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Design Sensitivities of Drag Power Kites

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1 Motivation

- only 1/10th of construction material of conventional plant, Fig. 1
- higher altitudes with stronger and more persistent winds
- therefore lowest cost of energy than any other technology
- Question: what does a good kite power plant design look like and what are the sensitivies of design decisions?
- basis: comprehensive multidisciplinary optimization model

2 Reference Scenario: Utility-Scale Biplane

All design parameters (e.g. tether length, tether voltage, tether resistance, kite aerodynamics) are optimized for reference, Fig. 2–3.

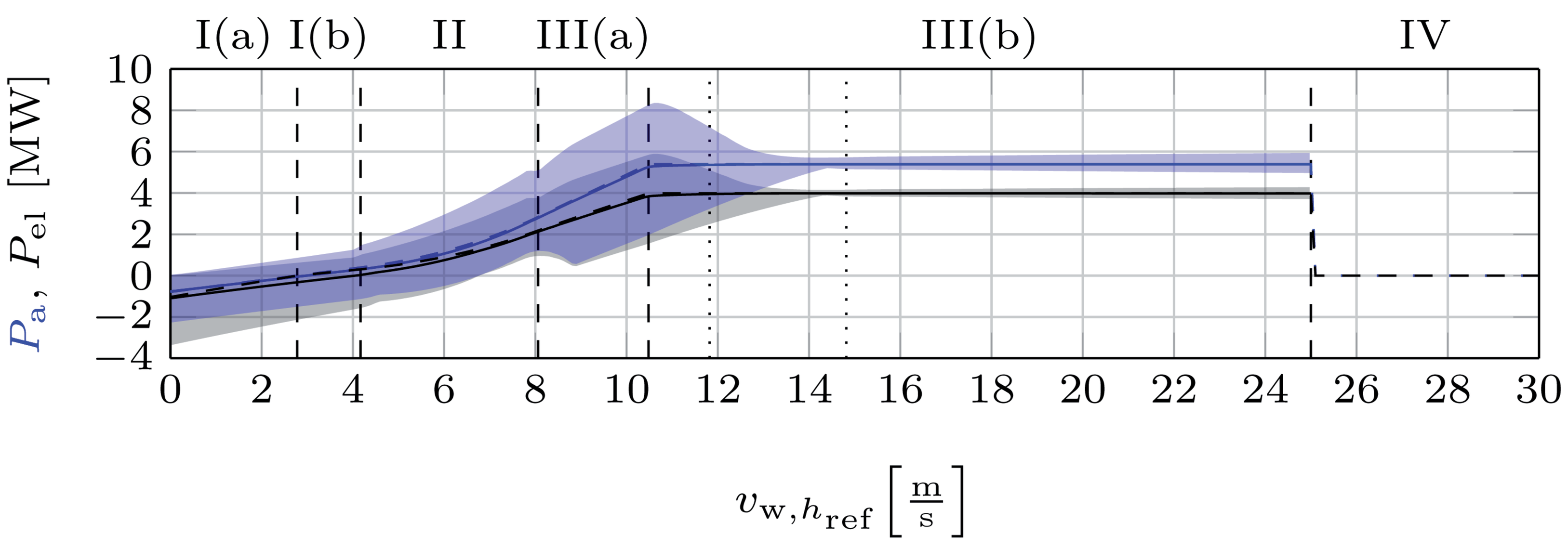

Fig. 2: Power curve of utility-scale biplane.

