AWESCO Workpackage 2 on System Design and Optimisation

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AWESCO Kick-Off Event
Freiburg, March 2, 2016

WP2 System Design and Optimisation

11:35 “Optimal Control of Dual Kites in PumpingCycle Operation” by Rachel Leuthold (ALUFR)

12:00 “Ground Station Design and Optimization for Airborne Wind Energy” by Mahdi Salari (UL)

12:25 Lunch

13:40 “Multidisciplinary System Design, Safety and Cost Optimisation of AWE” by Ashwin Candade (Enerkite)

14:05 “Grid Integration of Airborne Wind Energy Systems” by Elena Malz (CHAL)

System Design and Optimisation - Main Ideas

Aim: Decide on Design Questions for Airborne Wind Energy

Approach of WP2:

- use dynamic simulation **models of sufficient detail** (not more)
- use optimal control and derivative based nonlinear programming
- **simultaneously optimise design parameters and controls**

Some related design studies for inspiration

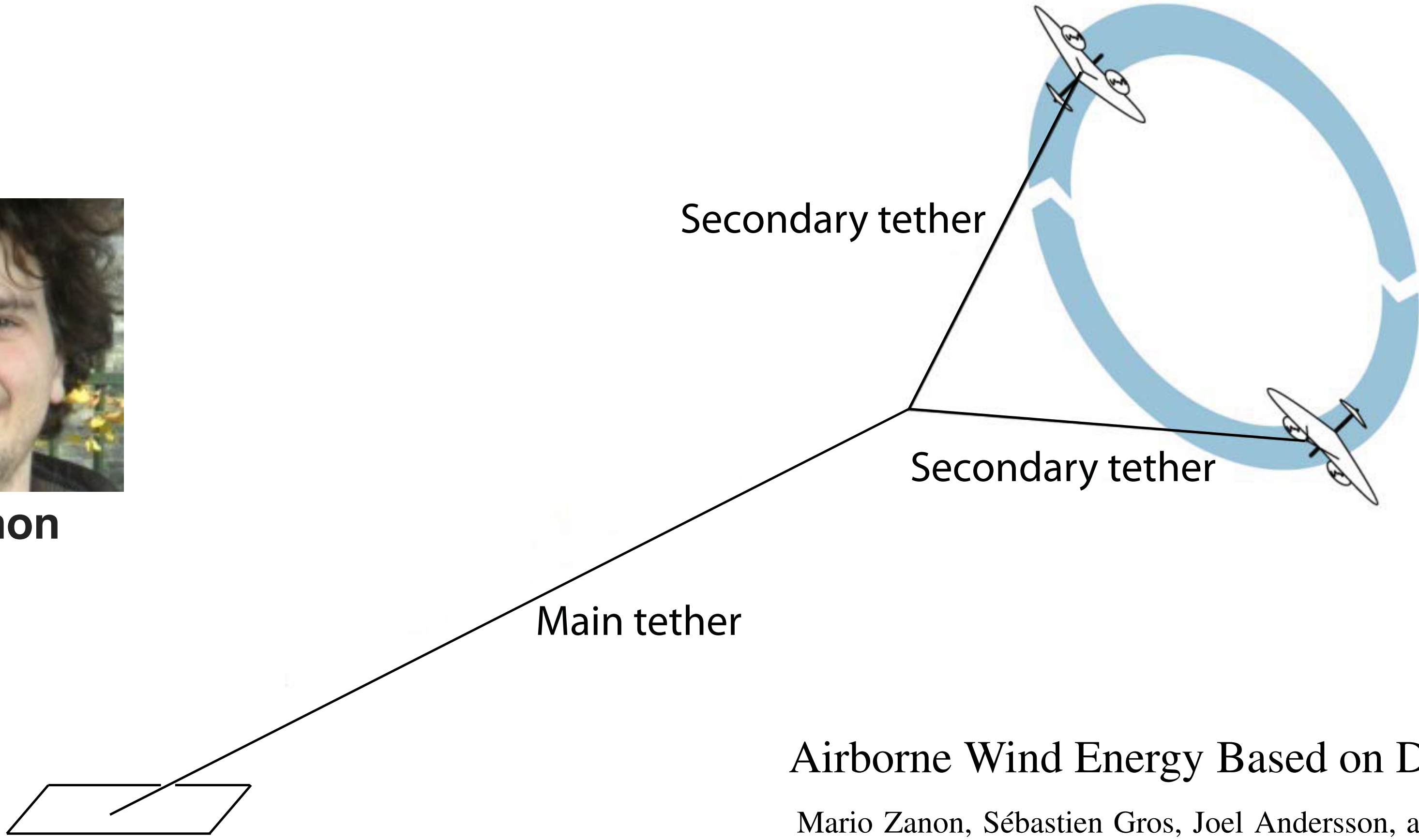
- Dual Kites (Mario Zanon)
- Pumping Cycles for AmpyxPlane (Greg Horn, Gianni Licitra)
- Year Power Optimisation for Makani (Greg Horn, Thomas Van Alsenoy)
- Pumping with Electrical Generator Efficiency (Greg Horn, Jeroen Stuyts)

