Introduction to Airborne Wind Energy

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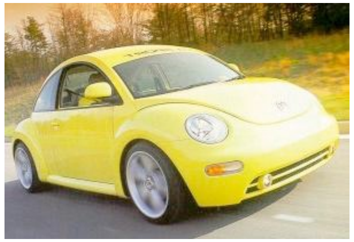
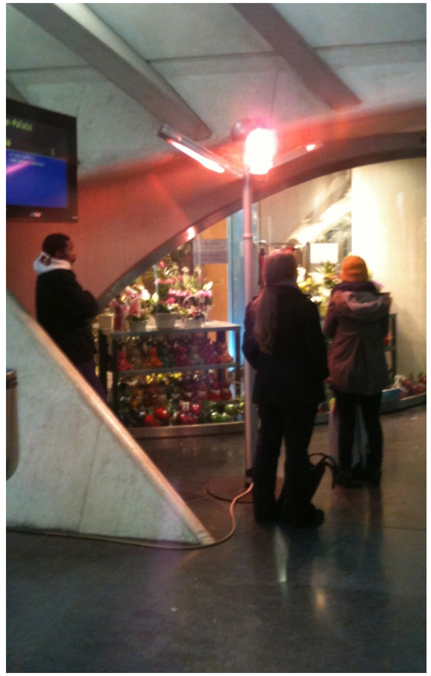
Freiburg, July 11, 2018

Recall: our personal energy consumption: 5 kW

- a typical European needs 5 kW
(1 kW electricity + transport + heating …)

- this equals 120 kWh, or 12 litres of petrol, per day

- one return flight from Europe to China consumes
about 1200 litres of kerosene per person (~100 days)

[MacKay 2009. wikipedia]

5 kW: one large electric heater, switched on from birth to death

Recall: capacity factor of wind and solar equals about 20%

5 MW installed capacity deliver on average about 1 MW.
This would be enough to cover all energy needs of 200 people.

What is needed for 5 MW installed power ?

Solar in Southern Europe: area of 125 m x 200 m

ns

What is needed for 5 MW installed power ?

Solar in Southern Europe: area of 125 m x 200 m

Wind in North Sea:
turbine of 150 m height

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:

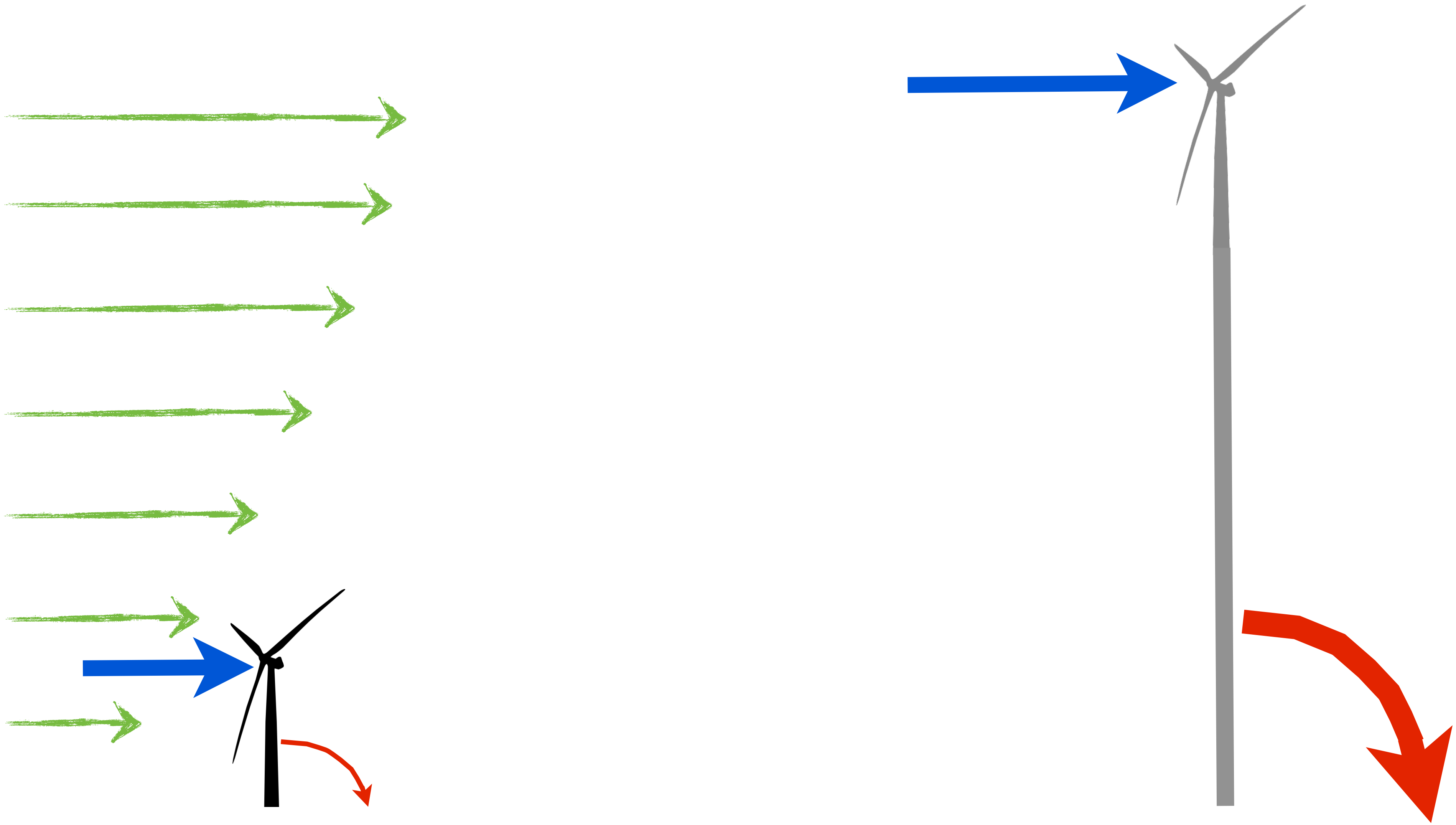
turbine of 150 m height

turbine and tower weigh 700 tons

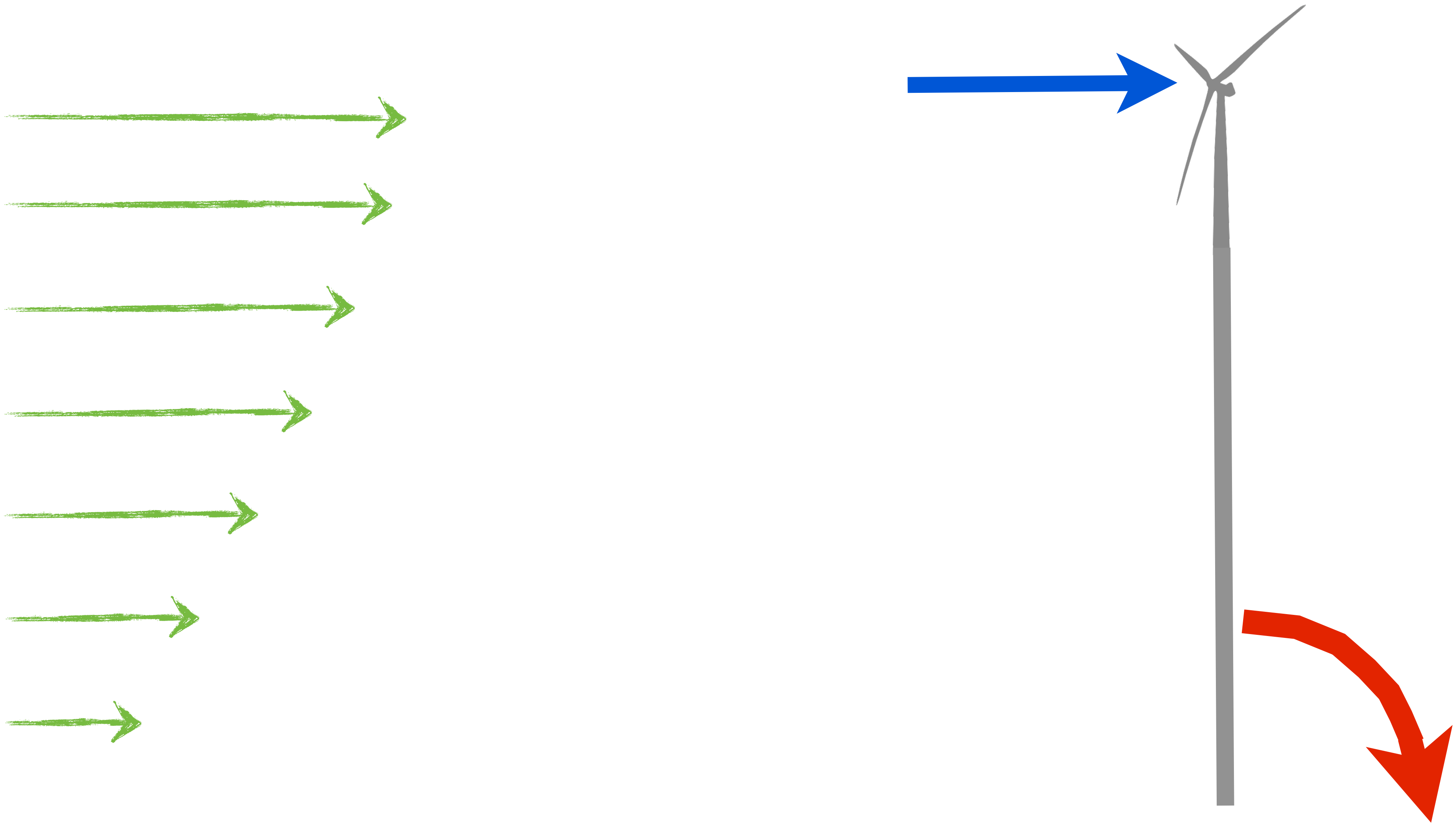
Could we harvest wind power in high altitudes with less material ?

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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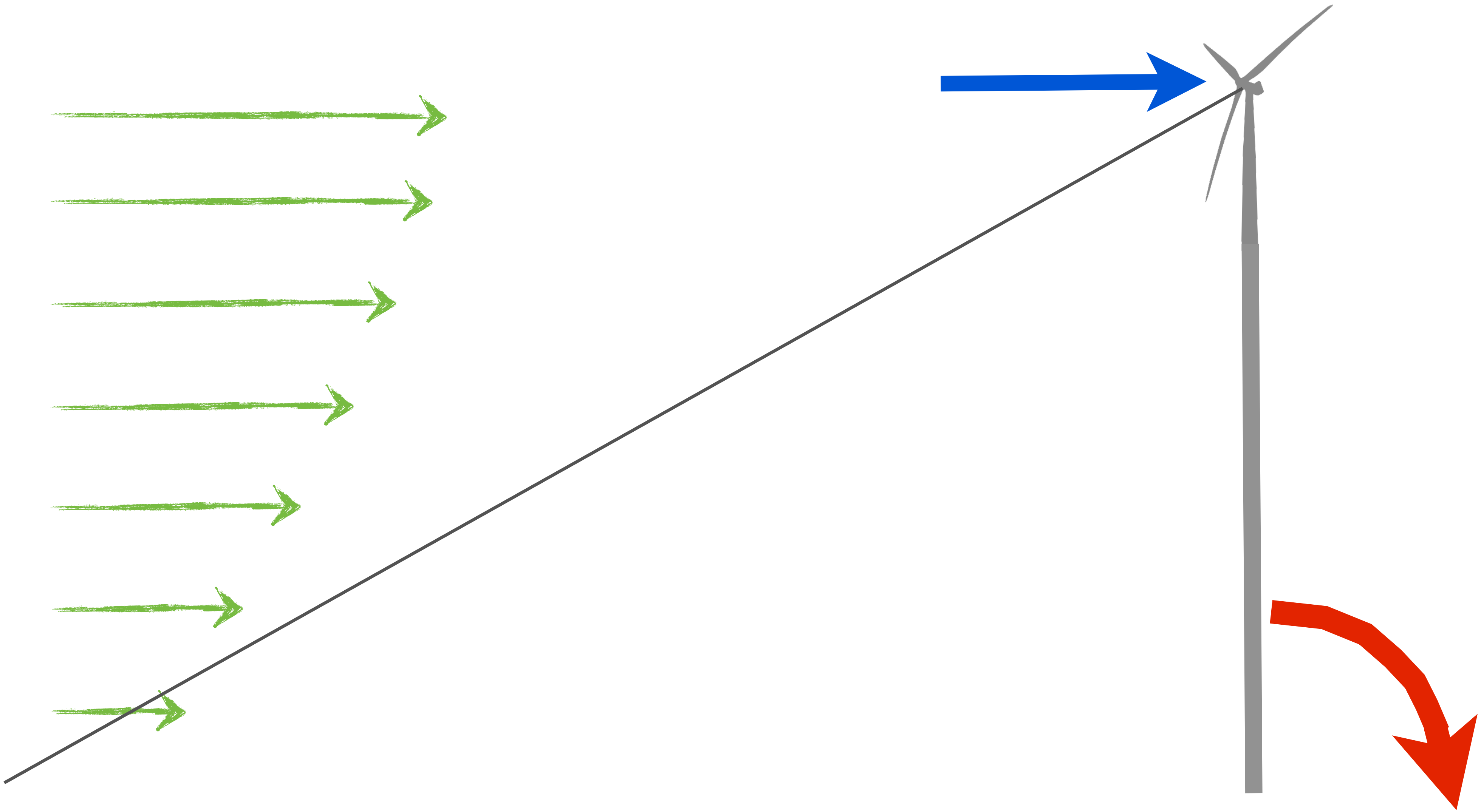

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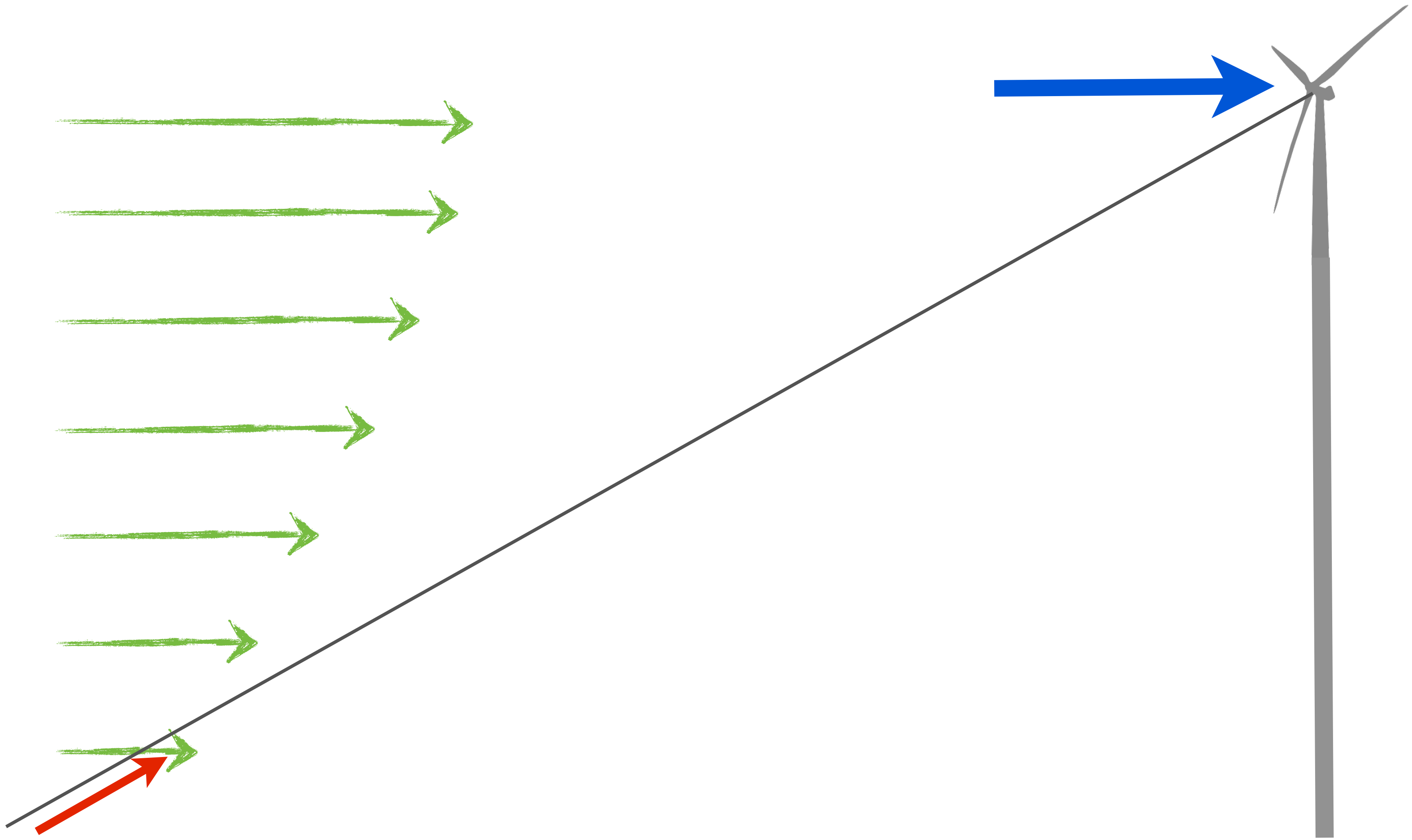

