Airborne Wind Energy - A Challenge for Optimization and Control

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AWESCO Winter School on Numerical Optimal Control
with Differential Algebraic Equations
Freiburg, February 24, 2016

European Research Council

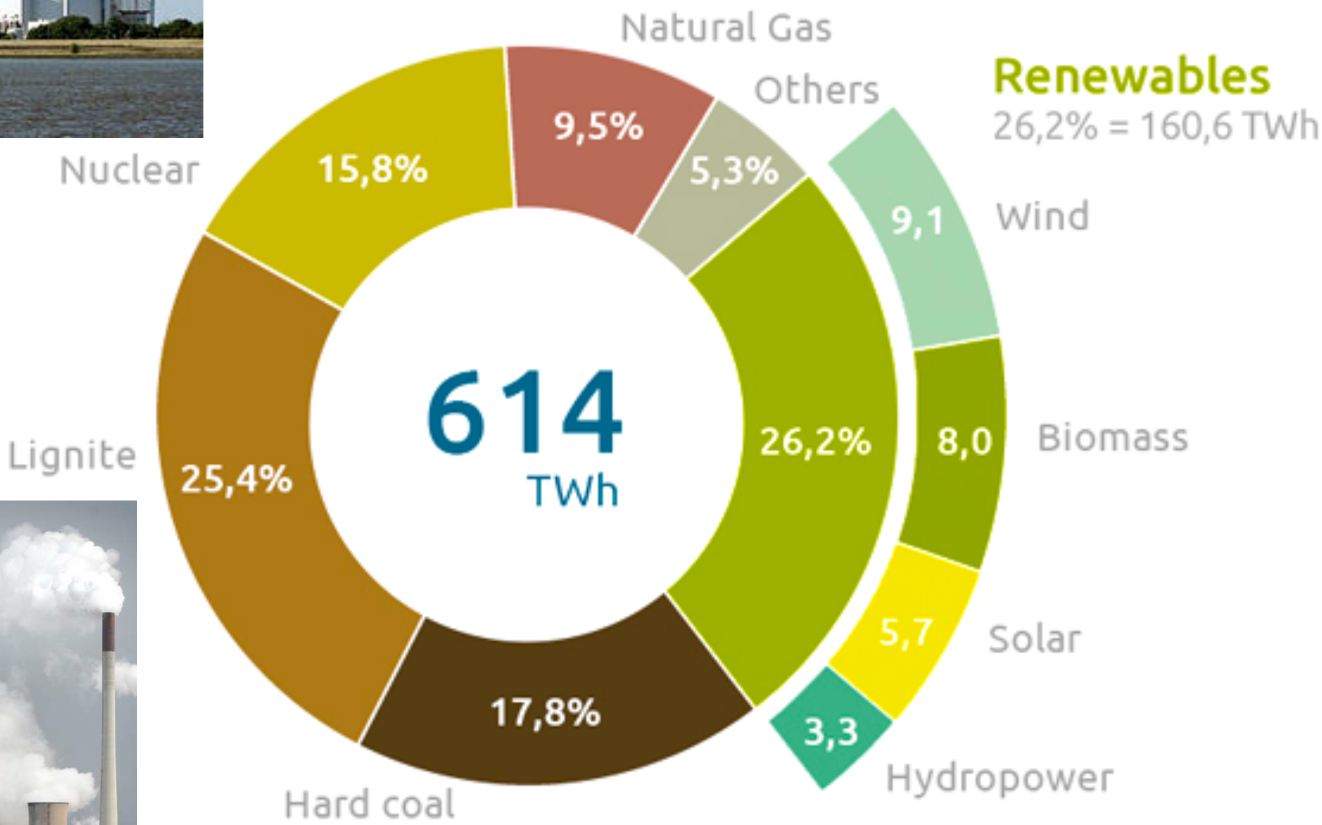
erc

UNI FREIBURG

2022: The last German nuclear power plant stops operation

Neckarwestheim (2 hours from Freiburg)

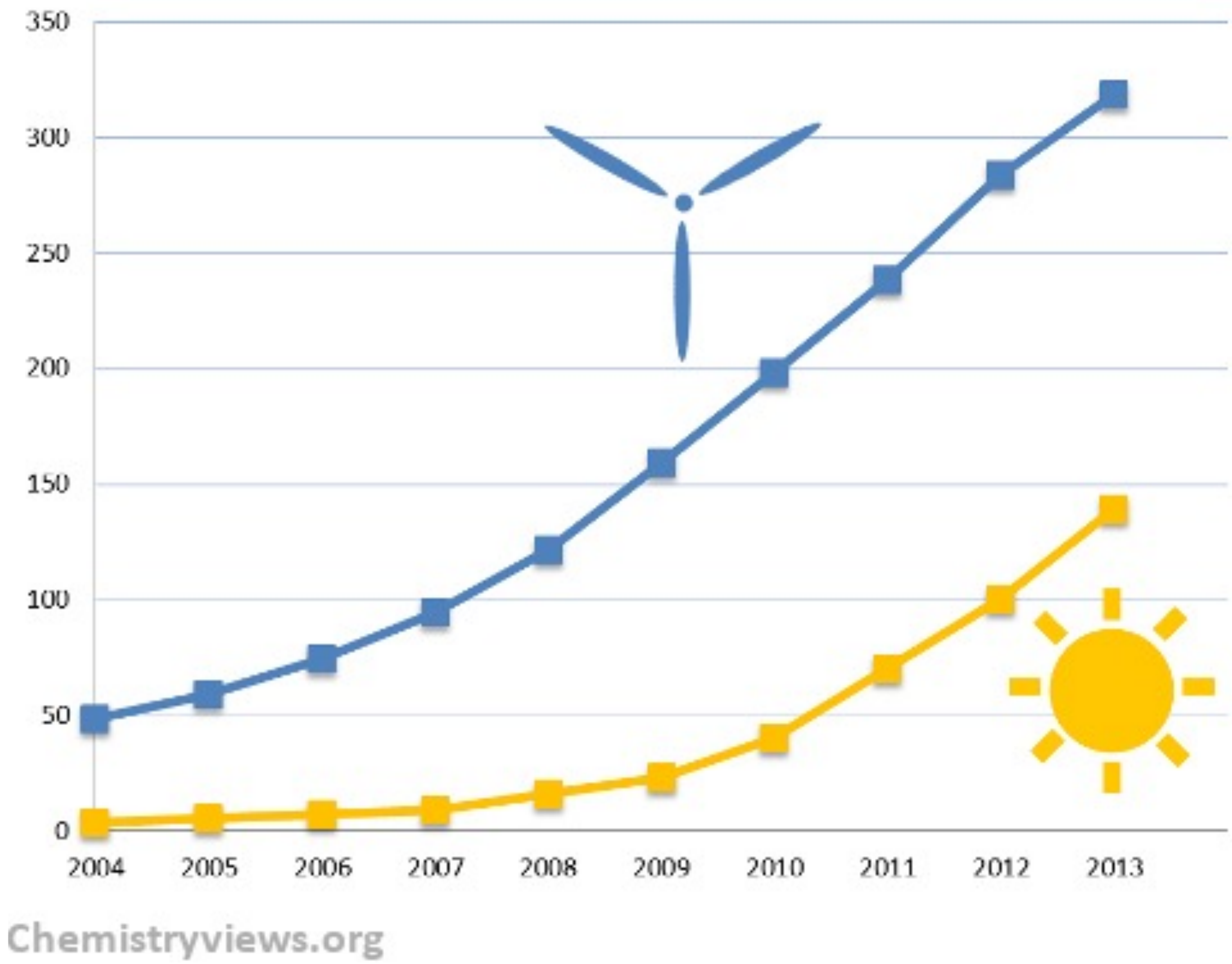
Today, 70% of Germany's electricity is of nuclear or fossil origin



[Data: Renewable Energy Agency, Strom-Report, 2014]

Wind and solar power grow strongly and provide already more electricity than 100 nuclear power plants worldwide

Worldwide installed capacity in GW (divide by 5 to get average production)



What is needed for 5 MW installed power ?

Solar in Italy: area of 125 m x 200 m

ns

What is needed for 5 MW installed power ?

Solar in Italy: area of 125 m x 200 m

Wind in North Sea:
turbine of 150 m height

ns

What is needed for 5 MW installed power ?

Wind in North Sea:
turbine of 150 m height

turbine and tower weigh 700 tons

What is needed for 5 MW installed power ?

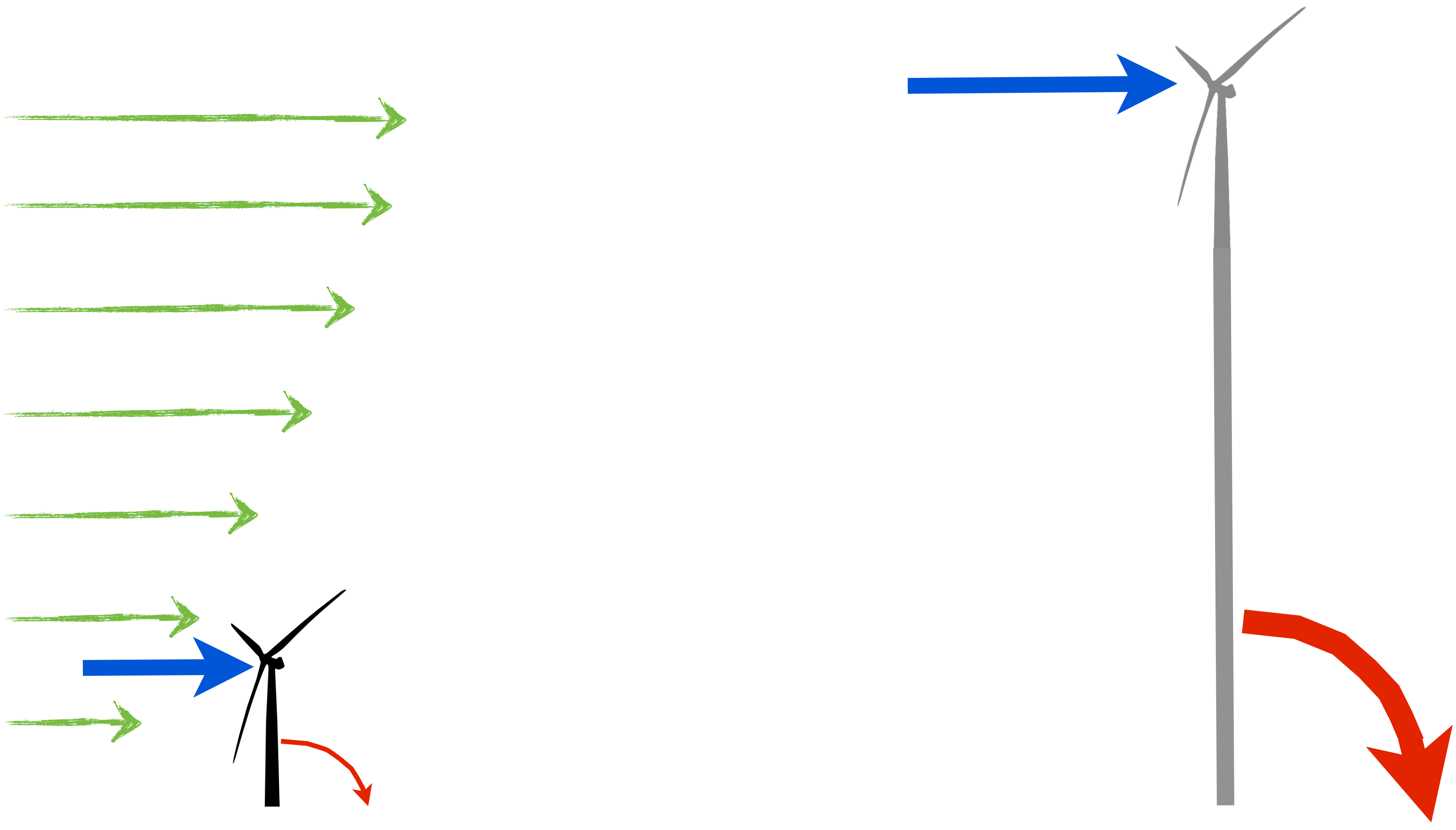
Wind in North Sea:
turbine of 150 m height

turbine and tower weigh 700 tons

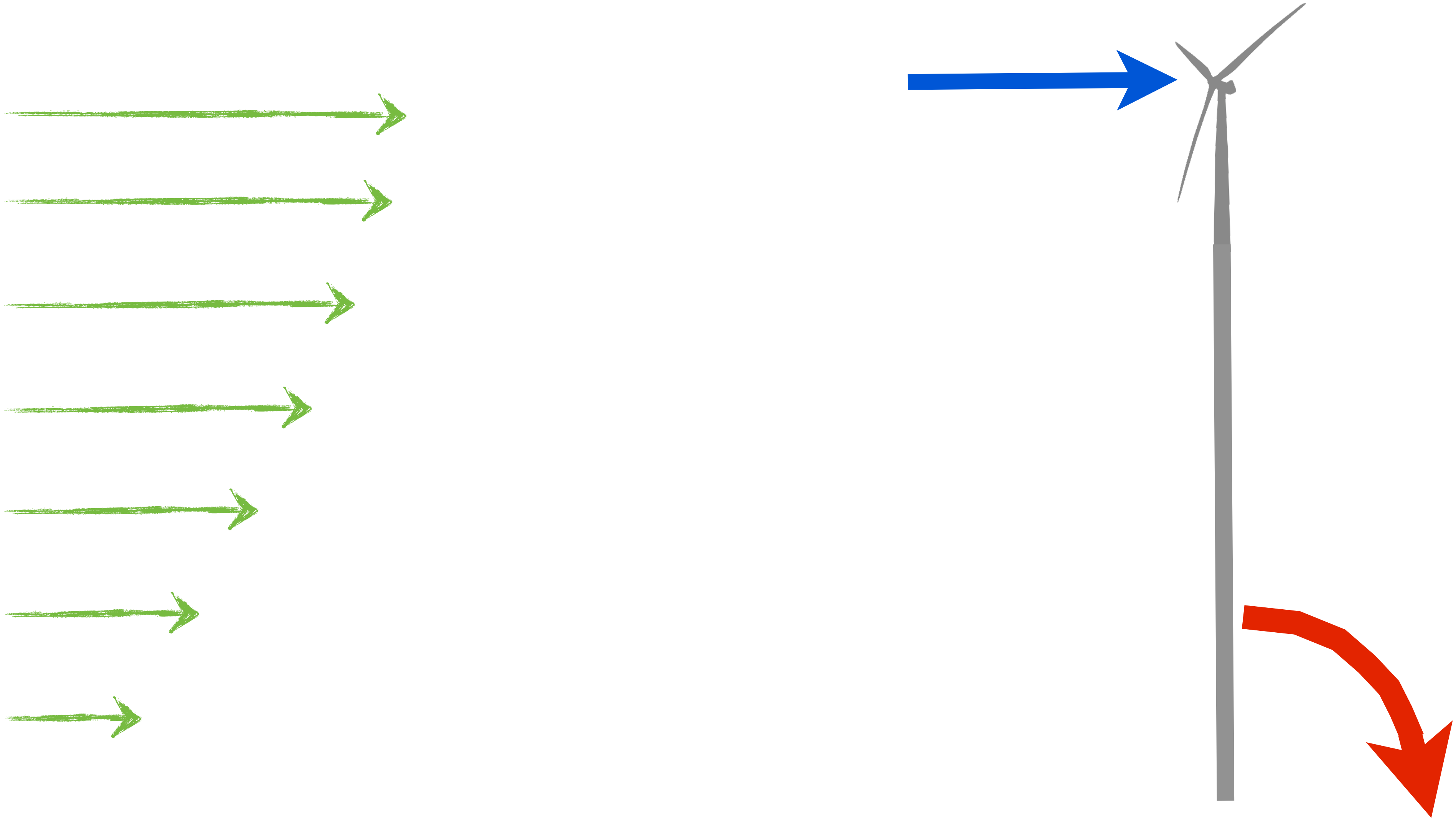
Could we harvest wind power in high altitudes with less material ?