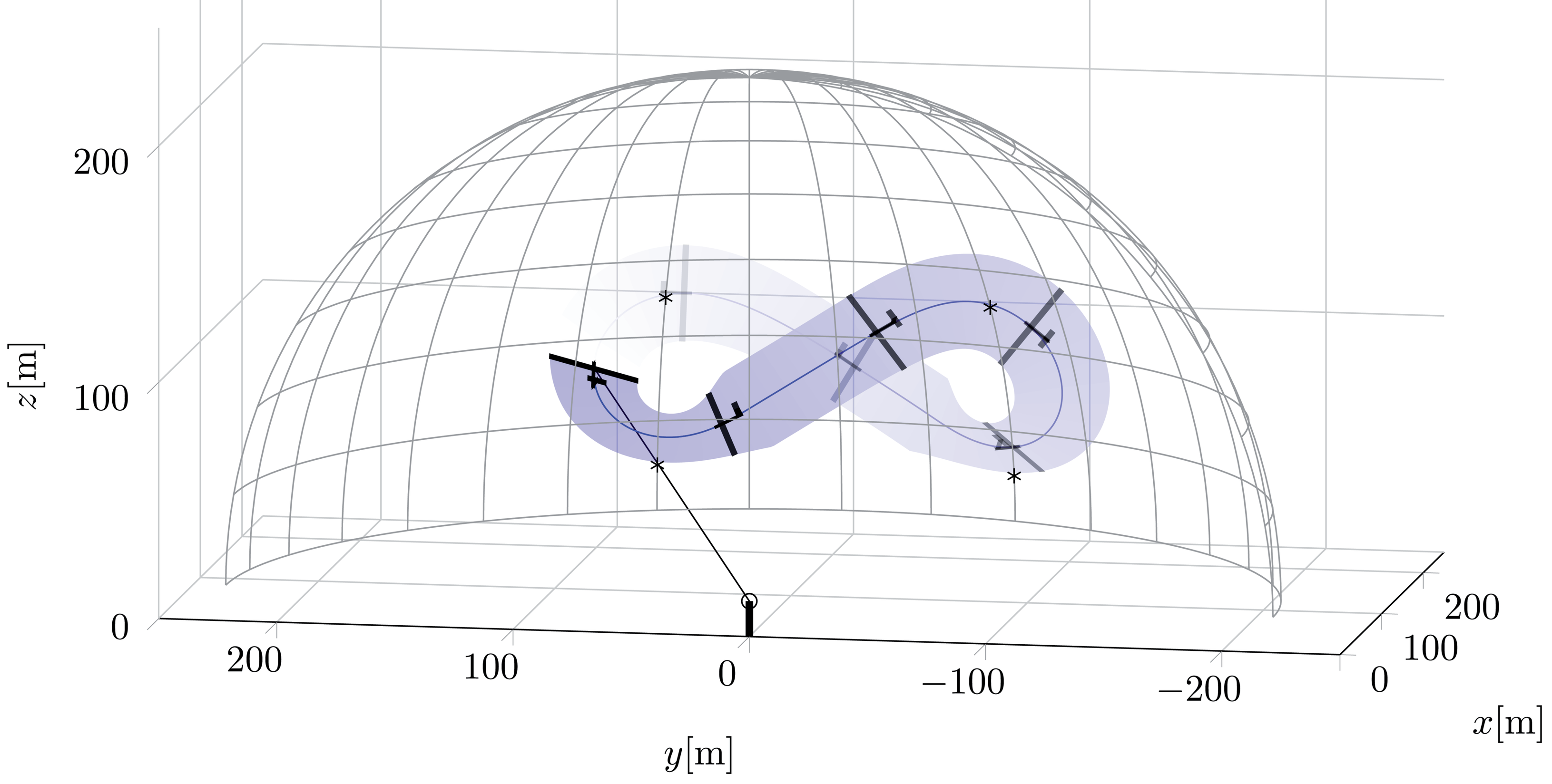

Fig. 3: Flight path of utility-scale biplane at 10 m/s wind speed.

3 Other Specific Systems

Optimization of other specific systems, including monoplane-, offshore-, small-scale-, and tiny-scale-variants. Results:

- biplane significantly outperforms monoplane
- offshore allows triple of maximum allowed costs and has double of nominal power
- capacity factor for optimized systems remains < 40 % ("capacity factor paradox")
- small-scale variants are economically interesting for self-consumption or off-grid use

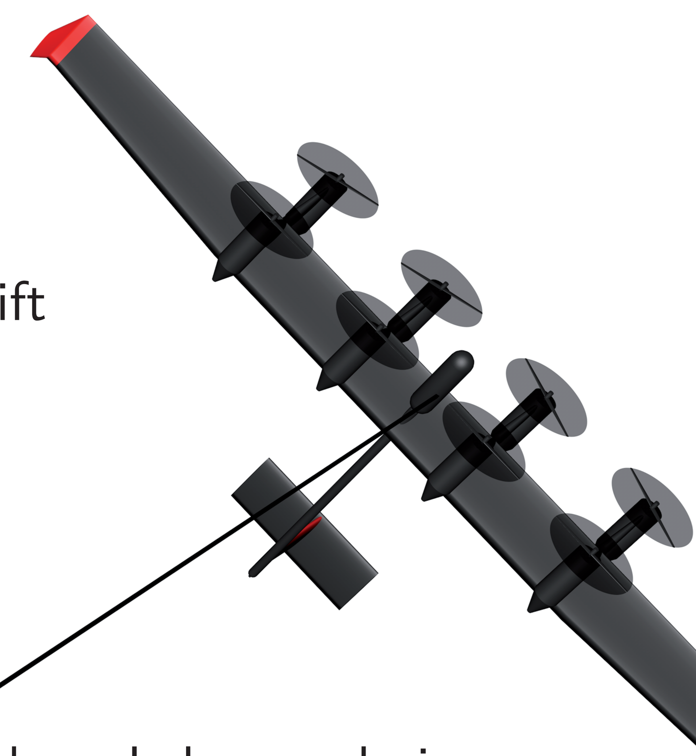

Fig. 1: Visualization of a "drag power" kite.