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

- decide on **strength and length of tether and orbit**

Mario Zanon



Airborne Wind Energy Based on Dual Airfoils

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

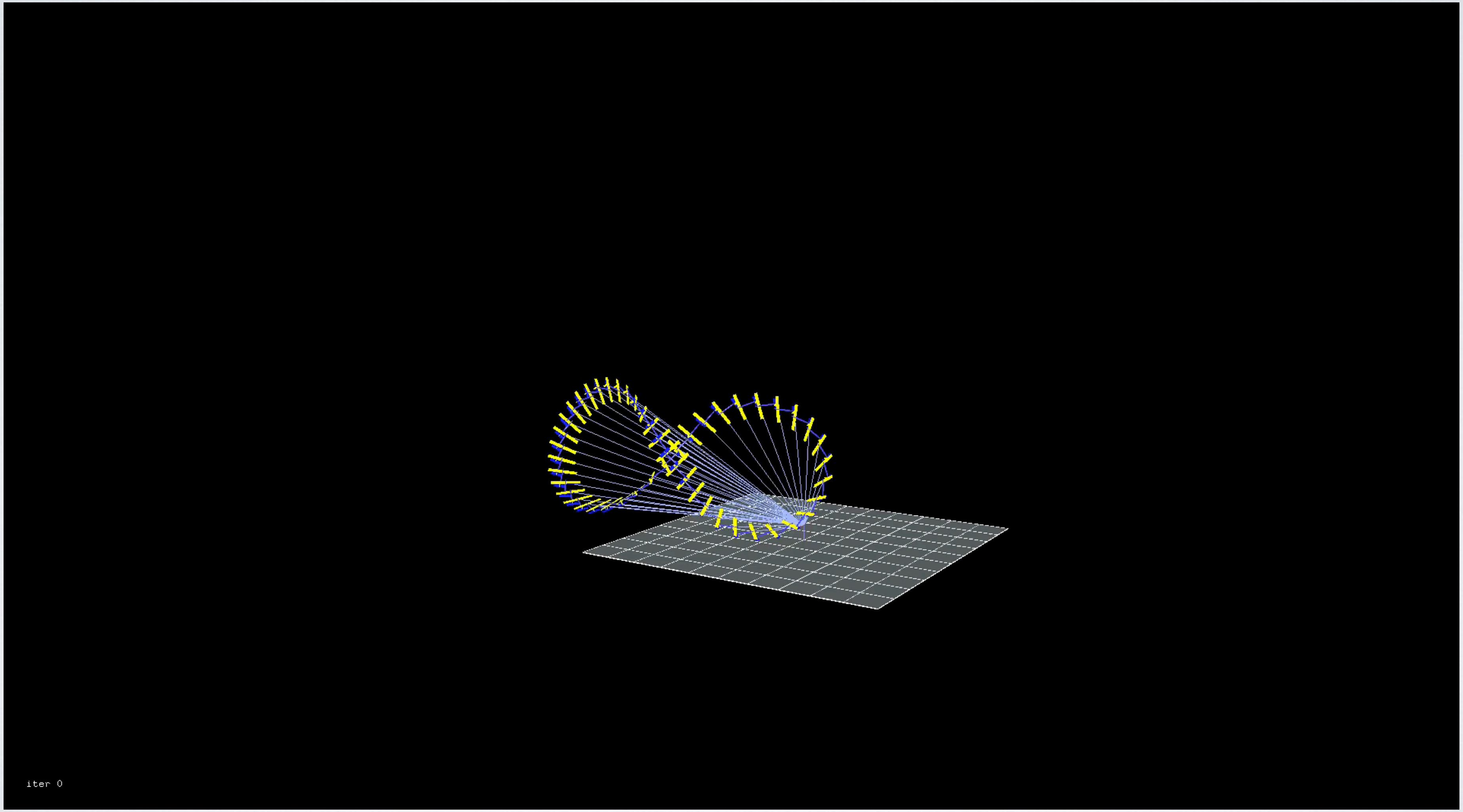
