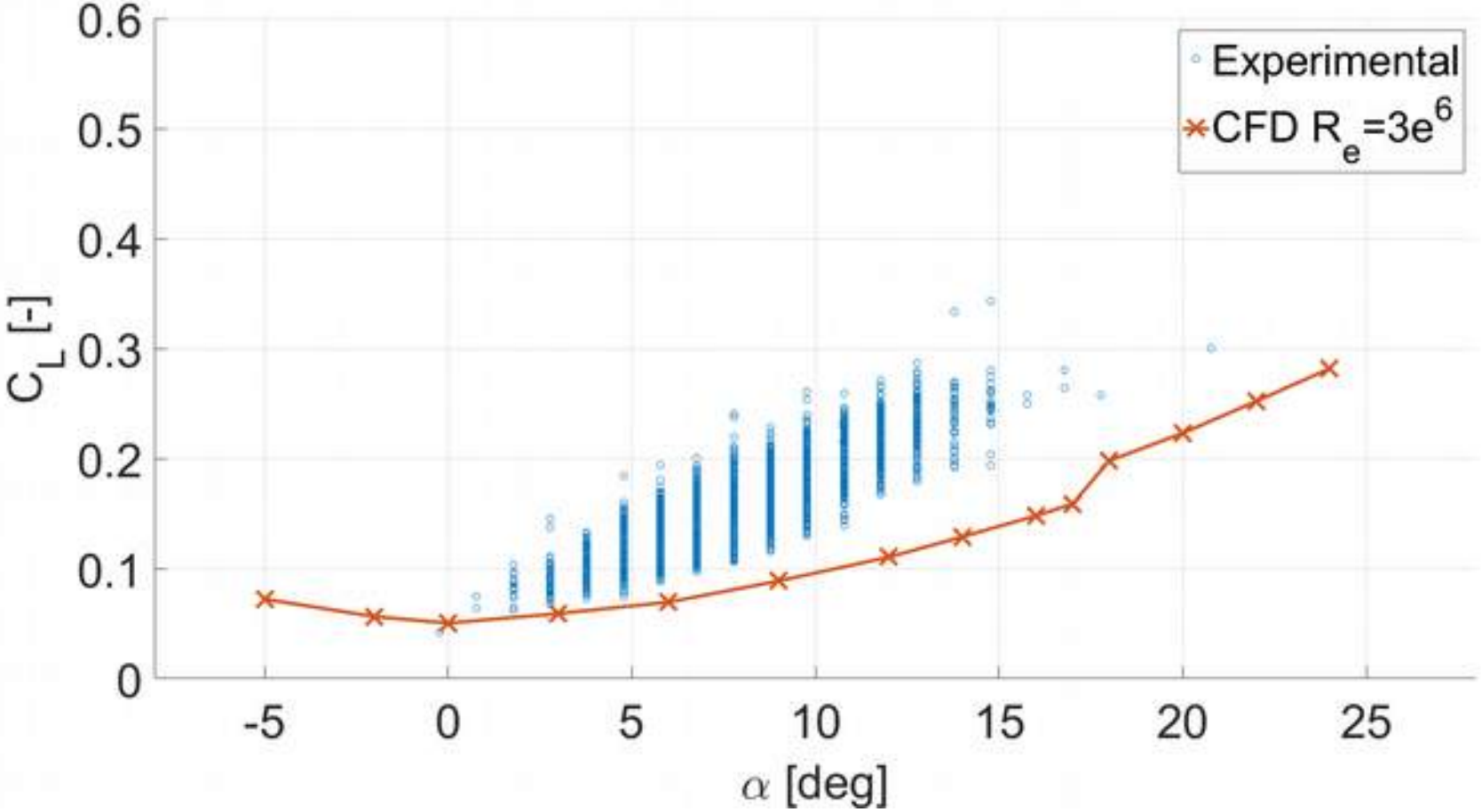
Oehler & Schmehl. "Aerodynamic characterization of a soft kite by in situ flow measurement". Wind Energy Science, 2019

Effect of power

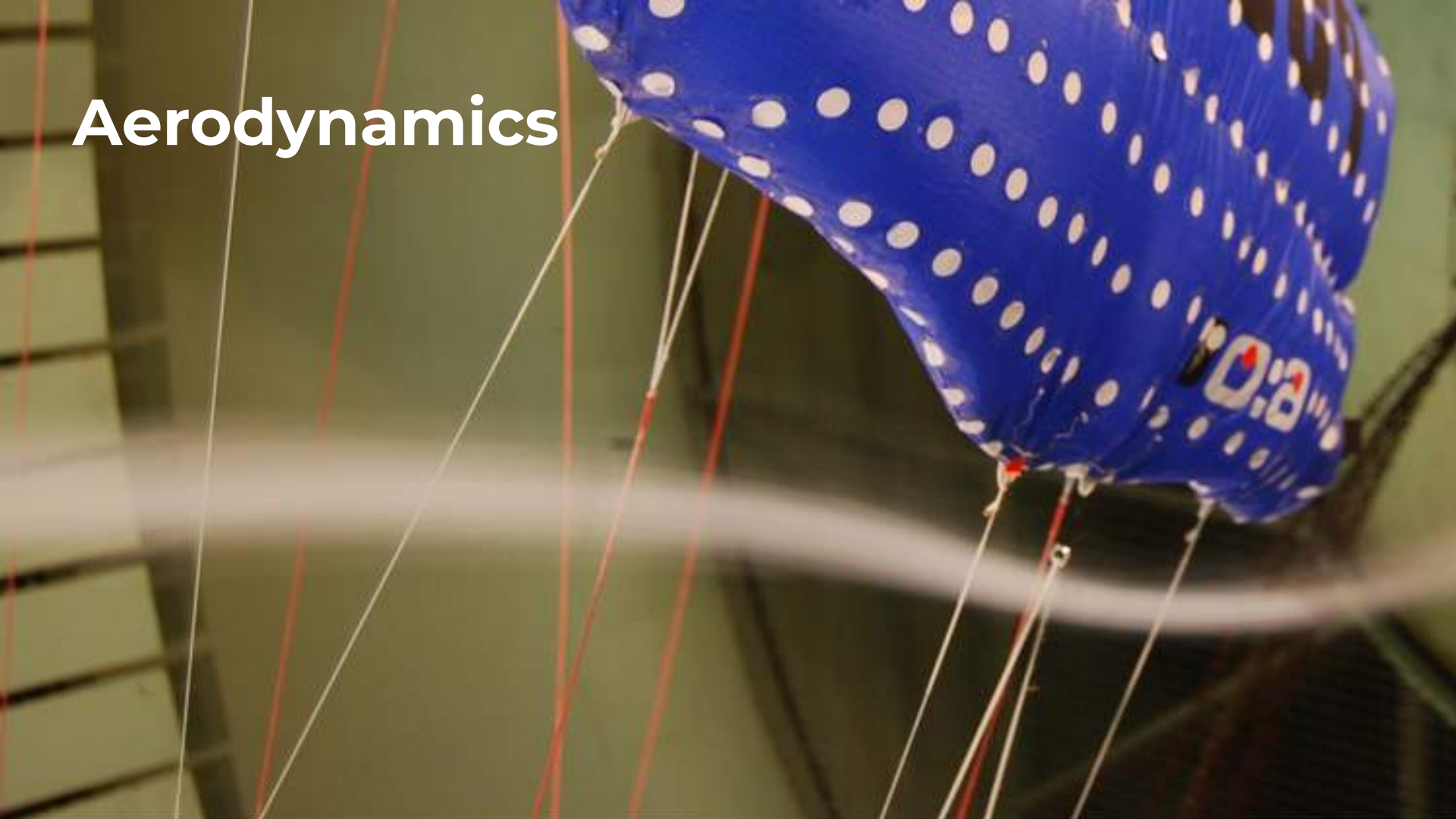
- Wing flattens
- Force increase also by area increase

