Five small vertical-axis turbines instead of one: designing a 5 × 1.5 kW cluster for a smart home on a digital-twin platform

TechUPGRADE Digital Twin Platform

TechUPGRADE technical report TU-TR-2026-004 (tenant `vawt`)

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Preprint: 5/8 requirements met, 2 partial

Abstract

A client who had a 5 kW vertical-axis turbine designed (VAWT-5, TU-TR-2026-003) asked whether five small vertical-axis turbines on lower towers could give the house the same yearly energy. We designed that cluster, VAWT-1×5, on the TechUPGRADE platform with the same site, wind data, battery and inverter: rotor-centre heights of 10, 12 and 18 m were compared, and the client chose 12 m with bought 1.5 kW generators and 48 V wind charge controllers. Each unit has an H-rotor of 1.15 m radius and 4.11 m blades, sized with the power coefficient taken 15 % below the calibrated model (0.239). At 248 rpm the blade-passing frequency sweeps through the shaft's own mode and no practical shaft lifts it out of the operating range, so the controller skips 98–130 rpm, which costs 9 kWh a year. Two independent wake models over ten years of hourly wind directions put the five units in a straight line on bearing 135°, 13.8 m apart; they agree on the layout and within 0.5 % on the energy. At the battery the cluster delivers 6,984 ± 607 kWh a year (Jensen wakes; 6,947 with Gaussian wakes; mean ± 95 % confidence interval over ten years), against VAWT-5's 7,185; year by year, in the same weather, the cluster is 201 ± 106 kWh short. It needs 1.3 t of tower steel instead of 2.4 t, more concrete, and five of everything to maintain, but every drivetrain part can be bought. The design (12 drawing sheets, the electrical system, a 124-part 3D model per unit) is on the platform as a 3D board, a Control Board diagram and a state machine. It is preliminary: nothing has been built or measured.

1 The question and how it was answered

The client set three rules: the five units together must match VAWT-5's yearly energy (7,185 kWh, ten years of hourly Varna wind); rotor centres at 10, 12 and 18 m are compared; and the generators and charge controllers are catalogue products, not designed. The house, its 14.4 kWh $LiFePO_4$ battery and its hybrid inverter stay as in VAWT-5, and the axis is vertical everywhere. The work followed the platform's phases: sizing (P1), the client's decision (P2), one unit in detail (P3: rotor, structure, joints, drawings, 3D), the cluster (P4: layout and wakes, electrics), with the controller (P5) and the live twin (P6) still to come. Every number in this report is produced by a script in the repository; a changed input re-issues the drawings, the diagrams and this report.

2 Sizing: three heights

Rotor proportions were kept from VAWT-5 (blade length 1.79 × diameter, solidity 0.36, three NACA0021 blades). The power coefficient comes from VAWT-5's double-multiple-streamtube model, calibrated on the measured Uppsala 12 kW H-rotor [2] (calibration factor 0.688), evaluated at the small rotor's Reynolds number (2.7×10^5 at rated) and then taken *15 % lower*, because measured small H-rotors often fall short of the models. With that prudent value every height reaches the energy (Fig. 1); 10 m puts the rotors at the roof and in the house's wake, 18 m needs more tower steel than VAWT-5's single tower. The client chose 12 m.

3 One unit

Rotor. Radius 1.15 m, blades 4.11 m of chord 137 mm, struts NACA0018 at the blades' Bessel points; rated 1,500 W at 10.85 m/s and 248 rpm (68 N m); overspeed trip 297 rpm. **Structure.** A free-standing, tiltable S355 tube of 219.1 → 168.3 × 6.3 mm (255 kg) carries a 139.7 × 8 mm shaft on a d70 journal and two 22214 E bearings. The first modes are 0.91 Hz (tower) and 5.63 Hz (shaft and rotor), own beam model; CalculiX on the stepped model gives 0.91 and 5.68 Hz. The finding that shaped the unit: at about 250 rpm the rotor's 1P and 3P ranges overlap and the shaft-rotor mode would