IEEE TRANSACTIONS ON CONTROL SYSTEMS TECHNOLOGY, VOL. 21, NO. 4, JULY 2013

Dual Kite Systems

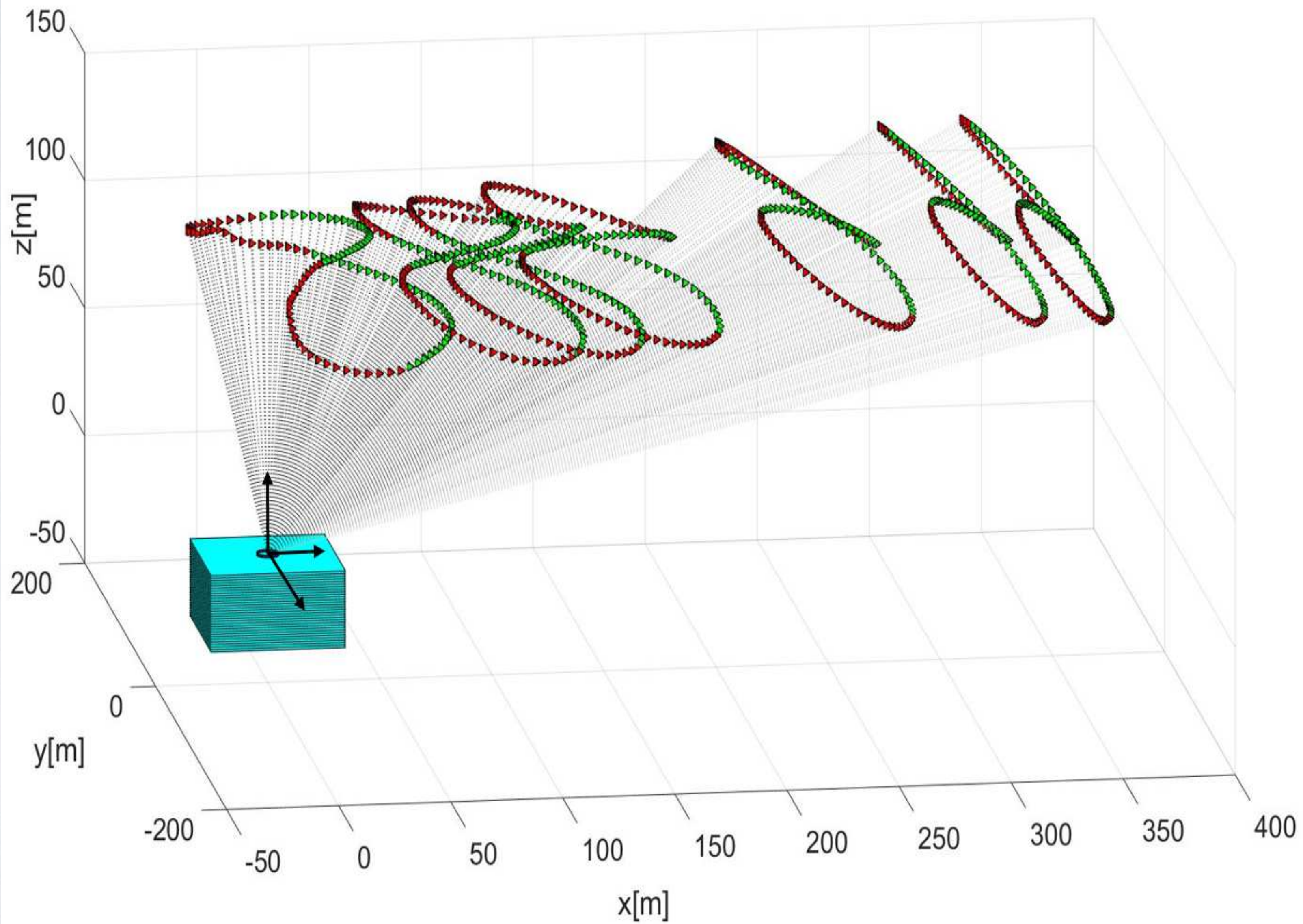
- Two airfoils circling around each other have **less tether drag**
- can reach 40 kW/m^2 already with small devices
- centrifugal forces compensate each other