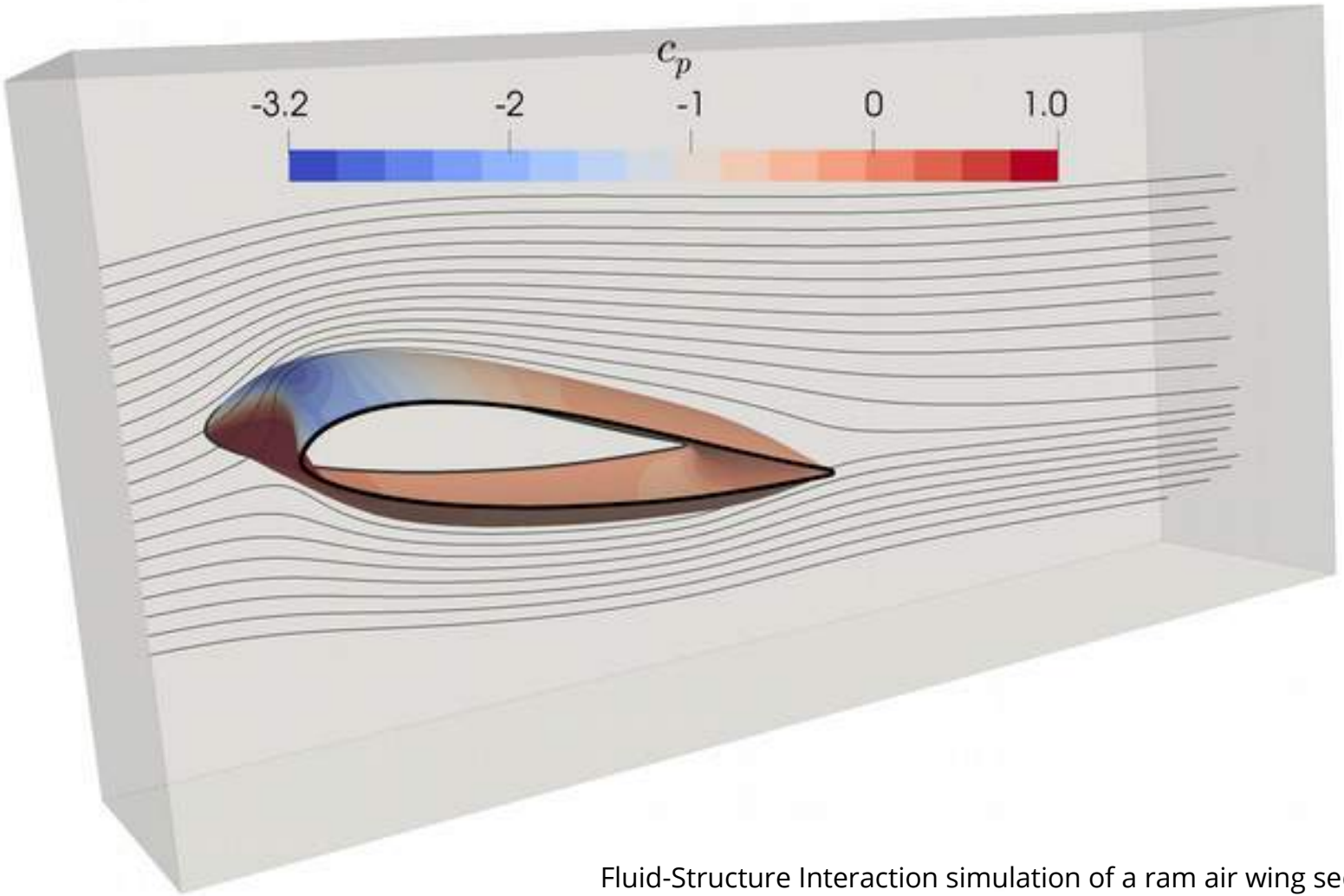
Oehler & Schmehl. "Aerodynamic characterization of a soft kite by in situ flow measurement". Wind Energy Science, 2019


Experimental
CFD R_e=3e^6
C_L [-]
1.2
1
0.8
0.6
0.4
0.2
0
-5
0
5
10
15
20
25
α [deg]


0.6
0.5
0.4
0.3
0.2
0.1
0
C_L [-]
-5
0
5
10
15
20
25
α [deg]
Experimental
CFD R_e=3e^6