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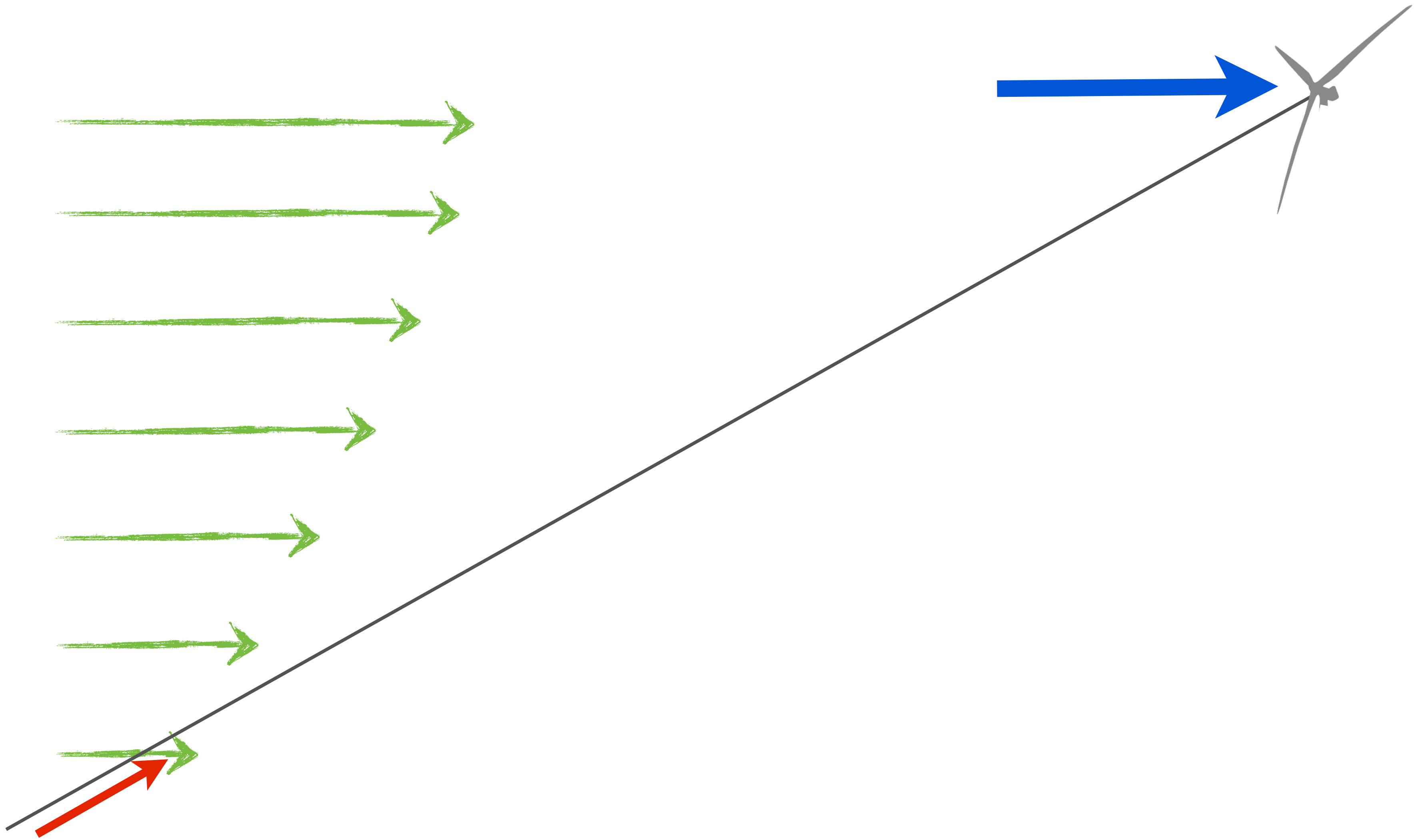

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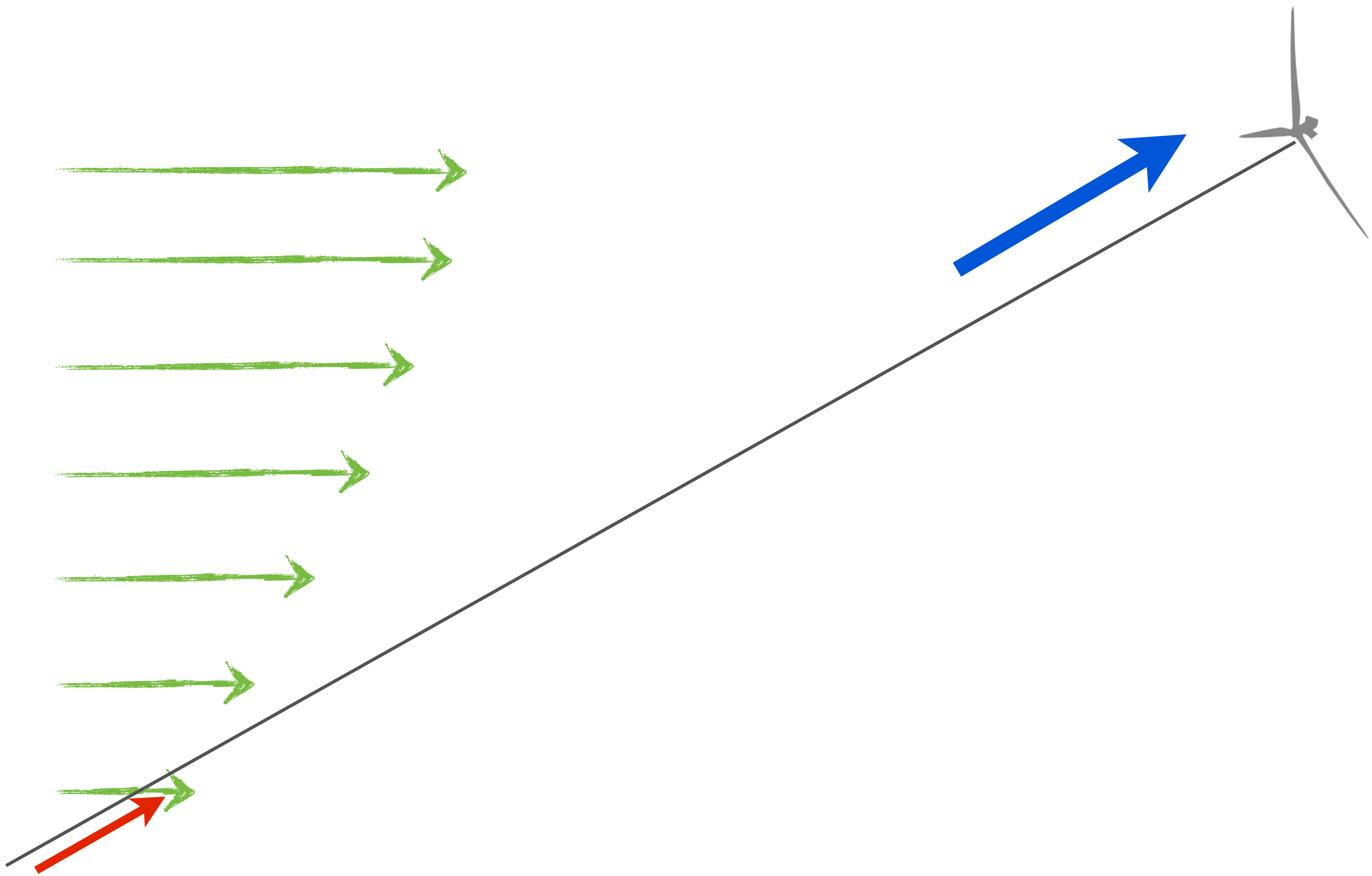
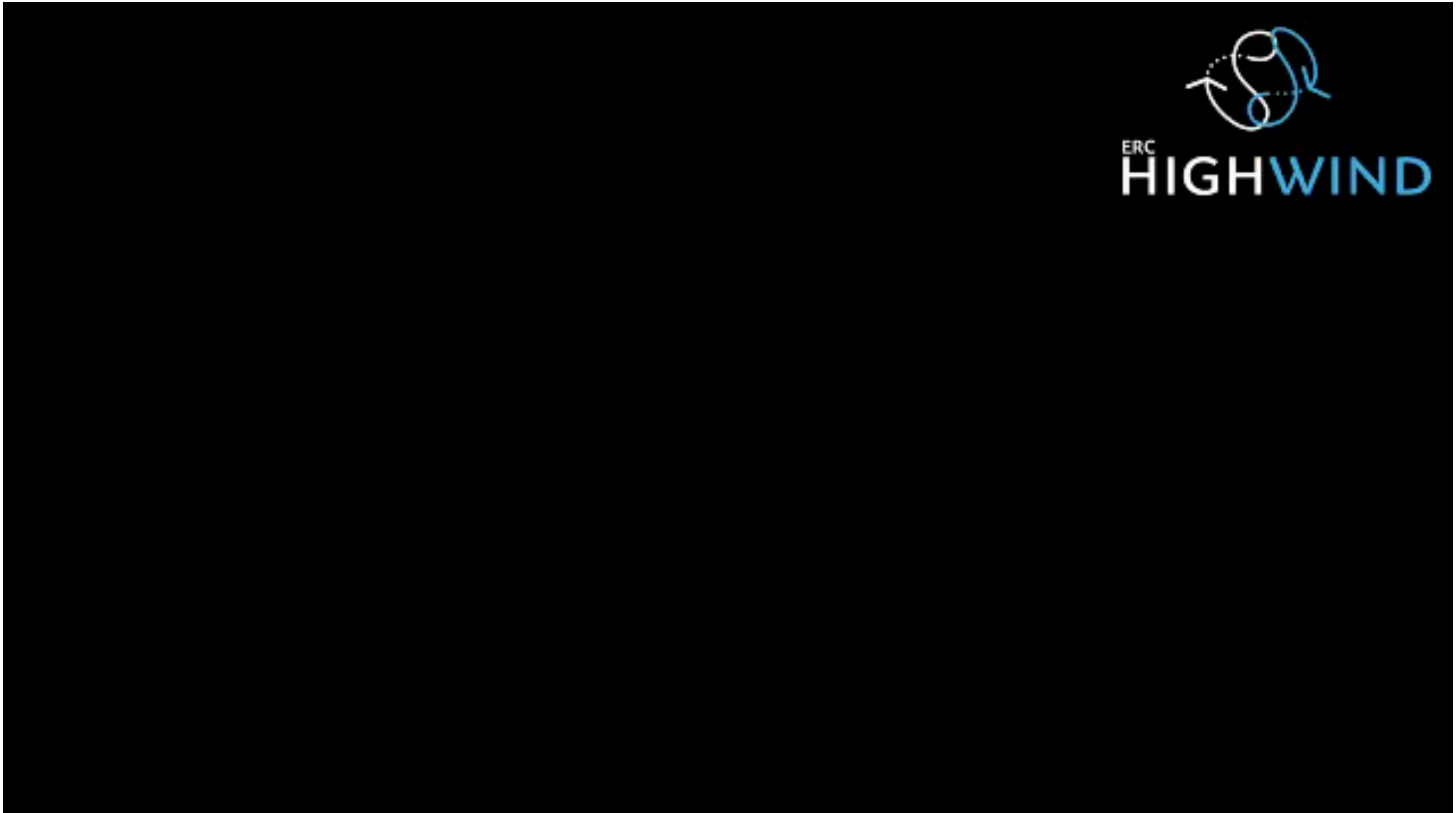
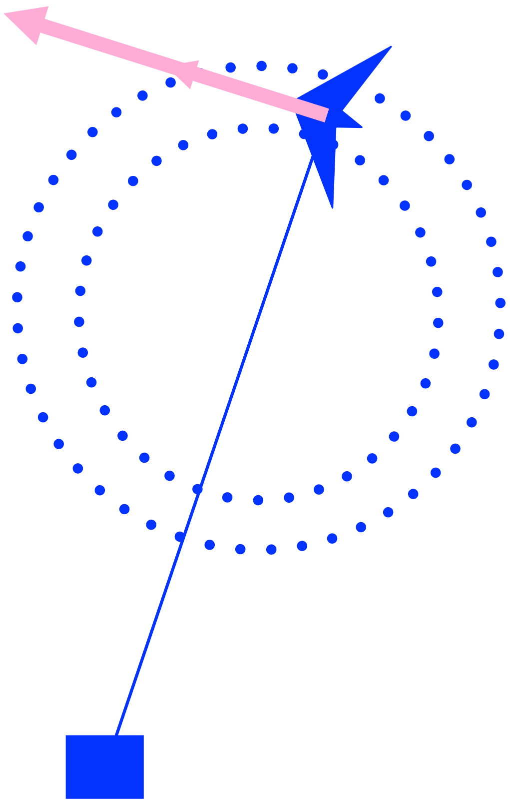