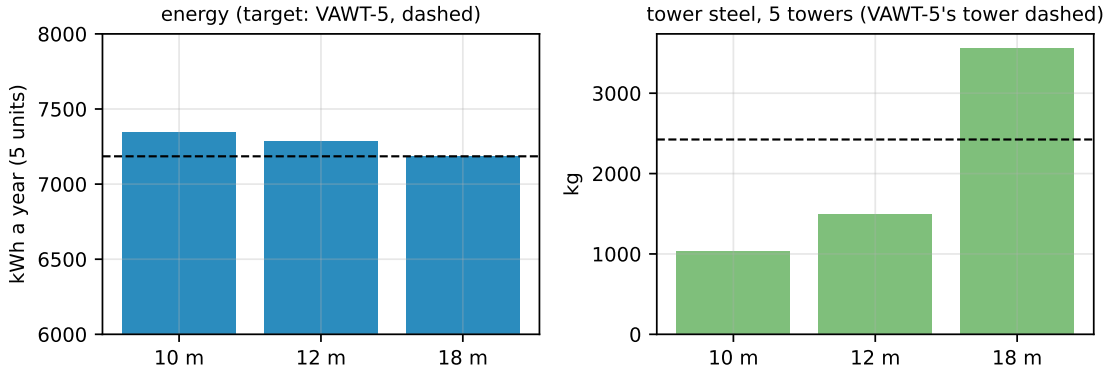


Figure 1: Five 1.5 kW units at three rotor-centre heights, power coefficient 15 % below the model: yearly energy and the five towers' steel. Dashed: VAWT-5.

have to exceed 14 Hz to stay above 3P at rated speed, which no practical shaft achieves. VAWT-5's frequency rule was therefore replaced by an energy cost: the controller does not dwell where a mode meets 1P or 3P. The design with the least energy lost keeps one band, 98–130 rpm (3P), crossed quickly: 8.5 kWh a year. The tower's own band (49–60 rpm) lies below cut-in and costs nothing. **Joints and drawings.** Clamp bolts 4 x M8 A4-80 at 21 N m, struts M10 in double shear at 50 N m, tower flange 8 x M20 10.9 HV at 593 N m, anchors M20 at 404 N m; a 2.4 m gravity block (4.8 m^3) and a spring-applied brake of 494 N m on a 300 mm disc. Twelve sheets (VAWT1-100 to 300) and a bill of materials describe the unit (Fig. 2); the 3D model of 124 parts is built from the same constants (Fig. 3).

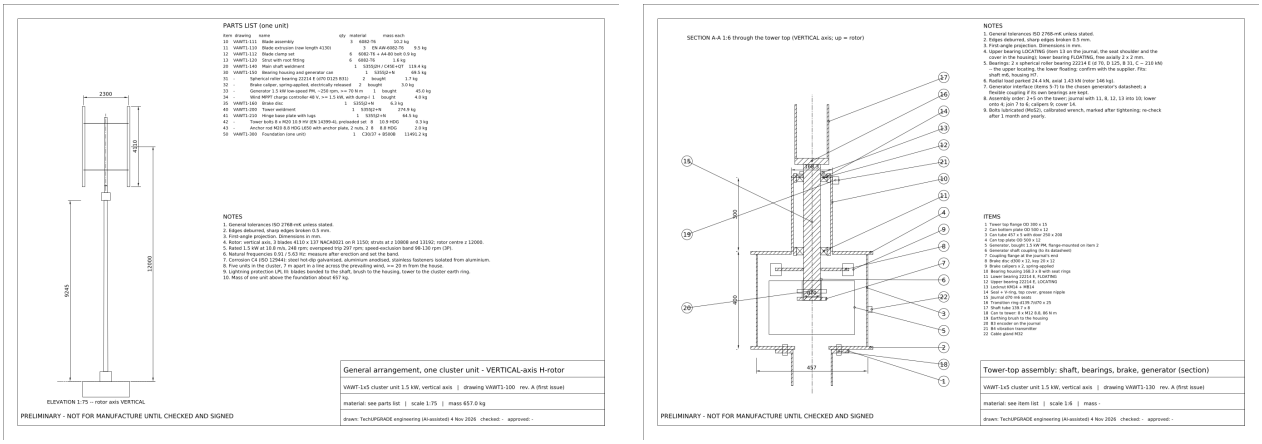


Figure 2: Two of the twelve sheets: the general arrangement (VAWT1-100) and the tower-top section (VAWT1-130). Preliminary until checked and signed.

