Vertical wind farms based on multi-wing airborne wind energy systems

Jochem De Schutter, Jakob Harzer, Moritz Diehl
University of Freiburg

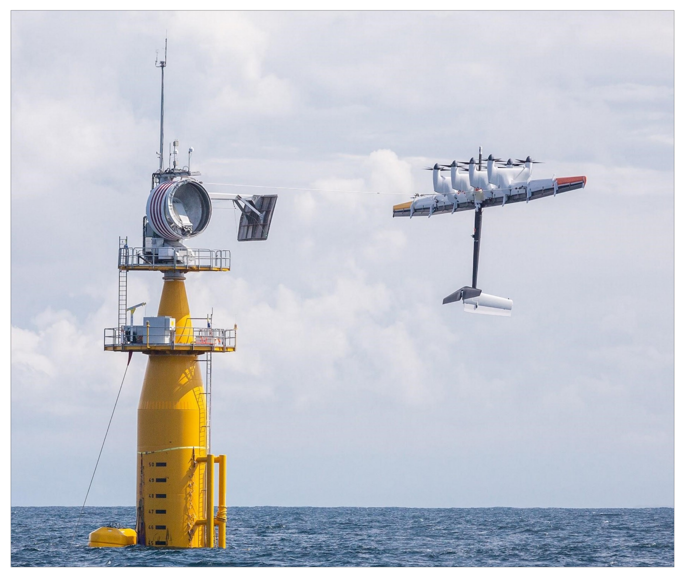
Problem statement

Harvesting wind "horizontally" leads to low power density (PD) due to wake interaction.

Courtesy by Bel Air Aviation

Airborne wind energy (AWE)

- idea: replace wind turbine rotor tips with tethered wind drones
- reach higher altitudes with stronger, more persistent winds at a fraction of the material cost
- electricity can be generated by a generator on the ground, driven by periodic reeling of the tether
- largest real-world prototype has wing span of 26 m



Courtesy by Makani Power

Vertical wind farms based on airborne wind energy dramatically reduce land usage compared to conventional wind power.