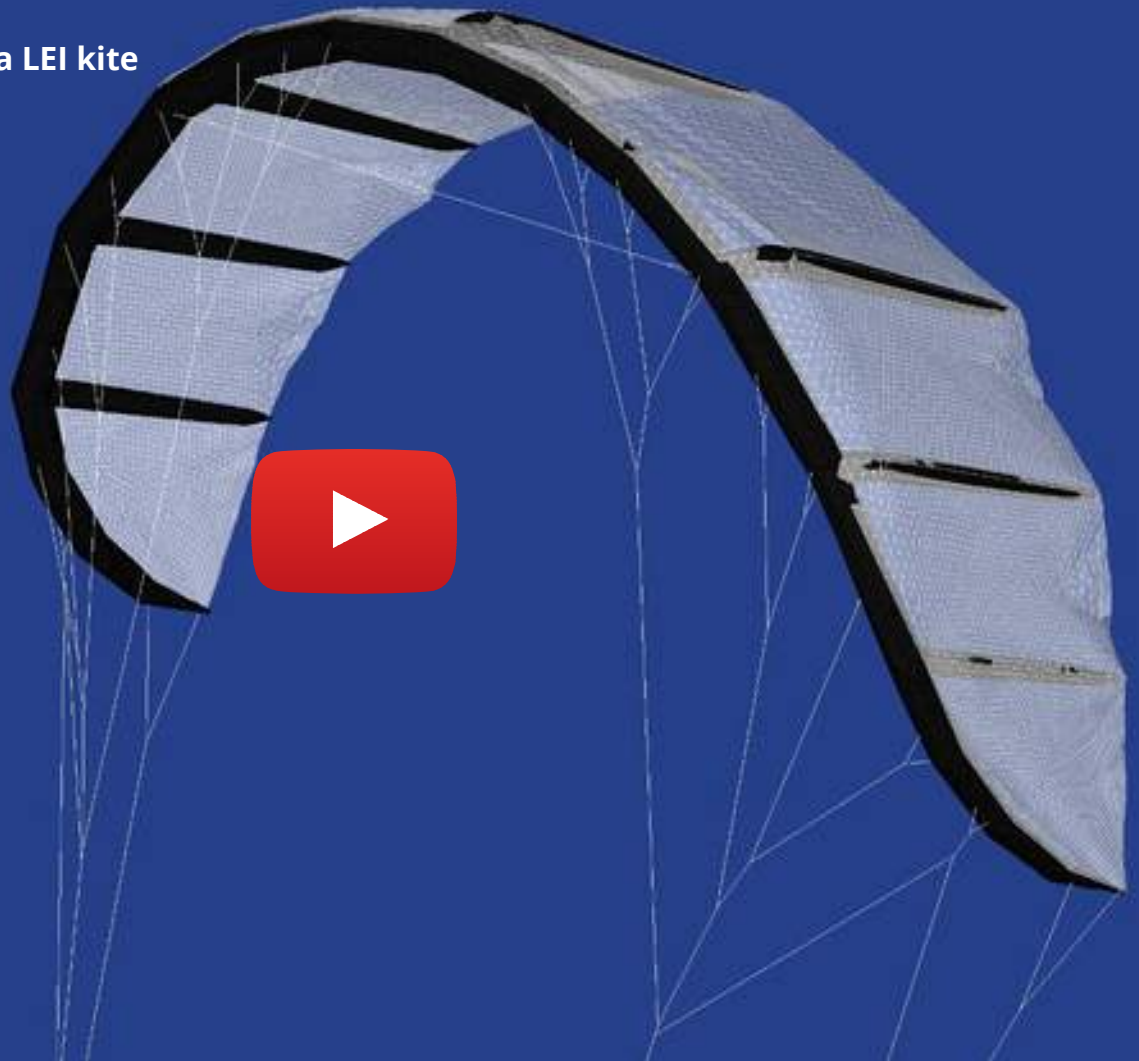
Aerodynamics



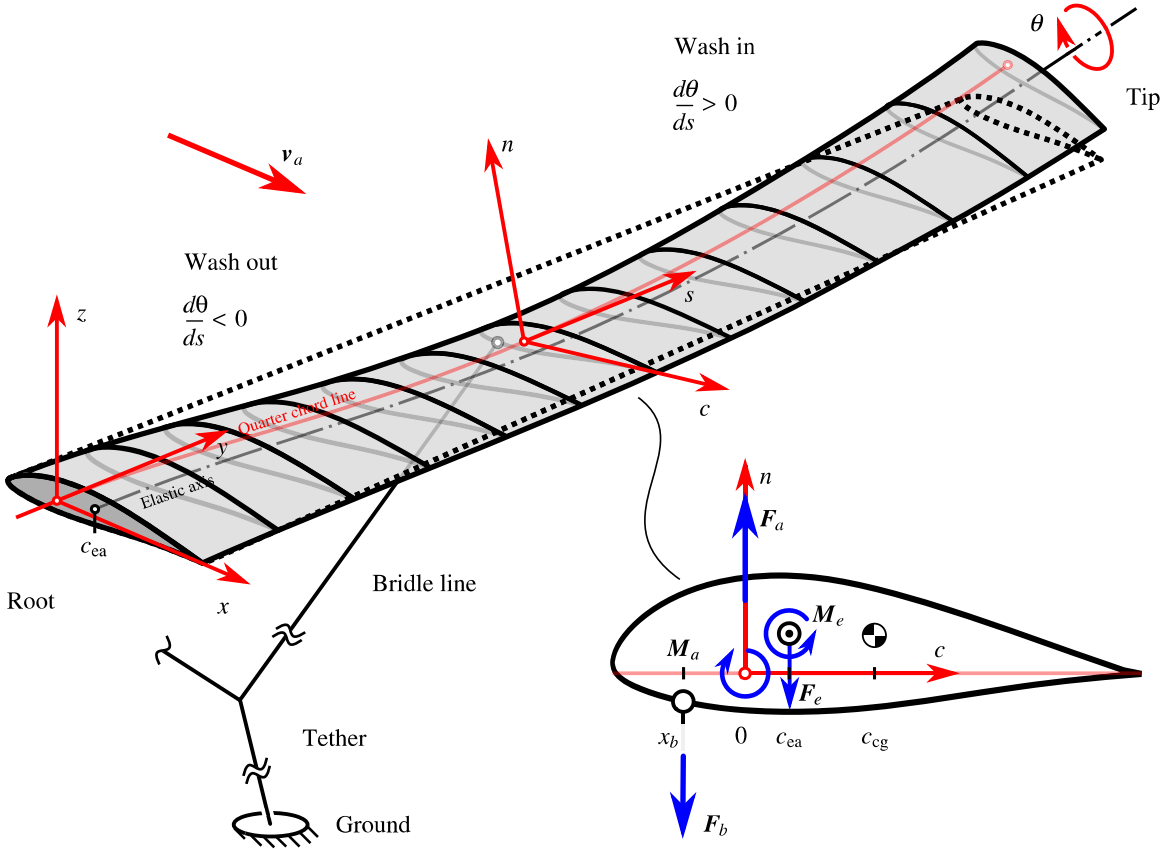


Fluid-Structure Interaction simulation of a ram air wing section

Finite element model of a LEI kite

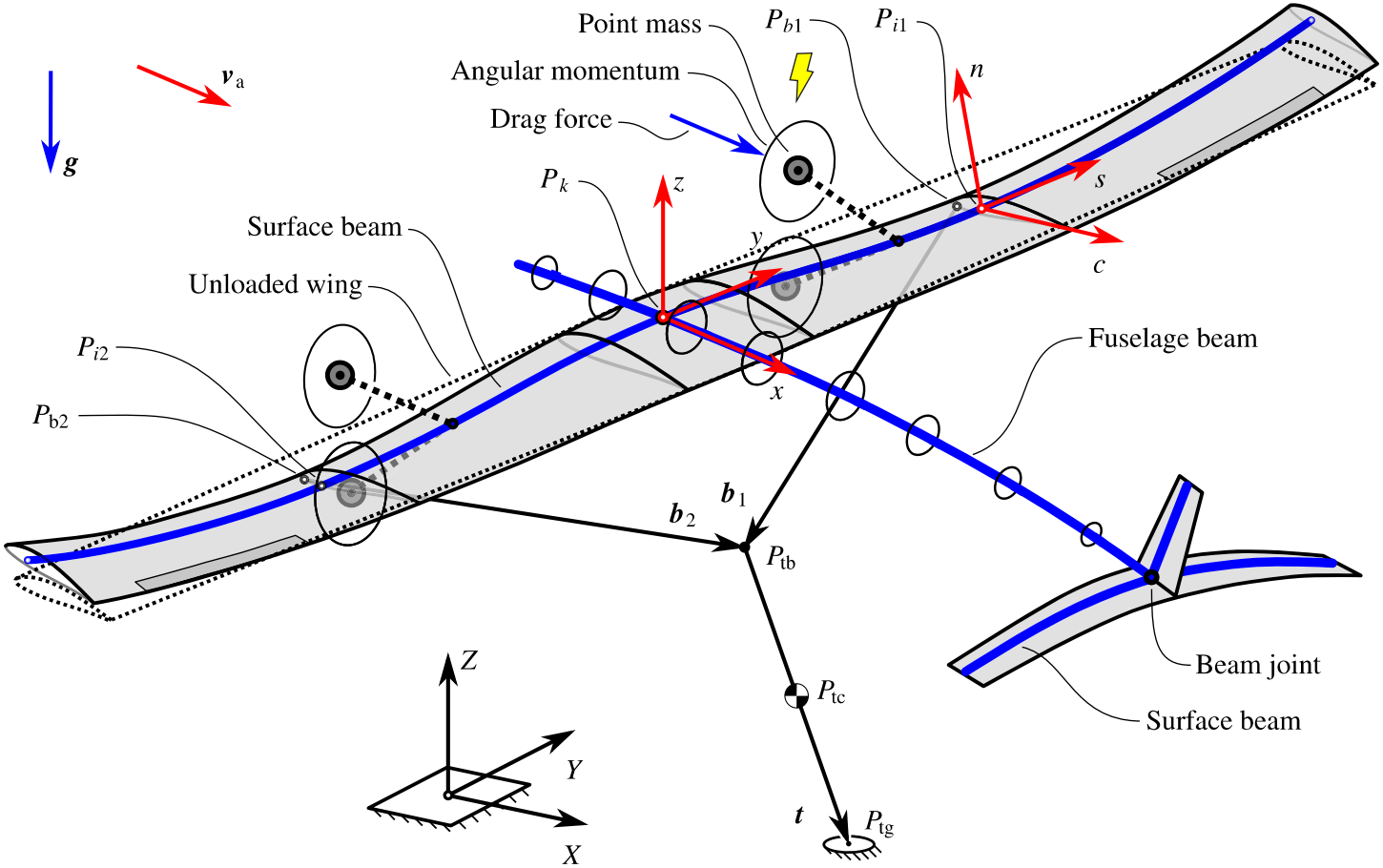