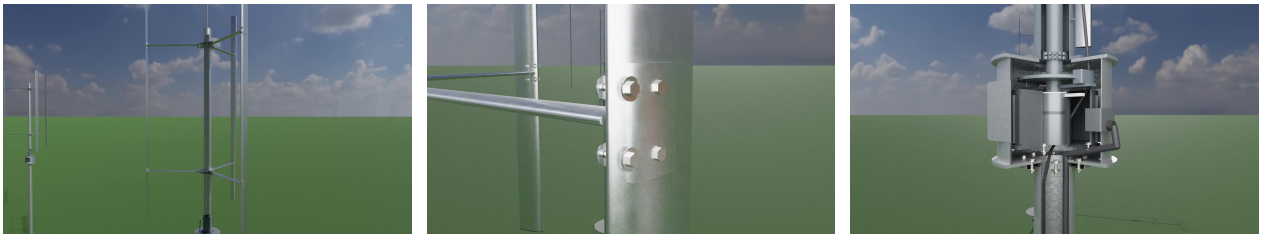


Figure 3: The unit's 3D model (Blender, Cycles): the rotor, the strut-to-blade clamp, the tower top cut open (shaft, bearings, brake, generator).

4 The cluster: layout and wakes

Five rotors in a line shade each other when the wind blows along it. We used ten years of hourly ERA5 wind directions [3] (N 19 %, NW 17 %, W 15 %, NE 14 %) and two independent wake models: Jensen's top-hat wake [4, 5] (growth

k = 0.075, thrust coefficient 0.7) and the Gaussian wake of Bastankhah and Porté-Agel [6] ($k^* = 0.47k$), both on an equivalent circular rotor and combined by the sum of squares. Both put the line on bearing 135° (NW–SE), at every spacing (Fig. 4). At 6 rotor diameters (13.8 m, a 55 m line) the wakes cost 3.2 % (Jensen) or 3.7 % (Gaussian); at 4 D, 5.5 % and 6.7 %; at 3 D, 8.3 %. A north–south line would lose twice as much, and a staggered line is worse here because the wind comes from every quarter. The design uses 6 D, with 4 D as the fallback for a shorter plot. Counter-rotating neighbours are reported to recover wakes faster in arrays of small VAWTs [7]; the rotors turn in opposite directions, but no credit is taken.

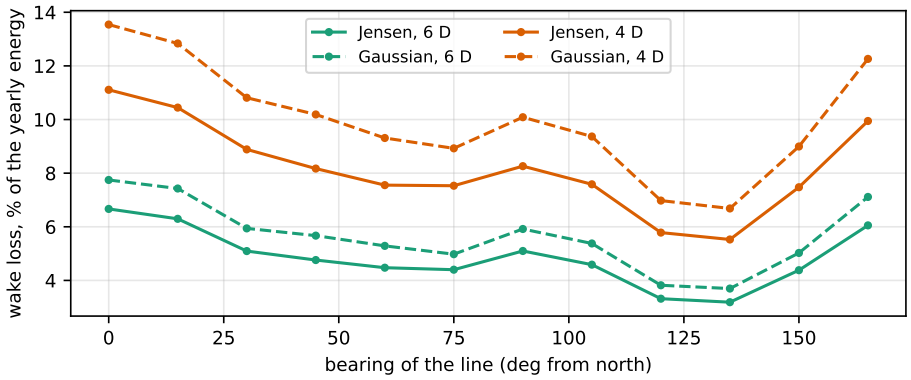


Figure 4: Wake loss against the line's bearing, both wake models, 4 and 6 rotor diameters apart.