Optimization of Ampyx-Type Pumping Cycle

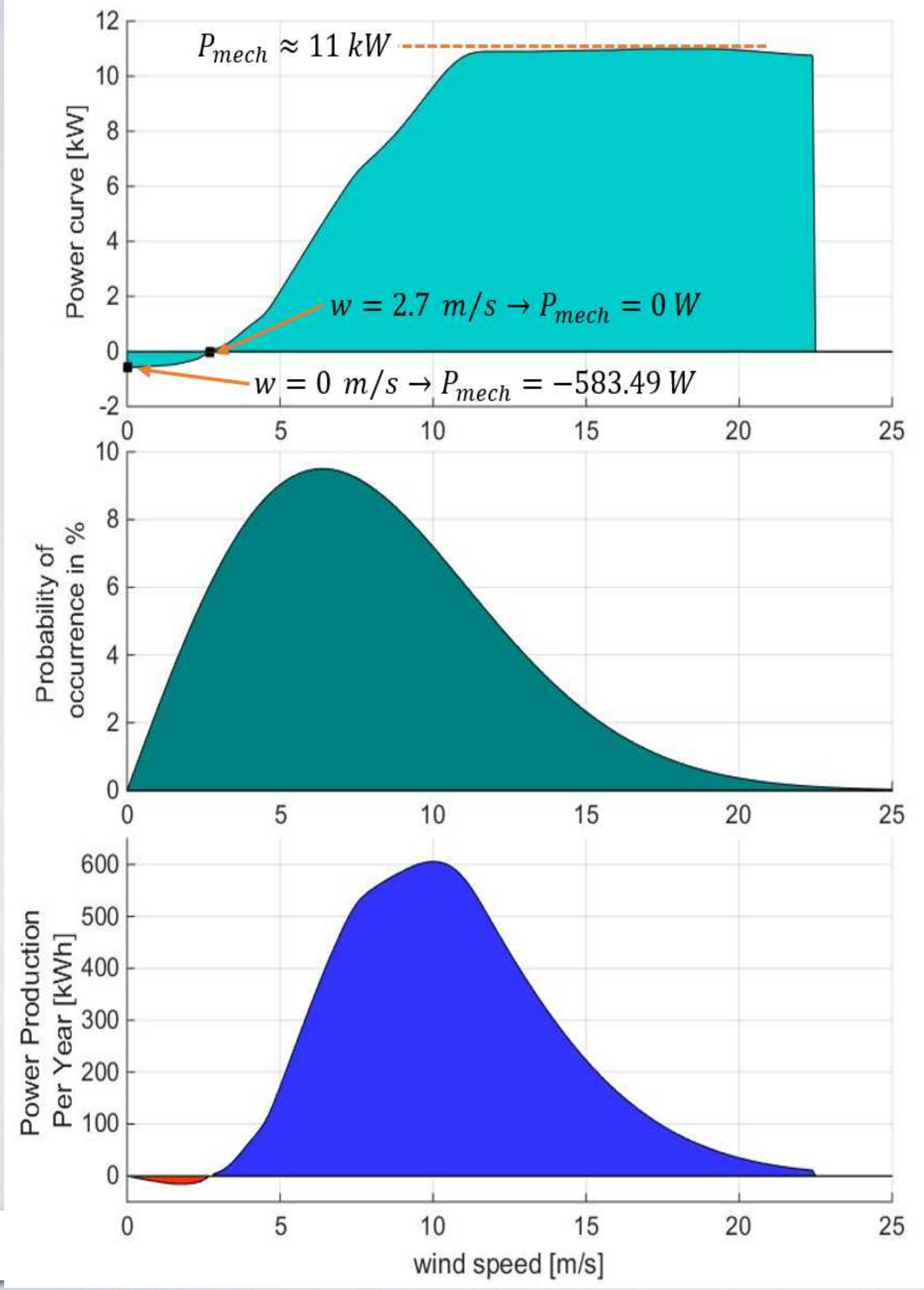
by Giovanni Licitra and Greg Horn (using CasADi, ipopt, 150 collocation intervals)