Metamorphosis of a Wind Turbine



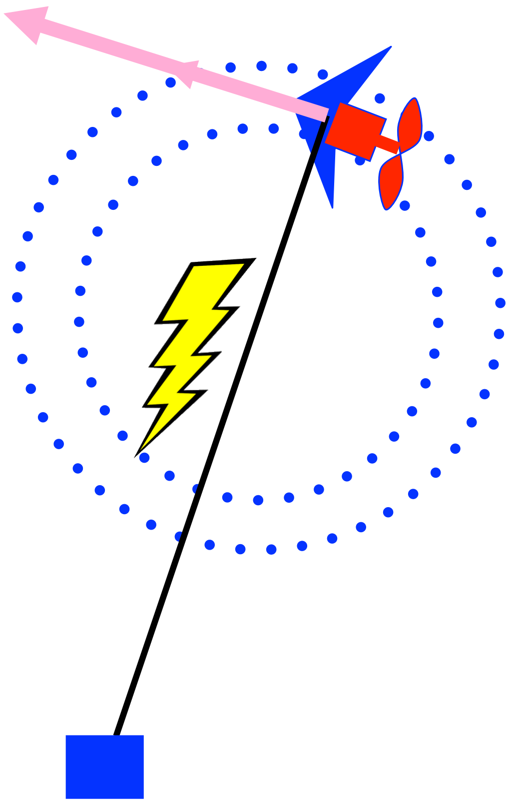
Crosswind Kite Power



- 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

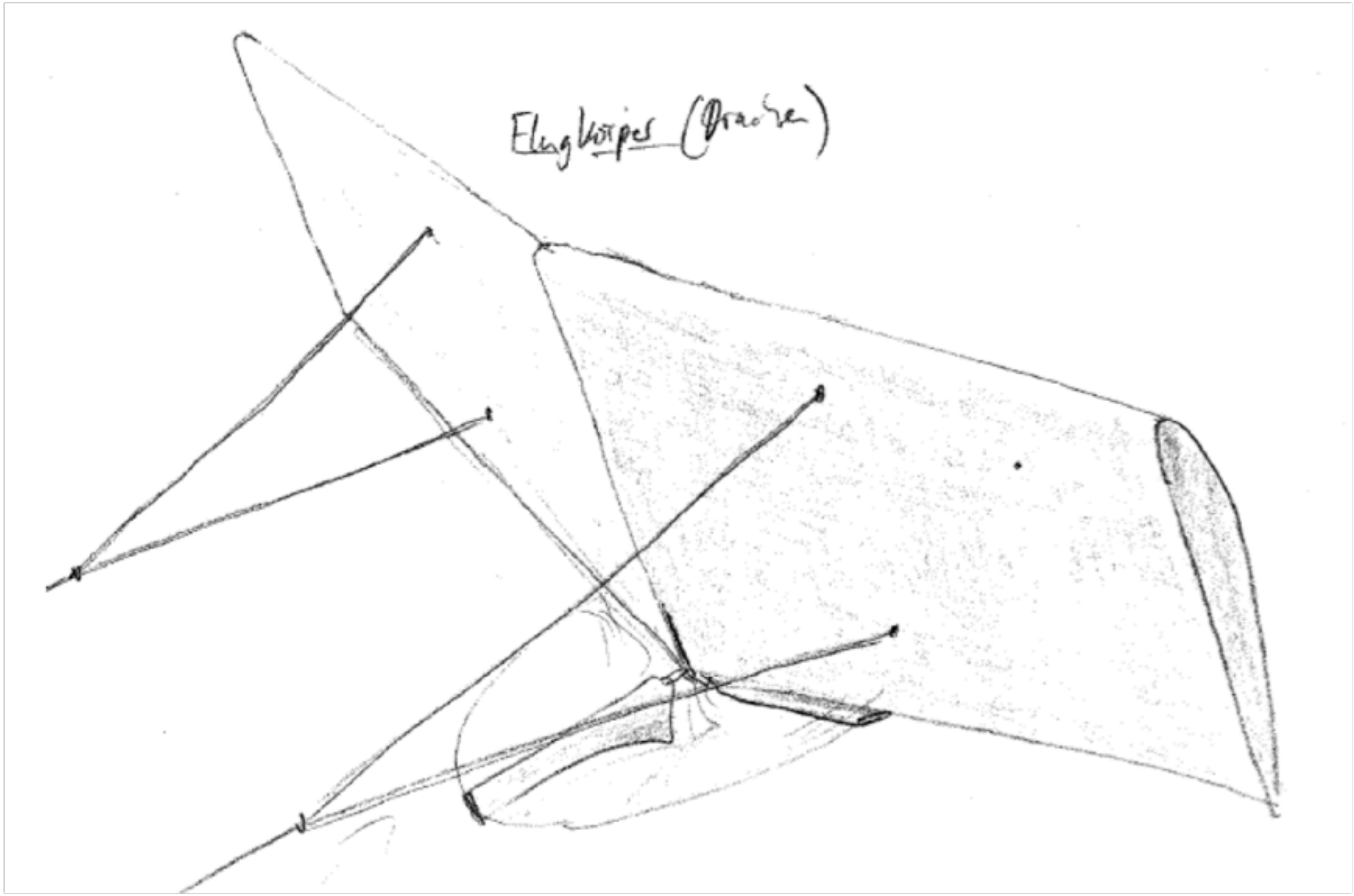
Pros:

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

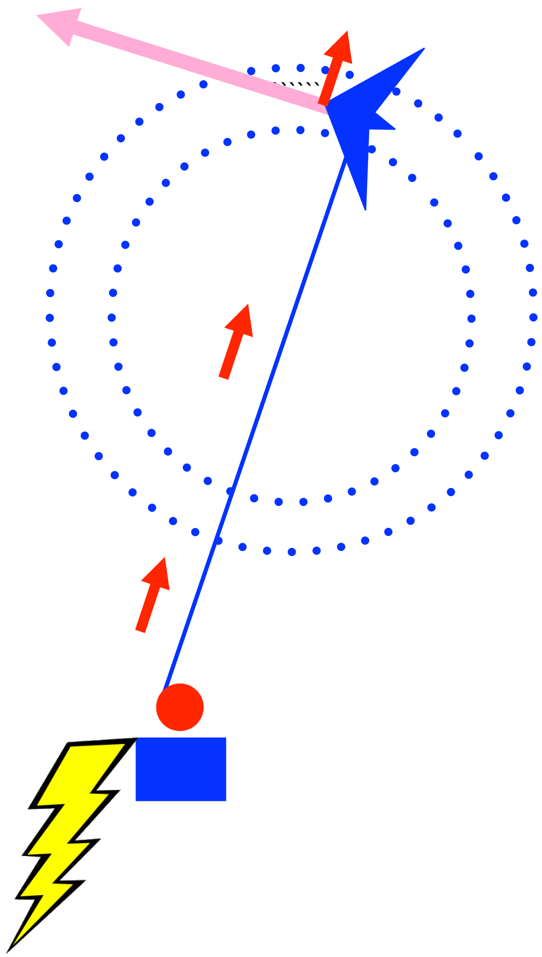
Cons:

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

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



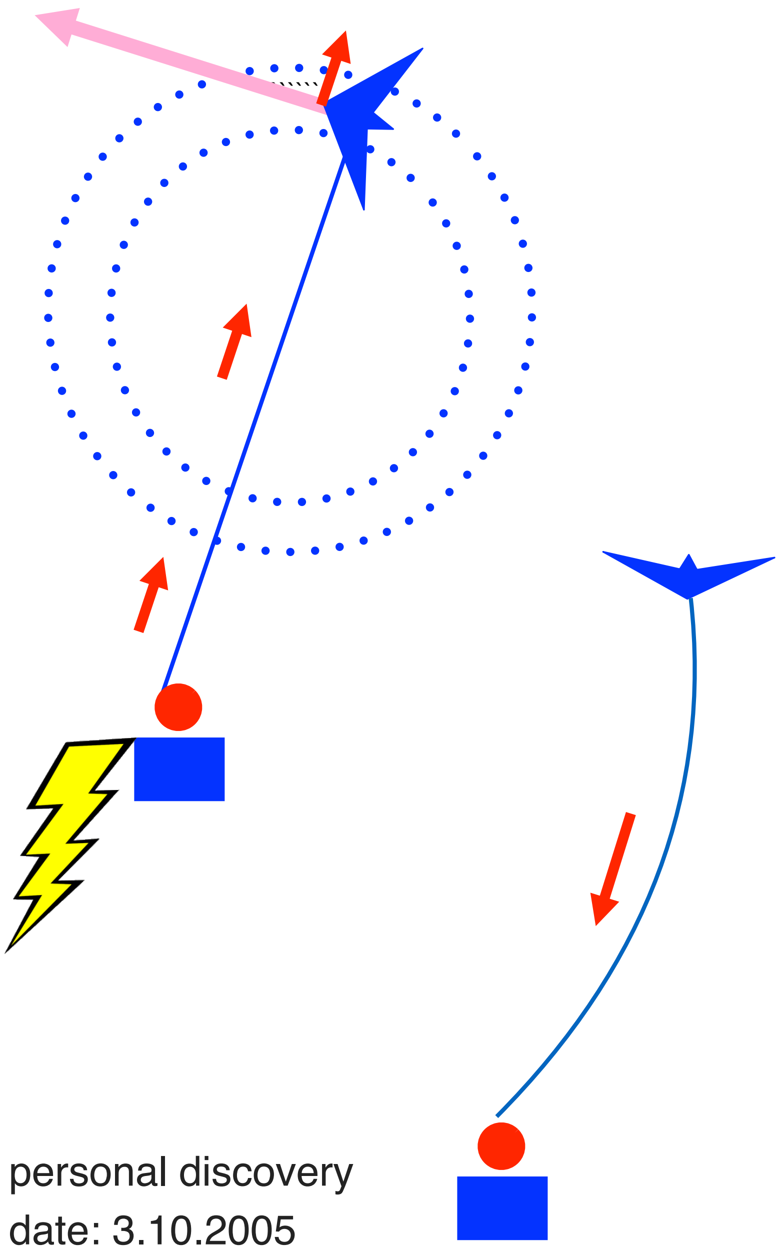
Variant 2: Generator on Ground (Pumping Cycle)



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.

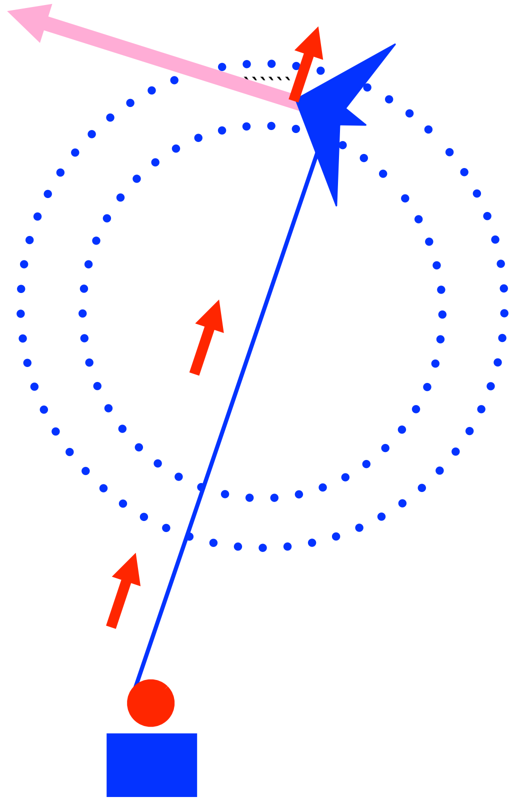
$$P = \frac{2}{27} \rho A w^3 C_L \left(\frac{C_L}{C_D} \right)^2$$

power P
air density ρ
wing area A
wind speed w

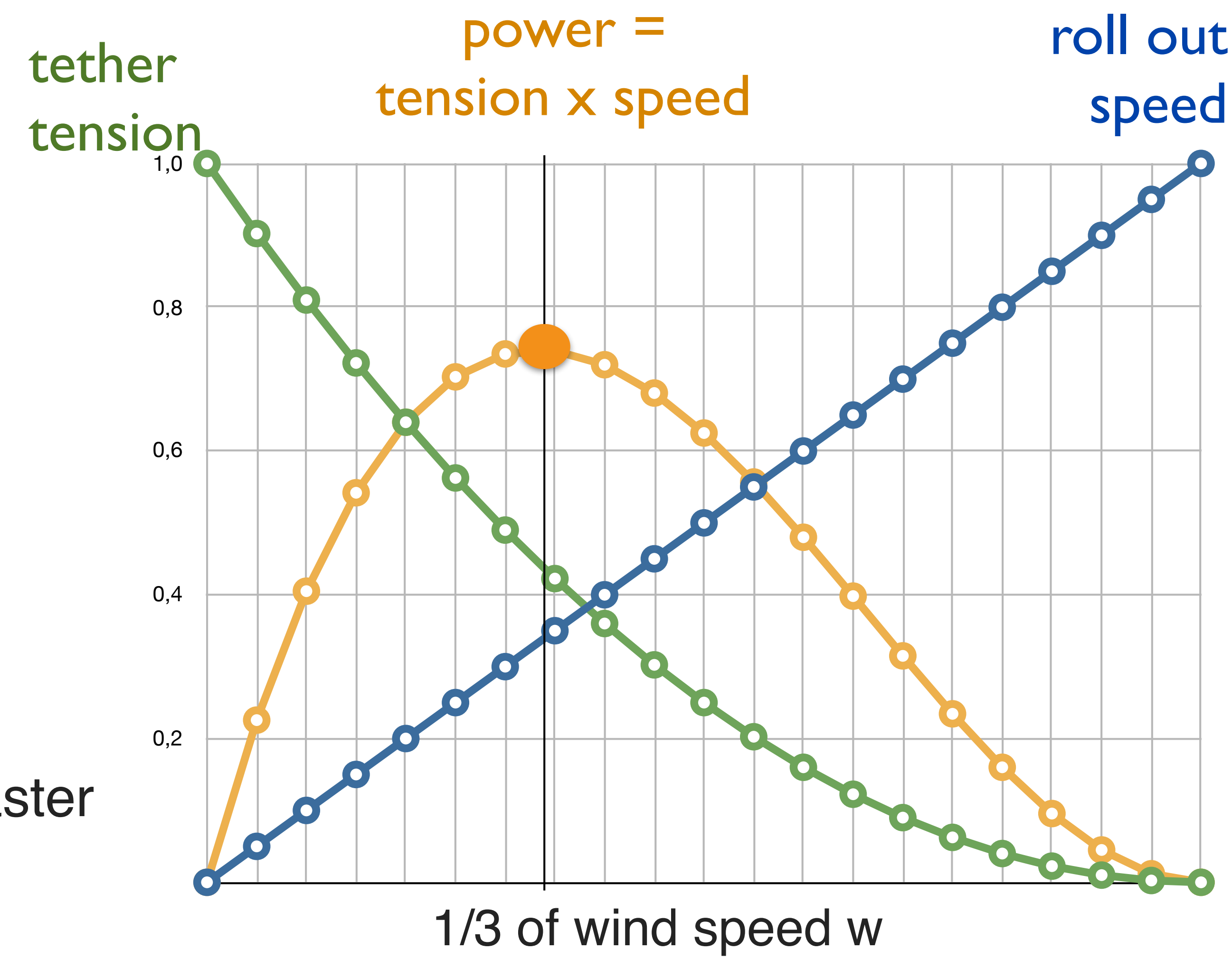
Lift-over-drag ratio (L/D) $\left(\frac{C_L}{C_D} \right)$

wing area of 1 m² 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 ?

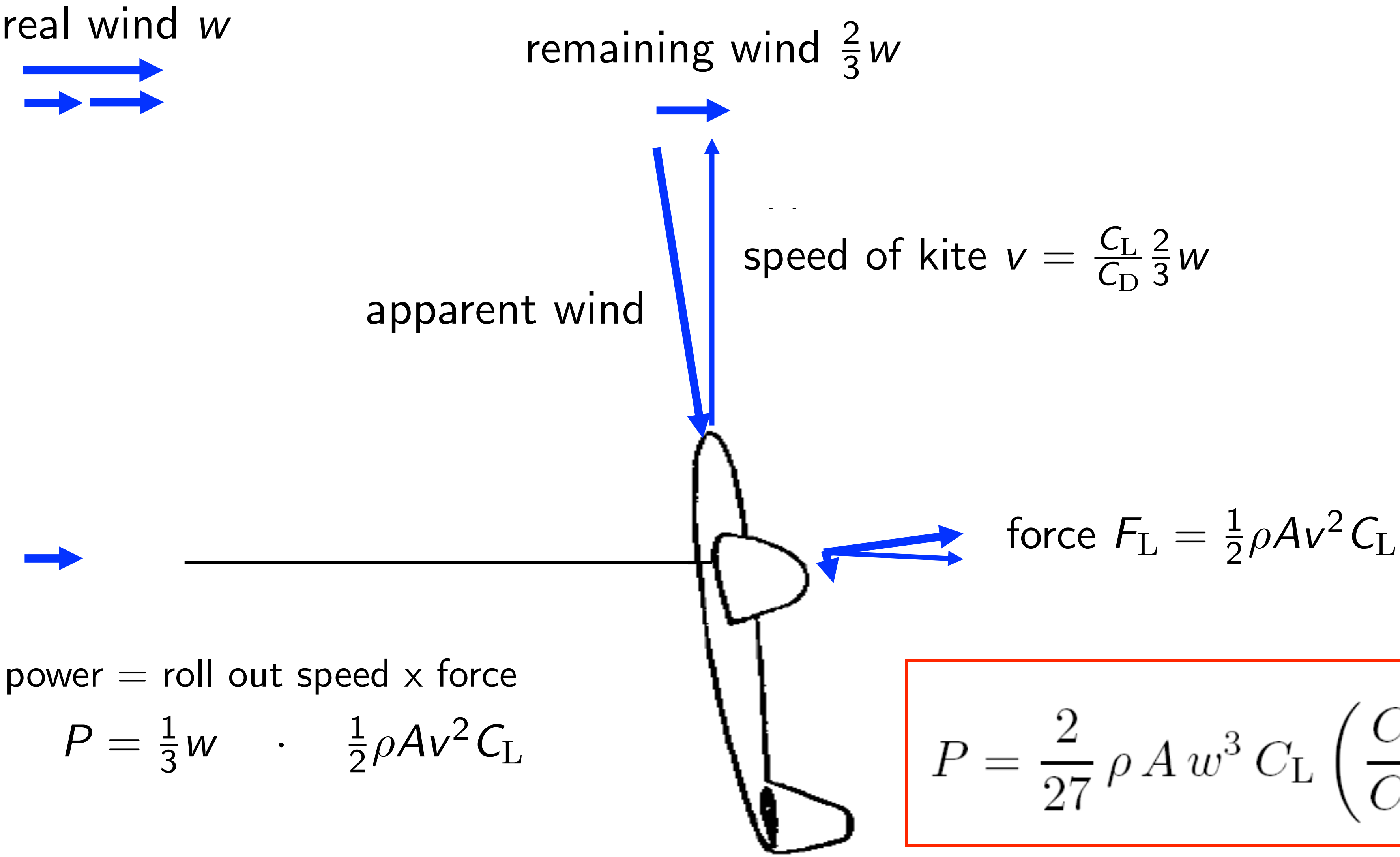


Maximum power reached at 1/3 of wind speed



Remark: kite flies much faster in crosswind direction…

How fast does the kite fly compared to the real wind ?



power = roll out speed x force

$$P = \frac{1}{3}w \quad \cdot \quad \frac{1}{2}\rho A v^2 C_\mathrm{L}$$

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

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 !