Aeroelastic bending and torsion of a half wing supported by a bridle line

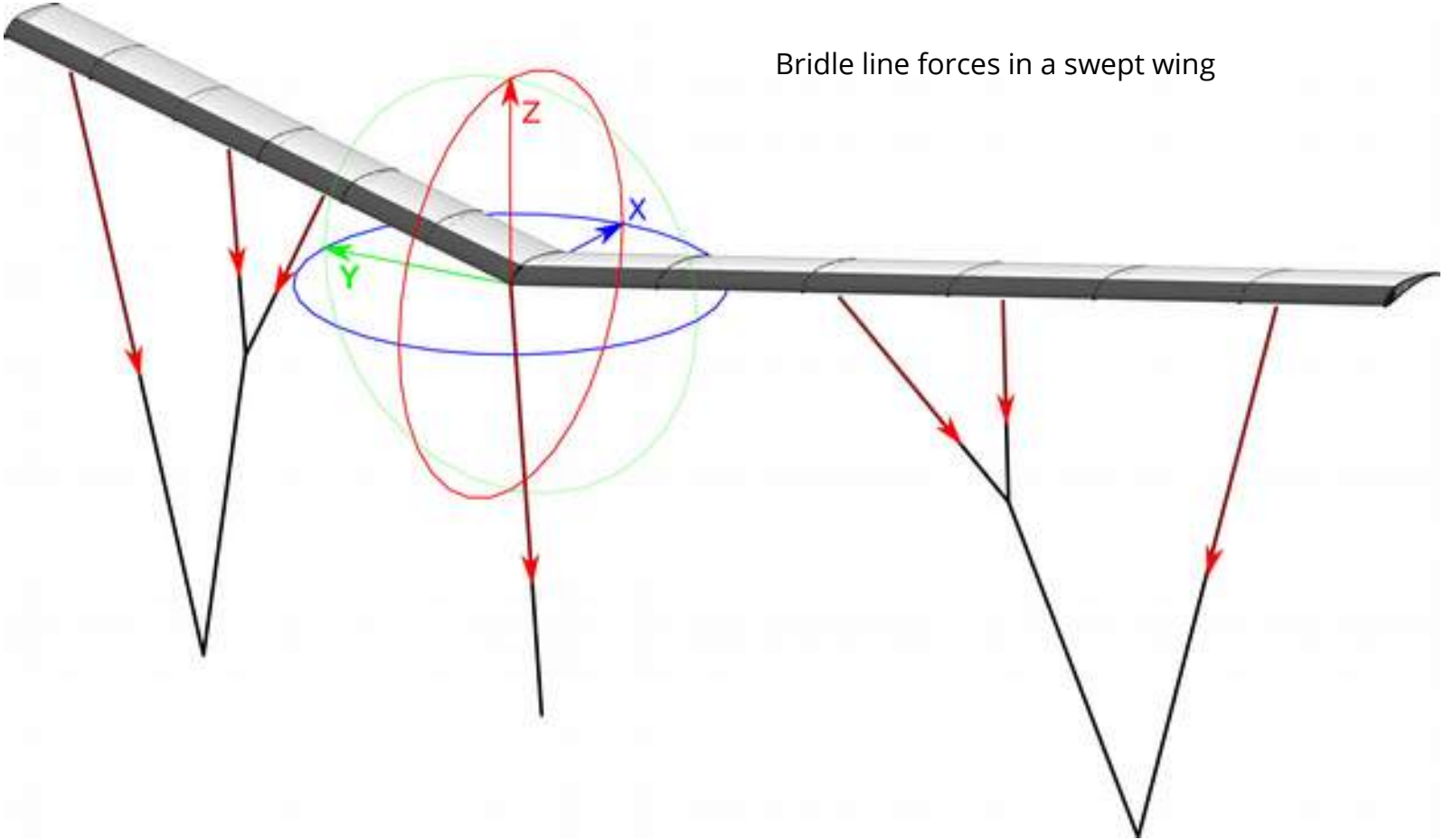


Wijnja, Schmehl, De Breuker, Jensen and Vander Lind: "Aeroelastic Analysis of a Large Airborne Wind Turbine". Journal of Guidance, Control and Dynamics, 2018