5 Electrics

Each generator has its own cable to its own 48 V wind MPPT controller in the house's plant room; all five feed one busbar with VAWT-5's battery and inverter (Fig. 5). The generator's voltage is set by the controller's input limit: its open-circuit voltage at 1.25 × the overspeed trip must stay below it. A 150 V controller would need cables above 25 mm^2; with a 250 V controller the generator is 113 V line-to-line at rated (152 V rectified) and the five cables are 10–16 mm^2 (133 kg of copper, 80 kWh a year lost). Each unit has a normally-closed brake contactor that shorts the generator on loss of control power, a stop command or an over-voltage relay, independent of the controller, and a diversion load of 21.2 Ω for a full battery; the mechanical brake is the second, independent brake.

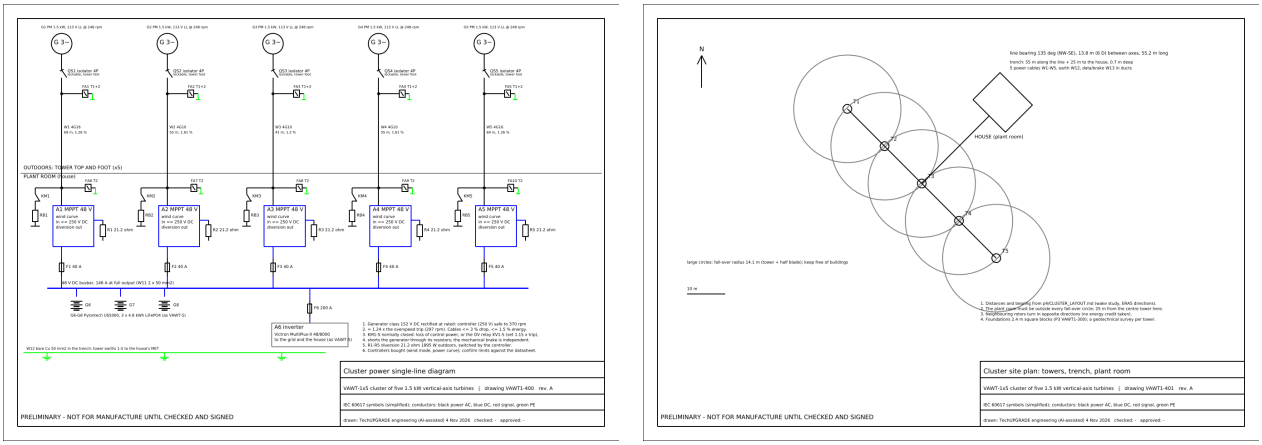


Figure 5: The cluster's single-line diagram (VAWT1-400) and the site plan with the trench (VAWT1-401).

6 On the platform

The cluster is a location of the tenant `vawt`, beside VAWT-5: a 3D board of the five units on their site, each of 124 parts with its drawing, material and mass, X-ray of the tower tops and the plant room, and an explode per unit (Fig. 6); a Control Board with the single-line diagram and 25 readings and controls; and the units' state machine (VAWT-5's controller states, which P5 will adapt to the unit). The readings stay empty until the cluster's twin (P6) runs.

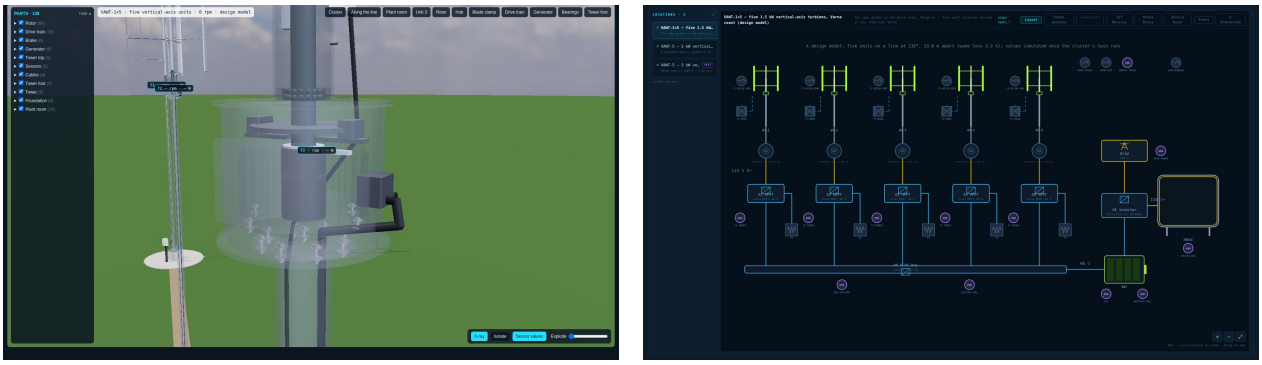


Figure 6: The platform: the 3D Cluster board (drive train under X-ray) and the Control Board.