4 Structured Sensitivity Analyses

One parameter and/or its bounds are changed in a range of values, while all other design parameters are re-optimized, Fig. 4–5.

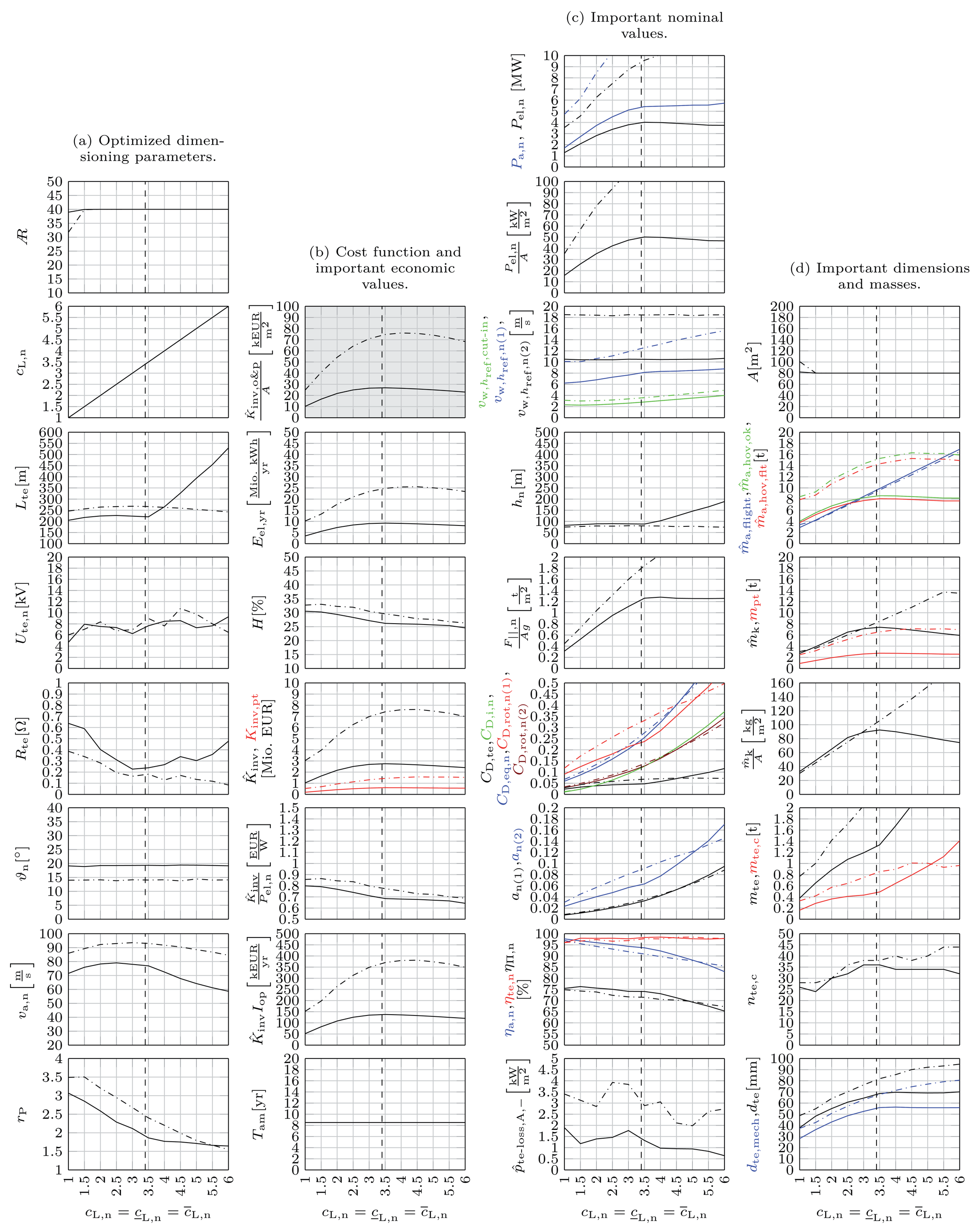

Fig. 5: Example: Sensitivity of nominal airfoil lift coefficient on all important results.

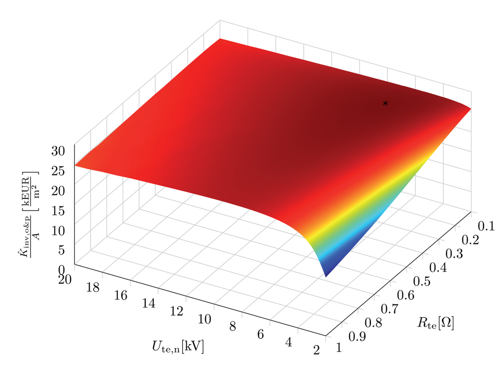

Fig. 4: Example: Optimization cost function in dependency of nominal tether voltage and tether resistance (tether conductor cross section area), showing a surprisingly flat optimum.