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

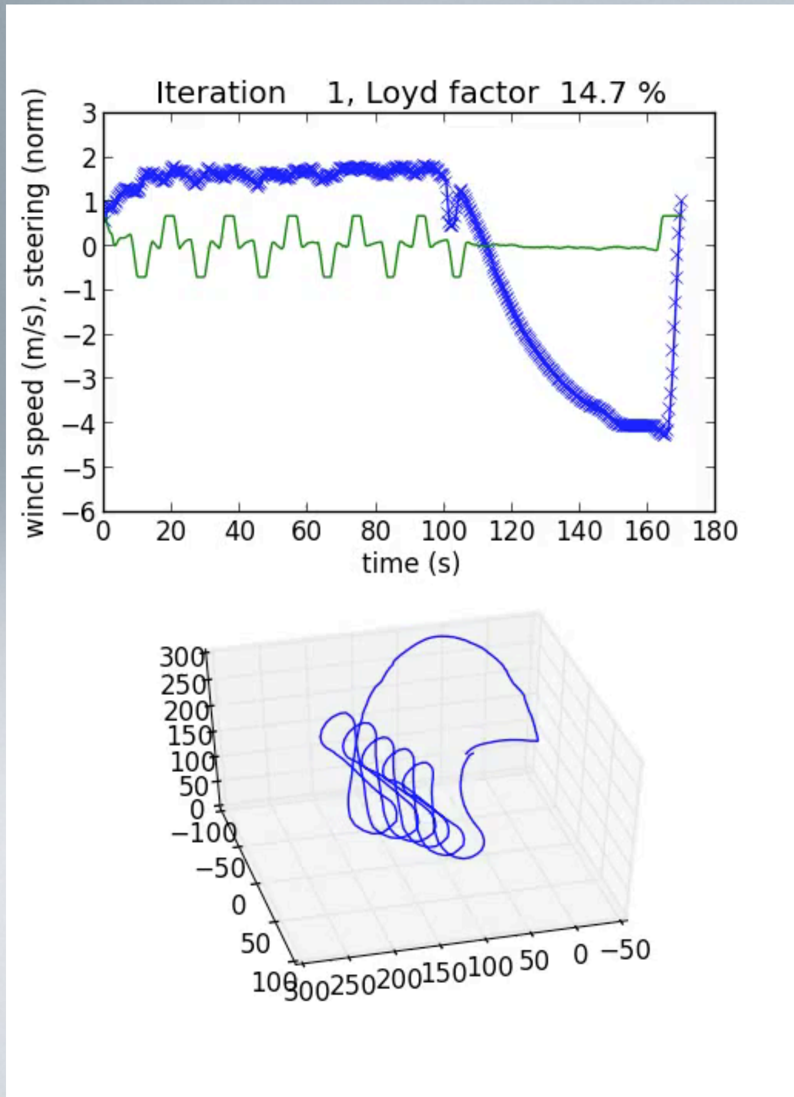
=

Contribution to yearly production

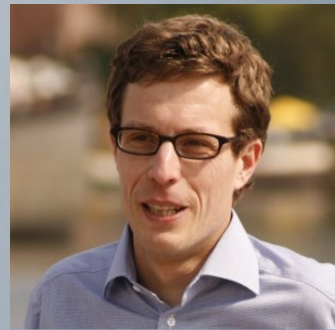
[study with 5.5m wing span plane]
Blue: 52,27 MWh, red 0,27 MWh.
Average power: 6 kW (tether drag)

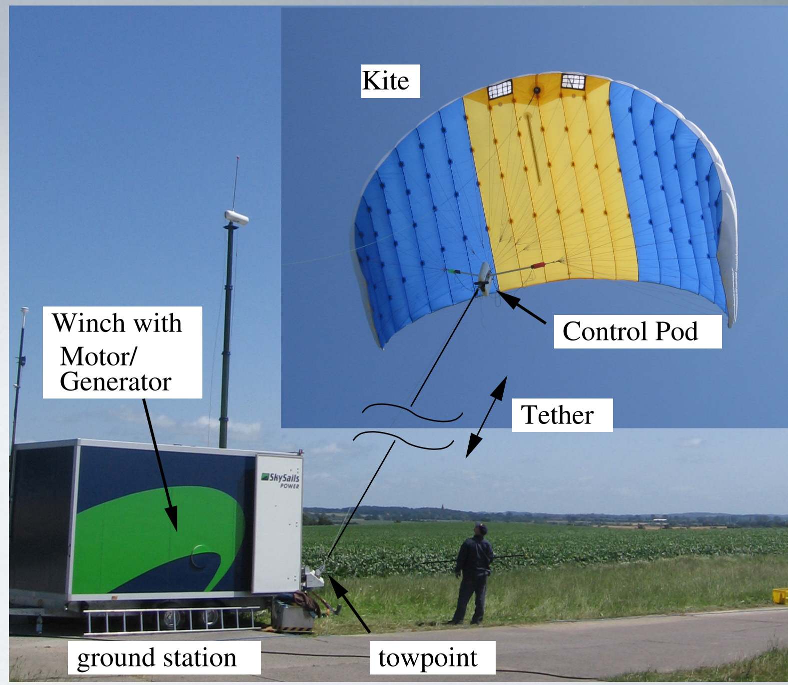
Optimization of SkySails' electricity generating orbits

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



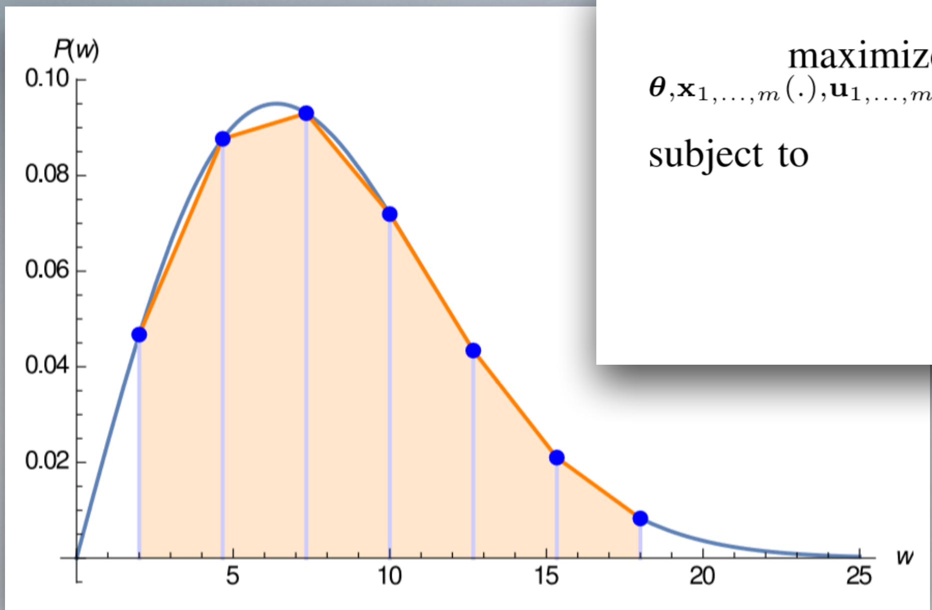


Small–Scale Functional Model (50kW peak power)