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

[master students Wouter Vandermeulen and Jeroen Stuyts]

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

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

Airborne Wind Energy Conferences 2010, 2011,…

AIRBORNE WIND ENERGY 2017 CONFERENCE

Albert-Ludwigs University Freiburg, Breisgau, Germany, 5-6 October 2017

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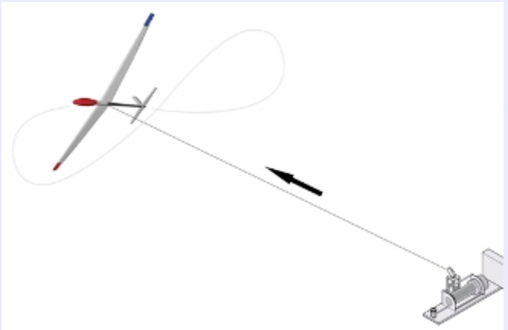
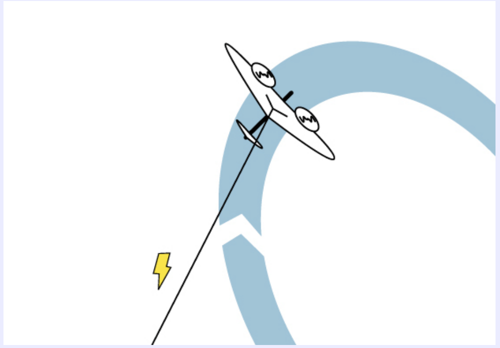
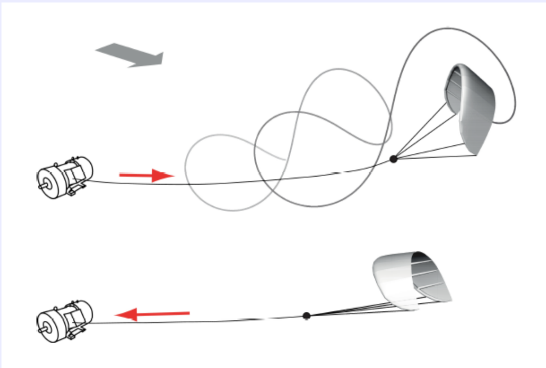
Categorization of crosswind systems

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

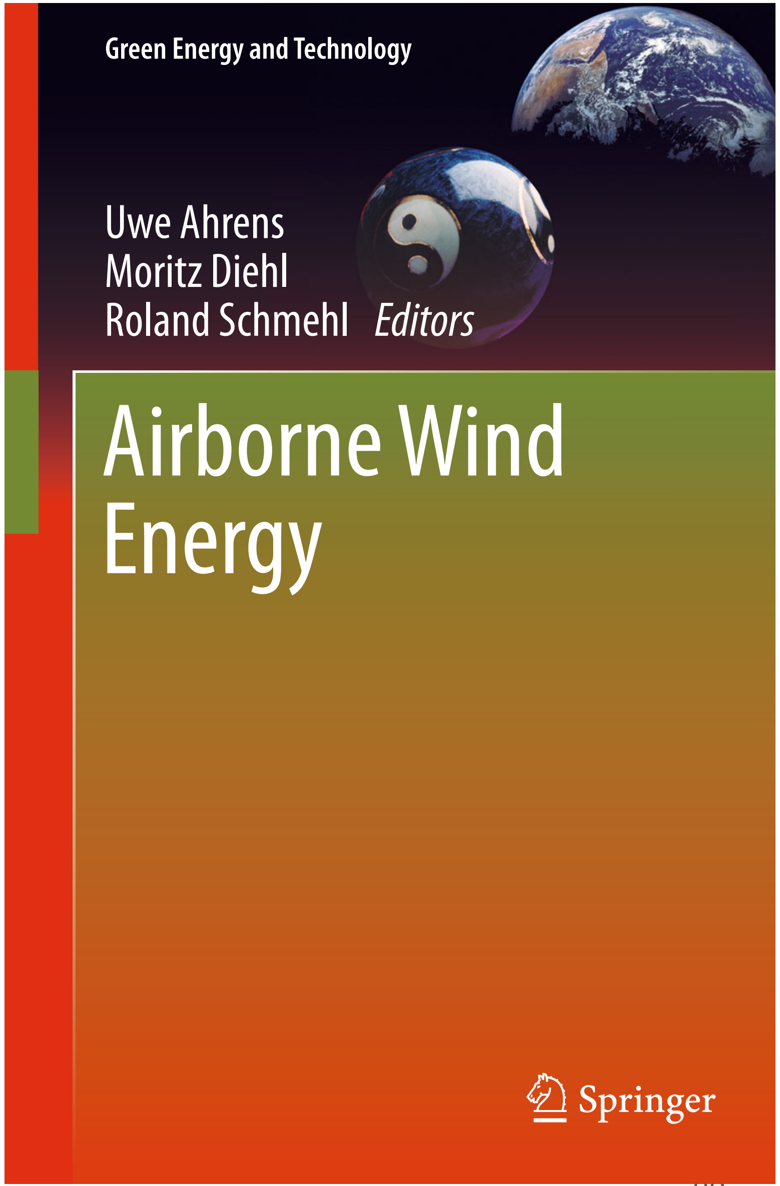
Categorization of crosswind systems

	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

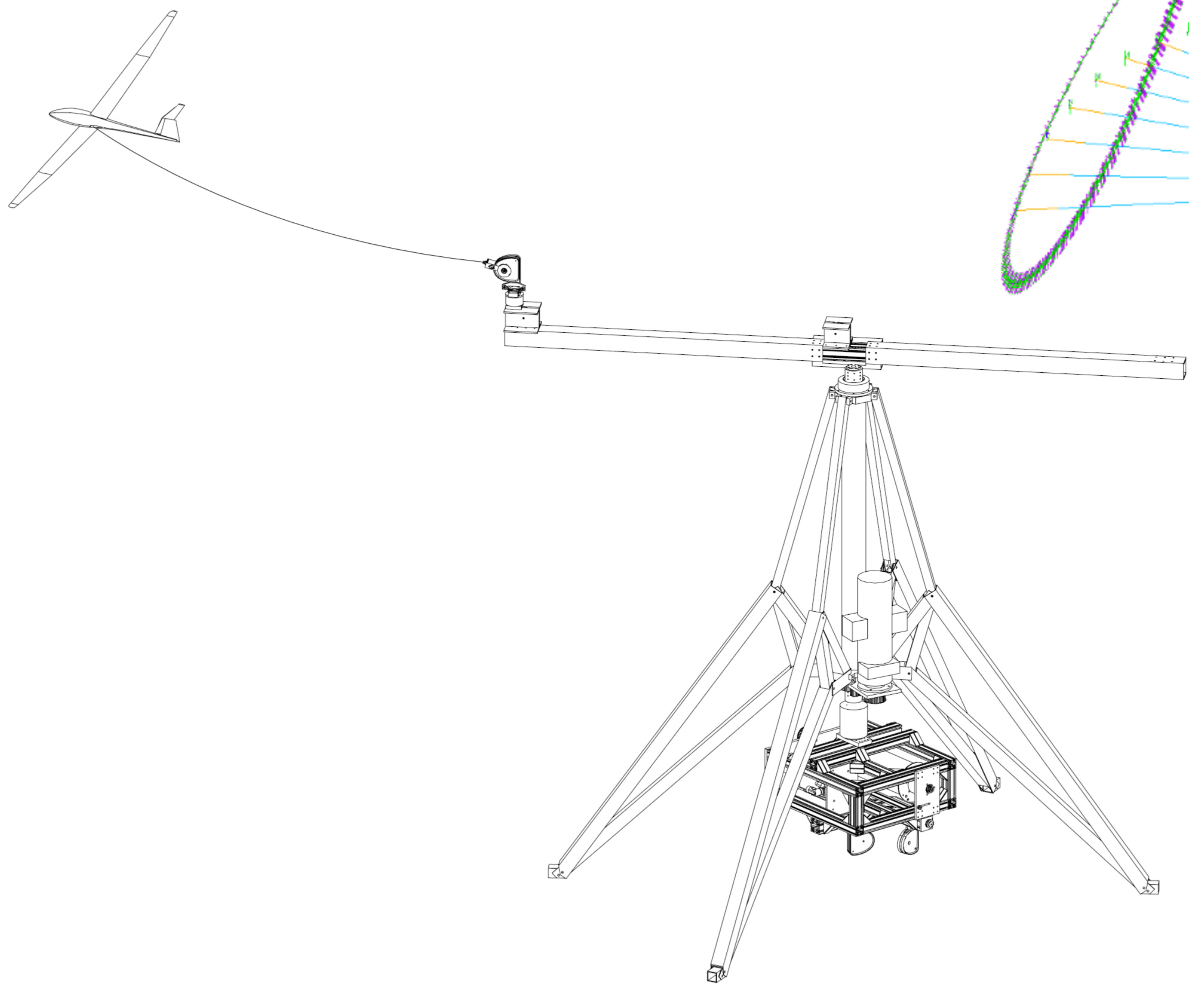
For simple plane attached to a tether:

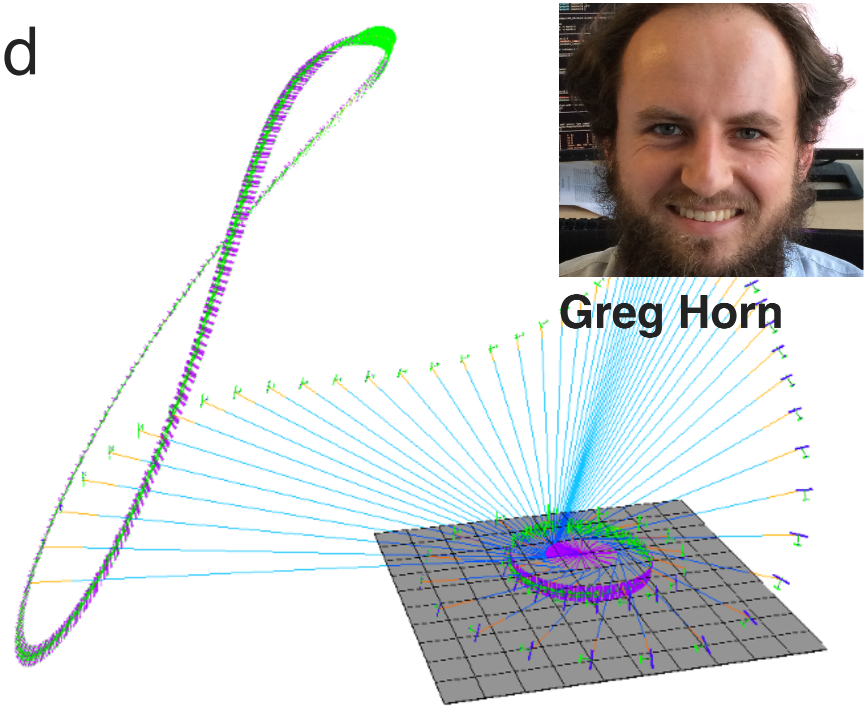
- 20 differential states (3+3 trans, 9+3 rotation, 1+1 tether)
- 1 algebraic state (tether force)
- 8 invariants (6 rotation, 2 due to tether constraint)
- 3 control inputs (aileron, elevator, tether length)

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]

Aim: Transition from Rotation to Power Orbit

Nontrivial Topology 1: Rotation Start for Tethered Wings

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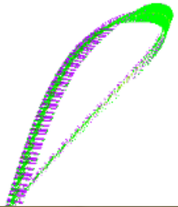
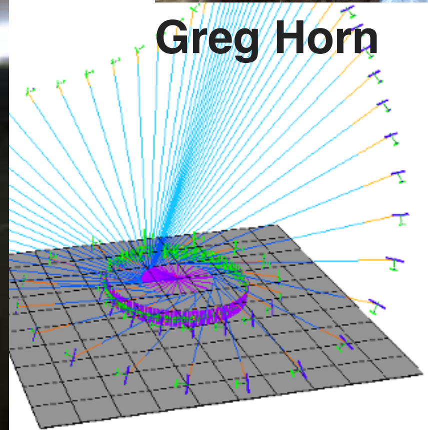
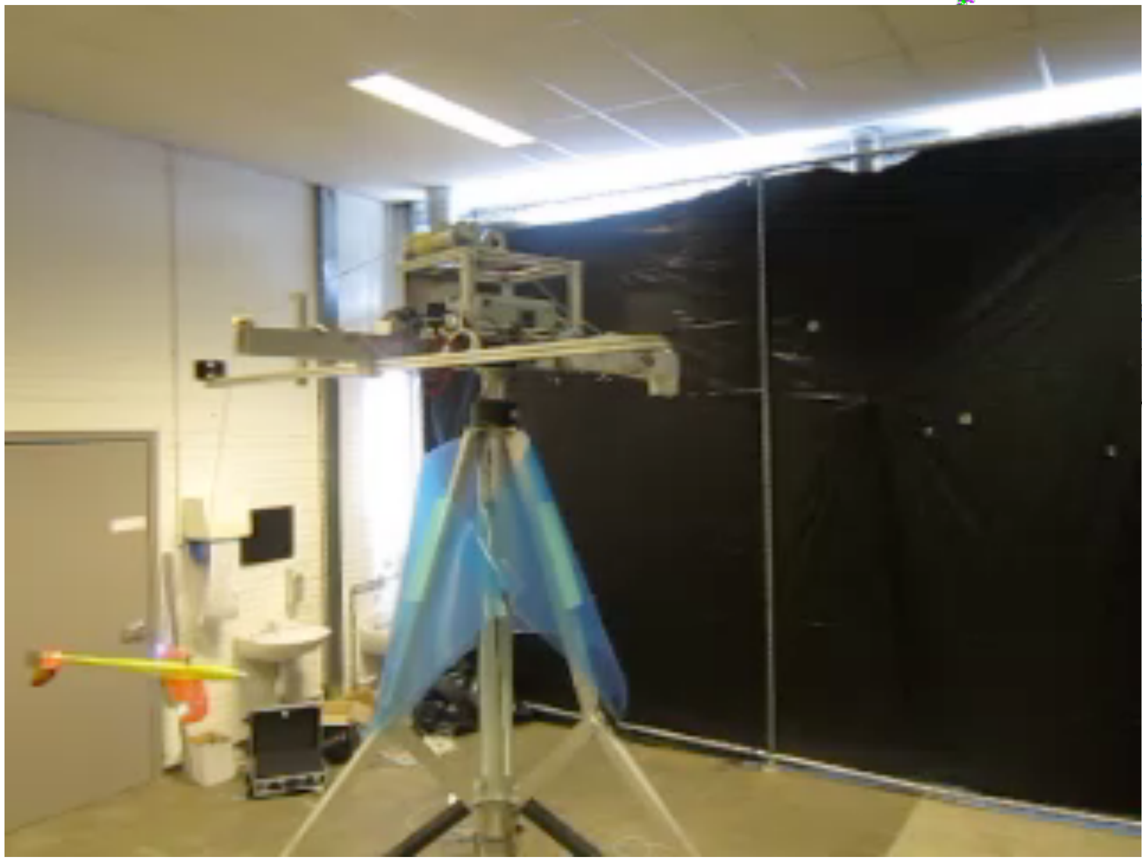
Greg Horn