A turbine of 500m height is difficult to build

Long lever arm leads to large torque



A turbine of 500m height is difficult to build



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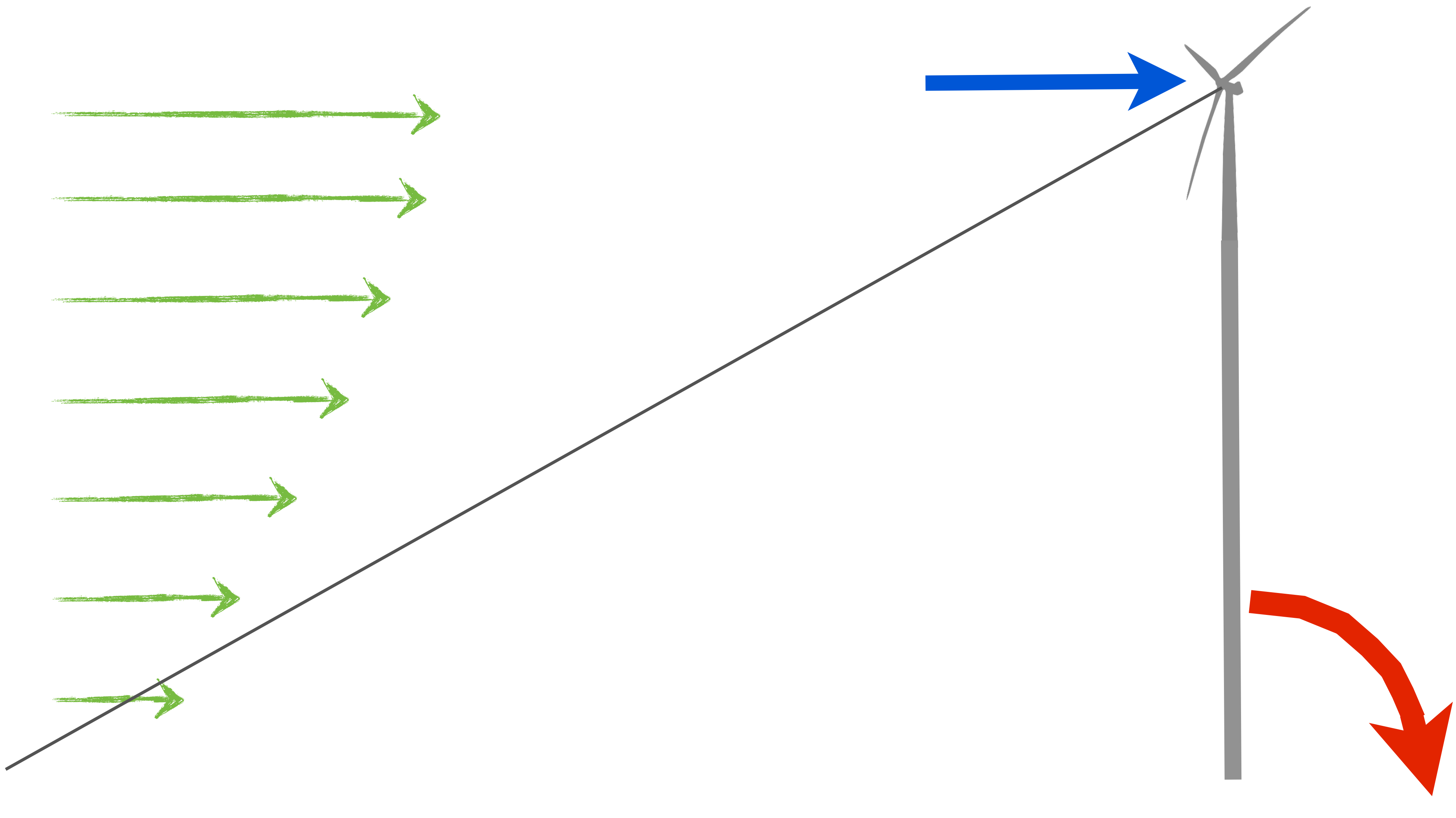

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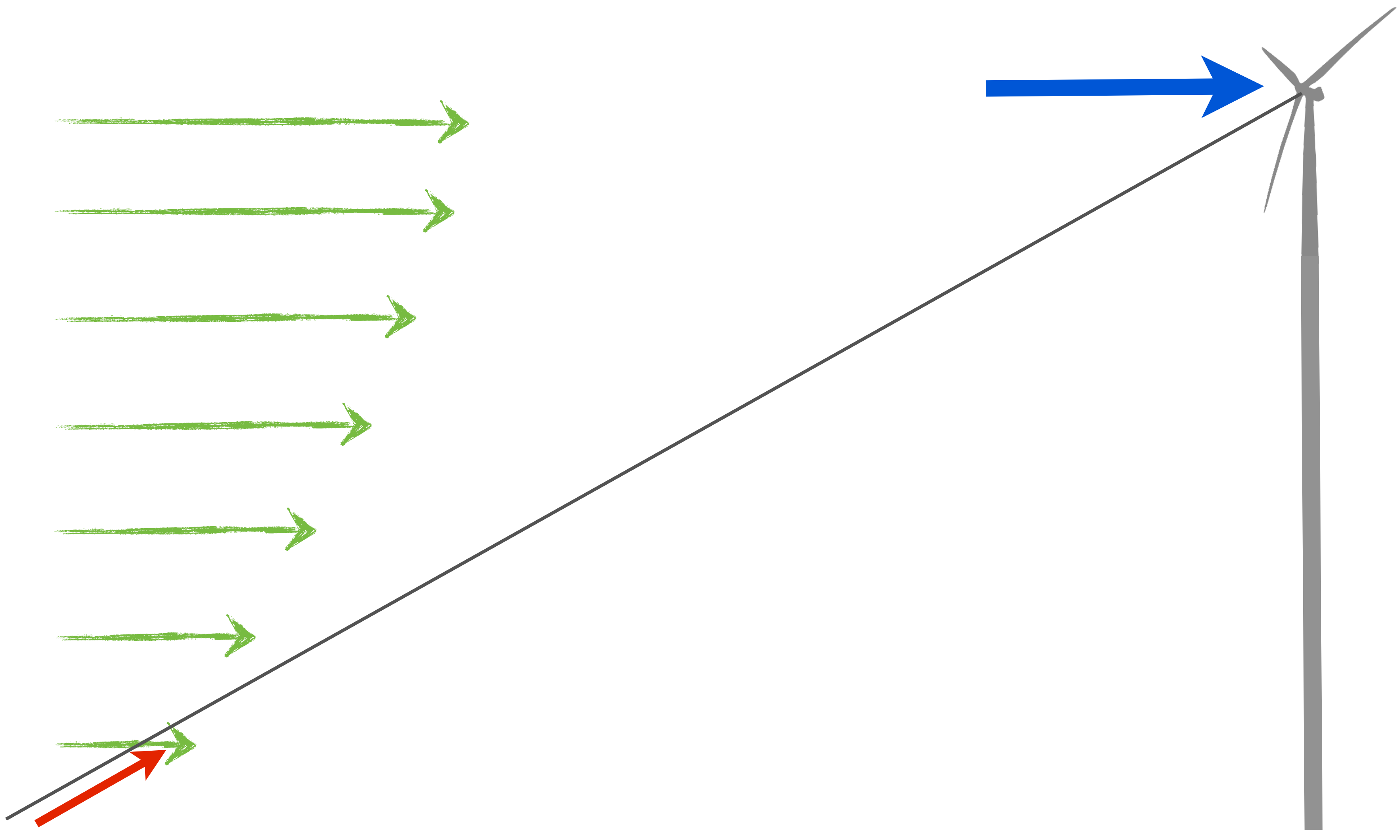

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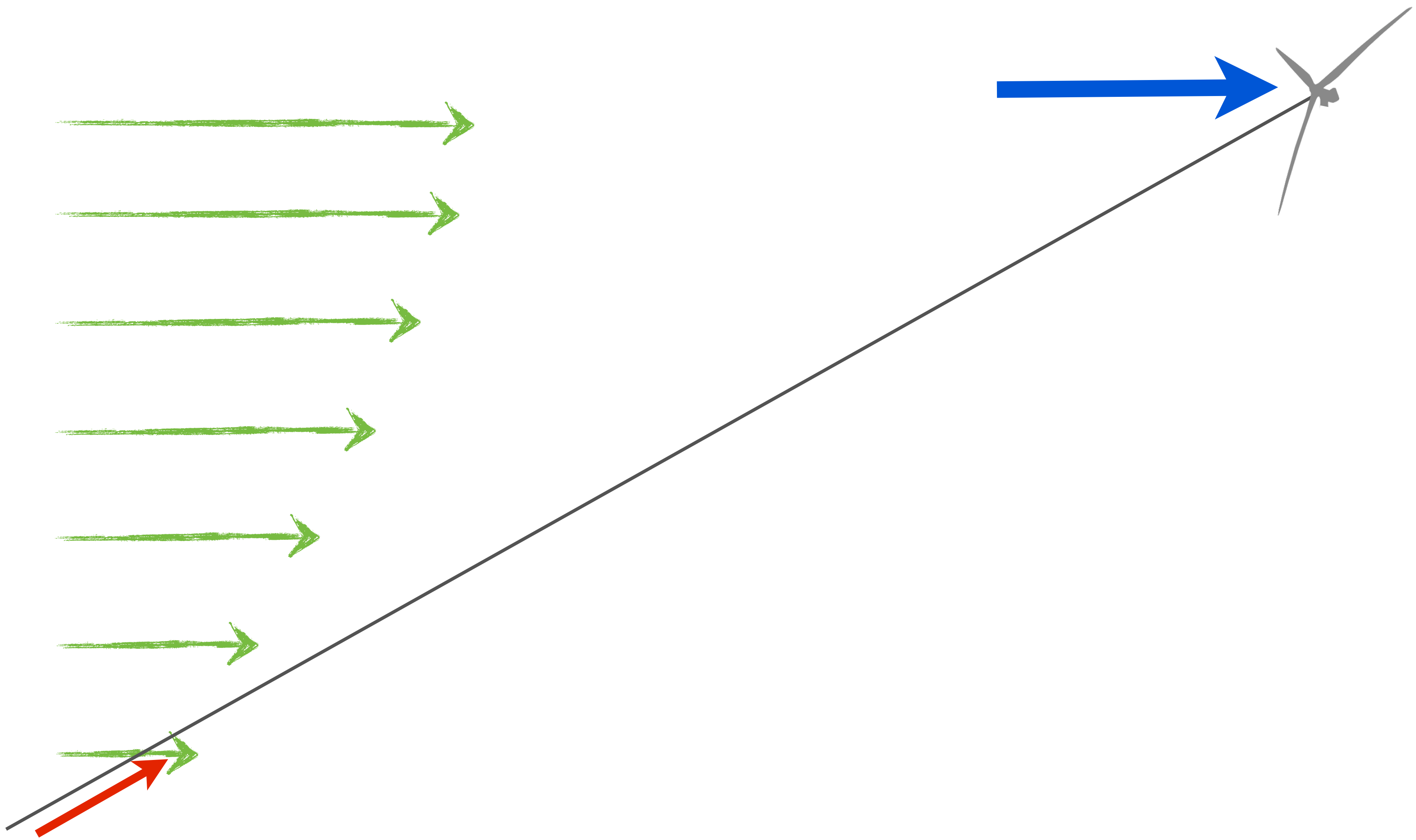