Makani power: yearly power output optimisation

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

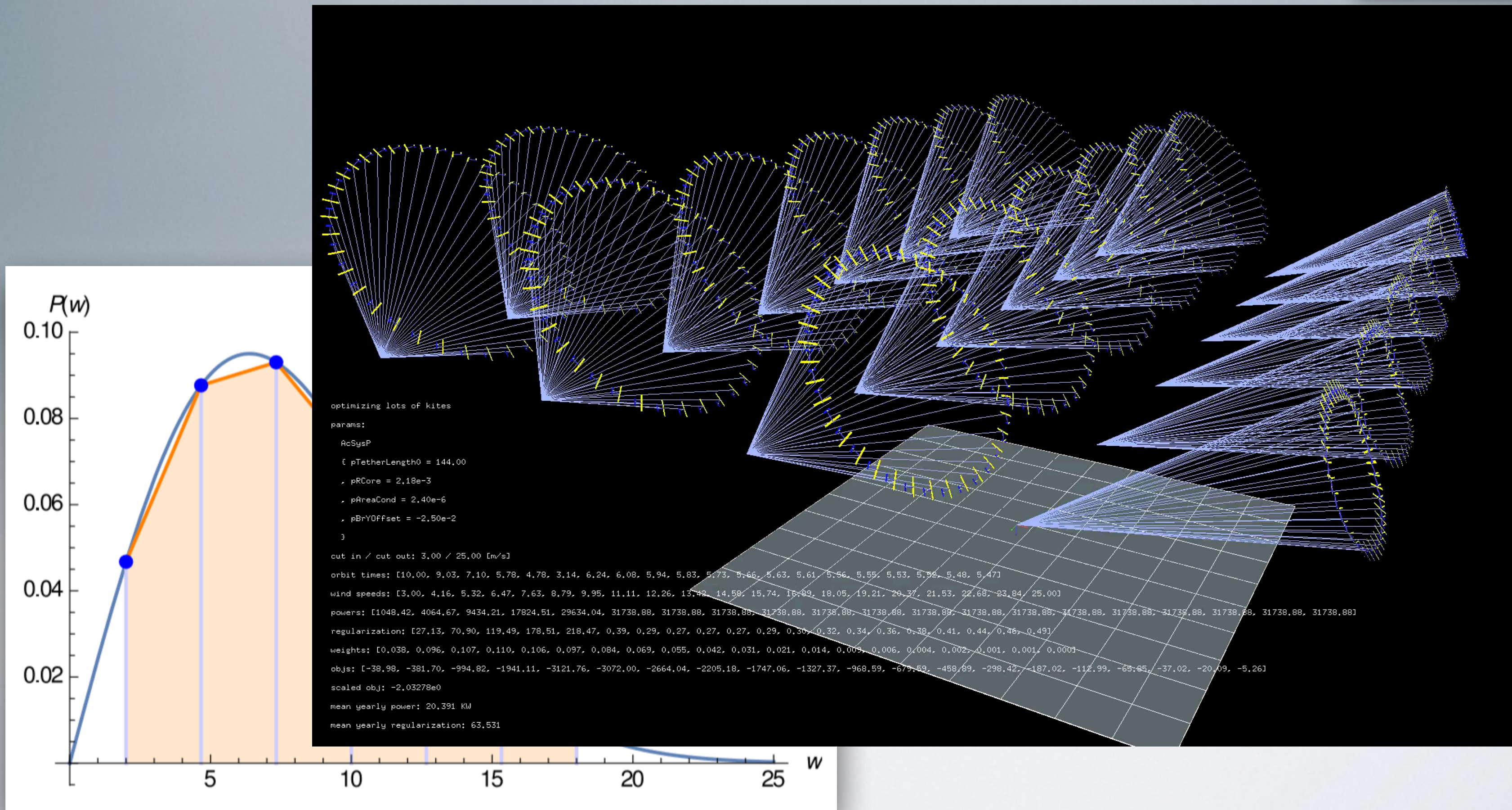
Multiple Setpoint Optimization: optimise fixed parameters (tether length and thickness, generator size) together with adaptable periodic control trajectories for all wind speeds, weighted with their frequency in the wind histogram



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

Makani power: yearly power output optimisation

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



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- **Pumping with Electrical Generator Efficiency (Greg Horn, Jeroen Stuyts)**

Electrical efficiency influences pumping cycles significantly

IEEE TRANSACTIONS ON SUSTAINABLE ENERGY, VOL. 6, NO. 1, JANUARY 2015

Effect of the Electrical Energy Conversion on Optimal Cycles for Pumping Airborne Wind Energy

Jeroen Stuyts, *Student Member, IEEE*, Greg Horn, Wouter Vandermeulen, Johan Driesen, *Senior Member, IEEE*, and Moritz Diehl, *Member, IEEE*

Jeroen Stuyts (S'14) was born in Belgium, in 1990. He received the B.Sc. degree in mechanical engineering and M.Sc. degree in energy engineering from KU Leuven, Leuven, Belgium, in 2011 and 2013, respectively. He is currently pursuing the Ph.D. degree at KU Leuven.