Kurt Geebelen

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

Milan Vukov

Moving Horizon Estimation and Nonlinear Model Predictive Control on the Flight Carousel

(sampling time 50 Hz, using ACADO Code Generation)

Closed loop experiments with NMPC & NMHE

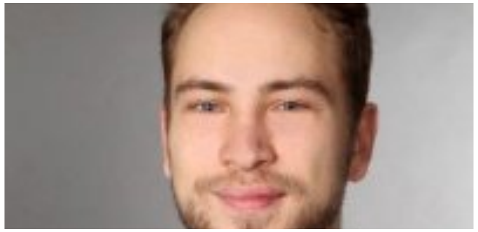
KU LEUVEN

UNI FREIBURG

ERC HIGHWIND

HIGHWIND Carousel in Freiburg

Predictive Control of Kite Carousel in Freiburg



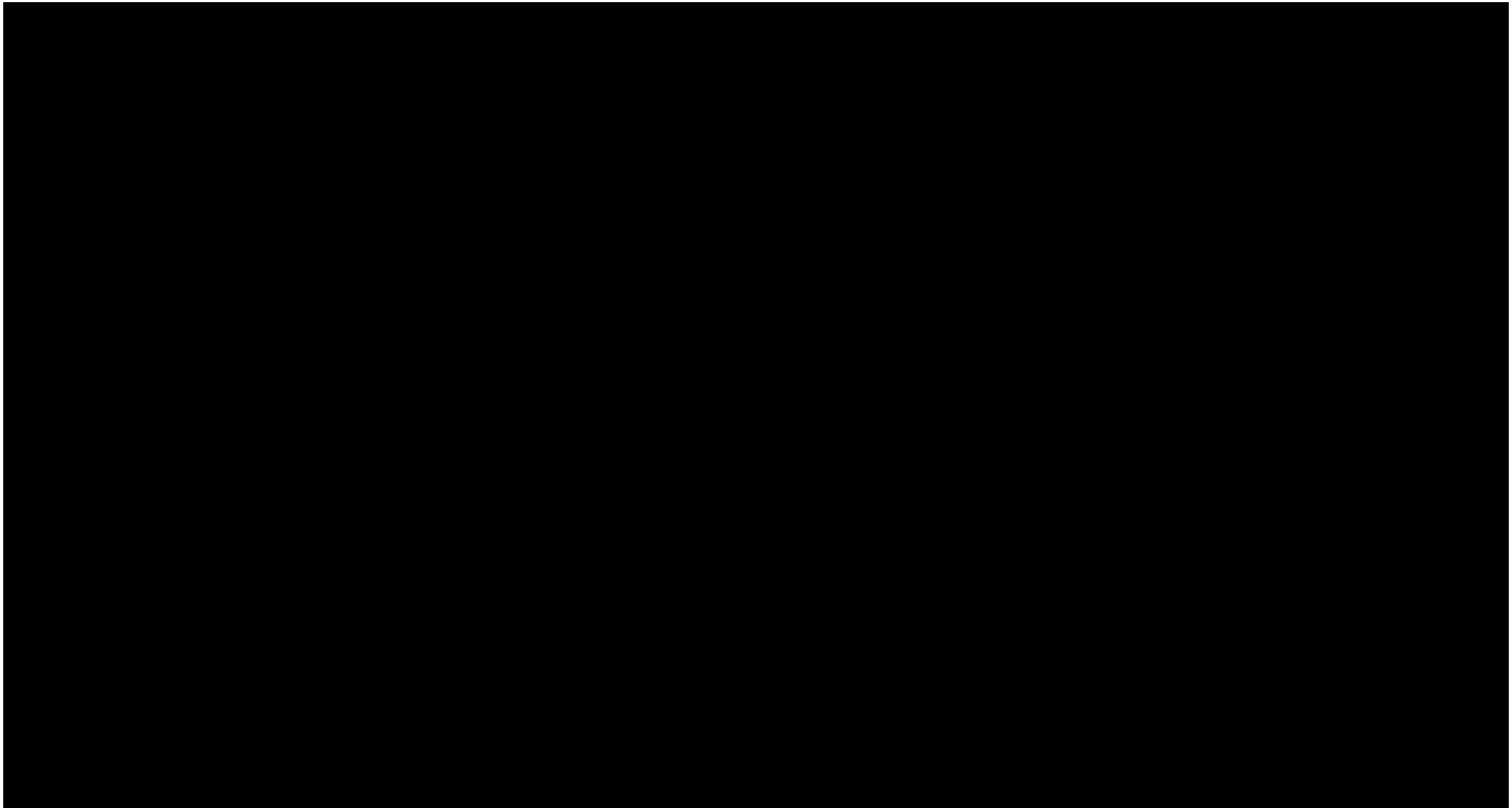
Jonas Schlangenhauf

Thorbjörn Jörger

20Hz/50ms sampling time using ACADO

(Nonlinear MPC video from 13.12.2016 in Freiburg)

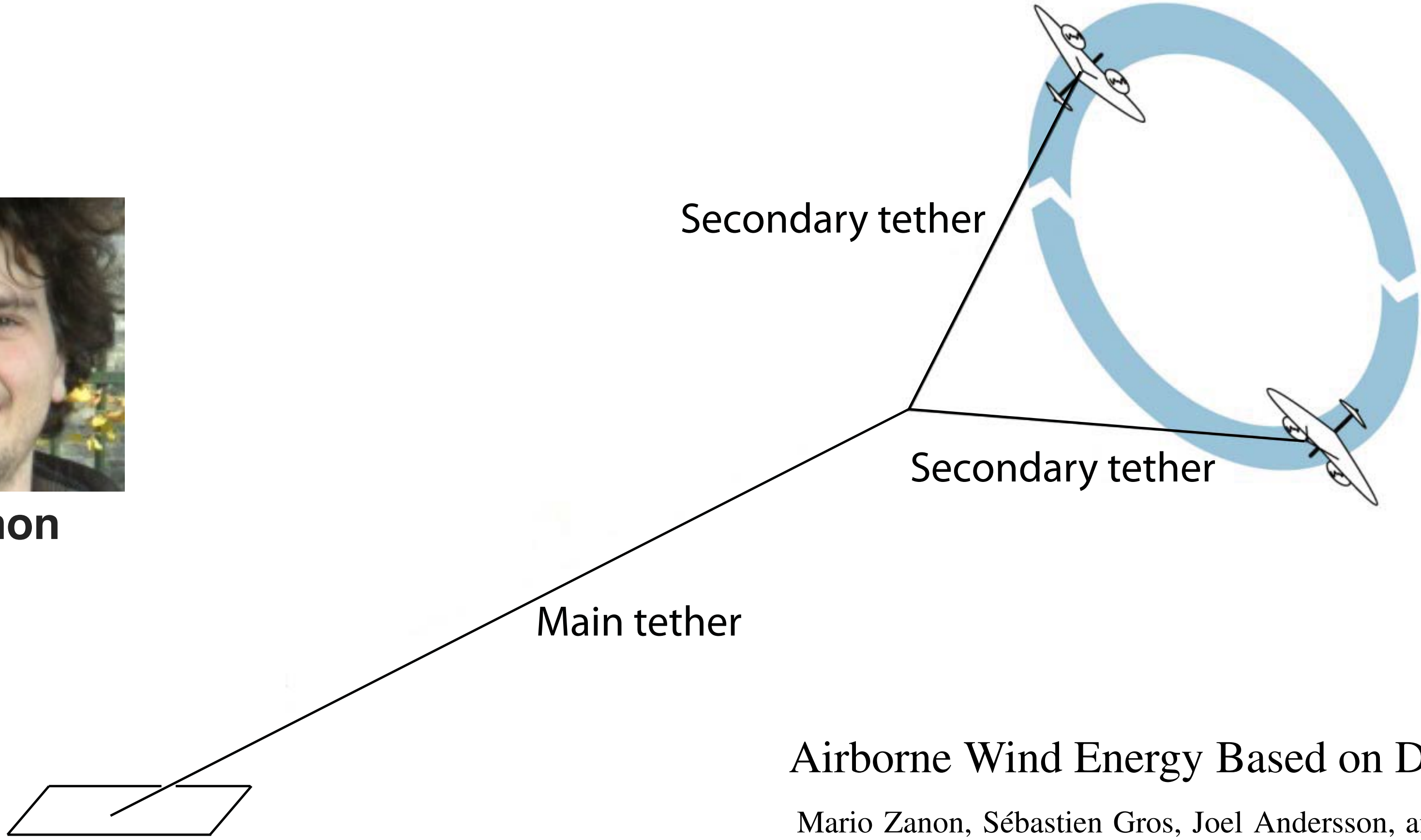
(video by Ben Schleusener)



Nontrivial Topology 2: Dual Kite Systems

- Two airfoils circling around each other have **less tether drag**
- can reach 40 kW/m² 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

Nontrivial Topology 2: Dual Kite Systems

- Two airfoils circling around each other have **less tether drag**
- can reach 40 kW/m² already with small devices
- centrifugal forces compensate each other

Startup Kiteswarms Ltd./GmbH in building 078 on our campus

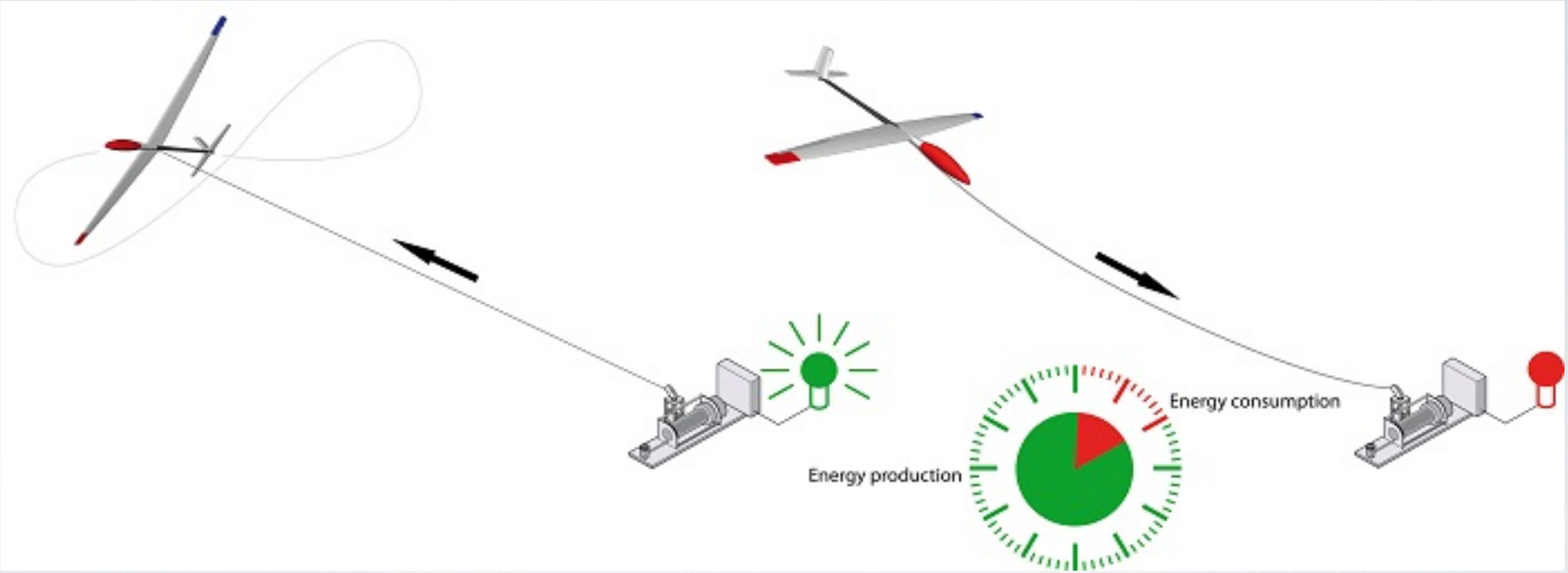
Kiteswarms founder: Reinhart Paelinck

The Company AmpyxPower

AmpyxPower

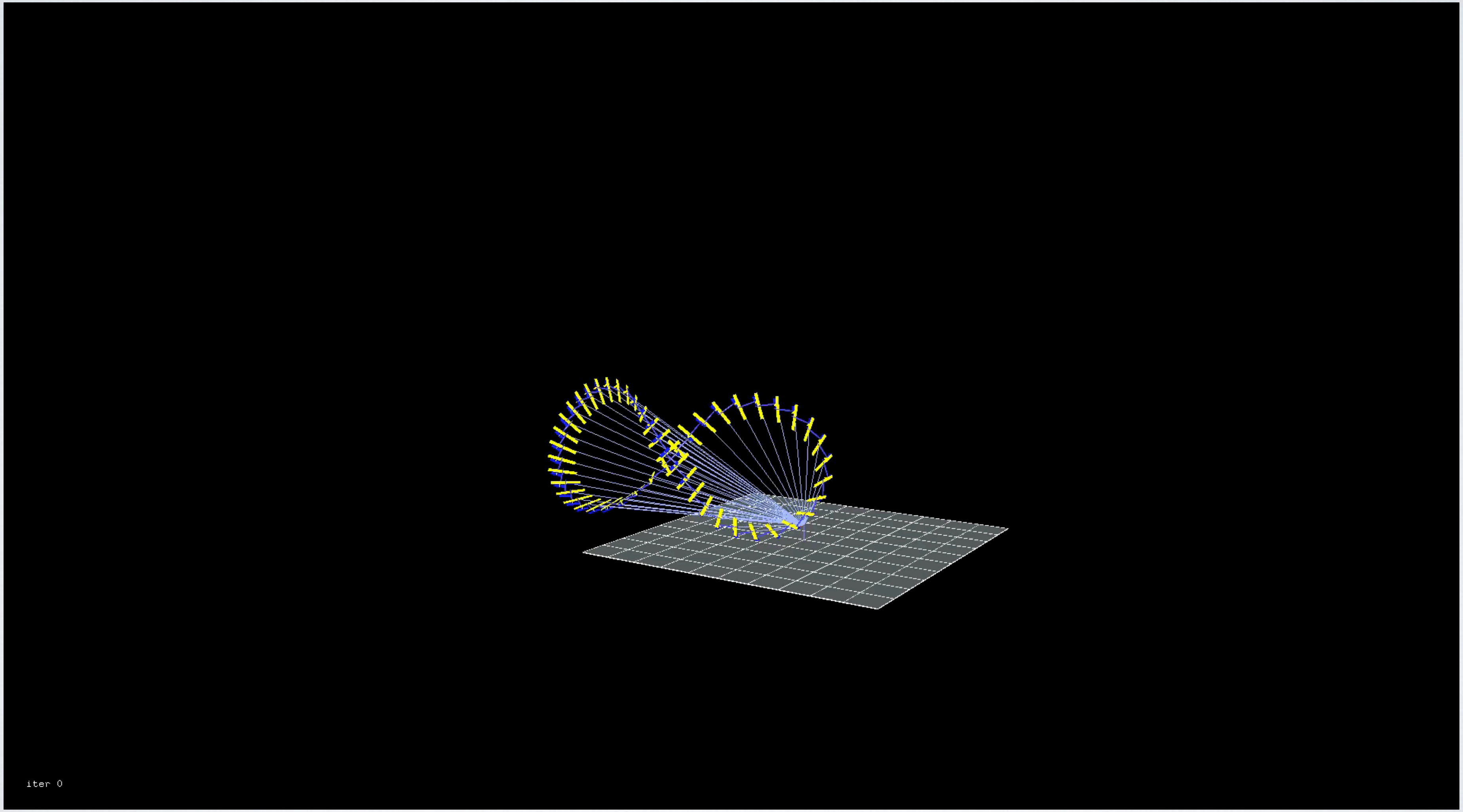
- startup from TU Delft
- now about 40 permanent staff
- financed via venture capital