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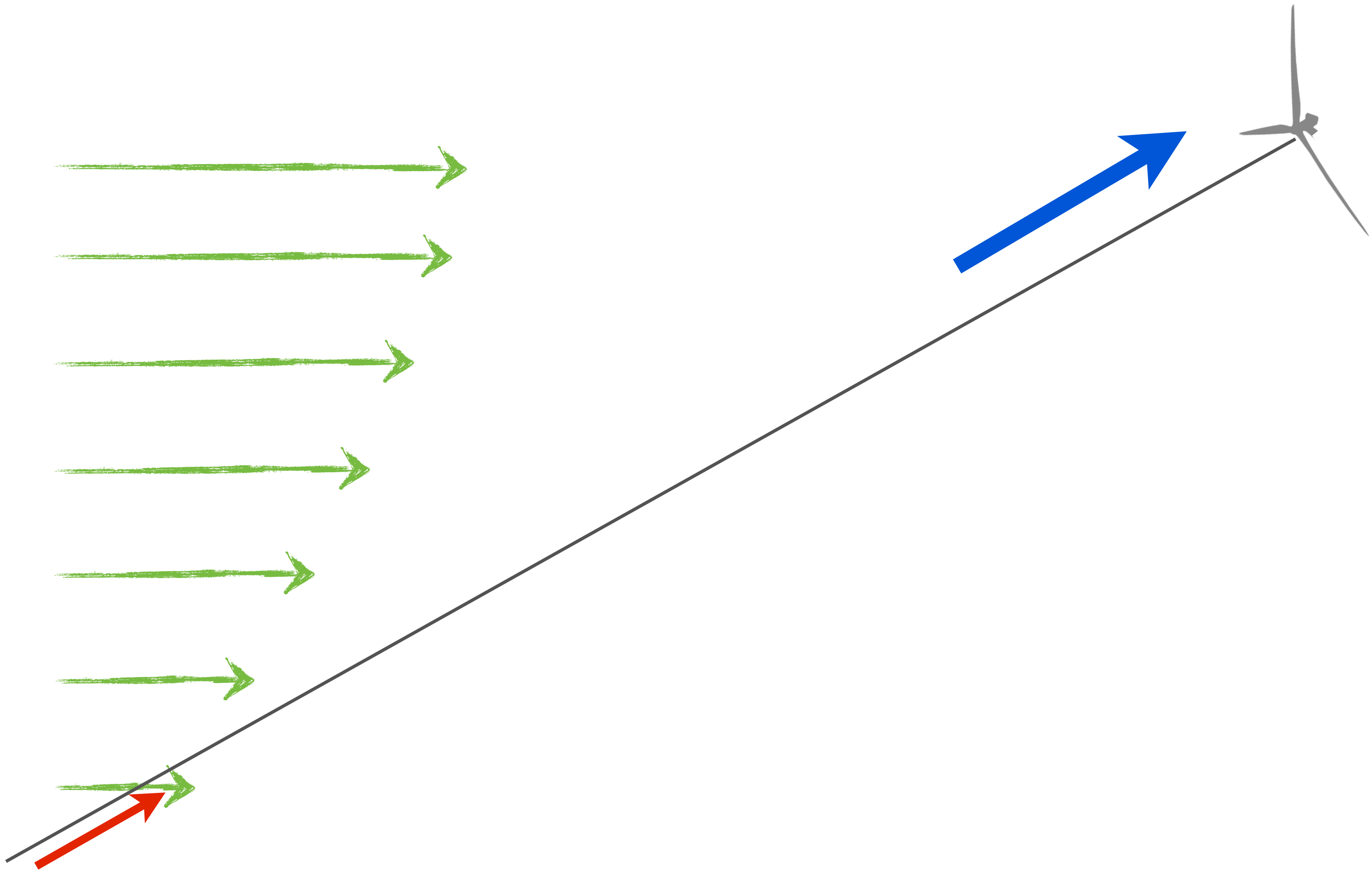
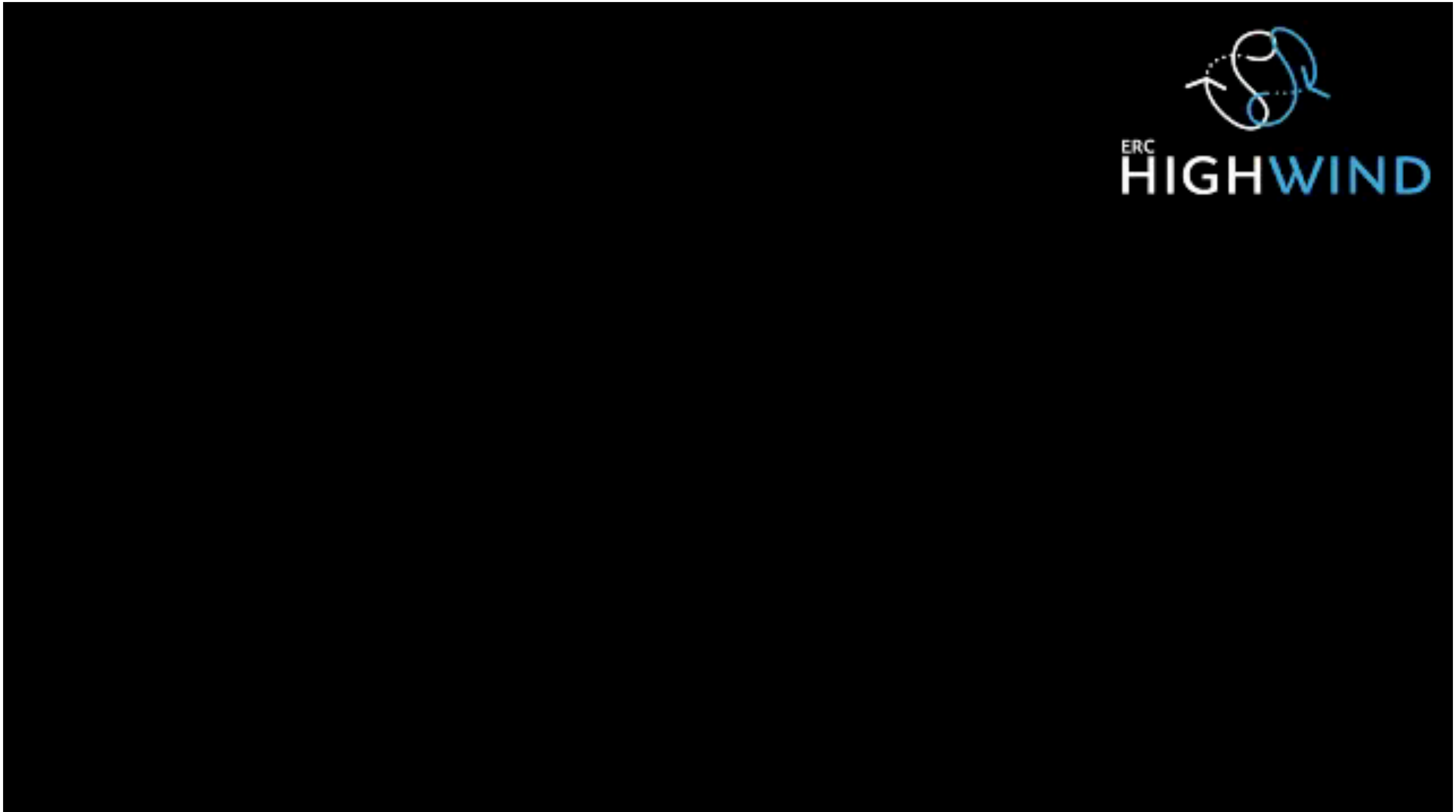
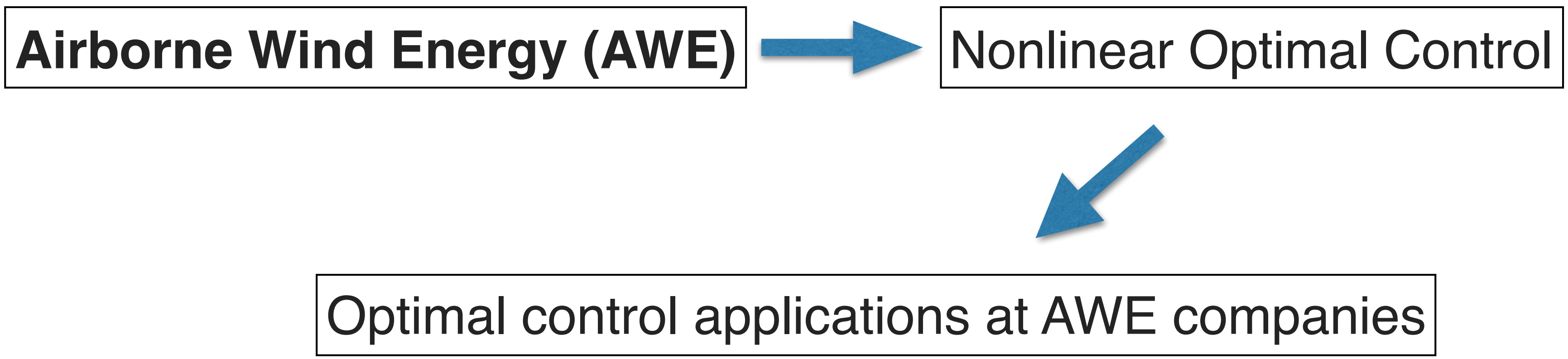


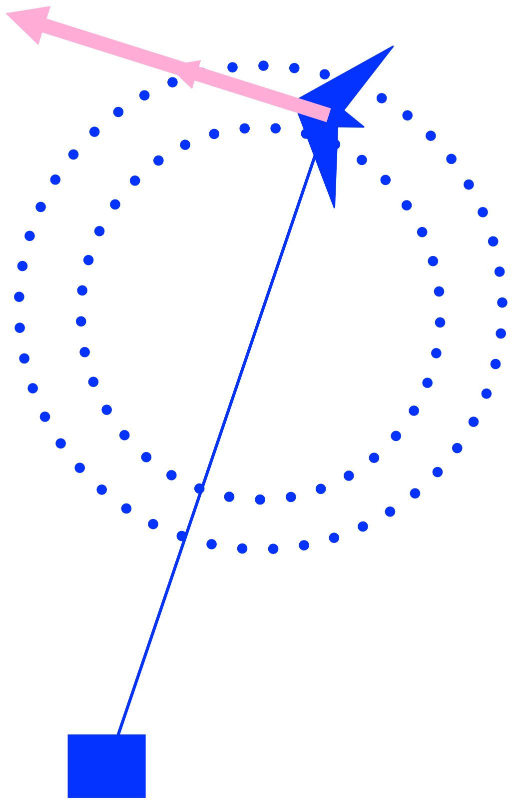
Metamorphosis of a Wind Turbine



Lecture Overview



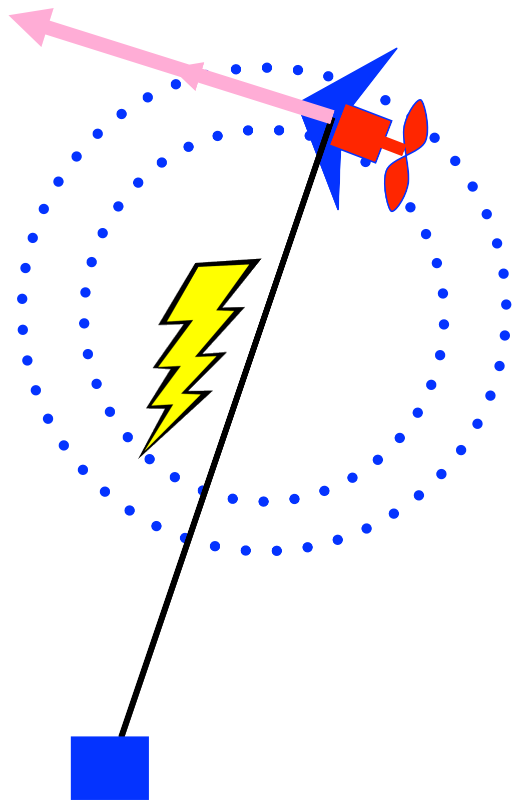
Crosswind Kite Power



- kite flies fast loops in **crosswind** direction
- very strong force on tether

But where could a **generator** be driven ?

Variant 1: On-Board Generator



- attach small wind turbines to kite
- cable transmits power

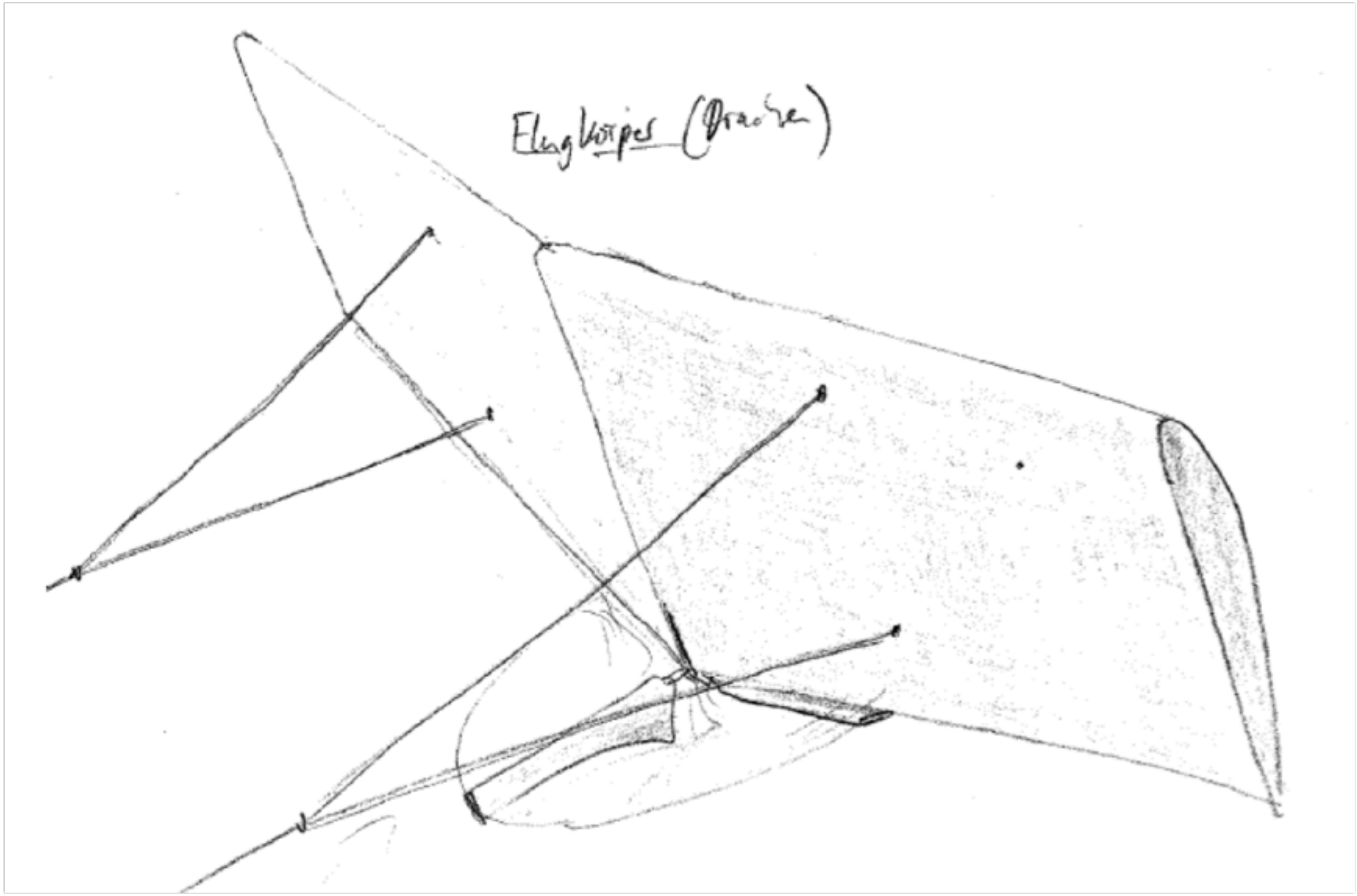
Pros:

- light, high speed generators
- propeller can be used to start and land

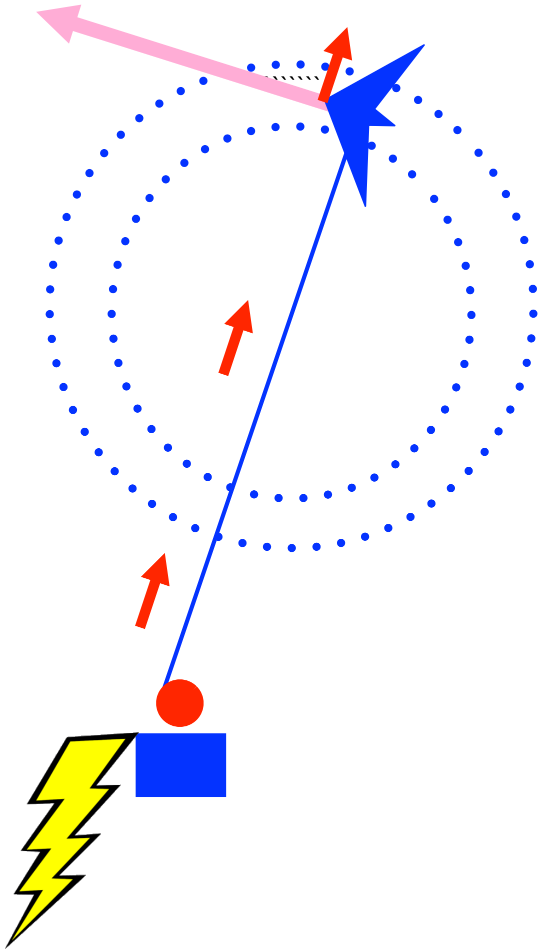
Cons:

- cable needs to transmit power
- generator and power electronics add weight

Variant 1: On-Board Generator — Artistic Vision [D 1992]



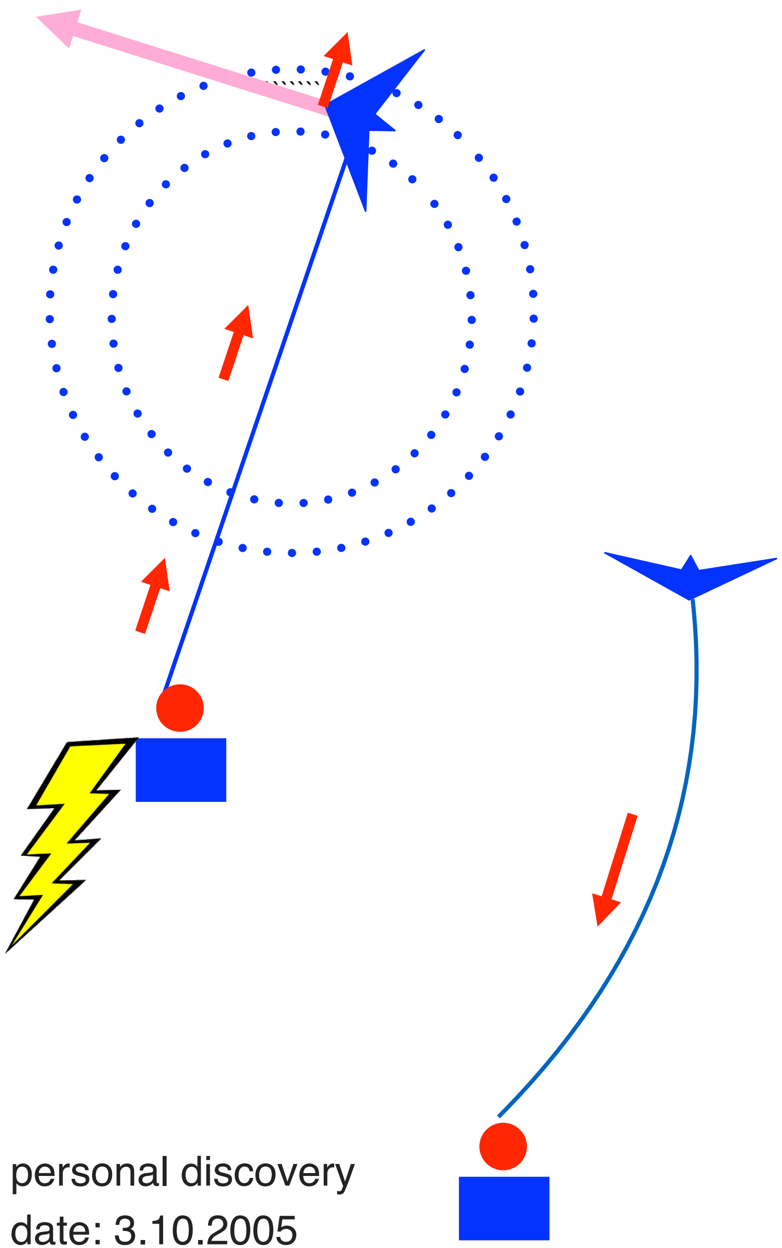
Variant 2: Generator on Ground (Pumping Cycle)



Cycle consists of two phases:

- **Power generation phase:**
    - Fly kite fast, have high force
    - unwind cable
    - generate power

Variant 2: Generator on Ground (Pumping Cycle)



personal discovery
date: 3.10.2005

Cycle consists of two phases:

- **Power generation phase:**
  - Fly kite fast, have high force
  - unwind cable
  - generate power

- Retraction phase:
  - Slow down kite, reduce force
  - pull back line
  - consume power

Pro: all electric parts on ground

Con: slowly turning generator

(…well, this variant leads to particularly beautiful nonlinear optimal control problems…)

Miles Loyd’s Formula

J. ENERGY VOL. 4, NO. 3

ARTICLE NO. 80-4075

1980

Crosswind Kite Power

Miles L. Loyd*

Lawrence Livermore National Laboratory, Livermore, Calif.

$$P = \frac{2}{27} \rho A w^3 C_\mathrm{L} \left(\frac{C_\mathrm{L}}{C_\mathrm{D}} \right)^2$$

power P

air density ρ

wing area A

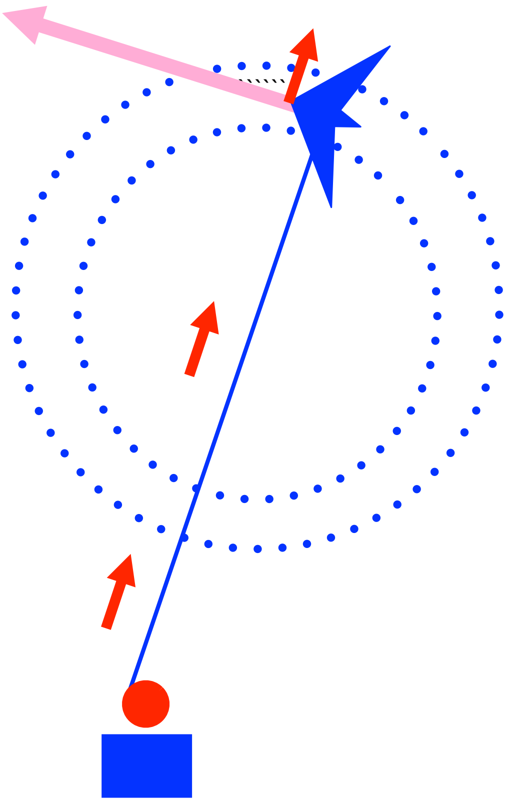
wind speed w

Lift-over-drag ratio (L/D) $\left(\frac{C_\mathrm{L}}{C_\mathrm{D}} \right)$

wing area of 1 m^2 generates 40 kW power (at 13 m/s wind speed and L/D of 15).

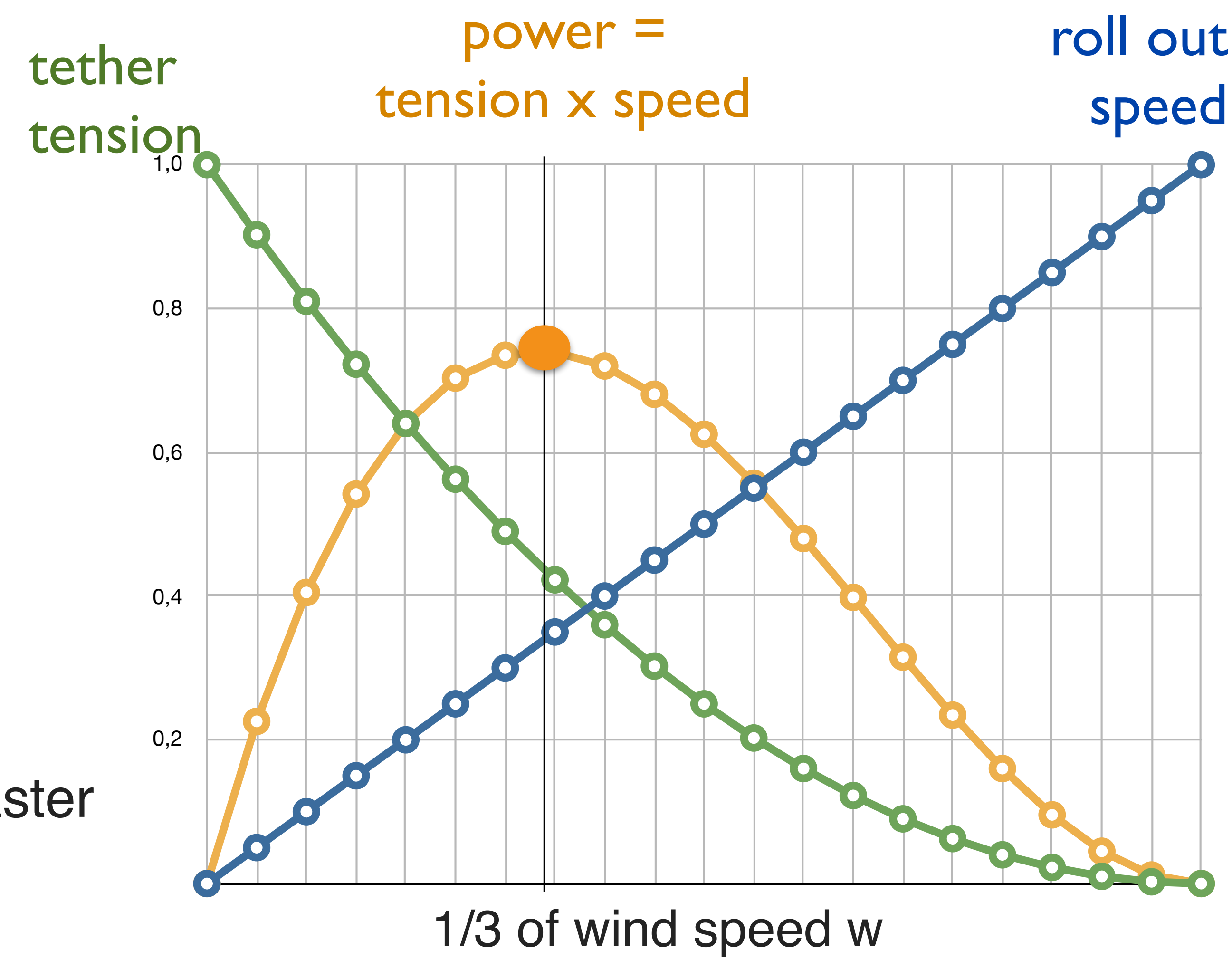
Same efficiency for both variants.

Which roll out speed is optimal ?



Remark: kite flies much faster in crosswind direction…

Maximum power reached at 1/3 of wind speed



How much is 40 kW per m^2 ?

More realistic estimate: wing produces full power only 25% of a year, so we get about **10 kW per m^2.**

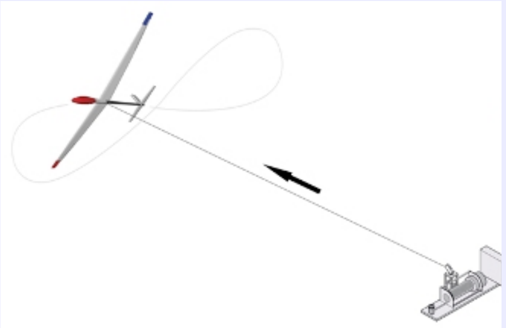
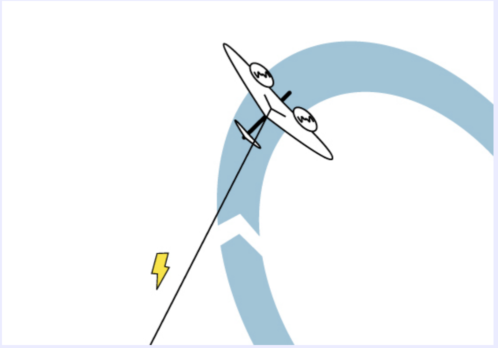
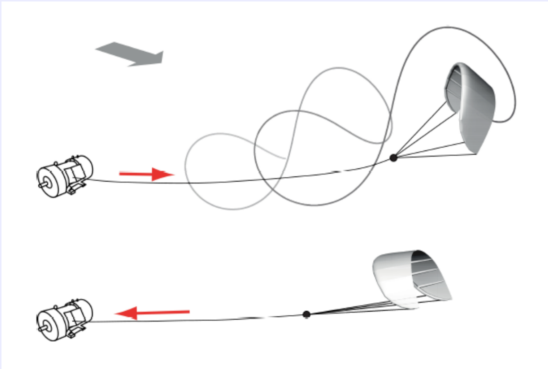
Two people need 1 m^2 wing surface to cover all their energy needs !