5 Conclusions

- economic and aerodynamic parameters (especially a high lift coefficient) are most important, tether parameters are rather insensitive, Tab. 1
- enormous figures of merit achievable, e.g. power density may exceed 100 kW/m²
- knowledge on design sensitivities can be of high value for a kite development team, as investment- and design decisions can be well-substantiated

Tab. 1: Determined sensitivities on important results for the utility-scale biplane expressed qualitatively.

Parameter	Sensitivity on $\hat{K}_{inv,o\&p}/A$	Sensitivity on $P_{el,n}$	Sensitivity on $\hat{m}_{a,flight}$	Sensitivity on $\hat{m}_{a,hov,flt}$
Environmental parameters for considered installation site.				
ρ	moderate	moderate	moderate	moderate
z_0	low	low	moderate	low
λ	low	high	moderate	high
μ	high	high	high	high
Economic parameters for targeted market.				
k_{LCOE}	high	moderate	moderate	moderate
I	high	moderate	low	moderate
T	high	moderate	low	low
I_{op}	high	moderate	low	low
Kite aerodynamics parameters.				
b	high	high	high	high
Æ	high	moderate	high	high
n_{mw}	high	high	high	high
$c_{D,2}$	high	high	high	high
$c_{L,n} = \underline{c}_{L,n} = \overline{c}_{L,n}$	high	high	high	high
e	high	high	high	high
$C_{D,k,o}$	high	moderate	moderate	moderate
Rotor parameters.				
n_{rot}	low	low	low	moderate
r_{rot}	moderate	moderate	low	high
$\eta_{rot,+}$	moderate	moderate	low	low
Tether parameters.				
$U_{te,n} = \underline{U}_{te,n} = \overline{U}_{te,n}$	low	low	low	low
$c_{D,te}$	high	high	low	moderate
$n_{te,c}$	low	low	low	low
tether materials	low	low	low	low
$w_{te,c,j}$	low	low	low	low
$S_{te,mech}$	low	low	low	low
$S_{te,ins}$	low	low	low	low
$f_{te,c,w}$	low	low	low	low
Powertrain subsystems parameters.				
k_{pt}	high	high	low	moderate
$S_{hov,flt}$	low	low	low	high
Ground station parameters and flight trajectory parameters.				
h_{to}	moderate	moderate	low	moderate
φ_n	moderate	moderate	low	low
Power curve "shaping" parameters.				
$v_{a,min}$	low	low	high	low
$v_{a,n}$	moderate	high	moderate	moderate
$r_P = \underline{r}_P = \overline{r}_P$	low	moderate	moderate	low
$v_{w,h_{ref},cut\text{-}out}$ (onshore)	low	low	low	low
Result bounds.				
$\overline{\omega}_n$	low	low	moderate	low
$\overline{h}_n$	low	low	moderate	low
$\overline{F_{\|\|,n}/(Ag)}$	high	high	high	high
$\underline{\hat{p}}_{te\text{-}loss,A,-}$	low	low	low	low

Further Reading:
[1] M. L. Loyd. "Crosswind kite power (for large-scale wind power production)". In: Journal of Energy 4.3 (May 1, 1980), pp. 106–111. ISSN: 0146-0412. DOI: 10.2514/3.48021. URL: https://arc.aiaa.org/doi/10.2514/3.48021 (visited on Apr. 19, 2018).
[2] X Development LLC. "Makani". URL: https://x.company/makani/ (visited on Apr. 19, 2018).
[3] F. Bauer, R. M. Kennel, C. M. Hackl, F. Campagnolo, M. Patt, and R. Schmehl. "Drag power kite with very high lift coefficient". In: Renewable Energy (Elsevier) 118.Supplement C (2018), pp. 290–305. ISSN: 0960-1481. DOI: 10.1016/j.renene.2017.10.073. URL: http://www.sciencedirect.com/science/article/pii/S0960148117310285 (visited on Apr. 19, 2018).
[4] F. Bauer, R. M. Kennel, C. M. Hackl, F. Campagnolo, M. Patt, and R. Schmehl. "Power Curve and Design Optimization of Drag Power Kites". In: Book of Abstracts of the Airborne Wind Energy Conference 2017. Ed. by Moriz Diehl, Rachel Leuthold, and Roland Schmehl. Freiburg, Germany: Albert Ludwigs University of Freiburg and Delft University of Technology, 2017, pp. 72–73. ISBN: 978-94-6186-846-6. DOI: 10.4233/uuid:4c361ef1-d2d2-4d14-9868-16541f60edc7. Conference video recording available from: www.awec2017.com (visited on Apr. 19, 2018).
[5] F. Bauer. "Multidisciplinary Optimization of Drag Power Kites". Dissertation. Technical University of Munich. Planned publication in 2018.