Pumping Cycle to Harvest Wind Power



Optimization of Ampyx-Type Pumping Cycle

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



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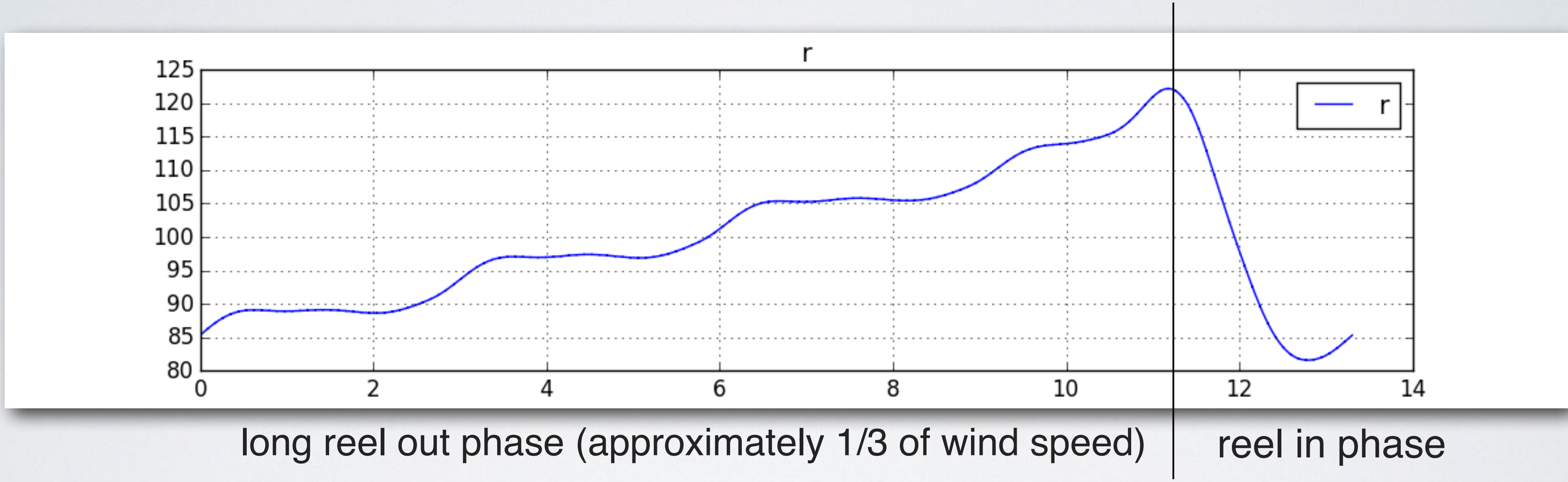
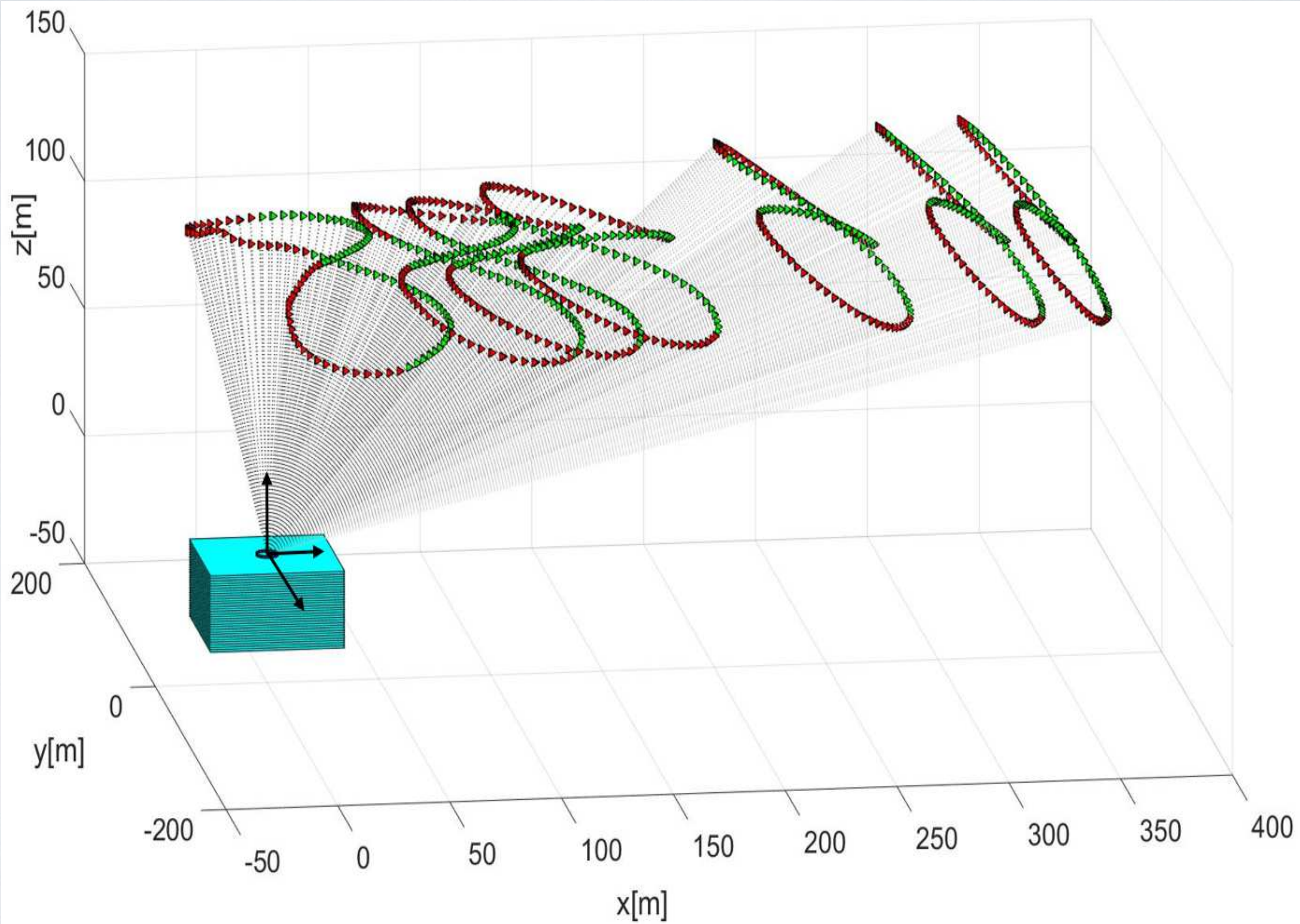


long reel out phase (approximately 1/3 of wind speed) | reel in phase

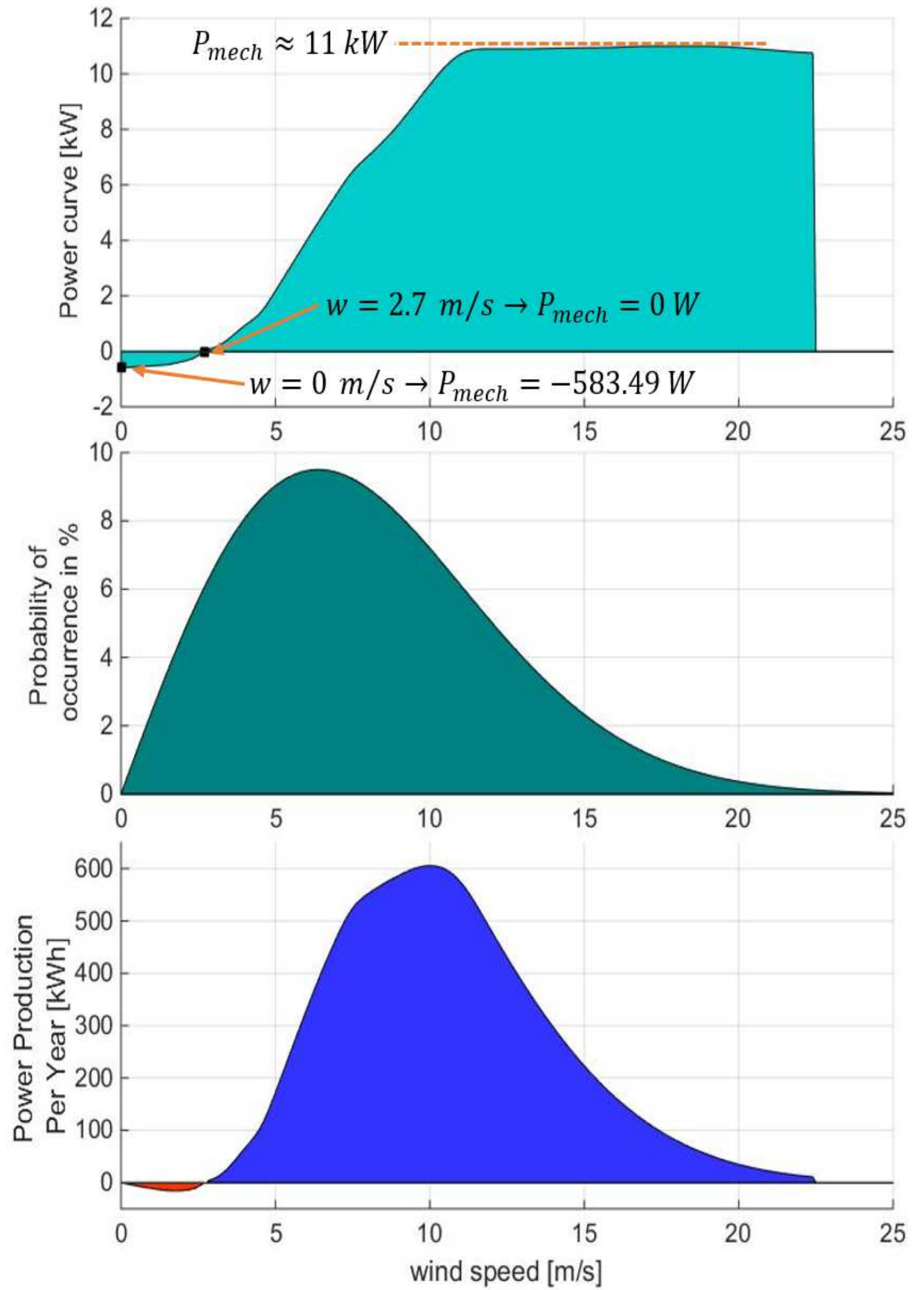
Giovanni Licitra (AmpyxPower) and Greg Horn (Univ. Freiburg)

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

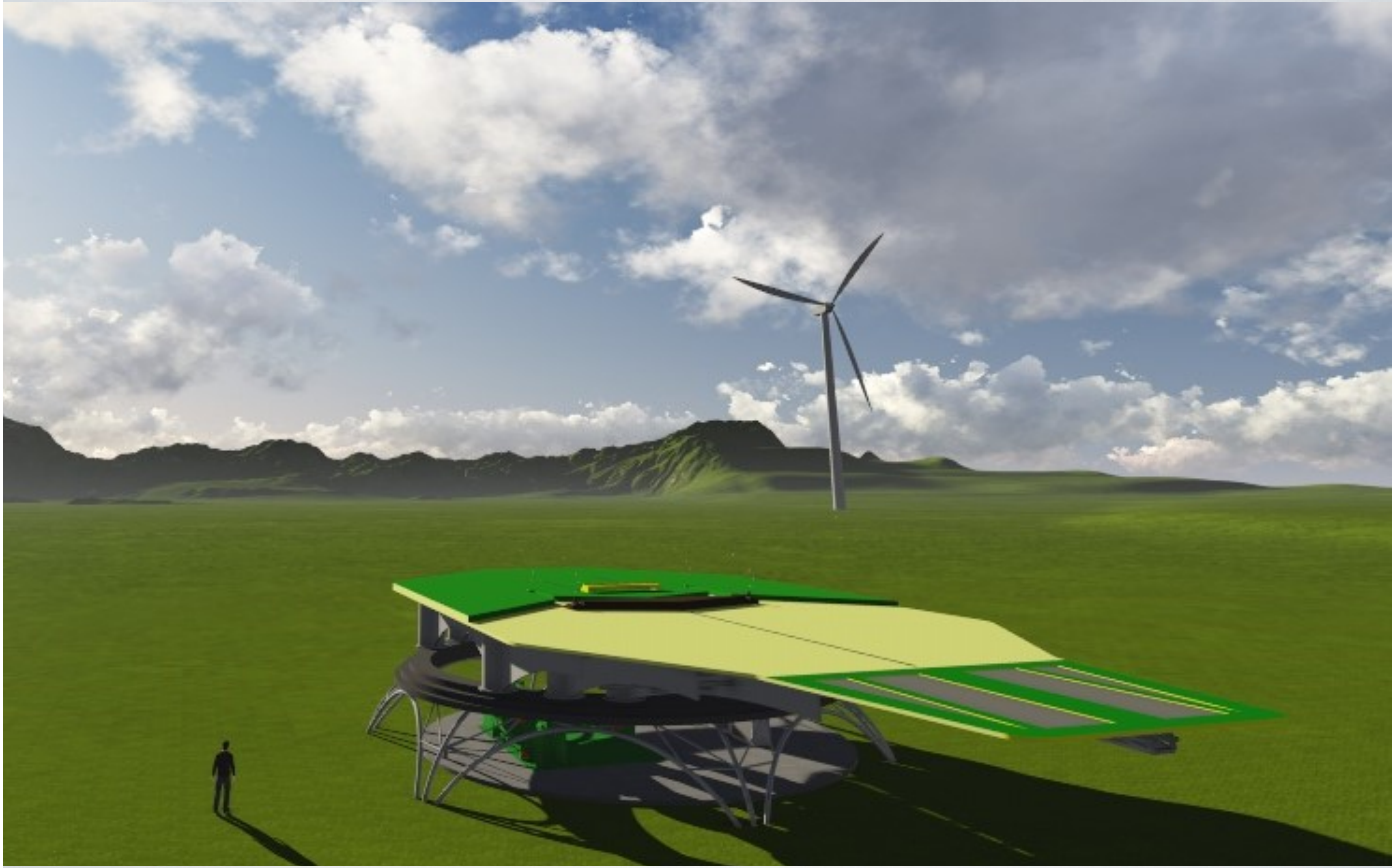
=

Contribution to yearly production

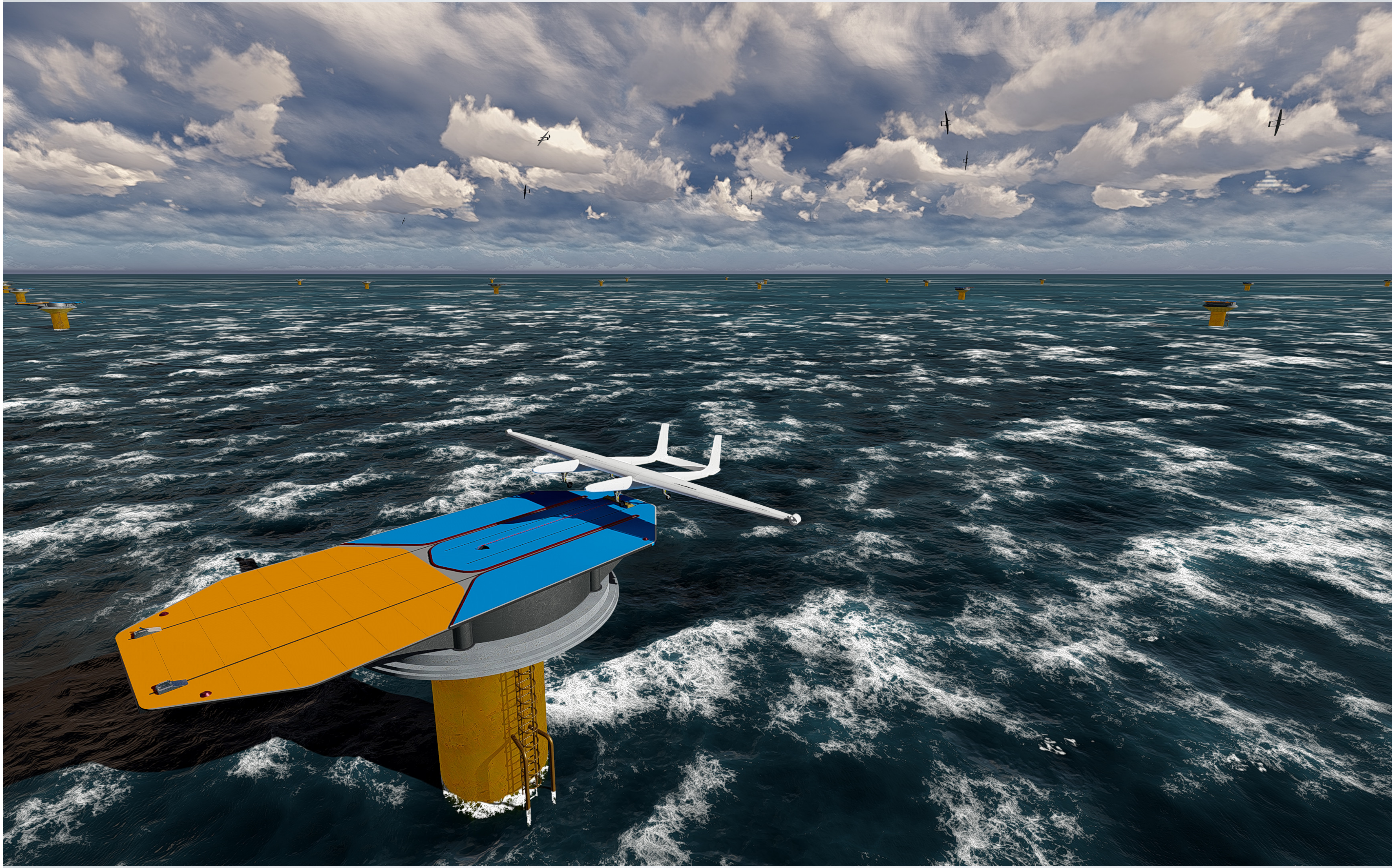
[study with 5.5m wing span plane]
Blue: 52,27 MWh, red 0,27 MWh.
Average power: 6 kW (tether drag)