[master students Wouter Vandermeulen and Jeroen Stuyts]

1 m^2 wing surface corresponds to 250 m^2 of photovoltaic cells in Italy

Airborne Wind Energy Conferences 2010, 2011, 2012, 2013, 2015,

Categorization of crosswind systems

	Ground-Based Generation	On-Board Generation
Fixed Wing		
Soft Wing		(not efficient due to low speed)

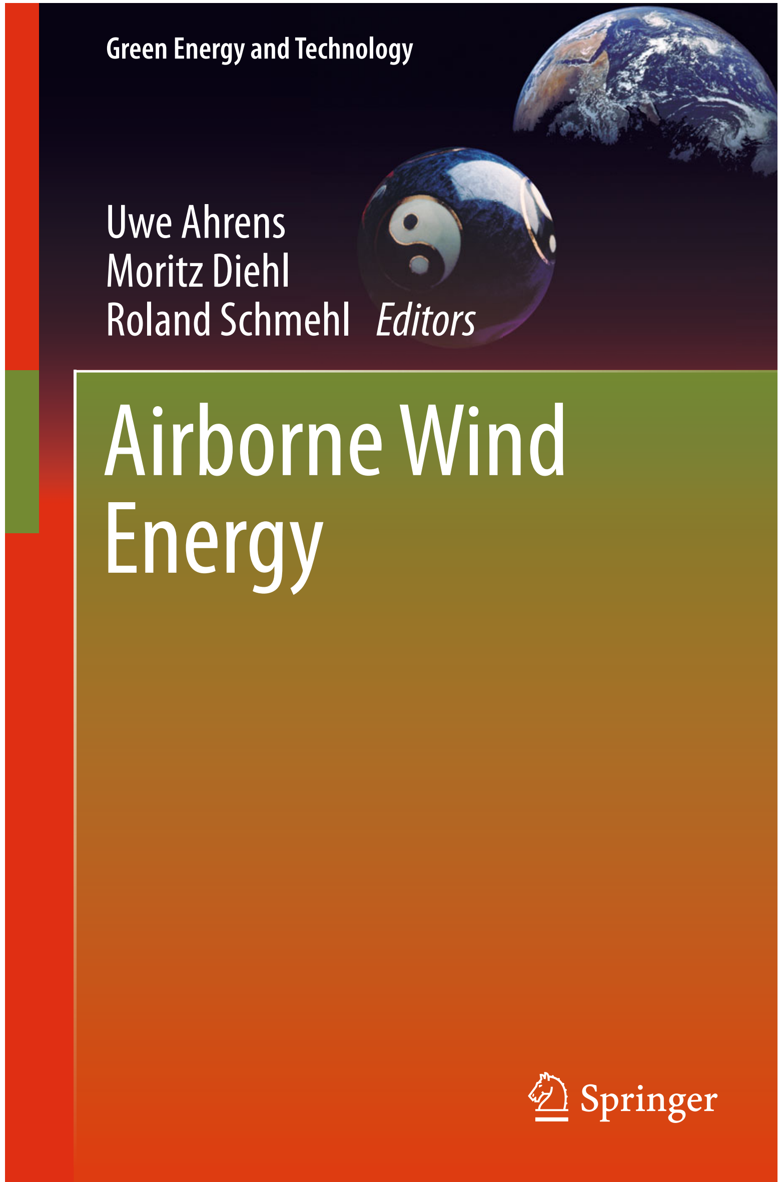
Categorization of crosswind systems

	Ground-Based Generation	On-Board Generation
Fixed Wing		
Soft Wing		(not efficient due to low speed)

Categorization of crosswind systems

	Ground-Based Generation	On-Board Generation
Fixed Wing	**AmpyxPower, Netherlands**	**Makani power, California**
Soft Wing	**SkySails, Hamburg**; Enerkite, Berlin; TU Delft, NTS, Torino, TU Munich, Swiss Kite Power, …	(not efficient due to low speed)

How to model Airborne Wind Energy systems ?



Differential Algebraic Equation (DAE) Models of Tethered Airplanes

For simple plane attached to a tether:

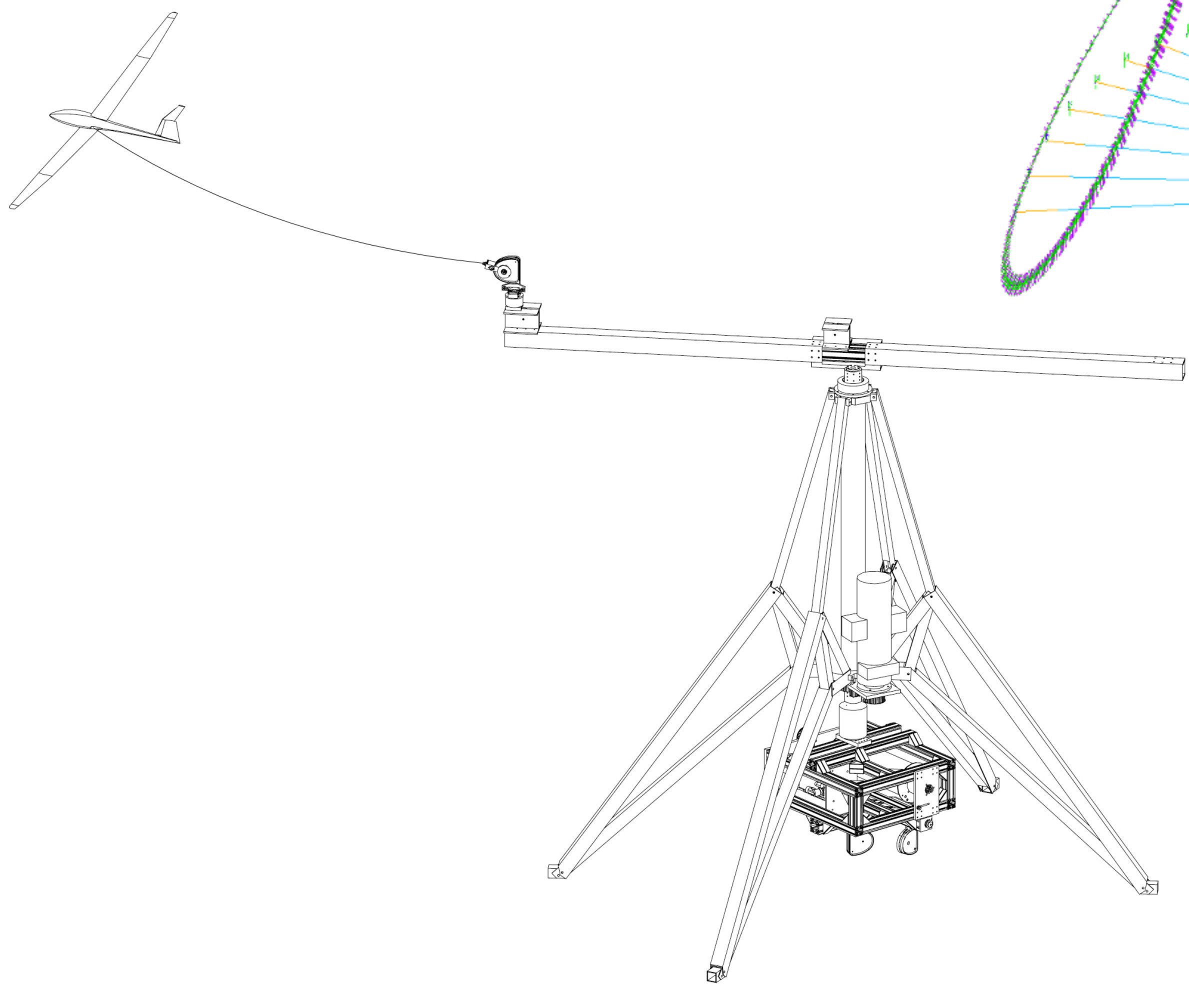
- 20 differential states (3+3 trans, 9+3 rotation, 1+1 tether)
- 1 algebraic state (tether force)
- 8 invariants (6 rotation, 2 due to tether constraint)
- 3 control inputs (aileron, elevator, tether length)

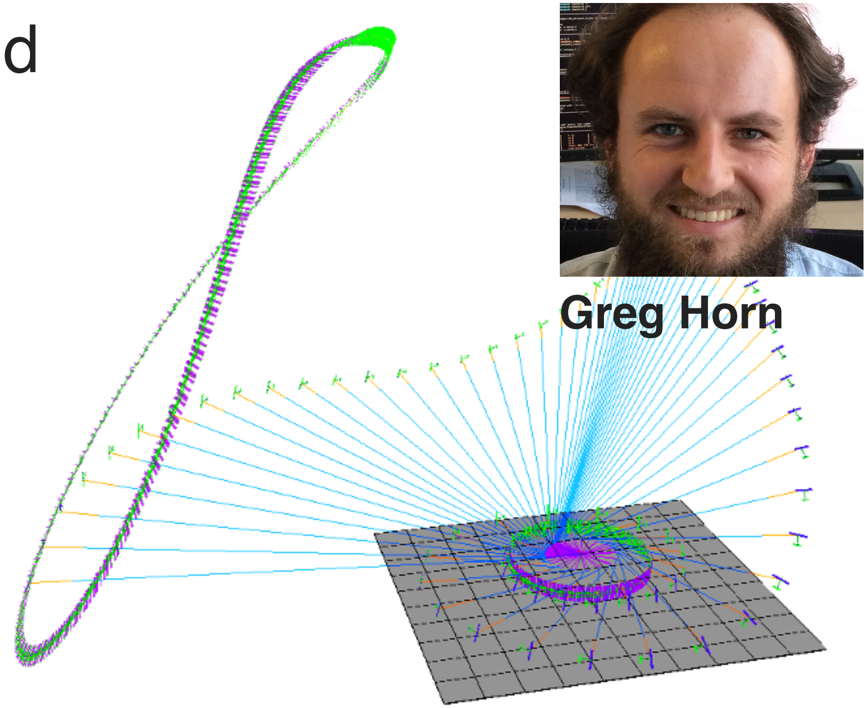
(more on models in talk by Sébastien Gros)

Sebastien Gros

Nontrivial Topology 1: Rotation Start for Tethered Wings

Idea: tethered planes can start and land using a "flight carousel"





Greg Horn

[Horn, Gros, D., in Airborne Wind Energy, Springer, 2013]

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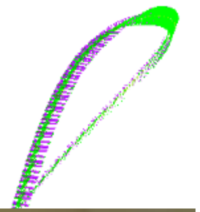
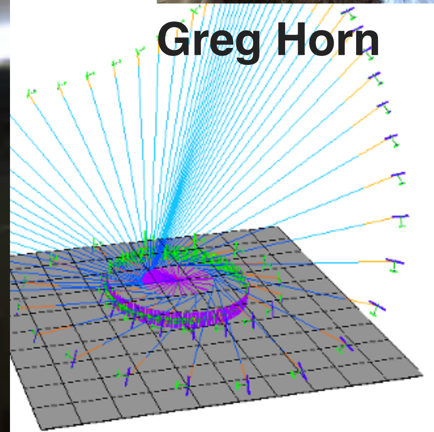
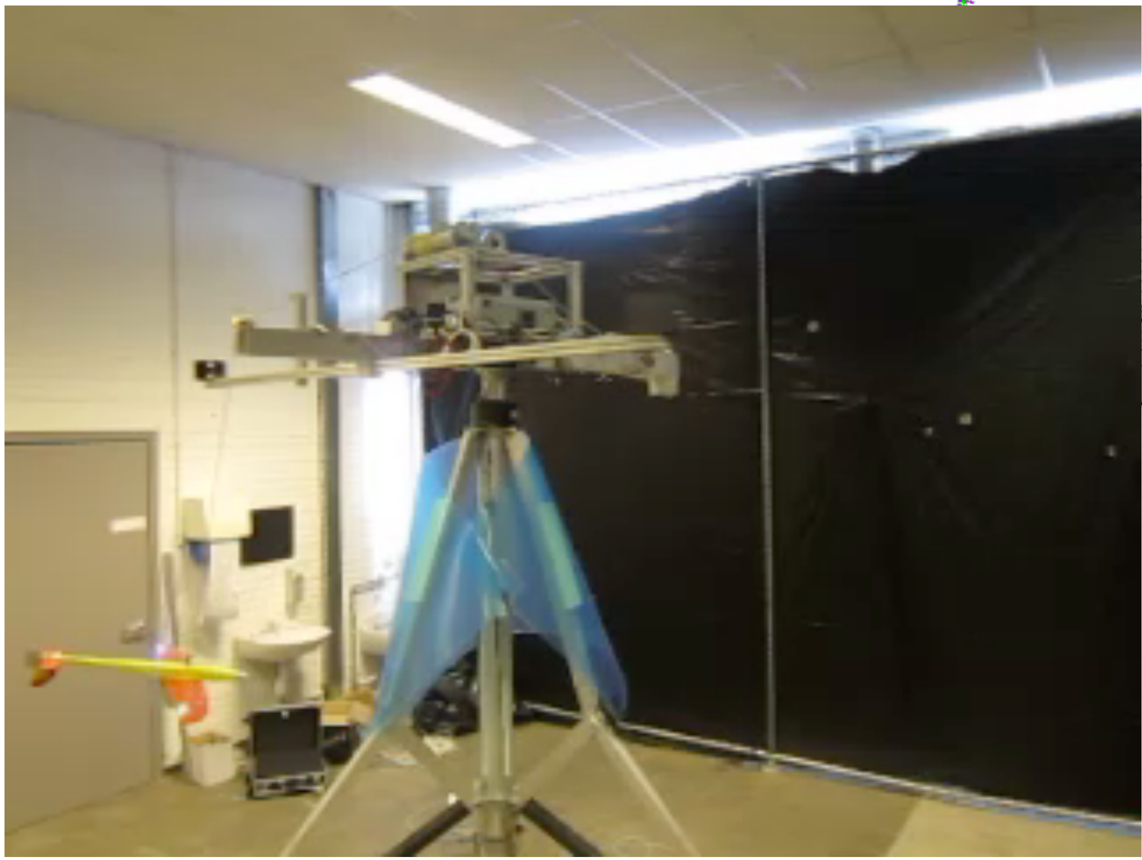