7 Results: five small against one large

Fig. 7 and Table 1 compare the cluster with VAWT-5 year by year in the same weather. The cluster comes out 2.8 % short on average; the paired interval excludes zero, so the shortfall is real, although smaller than the year-to-year spread of either design. Blades about 3 % longer would close it. The prudent C_p dominates the uncertainty: a rotor that reaches the calibrated model would give the cluster about 16 % more. Against VAWT-5 the cluster needs less tower steel but more concrete (five small blocks instead of one), every drivetrain part can be bought instead of a custom 700 N m generator, one unit down still leaves 80 % of the output, and each unit is raised by a hand winch; in exchange there are five rotors, brakes, bearings, generators and controllers to install and maintain.

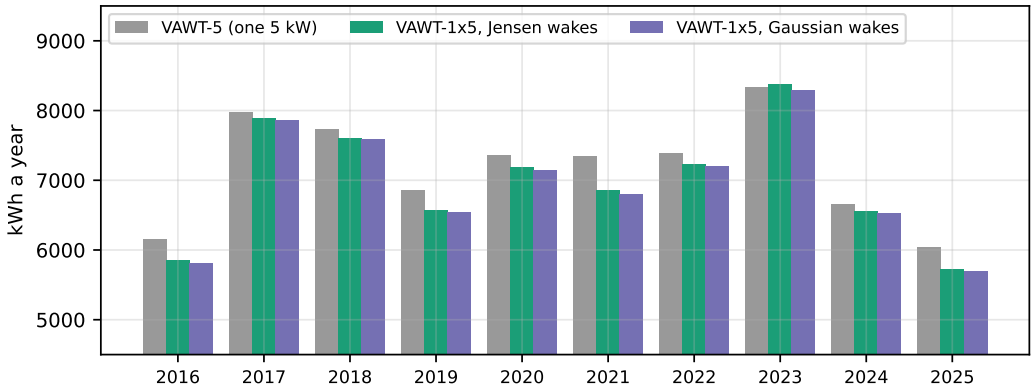


Figure 7: Yearly energy at the battery: VAWT-5 and the cluster with either wake model (2016–2025).

	kWh a year (mean ± 95 % CI, 10 years)	range
5 units, no wakes	7,294 ± 615	6,034–8,754
cluster, Jensen wakes	7,061 ± 613	5,791–8,466
cluster, Gaussian wakes	7,024 ± 608	5,762–8,388
cluster at the battery (Jensen; cables 1.1 %)	6,984 ± 607	5,728–8,373
VAWT-5 (TU-TR-2026-003)	7,185 ± 466	
paired difference, cluster − VAWT-5	-201 ± 106	-479 to 34
tower steel	1,273 kg (5 towers)	VAWT-5: 2,424 kg
foundation concrete	23.9 m^3 (5 blocks)	VAWT-5: 15.7 m^3

Table 1: The cluster against VAWT-5. Sensitivities: the Gaussian model's growth rate 0.05–0.10 gives 6,981–7,054 kWh; if the rotor reaches the calibrated model's C_p (0.280) instead of the design's 0.239, the five units give 8,428 kWh without wakes instead of 7,293.

8 Limitations

Nothing is built or measured. The rotor's power coefficient is a calibrated model taken 15 % lower; the wake models are published models for horizontal-axis turbines applied to small H-rotors without data; the house's and trees' shelter and

the added turbulence in the wakes (fatigue) are not modelled; the energy uses hourly wind, while VAWT-5's 10 s check reduced its energy by about 5 %, a check still to be repeated for the cluster. The bought generator and controller are specified by requirements (voltage, torque, input limit), not yet chosen from datasheets.