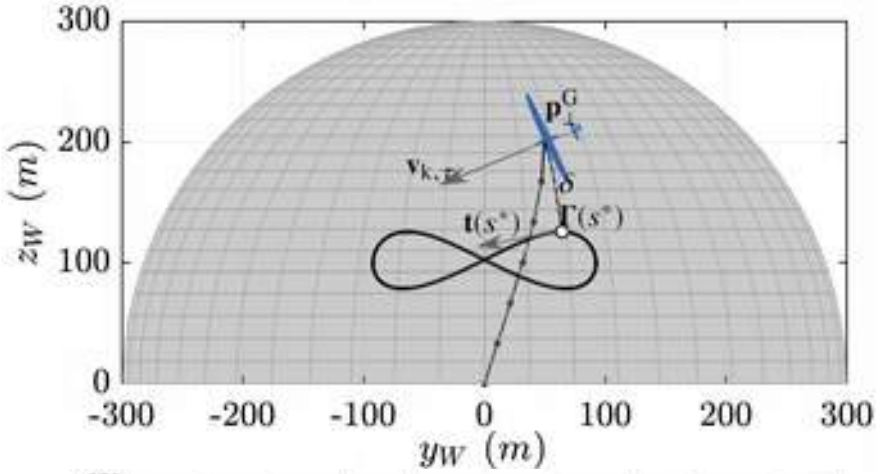
Aeroelastic model of an AWT and the tensile support system connecting it to the ground

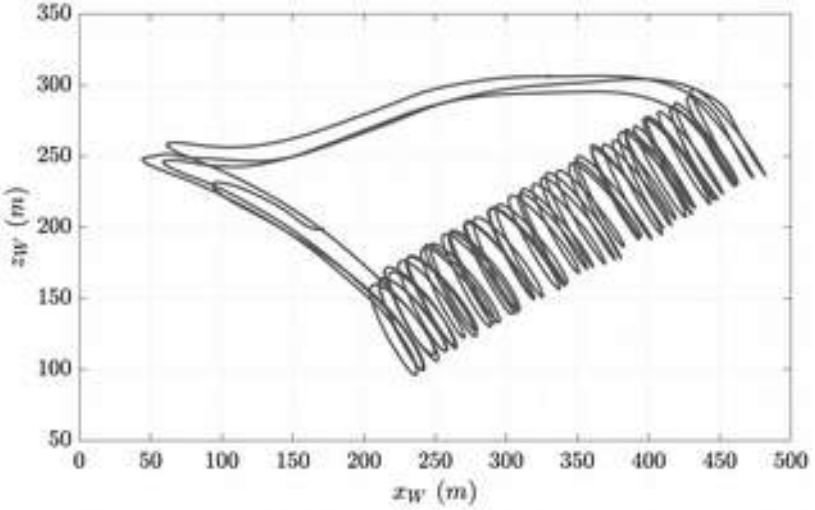


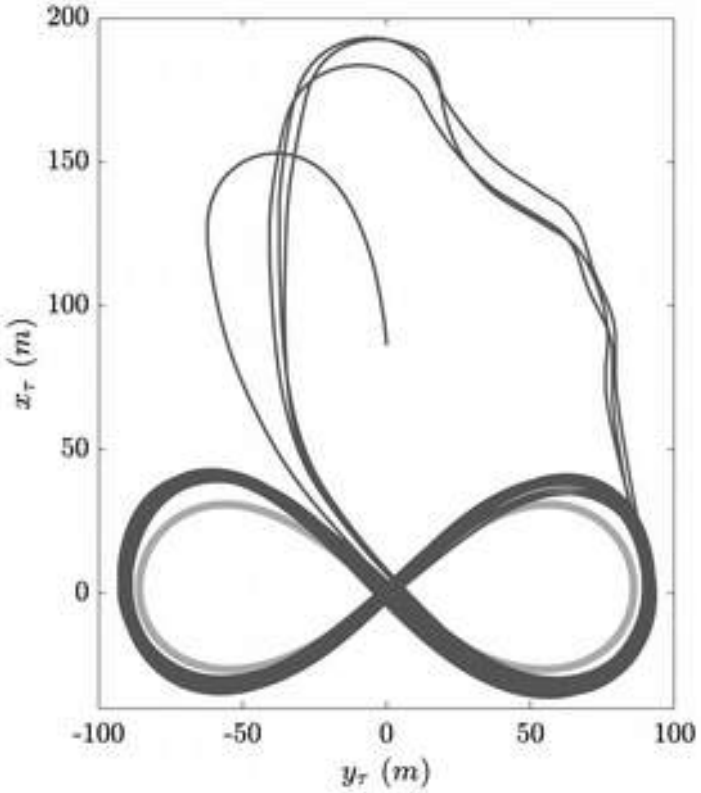
Wijnja, Schmehl, De Breuker, Jensen and Vander Lind: "Aeroelastic Analysis of a Large Airborne Wind Turbine". Journal of Guidance, Control and Dynamics, 2018