Greg Horn



Kurt Geebelen

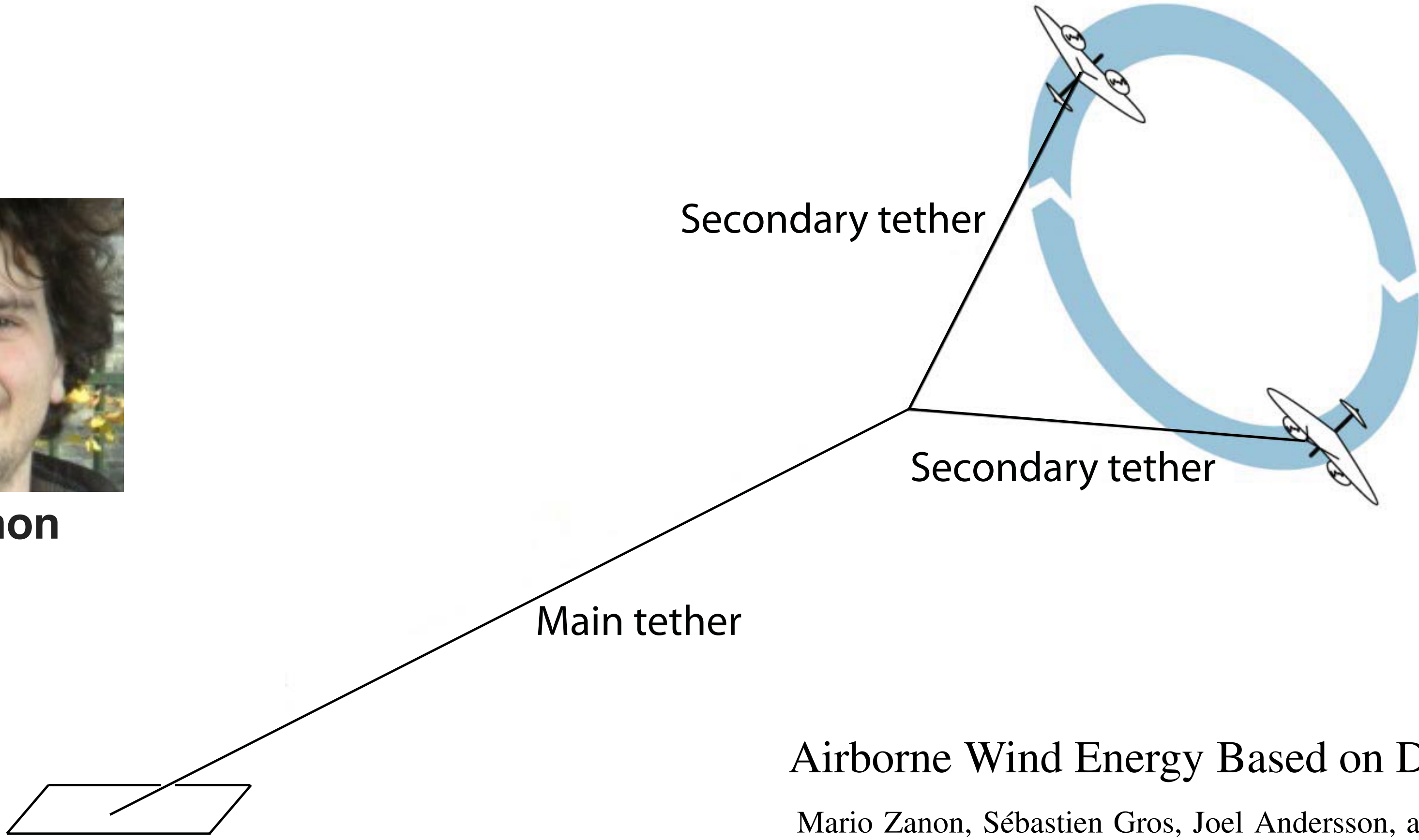


Flight experiments in Leuven, with Kurt Geebelen, Milan Vukov, Andrew Wagner, Mario Zanon, Sebastien Gros, Greg Horn, Jan Swevers

Nontrivial Topology 2: Dual Kite Systems

- Two airfoils circling around each other have **less tether drag**
- can reach 40 kW/m^2 already with small devices
- centrifugal forces compensate each other

Mario Zanon



Airborne Wind Energy Based on Dual Airfoils

Mario Zanon, Sébastien Gros, Joel Andersson, and Moritz Diehl

IEEE TRANSACTIONS ON CONTROL SYSTEMS TECHNOLOGY, VOL. 21, NO. 4, JULY 2013

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Lecture Overview

Airborne Wind Energy (AWE)

Nonlinear Optimal Control

(wait for talk by Sébastien Gros)

Optimal control applications at AWE companies

Lecture Overview

Airborne Wind Energy (AWE) → Nonlinear Optimal Control

(wait for talk by Sébastien Gros)

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Lecture Overview

Airborne Wind Energy (AWE) → Nonlinear Optimal Control

Optimal control applications at AWE companies

AmpyxPower, Netherlands

SkySails, Germany

Makani, California

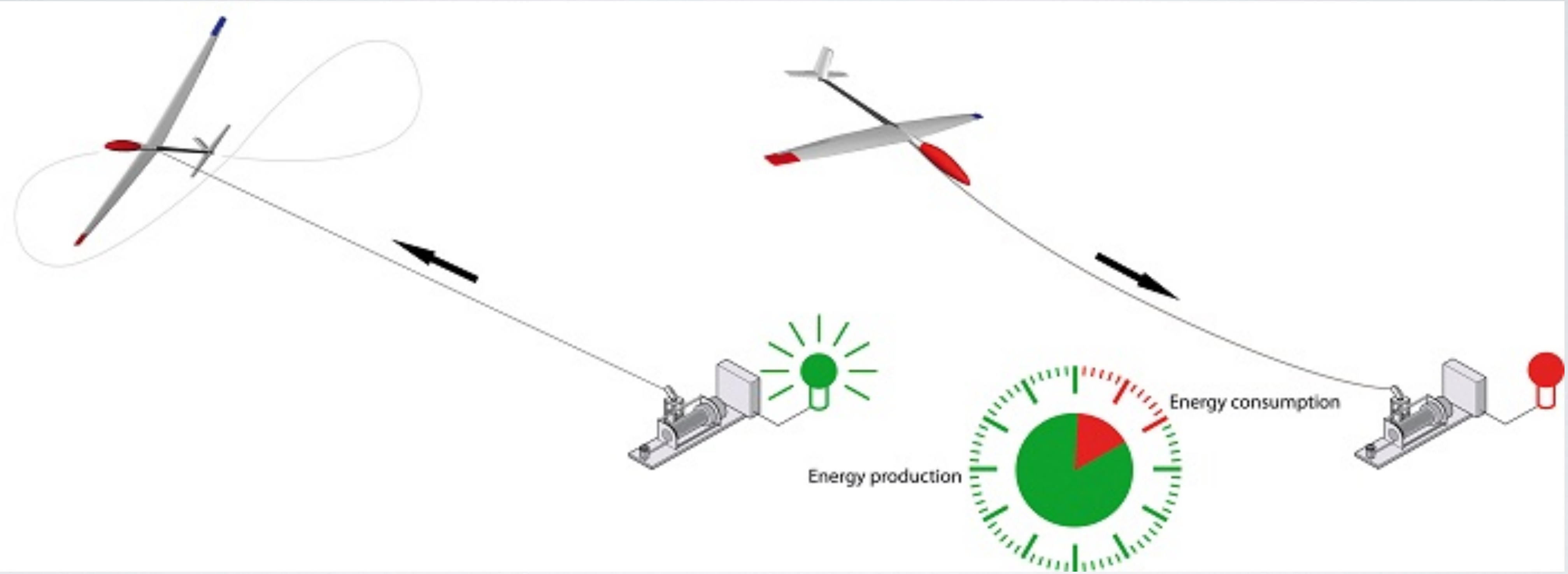
The Company AmpyxPower

AmpyxPower

- startup from TU Delft
- now ~50 full time staff
- financed via venture capital

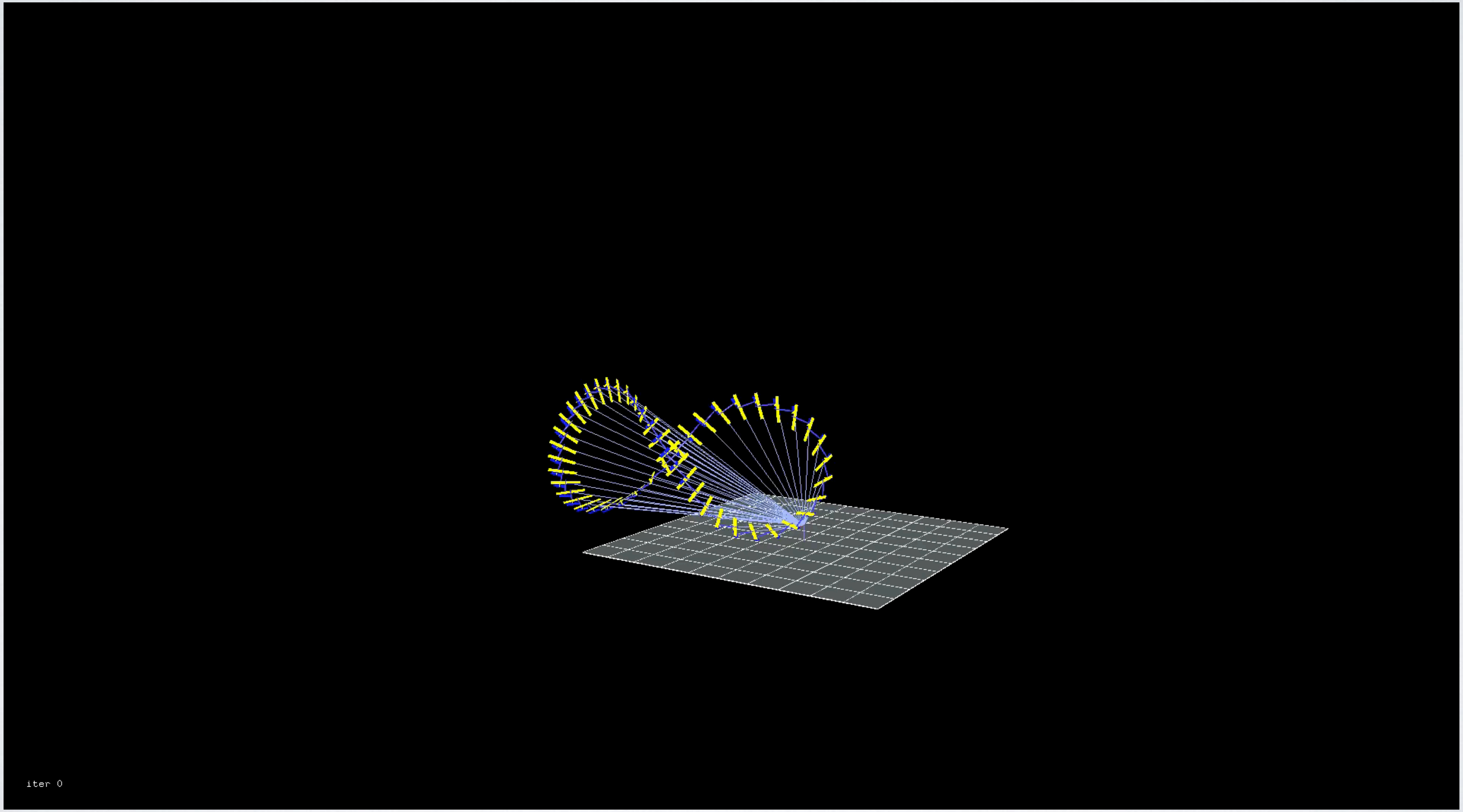
Two joint PhD students with Univ. Freiburg, both here, one in AWESCO

Pumping Cycle to Harvest Wind Power



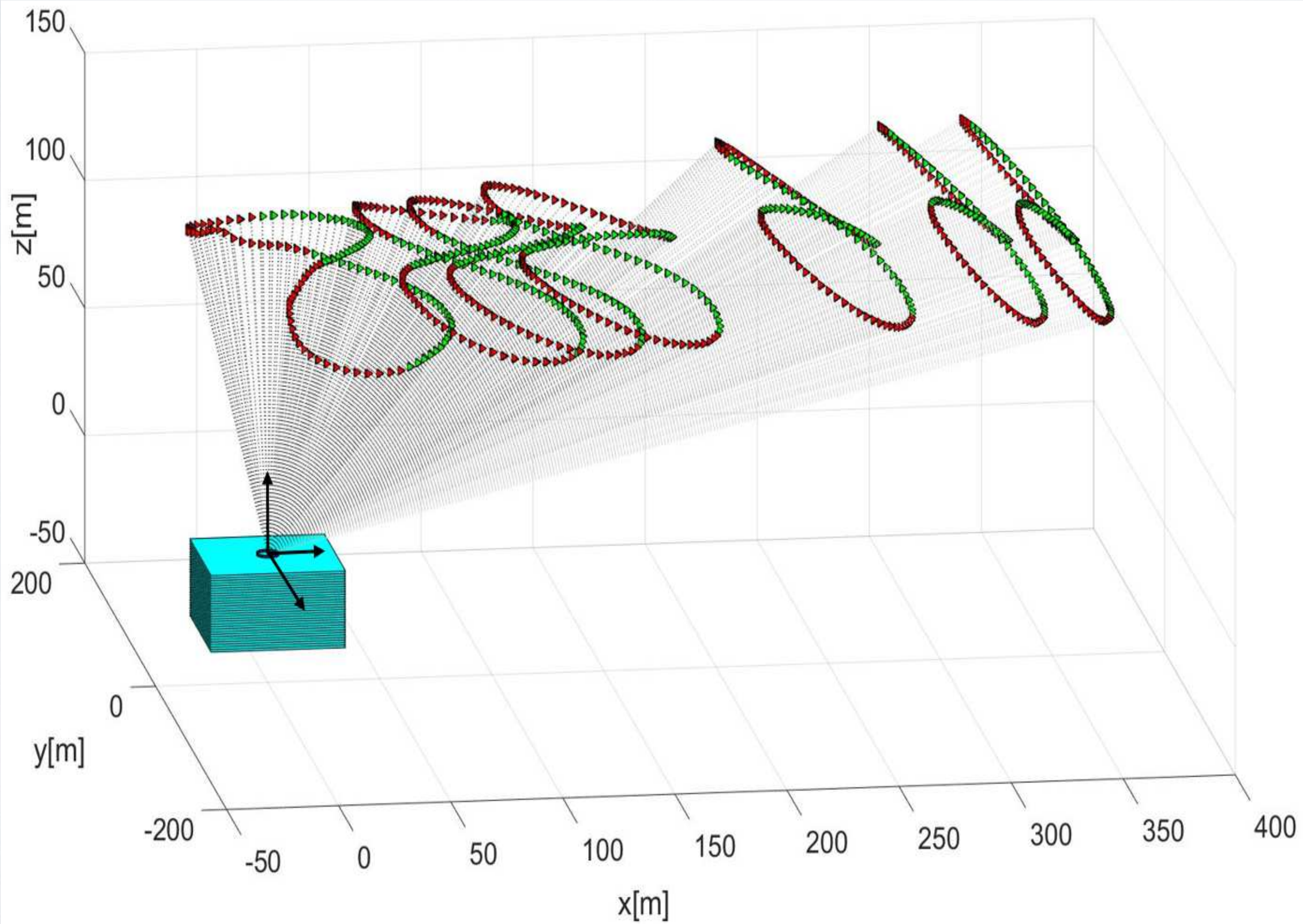
Optimization of Ampyx-Type Pumping Cycle

by Giovanni Licitra and Greg Horn (using CasADi, ipopt, 150 collocation intervals)