Contributions

- A like-for-like comparison of one 5 kW vertical-axis turbine with five 1.5 kW units for the same house, weather, battery and inverter, year by year with a paired confidence interval.
- The finding that a 1.5 kW H-rotor at about 250 rpm cannot keep its shaft mode above 3P, and an energy-based speed-exclusion rule in place of the frequency rule (9 kWh a year).
- A layout chosen with two independent wake models over ten years of wind directions, which agree on the layout.
- A generator voltage chosen from the bought controller's input limit, which keeps the five cables at 10–16 mm^2 (the 150 V class would need more than 25 mm^2).
- The whole design as platform objects: drawings, a 3D board, a Control Board diagram and a state machine, regenerated from the scripts.

Publication requirements

Every TechUPGRADE technical report is assessed against eight requirements for a publishable paper (reproducibility, baselines, validation, statistics, sensitivity, generalisation, contribution, independent review). This report is a **preprint**: 5 of 8 requirements are met and 2 partly; the open items are listed.

requirement	status	evidence
R1 Reproducibility	met	Every number from scripts in docs/projects/vawt-1kw-cluster (p1 cluster_sizing.py, p3 aero/structure/joints/drawings/cad, p4 cluster_layout.py and electrical.py) and this report's make_results.py; tools image tools/vawt-eng (pinned versions); data: ERA5 + Varna airport (sim-manager/antarctic_hut/data), ERA5 directions (p4); report: make_results.py, make_figures.py, gen_tex.py
R2 Baseline comparison	met	Wakes: Jensen top-hat and the Gaussian wake of Bastankhah & Porte-Agel (independent formulations) give the same layout and 0.5 % apart in energy; structure: own beam FE and CalculiX (within 1 %)
R3 Validation	partial	The rotor model is calibrated on the measured power coefficient of the Uppsala 12 kW H-rotor (Kjellin et al. 2011) and taken 15 % lower for the small rotor; the wake models are published models, not validated on VAWT arrays of this size *Open:* power curve and wake measurement on the first two prototype units
R4 Statistical analysis	met	The cluster's energy for each of ten weather years with both wake models, 95 % confidence intervals (t, 9 d.o.f.), and the paired year-by-year difference against VAWT-5
R5 Sensitivity analysis	met	Rotor-centre height 10/12/18 m; spacing 3-6 D; line bearing 0-165 deg; straight vs staggered; wake growth k and thrust Ct (both models); the rotor's Cp (model vs 15 % penalty); generator voltage class vs cable size
R6 Generalisation	partial	The rotor calibration (one measured rotor, Re about 1e6) is applied at Re 2.7e5 with a 15 % penalty, not tested there; the wake models are applied to small H-rotors at 6 D without data *Open:* prototype measurements (R3)
R7 Scientific contribution	met	Contributions section
R8 Independent review	missing	– *Open:* review by an independent wind-turbine engineer

References

[1] TechUPGRADE Digital Twin Platform, *Designing a 5 kW vertical-axis wind turbine for a smart home on a digital-twin platform*, technical report TU-TR-2026-003, 2026.

[2] J. Kjellin, F. Bülow, S. Eriksson, P. Deglaire, M. Leijon, H. Bernhoff, Power coefficient measurement on a 12 kW straight bladed vertical axis wind turbine, *Renewable Energy* 36 (2011) 3050–3053.

[3] H. Hersbach et al., The ERA5 global reanalysis, *Q. J. R. Meteorol. Soc.* 146 (2020) 1999–2049.

[4] N. O. Jensen, A note on wind generator interaction, Risø-M-2411, Risø National Laboratory, 1983.

[5] I. Katić, J. Højstrup, N. O. Jensen, A simple model for cluster efficiency, *EWEC'86*, Rome, 1986, 407–410.

[6] M. Bastankhah, F. Porté-Agel, A new analytical model for wind-turbine wakes, *Renewable Energy* 70 (2014) 116–123.

[7] J. O. Dabiri, Potential order-of-magnitude enhancement of wind farm power density via counter-rotating vertical-axis wind turbine arrays, *J. Renewable Sustainable Energy* 3 (2011) 043104.

[8] IEC 61400-2:2013, Wind turbines – Part 2: Small wind turbines.