Under construction: AP 3 (12 m wingspan)

Plans for 2022: AP 4 with catapult start



Plans for 2022: AP 4 with catapult start



SkySails:
Soft Kites with Ground-Based Generator

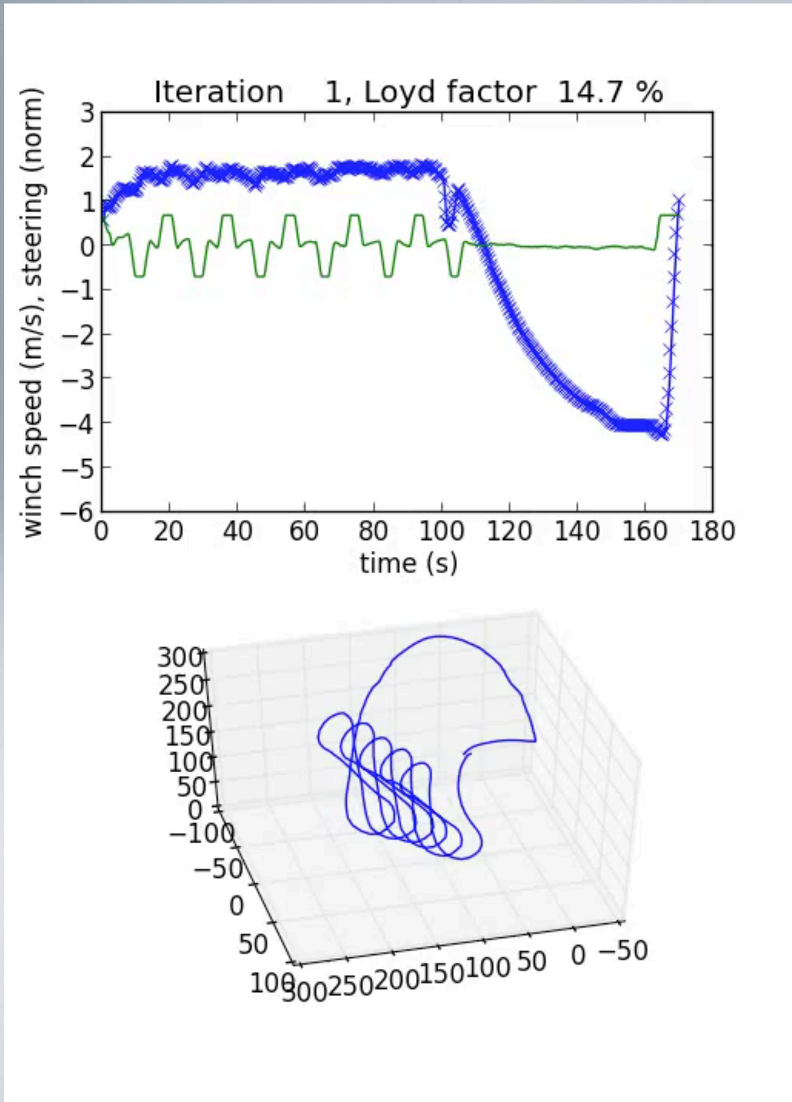
SkySails

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

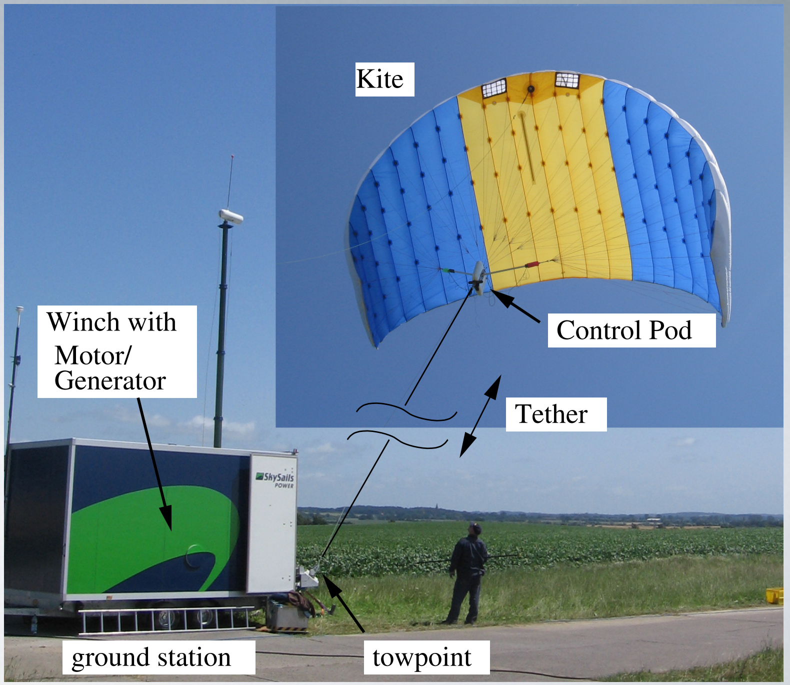
SkySails: soft kites with ground-based generator

Optimization of SkySails' electricity generating orbits

by **Michael Erhard**, who was Chief Control Engineer at SkySails, and 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

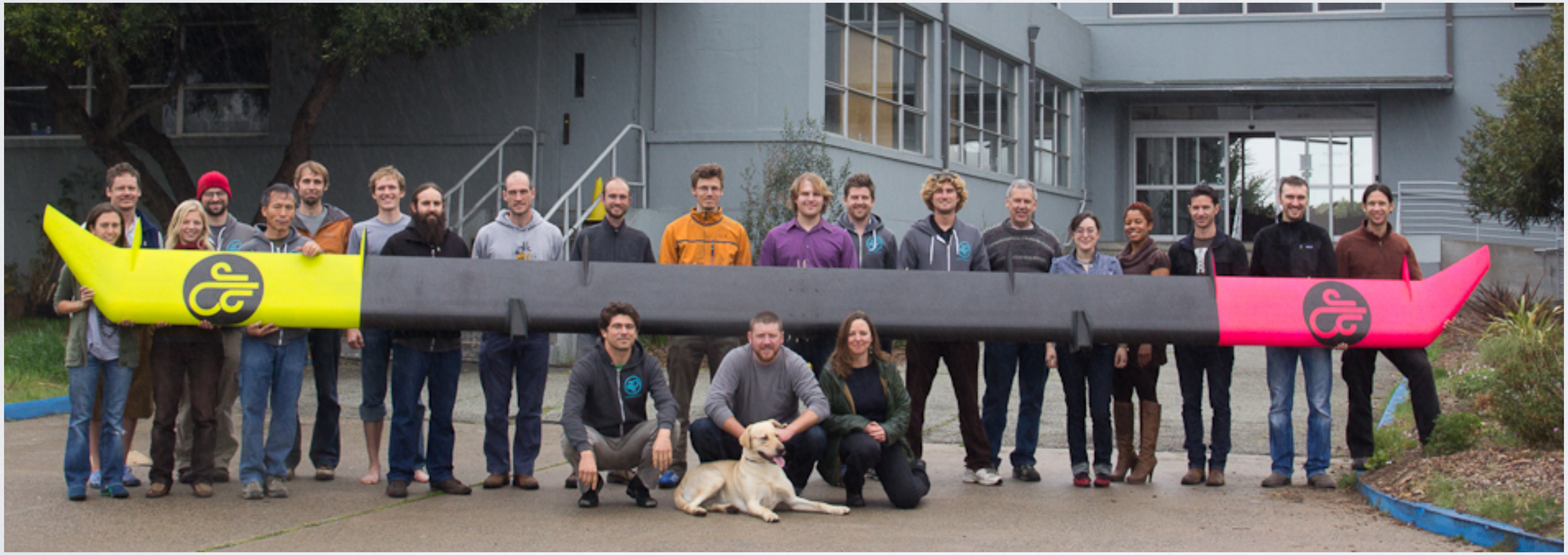


Small–Scale Functional Model (50kW peak power)

Makani Power:
Rigid wing with on-board generator

Makani Power

- Californian start-up since 2006
- ~40 people
- fixed wings with on-board generators
- since 2013 part of Google X

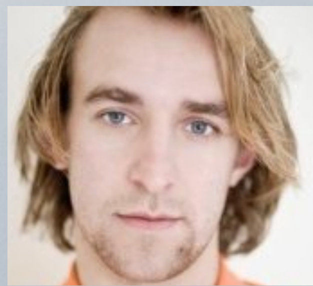


Makani Power

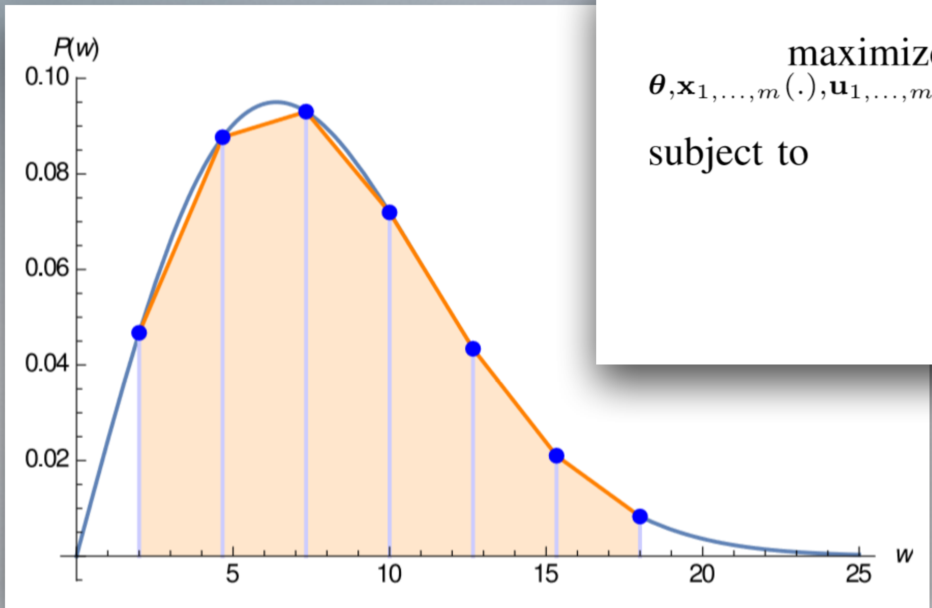
Makani Power: turbines on-board allow take-off and landing as quadcopter

Makani power: yearly power output optimisation

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



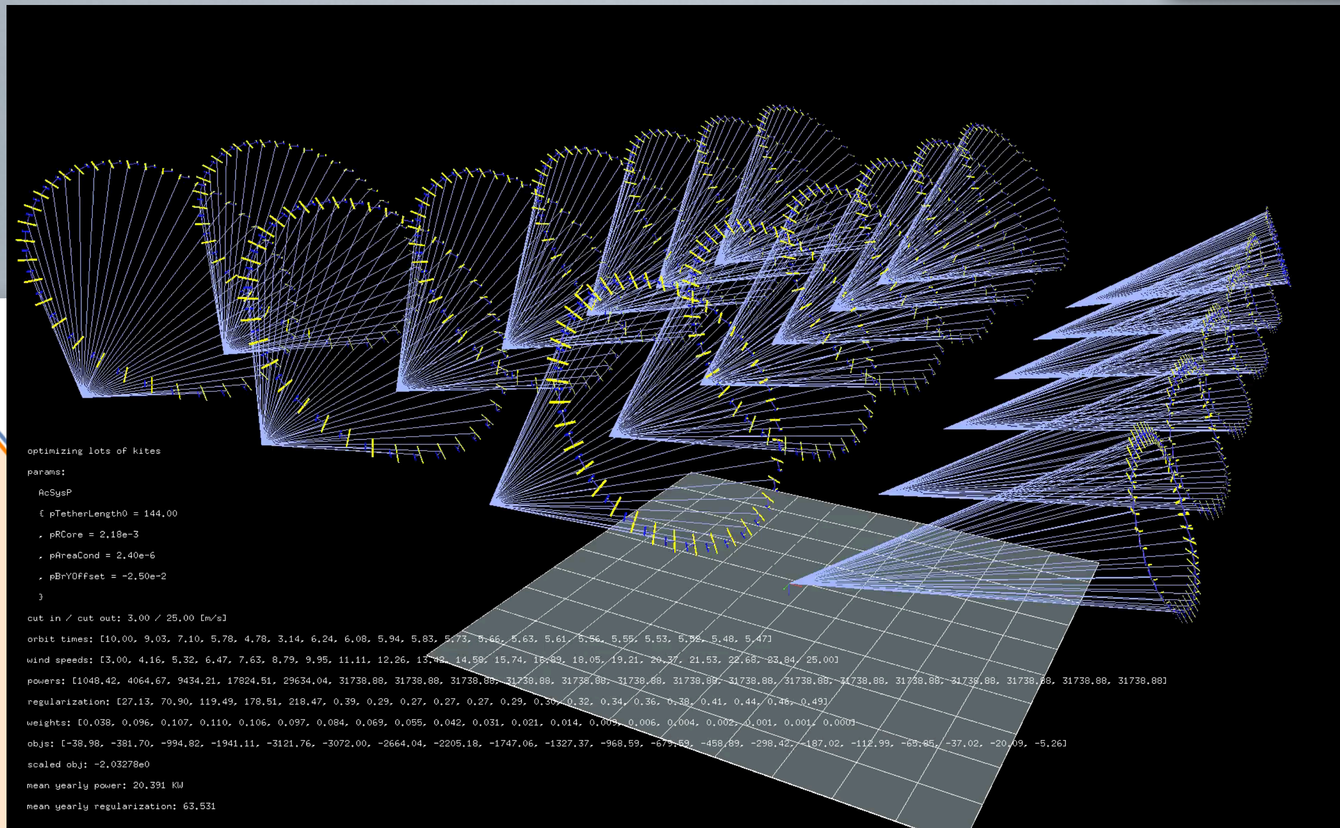
Multiple Setpoint Optimization: optimise fixed parameters (tether length and thickness, generator size) together with adaptable periodic control trajectories for all wind speeds, weighted with their frequency in the wind histogram