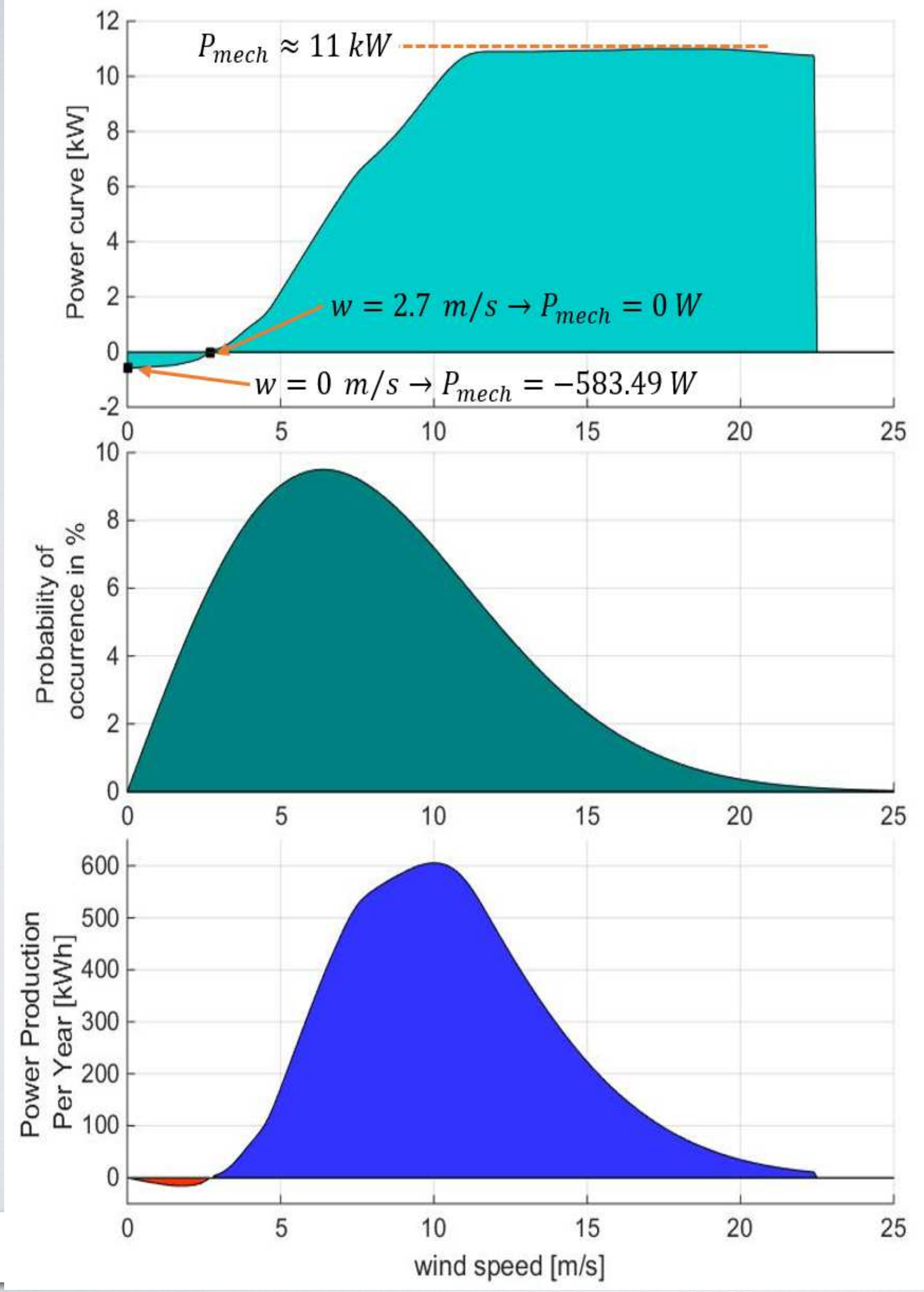


AmpyxPower:
Autonomous Energy Harvesting Flight

Power Optimization for Low Wind Speeds



Licitra, Sieberling, Williams, Ruiterkamp, Diehl 2016 (submitted to ECC)



"Never landing" costs only 0.5 %

Power at specific wind speed

×

Frequency of occurrence per year

=

Contribution to yearly production

[study with 5.5m wing span plane]
Blue: 52,27 MWh, red 0,27 MWh.
Average power: 6 kW (tether drag)

SkySails:
Soft Kites with Ground-Based Generator

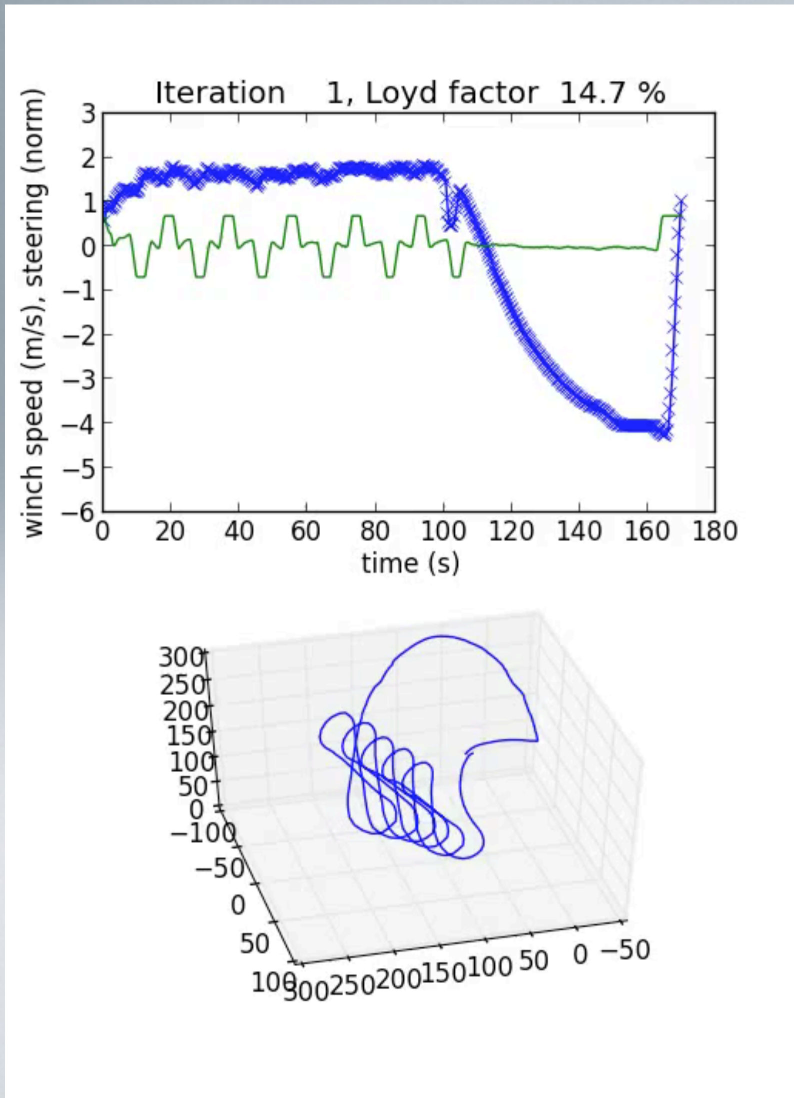
SkySails

- Startup since 2001
- ~30 people
- traction kites for vessels
- since 2011 also power generation
- financed by private investors and subsidies

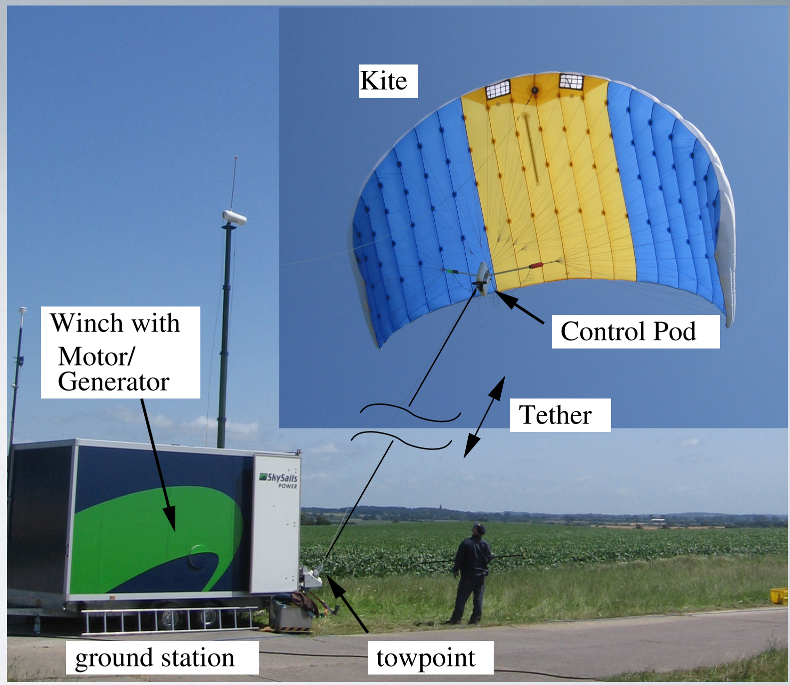
SkySails:
soft kites with ground-based generator

Optimization of SkySails' electricity generating orbits

by **Michael Erhard**, Chief Control Engineer at SkySails, partly Univ. Freiburg, using CasADi/ipopt



- Initialization with experimentally flown orbit
- Optimization improves from 15% to 25% of Loyd's limit
- large time losses due to slow retraction phase

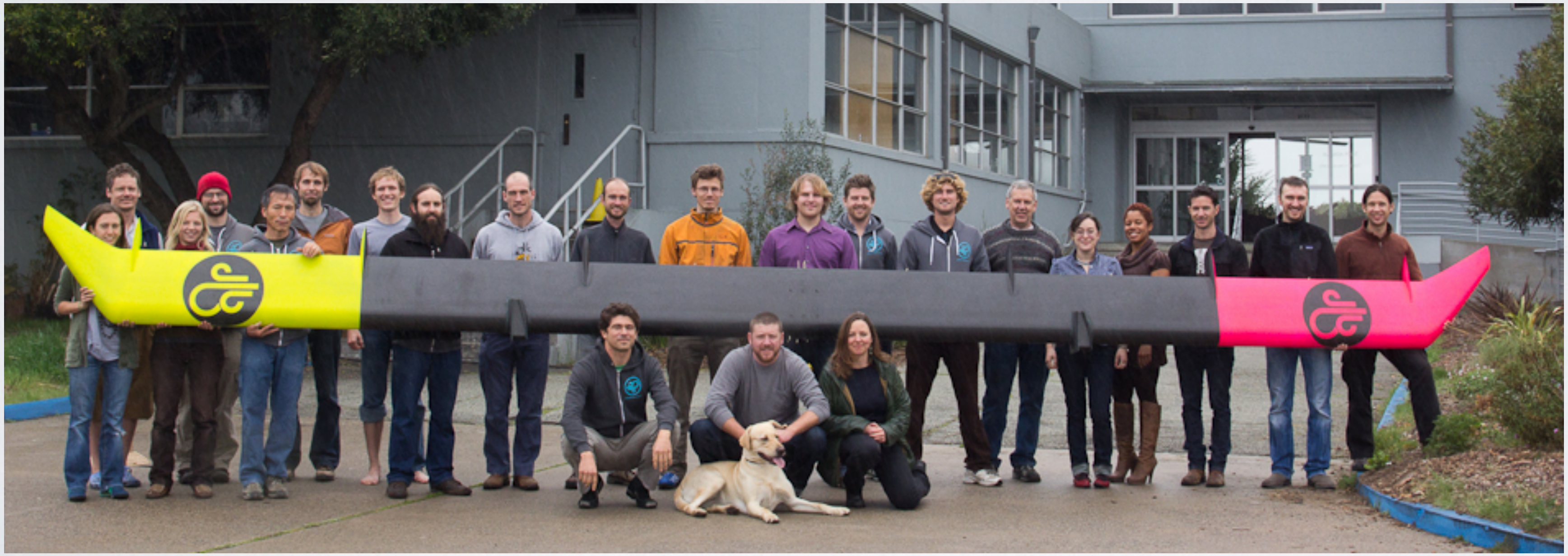


Small–Scale Functional Model (50kW peak power)