His research interests include power electronics, drives, renewable energy sources, and the grid coupling thereof. Currently, he conducts research on high-power grid-friendly converters with fault ride-through capabilities in a distorted low-voltage grid.

Greg Horn was born in the United States, in 1985. He received the B.S. degree in physics from the University of California, Santa Cruz, CA, USA, and the M.S. degree in aeronautics and astronautics from Stanford University, Stanford, CA, USA, in 2009 and 2012, respectively. He is currently pursuing the Ph.D. degree in electrical engineering at KU Leuven, Leuven, Belgium.

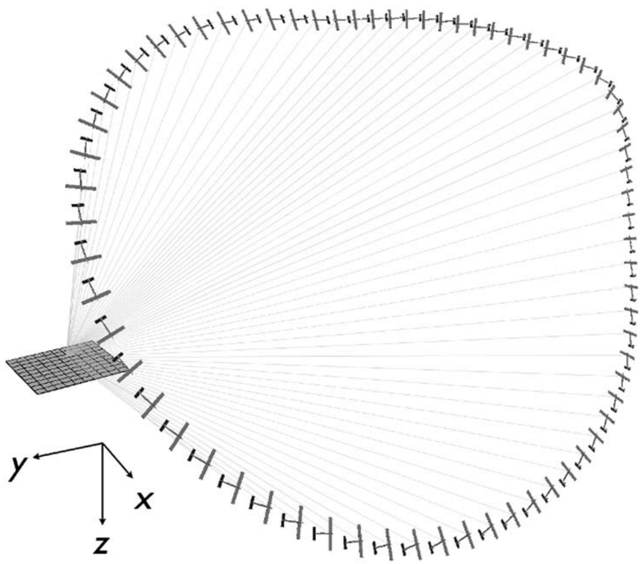


Fig. 7. Typical optimized power-generating trajectory.