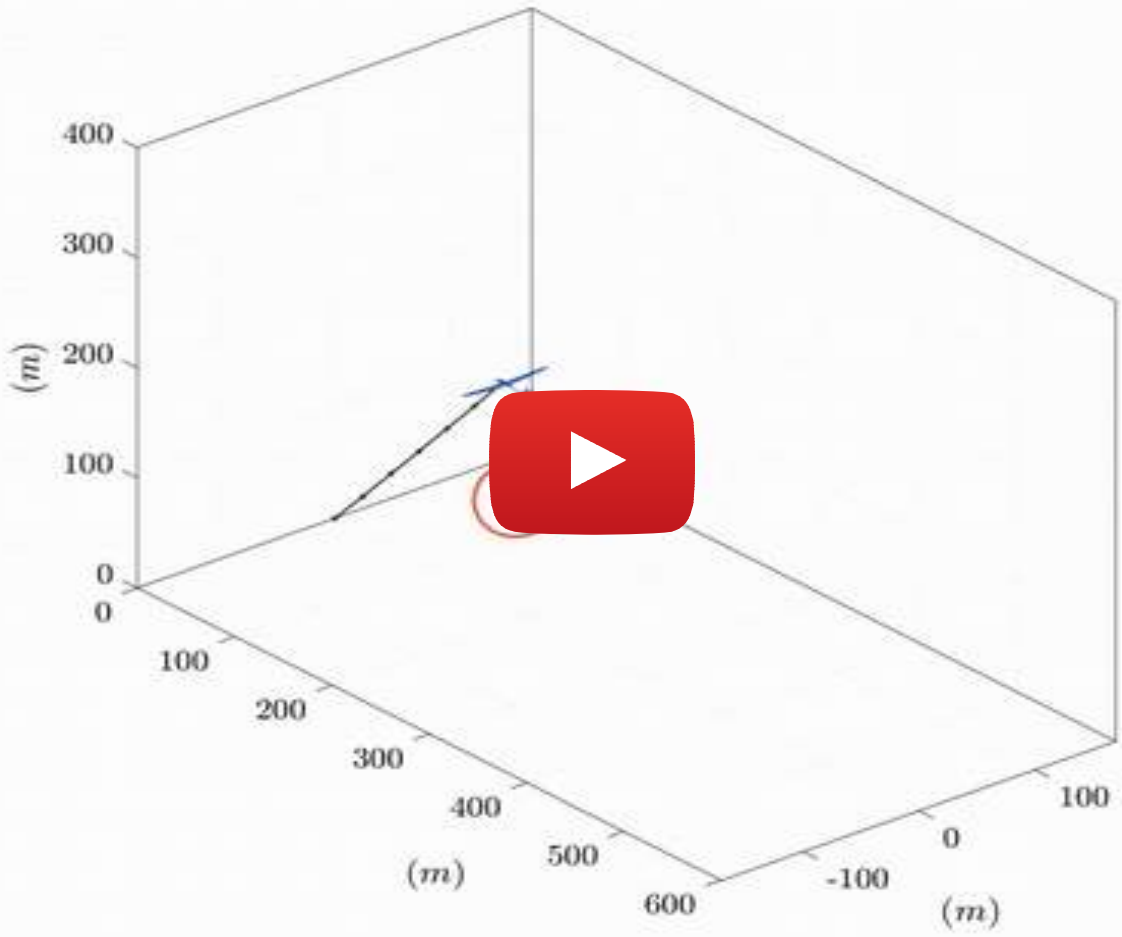
Candade, Ranneberg & Schmehl. "Structural Analysis and Optimization of a Tethered Swept Wing for Airborne Wind Energy Generation". Wind Energy, 2020





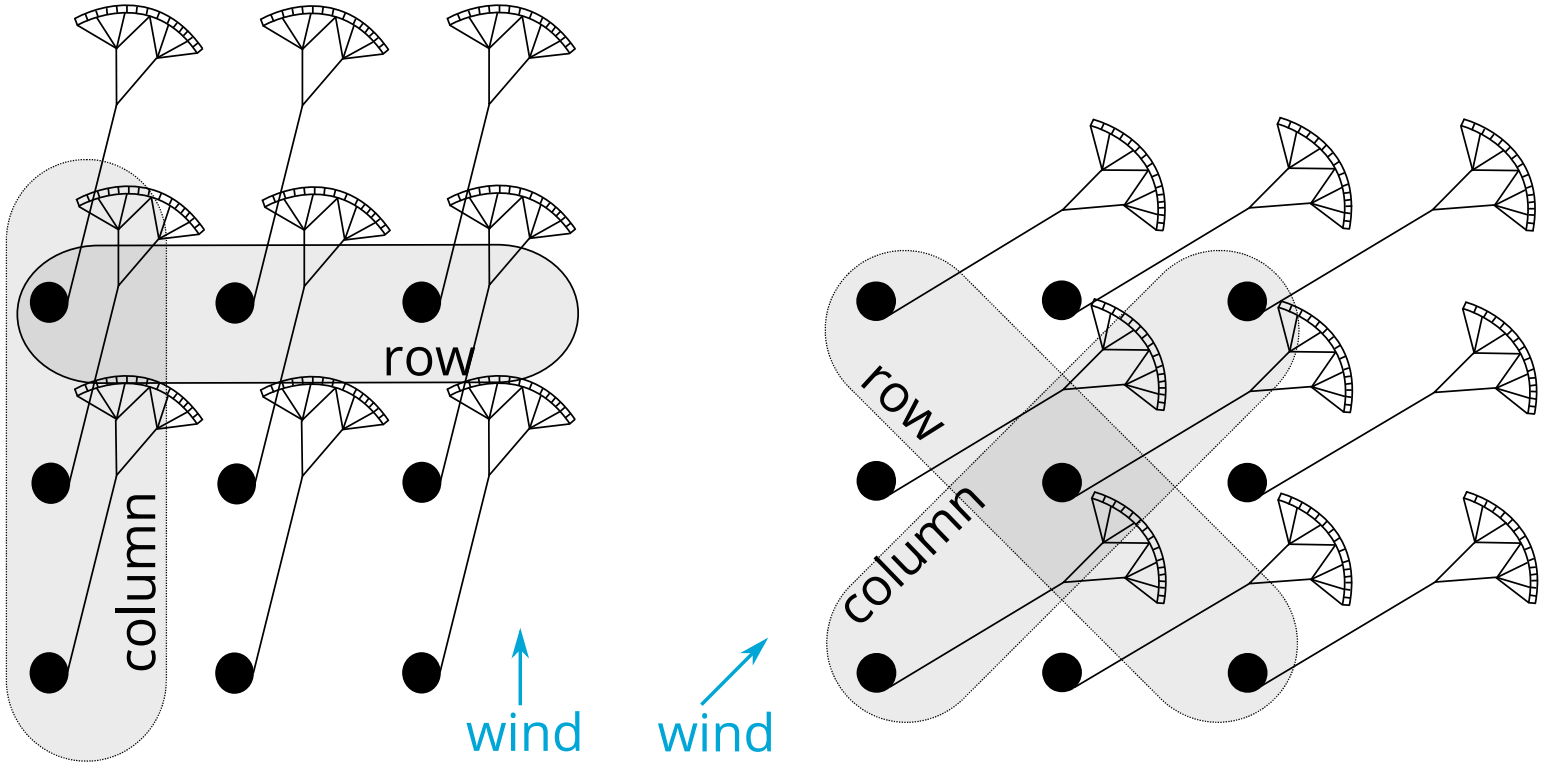


Rapp, Schmehl, Oland, Haas. "Cascaded Pumping Cycle Control for Rigid Wing Airborne Wind Energy Systems". AIAA Journal of Guidance, Control and Dynamics, 2019