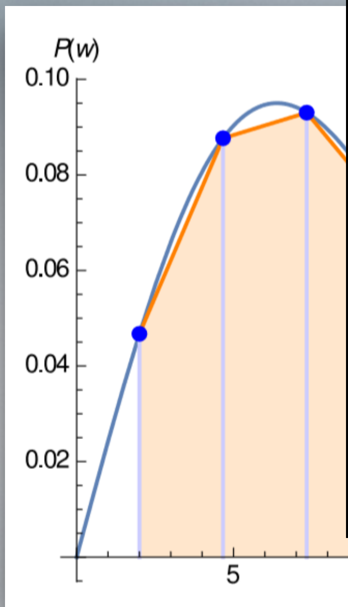


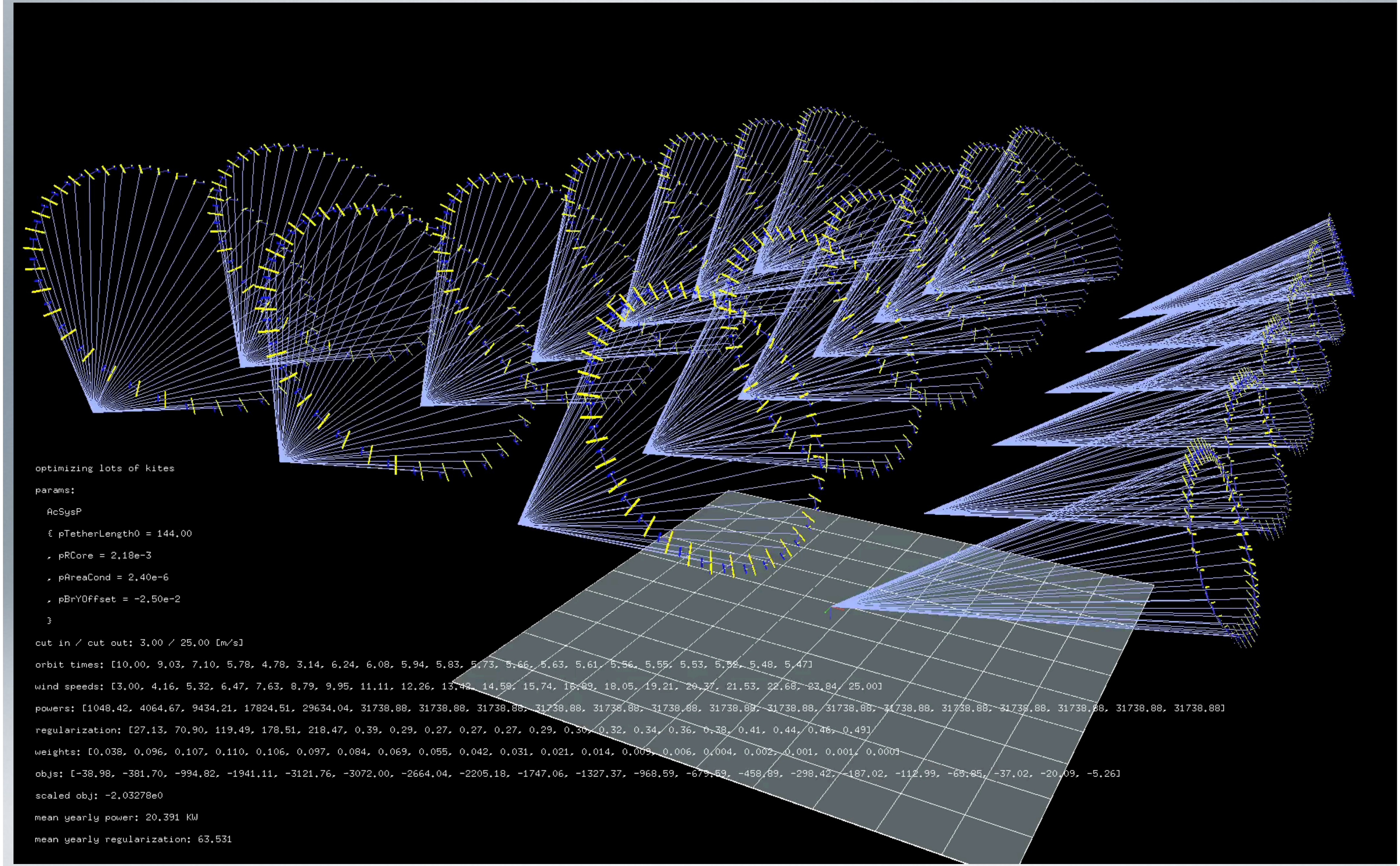
$$
\begin{aligned}
\underset{\boldsymbol{\theta},\mathbf{x}_{1,\ldots,m}(.),\mathbf{u}_{1,\ldots,m}(.),T_{1,\ldots,m}}{\text{maximize}} \quad & \sum_{k=1}^{m} \pi_{\mathrm{O}}\left(\boldsymbol{\theta},\, T_k\right)^{-1} P_{\boldsymbol{\chi}}\left(\boldsymbol{\chi}_k\right) \int_0^{T_k} P(\mathbf{x}_k(t),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

Makani power: yearly power output optimisation

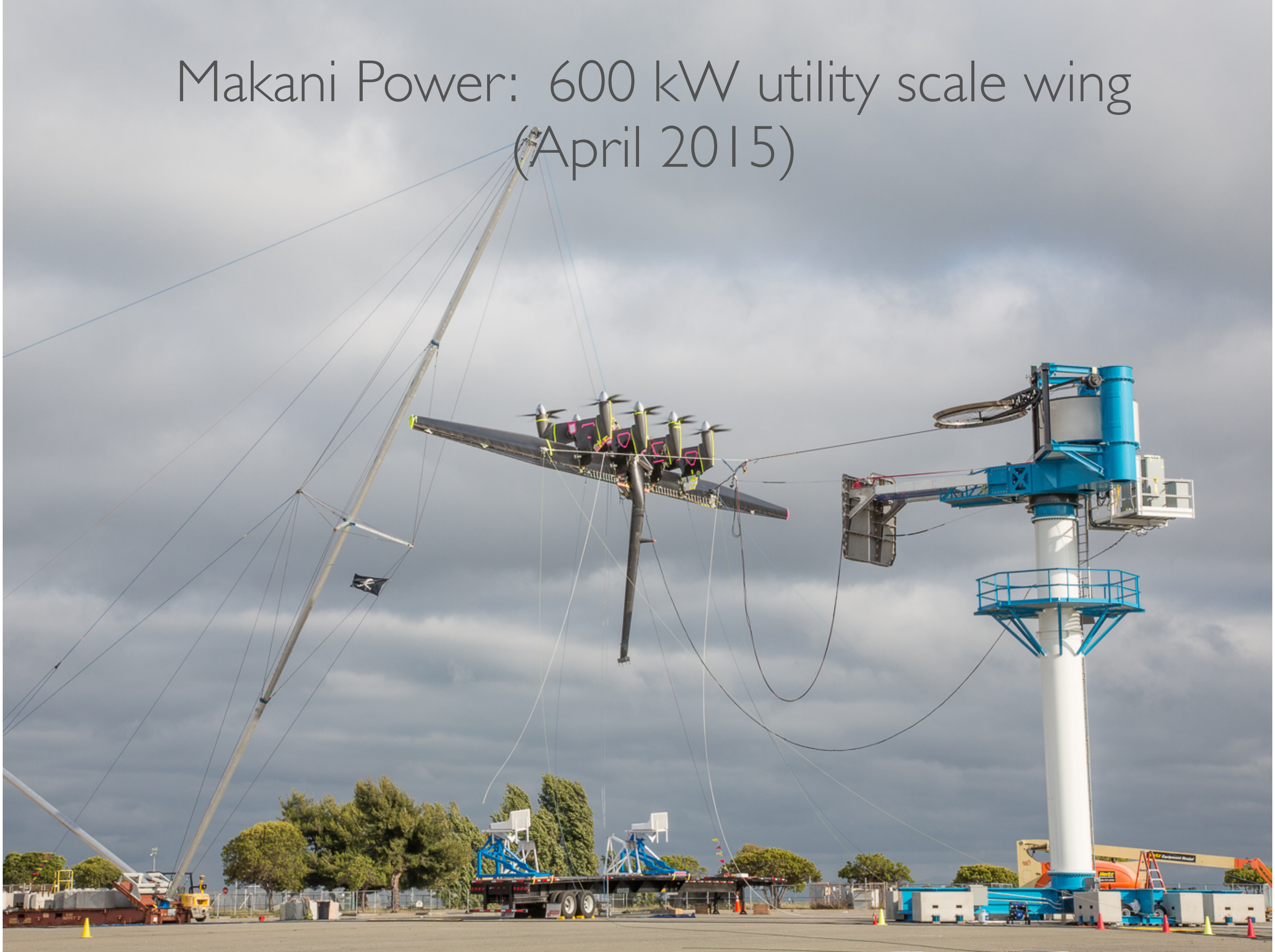
by Greg Horn, Univ. Freiburg, and Thomas Van Alsenoy, Makani






optimizing lots of kites
params:
AcSysP
{ pTetherLength0 = 144.00
, pRCore = 2.18e-3
, pAreaCond = 2.40e-6
, pBrYOffset = -2.50e-2
}
cut in / cut out: 3.00 / 25.00 [m/s]
orbit times: [10.00, 9.03, 7.10, 5.78, 4.78, 3.14, 6.24, 6.08, 5.94, 5.83, 5.73, 5.66, 5.63, 5.61, 5.56, 5.55, 5.53, 5.52, 5.48, 5.47]
wind speeds: [3.00, 4.16, 5.32, 6.47, 7.63, 8.79, 9.95, 11.11, 12.26, 13.42, 14.58, 15.74, 16.89, 18.05, 19.21, 20.37, 21.53, 22.68, 23.84, 25.00]
powers: [1048.42, 4064.67, 9434.21, 17824.51, 29634.04, 31738.88, 31738.88, 31738.88, 31738.88, 31738.88, 31738.88, 31738.88, 31738.88, 31738.88, 31738.88, 31738.88, 31738.88, 31738.88, 31738.88, 31738.88]
regularization: [27.13, 70.90, 119.49, 178.51, 218.47, 0.39, 0.29, 0.27, 0.27, 0.27, 0.29, 0.30, 0.32, 0.34, 0.36, 0.38, 0.41, 0.44, 0.46, 0.49]
weights: [0.038, 0.096, 0.107, 0.110, 0.106, 0.097, 0.084, 0.069, 0.055, 0.042, 0.031, 0.021, 0.014, 0.009, 0.006, 0.004, 0.002, 0.001, 0.001, 0.000]
objs: [-38.98, -381.70, -994.82, -1941.11, -3121.76, -3072.00, -2664.04, -2205.18, -1747.06, -1327.37, -968.59, -679.59, -458.89, -298.42, -187.02, -112.99, -65.85, -37.02, -20.09, -5.26]
scaled obj: -2.03278e0
mean yearly power: 20.391 KW
mean yearly regularization: 63.531

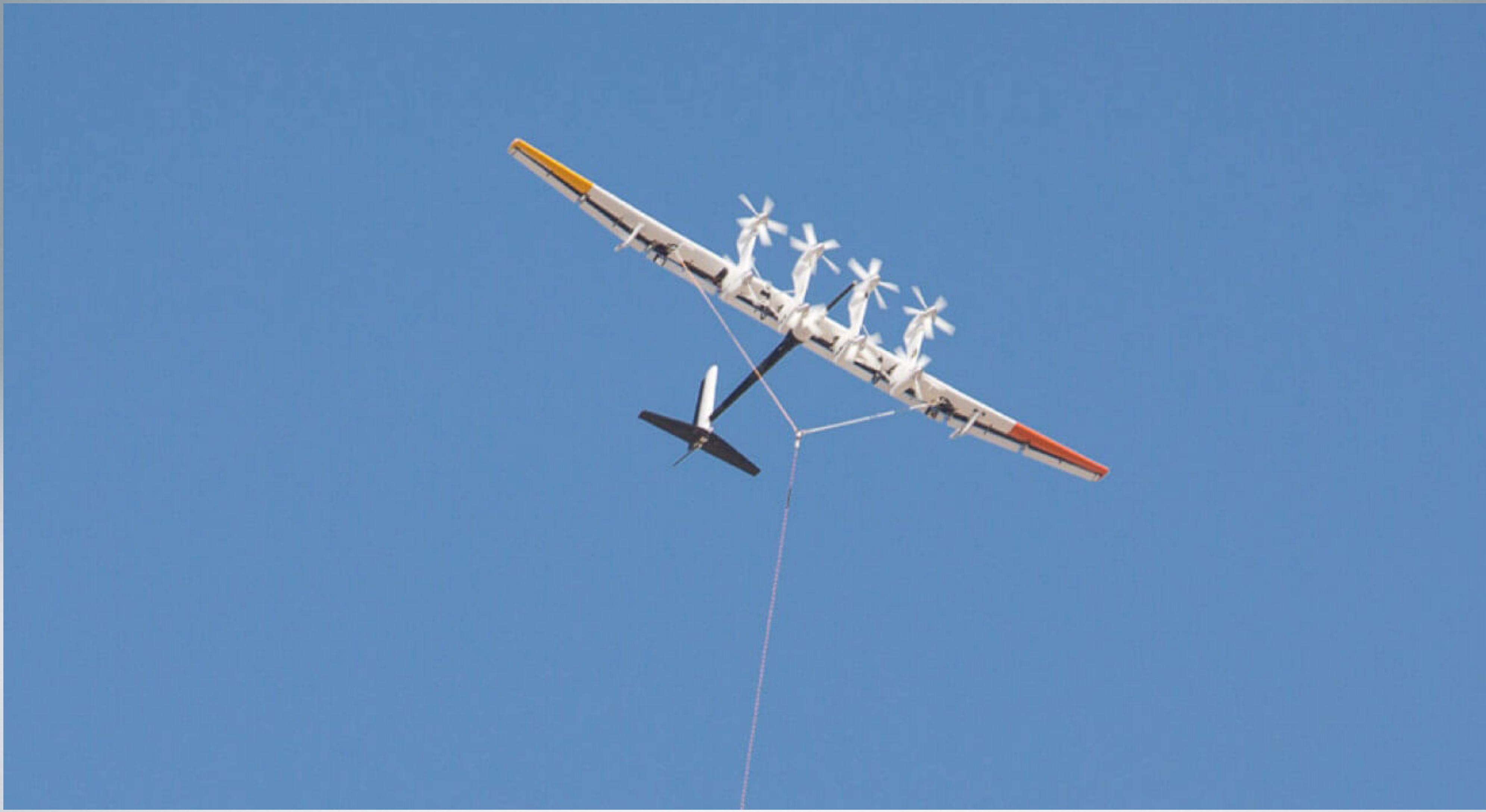
Makani Power: 600 kW utility scale wing (April 2015)

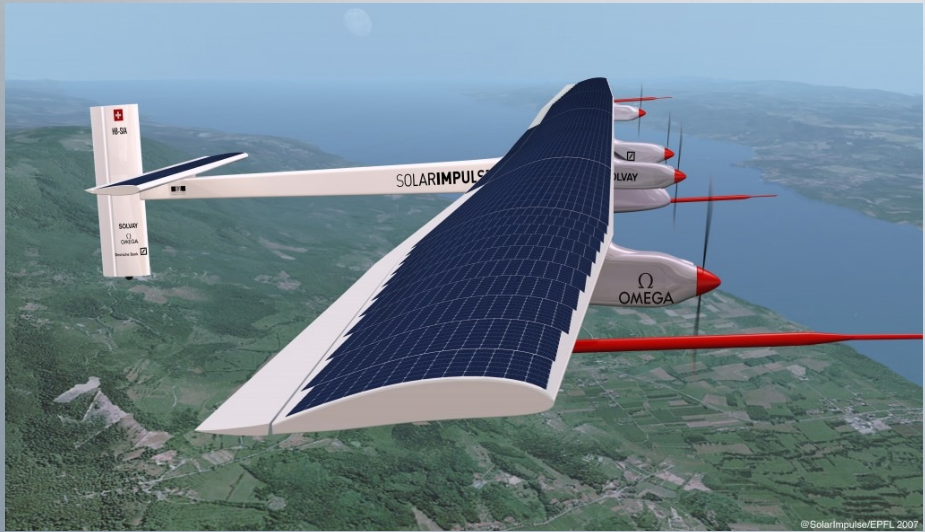


Makani 600 kW System Tests in 2017

Makani 600 kW System Tests in 2017

Makani 600 kW System Tests in 2017





+

Solarimpulse + Crosswind = ?

Question:
How much more power would a makani plane with solar cells on the wing deliver ?

50 %   10%   5%   0.5%

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