Electrically vs. mechanically optimised orbits

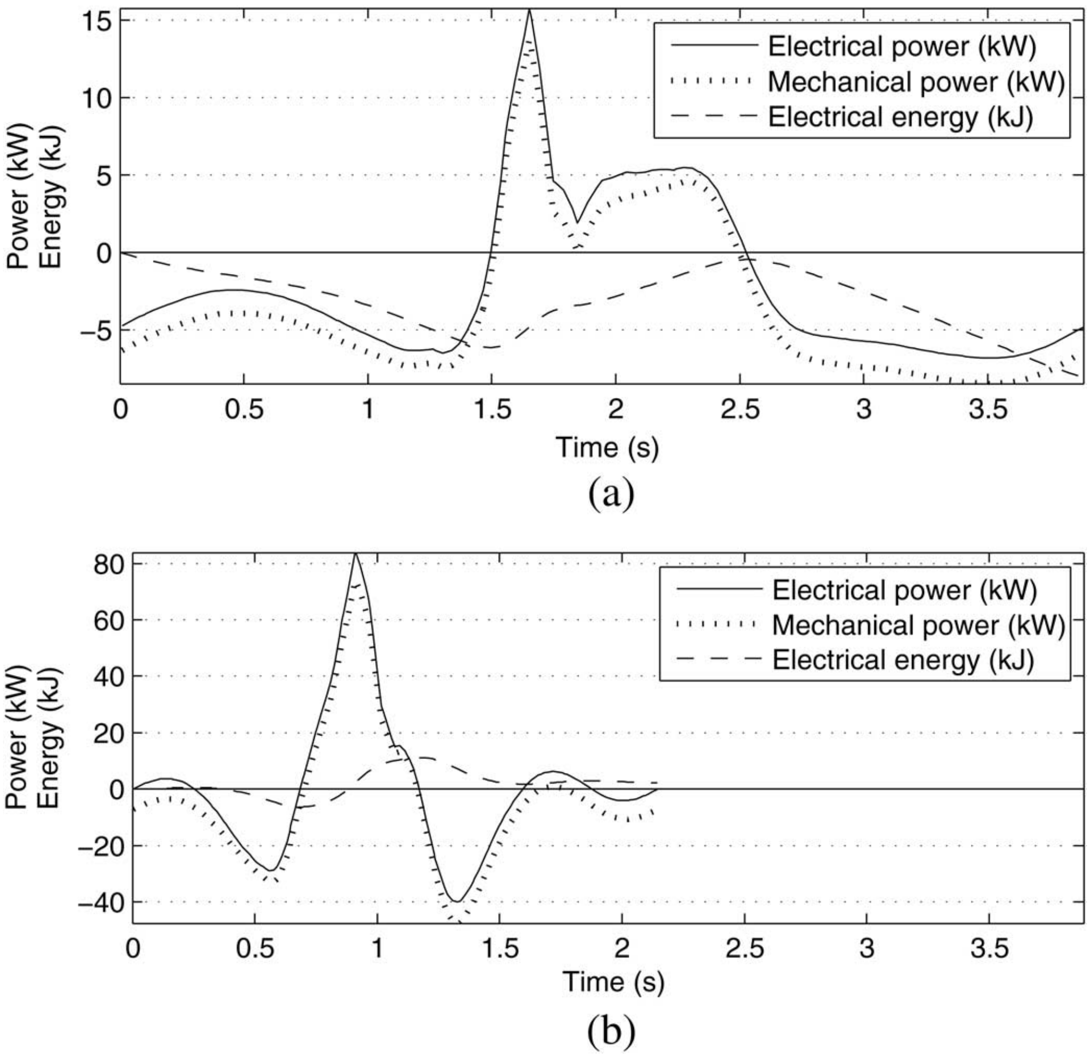


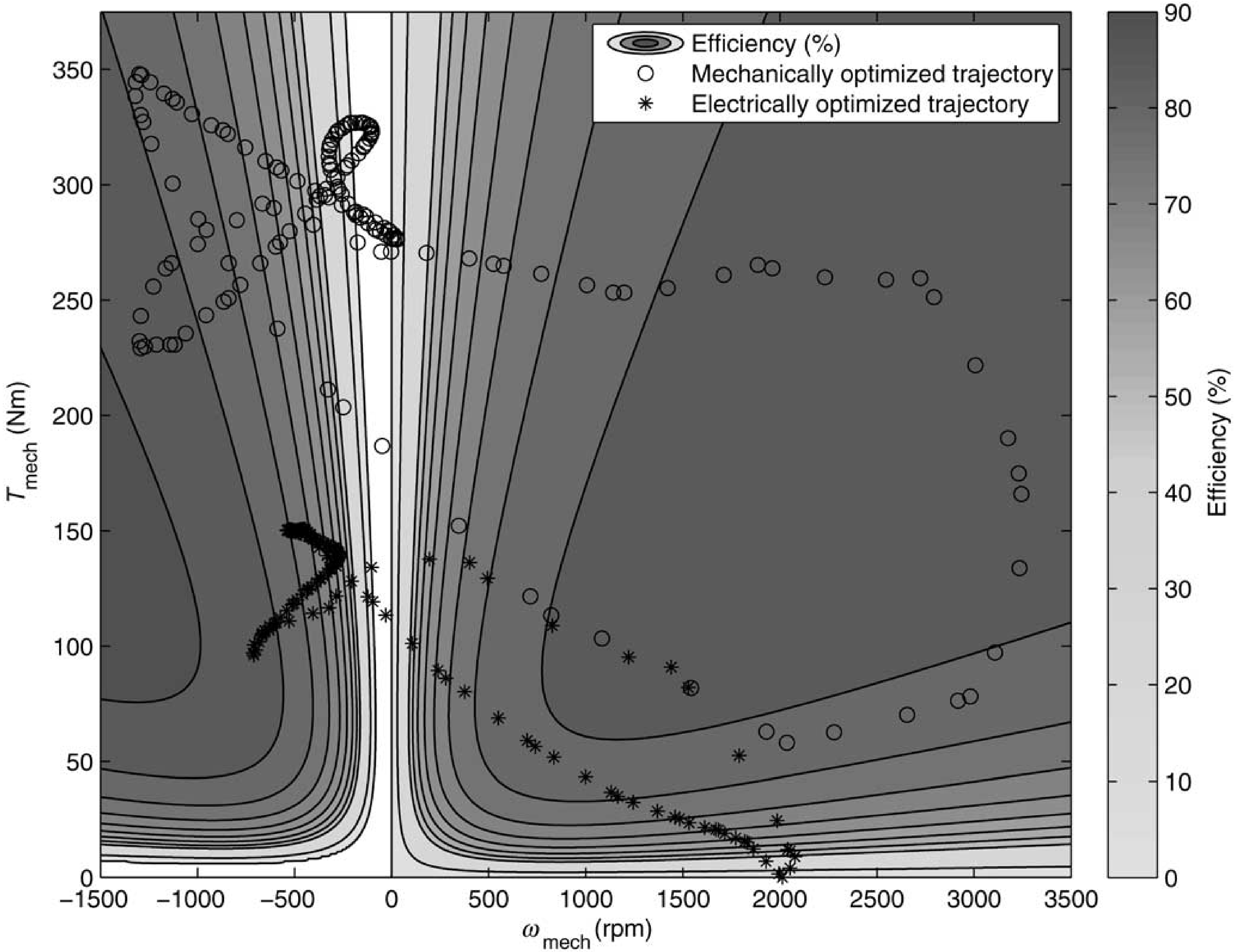
Fig. 10. Comparison in power flows between a mechanically and electrically optimized unconstrained cycle at 10 m/s. (a) Electrically optimized. (b) Mechanically optimized.

(negative= good)

- optimized electrical power

- optimized mechanical power

Electrically vs. mechanically optimised



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