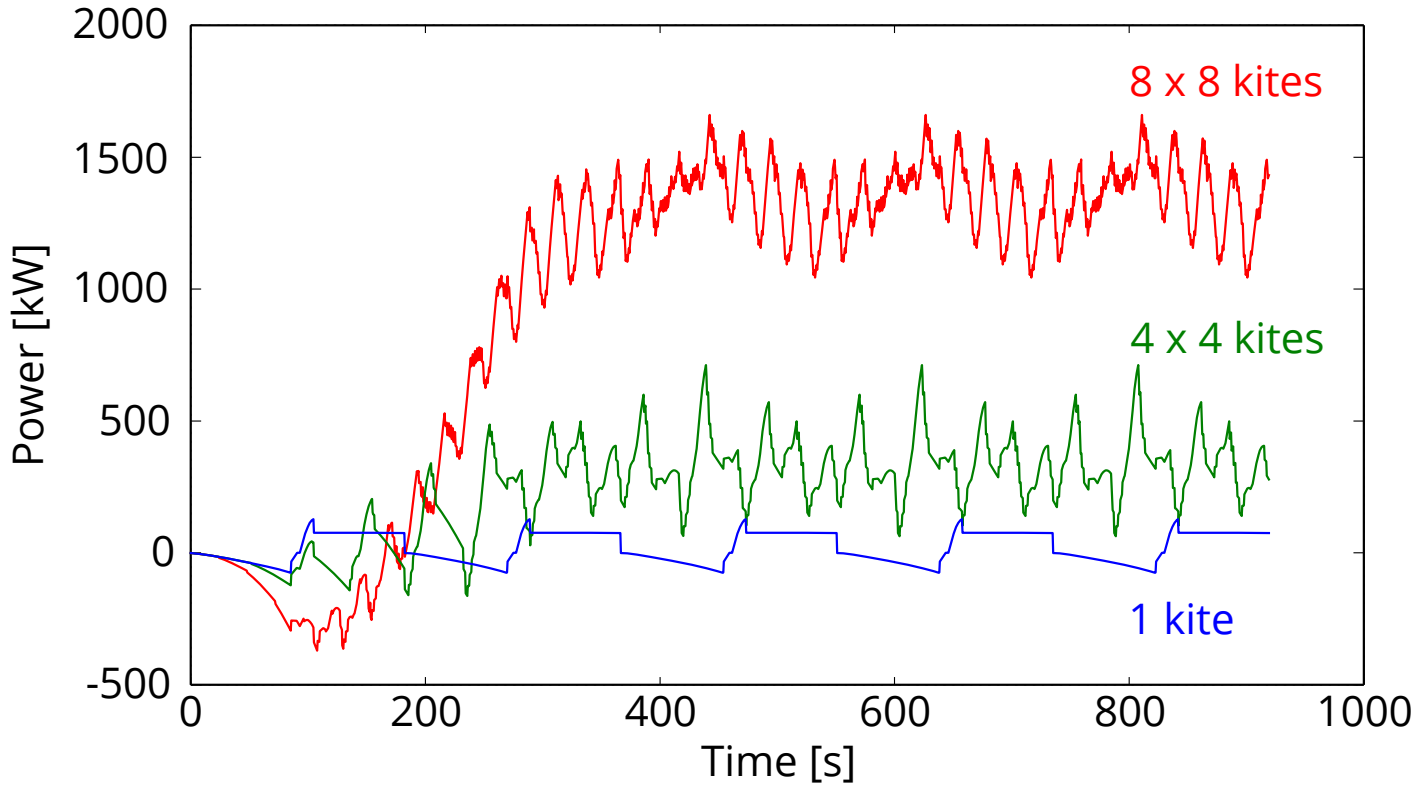
Rapp, Schmehl, Oland, Haas. "Cascaded Pumping Cycle Control for Rigid Wing Airborne Wind Energy Systems". AIAA Journal of Guidance, Control and Dynamics, 2019

Kite park layout



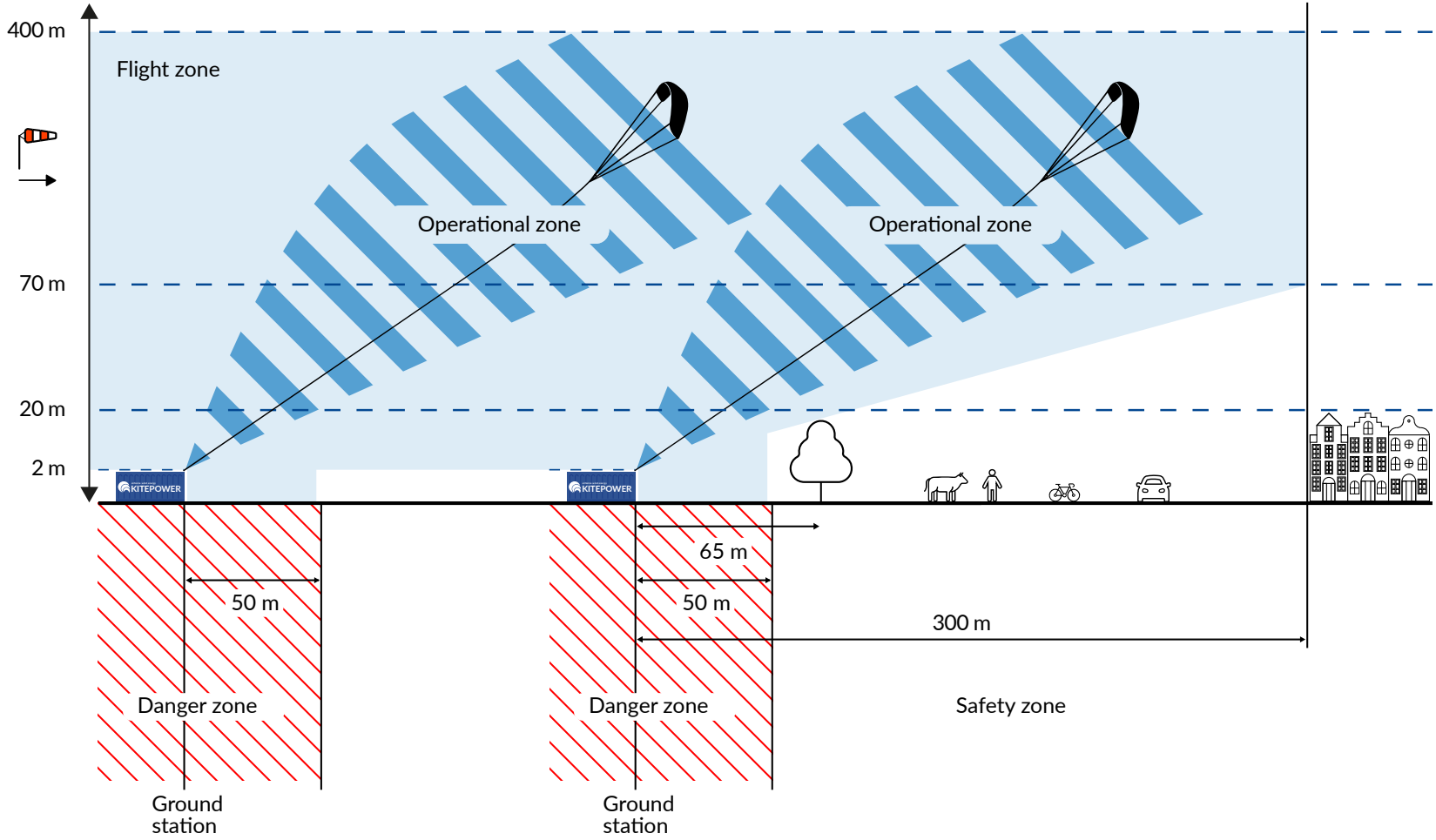
Faggiani & Schmehl. “Design and Economics of a Pumping Kite Wind Park". In: Schmehl (ed.) "Airborne Wind Energy - Advances in Technology Development and Research", Springer, 2018