Makani Power:
Rigid wing with on-board generator

Makani Power

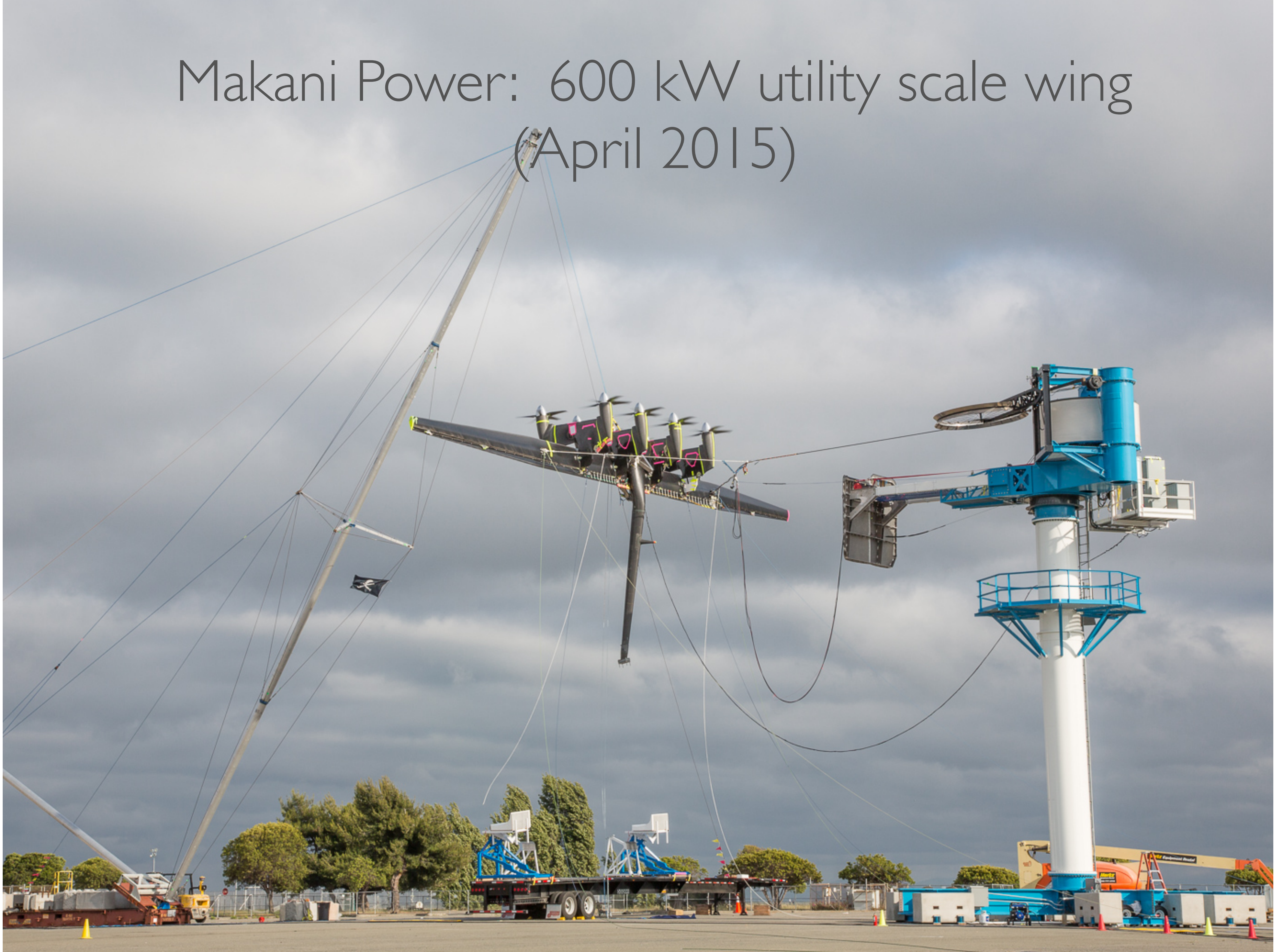
- Californian start-up since 2006
- 50-100 people (probably)
- fixed wings with on-board generators
- since 2013 part of Google X



Makani Power

Makani Power: turbines on-board allow take-off and landing as quadcopter

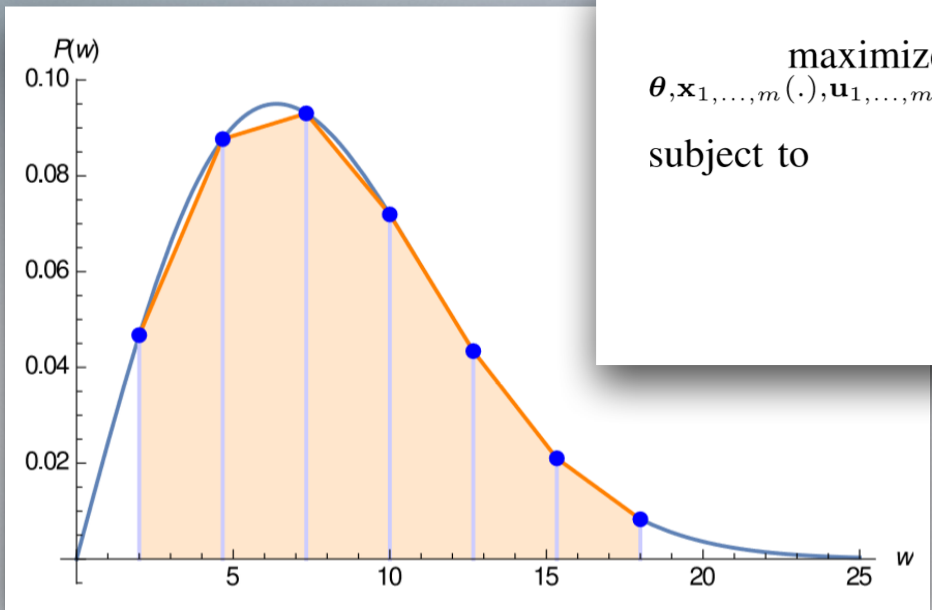
Makani Power: 600 kW utility scale wing (April 2015)



Makani power: yearly power output optimisation

by Greg Horn, Univ. Freiburg, and Thomas Van Alsenoy, Makani

Multiple Setpoint Optimization: optimise fixed parameters (tether length and thickness, generator size) together with adaptable periodic control trajectories for all wind speeds, weighted with their frequency in the wind histogram



$$
\begin{array}{lll}
\underset{\boldsymbol{\theta},\mathbf{x}_{1,\dots,m}(\cdot),\mathbf{u}_{1,\dots,m}(\cdot),T_{1,\dots,m}}{\text{maximize}} & \displaystyle\sum_{k=1}^{m} \pi_{\mathrm{O}}\left(\boldsymbol{\theta},\, T_k\right)^{-1} P_{\boldsymbol{\chi}}\left(\boldsymbol{\chi}_k\right) \int_0^{T_k} P(\mathbf{x}_k(t), \boldsymbol{\chi}_k)\,\mathrm{d}t & \\
\text{subject to} & \dot{\mathbf{x}}_k(t) = \mathbf{f}(\mathbf{x}_k(t), \mathbf{u}_k(t), \boldsymbol{\theta}, \boldsymbol{\chi}_k, t), & t \in [0, T_{\mathbf{k}}] \\
& 0 \geq \mathbf{h}(\mathbf{x}_k(t), \mathbf{u}_k(t), \boldsymbol{\theta}, t), & t \in [0, T_{\mathbf{k}}] \\
& \mathbf{c}(\mathbf{x}_k(0), \mathbf{x}_k(T)) = 0, \quad C\left(\mathbf{x}_k(0)\right) = 0 & \\
& \boldsymbol{\theta} \in \Theta. &
\end{array}
$$

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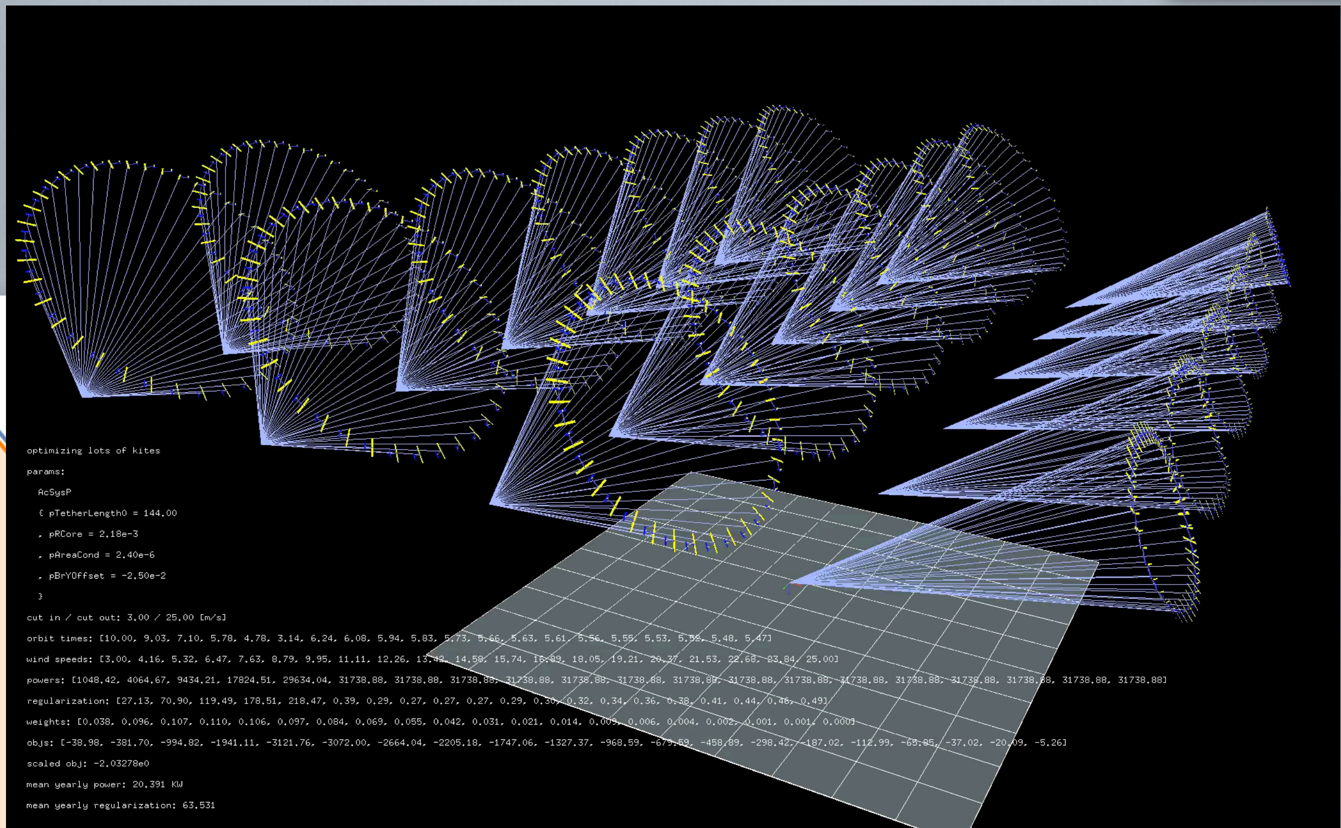
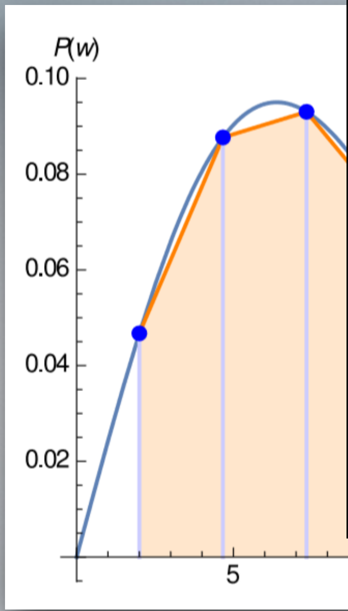
by Greg Horn, Univ. Freiburg, and Thomas Van Alsenoy, Makani





Conclusions

- Airborne wind energy promises power densities up to 40 kW per m^2 wing area
- nonlinear optimal control can answer relevant design and control questions

Our Vision: replace tons of steel and concrete...

Our Vision: replace tons of steel and concrete...
...by a cable and optimal control

Thank you

Two Advertisements for PhD students
and young postdocs
(Max Planck — Mc Kinsey):

Max-Planck-Institut für biologische Kybernetik

Max Planck Institute for Biological Cybernetics

Postdoc position in real-time, optimization-based motion cueing algorithms for driving simulation

In the Motion Perception and Simulation Research group at the Max Planck Institute (MPI) for Biological Cybernetics[1], department of Human Perception, Cognition and Action (Prof. Dr. Heinrich Bülthoff), we are starting a research project in collaboration with Daimler AG with the aim of dramatically improving the performance of motion cueing algorithms (MCAs) for driving simulation.
MCAs convert a desired physical motion, obtained from, e.g., a vehicle model, into simulator input commands. We have developed an optimization-based MCA, which optimizes simulator input commands using non-linear model predictive control. The current MCA operates “off-line” through optimizing pre-defined reference trajectories, which can then be replayed in the simulator. However, for human-in-the-loop driving simulation, the optimization must run real-time (“on-line”). **The goal of the project is to enable real-time applications of the existing motion cueing algorithm to operate on Daimler’s[2] and MPI’s[3] simulators, which are among the most advanced simulators in the world**.

Requirements

- PhD in Control Engineering, Mathematics, Physics or equivalent
- Sound knowledge of Control Theory, Model-Predictive Control, and Optimization
- Proven experience in working with Python, C++, MATLAB/Simulink
- Experience with motion cueing, ACADO toolkit, and CasADi is considered beneficial
- Good spoken and written English (working language)
- Team spirit and interpersonal communication skills
- Independence and responsibility to managing time, resources and information

The position is available for two years, starting as soon as possible. The salary is according to full-time TVöD E13 (German public employees’ pay scale).
The Max Planck Society is an equal opportunity employer: Handicapped individuals are strongly encouraged to apply, and so are women in areas in which they are underrepresented.
Full applications including CV, letter of motivation, list of publications, and reference letters must be submitted electronically (as single PDF) to:

Dr. Paolo Pretto / Dr. Joost Venrooij
Max-Planck Institute for Biological Cybernetics
Department of Human Perception, Cognition and Action
Spemannstrasse 44, 72076 Tübingen, Germany
paolo.pretto@tuebingen.mpg.de / joost.venrooij@tuebingen.mpg.de