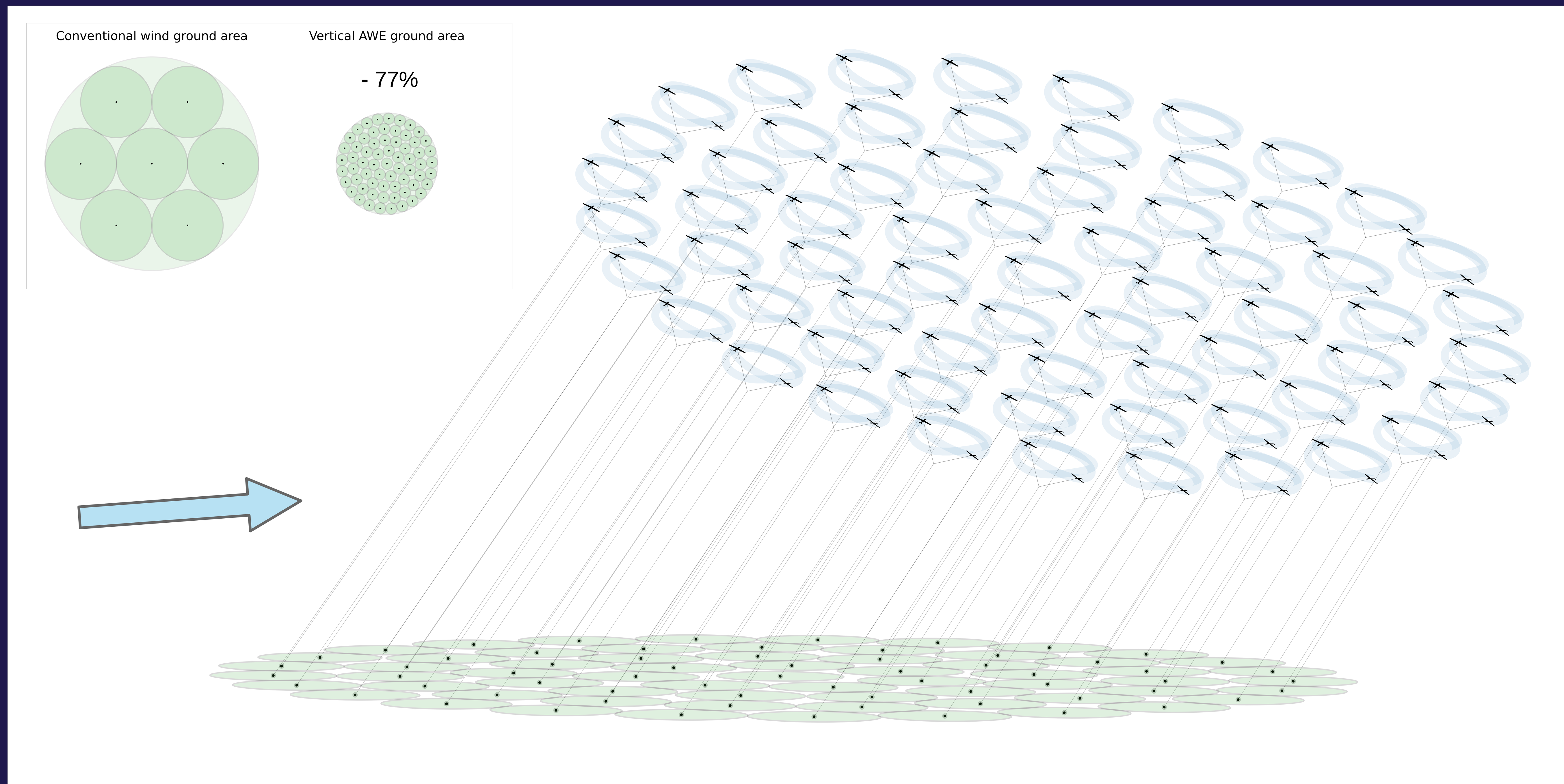


Fig.: 20 MW vertical wind farm with dual-wing AWE systems flying PD-optimal trajectories @ v_{wind} = 7 m/s

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Vertical wind farms

- AWE systems drastically reduce material costs and increase the capacity factor. Can they also improve the attainable PD?
- "Vertical" AWE farms avoid wake interaction, allowing high packing densities.
- BUT: dual-wing systems needed, which can operate at arbitrary altitude.

Flight trajectory optimization

- system model with 6DOF aircraft dynamics, flight envelope and averaged wake
- assign operating cylinder with corresponding ground area
- simultaneously optimize cylinder radius, elevation, flight trajectory and secondary tether lengths for optimal PD:

$$\begin{aligned} \underset{x(\cdot),u(\cdot),\theta,T}{\text{minimize}} \quad & -\frac{1}{T}\int_0^T \frac{P(t)}{\pi R^2}\mathrm{d}t \\ \text{subject to} \quad & F(\dot{x}(t),x(t),u(t),\theta)=0,\ \forall t\in[0,T], \\ & h(x(t),u(t),\theta)\geq 0,\ \forall t\in[0,T], \\ & x(0)-x(T)=0 \end{aligned}$$

Results

@7 m/s wind speed	**Conventional wind**	**Vertical AWE**
Nominal power	20 MW	20 MW
PD	2.6 MW/km^2	11.7 MW/km^2
Number of units	7	65
Unit capacity	2.8 MW	308 kW
Unit size	86 m rotor blade	26 m wing span
Farm ground area	7.6 km^2	1.7 km^2 **(- 77%)**

Literature

J. De Schutter, J. Harzer, M. Diehl, *Vertical Airborne Wind Energy Farms with High Power Density per Ground Area based on Multi-Aircraft Systems*, European Journal of Control, Vol. 74 (2023).