Kite park power output



Faggiani & Schmehl. “Design and Economics of a Pumping Kite Wind Park". In: Schmehl (ed.) "Airborne Wind Energy - Advances in Technology Development and Research", Springer, 2018

Safety & reliability



Salma, Friedl & Schmehl: "Improving Reliability and Safety of Airborne Wind Energy Systems", Wind Energy, 2019

2012/08/02

Salma, Friedl & Schmehl: "Improving Reliability and Safety of Airborne Wind Energy Systems", Wind Energy, 2019


ETH zürich
DTU
TU Delft

Development as an industry

- Many bottom-up initiatives, e.g. by students and PhD researchers, only later picked up by academic staff
- Initially driven by research on control & optimization
- Full automation, reliability and materials are critical technical challenges
- Developed in parallel to conventional wind energy
- Since a few years also the wind energy community shows interest

Infrastructure

- EU-H2020 doctoral school AWESCO (2015-2018)
- Industry association “Airborne Wind Europe”
- EAWE Technical Committee “Airborne Wind Energy”

AWESCO
Airborne Wind Energy
System Modelling, Control & Optimisation

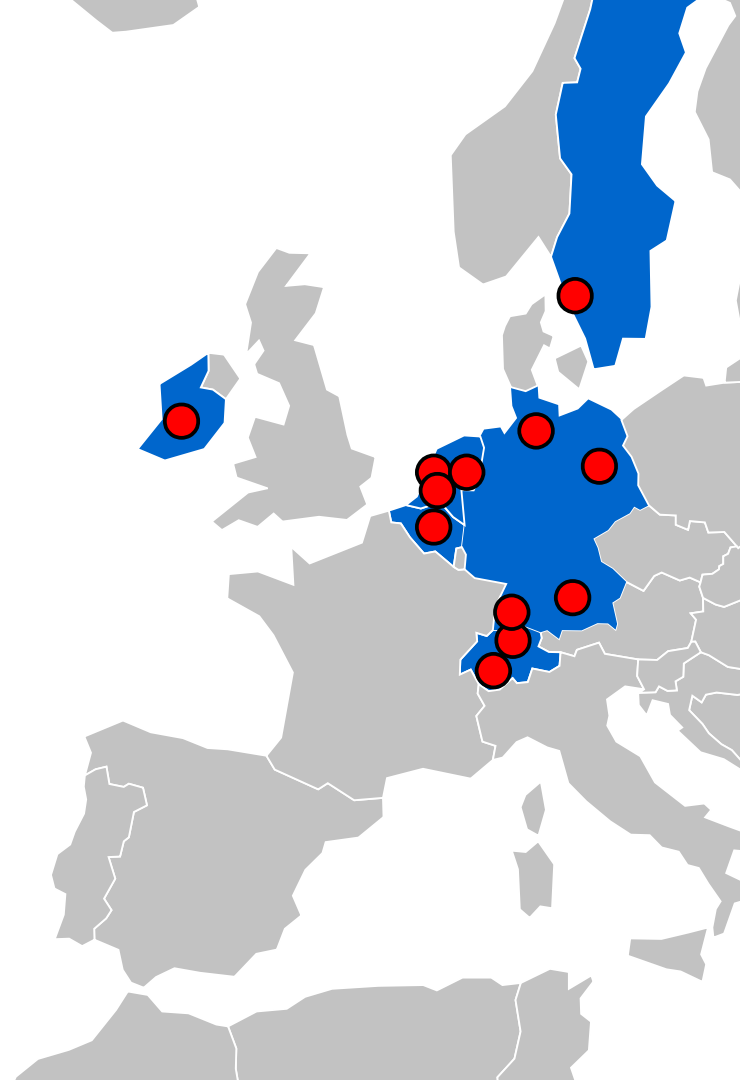
- Marie Skłodowska-Curie Initial Training Network
- 4 work packages focussing on scientific challenges:
  - **Modelling and Simulation** (WP lead: TUD)
  - **System Design and Optimisation** (WP lead: ALU-FR)
  - **Sensors and Estimation** (WP lead: Xsens)
  - **Control Systems** (WP lead: TUM)

AWESCO

Airborne Wind Energy

System Modelling, Control & Optimisation

- 14 PhD projects, all contributing to relevant questions of industry
- 4 PhD projects supervised by TU Delft
- 10 EU-funded partners
- 2 CH-funded partners
- 3.4 M€ total budget



TU Delft TU Delft UNI FREIBURG UNI FREIBURG CHALMERS UNIVERSITY OF TECHNOLOGY KU LEUVEN Technische Universität München

University of Limerick Ollscoil Luimnigh ampyx power UNI FREIBURG xsens EnerKite ETH zürich EPFL École polytechnique fédérale de Lausanne

AWESCO members: (above) at the midterm project meeting (8 February, 2017), and (below) during a course (3–4 March, 2016)

Impact of EU funding

FP7

- **HAWE** - FP7-ENERGY
- **Highwind** - ERC

Horizon 2020

- **AWESCO** - European Training Network
- **AMPYXAP3** - SME Instrument Phase I & II
- **REACH** - Fast Track to Innovation Pilot

AWESCO
Airborne Wind Energy
System Modelling, Control & Optimisation

Impact of EU funding

Horizon 2020

- **NEXTWIND** - SME Instrument Phase I & II
- **AWESOME** - SME Instrument Phase I & II
- **SKYPULL** - SME Instrument Phase I
- **TWINGTEC** - SME Instrument Phase I
- **TWINGPOWER** - Eurostars

AWEC 2015 in Delft

AWEC 2019, 15-16 October, 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
shortdoi:10/dcjm

AWEC 2017, 5-6 October, 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
shortdoi:10/cd54

AWEC 2015, 15-16 June, 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
shortdoi:10/bjhs

AWEC 2013, 10-11 September, 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
shortdoi:10/c5j3

AWEC 2011, 24-25 May, 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
shortdoi:10/czgh

Questions?

r.schmehl@tudelft.nl

twitter.com/kite_power

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