Designing a 5 kW vertical-axis wind turbine for a smart home on a digital-twin platform: from the site's wind to a production package

TechUPGRADE Digital Twin Platform

TechUPGRADE technical report TU-TR-2026-003 (tenant `vawt`)

4 November 2026

Preprint: 6/8 requirements met, 1 partial

Abstract

We report the design of VAWT-5, a 5 kW *vertical-axis* H-rotor wind turbine with a 14.4 kWh battery and a hybrid inverter for a house on the Varna coast, carried out on the TechUPGRADE platform by an engineering manager (an AI agent), nine component-owner agents and the client, from the site's wind to drawings, two circuit boards and a controller specification, and a live digital twin. Ten years of the site's hourly wind (mean 4.03 m/s at the 18 m rotor centre) sized a rotor of 4.2 m × 7.5 m. Two independent rotor models, calibrated on the measured power coefficient of a 12 kW H-rotor (0.29), over-predicted it (0.42 and 0.34), so the design uses the measured value. The tower and shaft were sized by their natural frequencies, not by strength; the drawn masses were fed back into the structural model until it converged (1.26 and 6.76 Hz, own beam model and CalculiX within 1 %); a guyed tower was evaluated at the client's request and not adopted. The twin gives 7,185 ± 466 kWh a year (mean ± 95 % confidence interval over ten years) with hourly wind, and about 6,805 kWh with turbulence. A simulated gust showed that electrical braking alone lets the rotor run away (500 rpm); the controller therefore applies the mechanical brake (peak 124 rpm). The firmware was then written and tested against the plant model (95/95 unit checks, 8/8 software-in-the-loop scenarios, energy within 0.38 % of the electrical design); its tests changed the design twice: the dump load was halved to 12 Ω, and the speed band's upward crossing time was respecified. The image is built, signed and released in the platform's firmware library for state machine 1.1.0, which the turbine's connector runs. A detailed model of 135 parts (drive train, sensors, cables, the cabinet with the real boards) is the platform's inspectable 3D board, and the 15-sheet drawing set is issued for the prototype build. Of 42 requirements, 6 are met, 22 met by design and awaiting the prototype tests, 12 partly and 2 open. The package is preliminary: not for manufacture until checked and signed by qualified engineers.

1 The task and how it was organised

The client asked for a 5 kW vertical-axis wind turbine for smart homes, every part designed (mechanical, electrical, electronics, firmware), 2D and 3D views and a control board on the platform, development teams and component-owner agents where needed, and a package "detailed enough to send to a manufacturer". The client decided the rated power, the site (Varna coast), a hybrid battery-and-grid system, the rotor and tower option, what to buy (inverter, battery, generator) and, after the aerodynamics, the blade length; the client also insisted, twice, that the axis is vertical, which became requirement SYS-00. Nine component owners (rotor, drivetrain, tower, generator, power electronics, battery and inverter, controller, firmware, the platform's twin), each backed by an agent with its own documents, answer for their parts; software goes to the platform's local development team through owner proposals and an approval gate. Every calculation is a script in the repository; the drawings, boards and the twin read its results, so a changed number re-issues them.

2 The site and the requirements

The wind is ten years (2016–2025) of hourly ERA5 at Varna, corrected with the airport's station; the shear exponent from the data is 0.15, giving at 18 m a mean of 4.03 m/s (Weibull k 1.63, c 5.17 m/s). The site is less windy than first assumed, which is why the client chose the largest rotor on the tallest tower (Fig. 1). The requirements specification (42 requirements, v0.5) covers the system, performance, site (IEC 61400-2 class III, coastal corrosion C4), structure, electrics, controller and the platform.

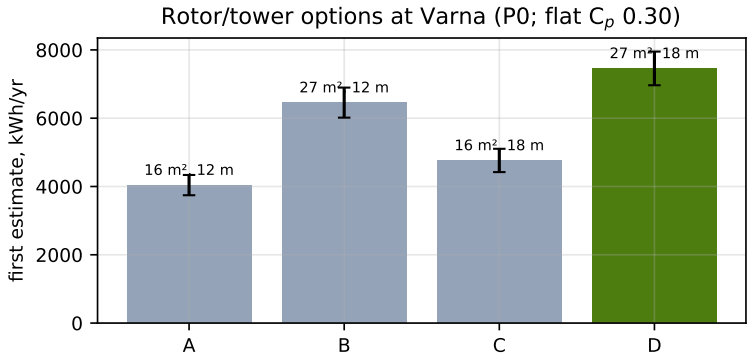


Figure 1: First energy estimates of the four options (flat C_p 0.30); the client chose D.

3 Rotor aerodynamics

Two independent models were written: a double-multiple streamtube model (DMST) with airfoil polars from NeuralFoil and a post-stall extension, dynamic stall, finite aspect ratio and strut drag; and Madsen's actuator-cylinder model. Both were run on the Uppsala 12 kW H-rotor (R 3 m, 5 m NACA0021 blades), whose power coefficient was measured: 0.29 at λ 3.3 [1]. Both over-predict (Fig. 2): DMST 0.421, the actuator cylinder 0.344. The validation also caught a factor-two error in our first streamtube width (it gave C_p 0.90). The design therefore uses the *measured* maximum 0.29 with the model's $C_p(\lambda)$ shape; chord 0.25 m (the Uppsala chord, solidity 0.36), λ_{opt} 2.5. With that value and an 86 % drivetrain, the chosen 6.4 m blade missed the energy requirement (6,058 kWh against 6,500); the client chose 7.5 m (Fig. 3): rated 5 kW at 10.1 m/s, 115 rpm, 481 N m.

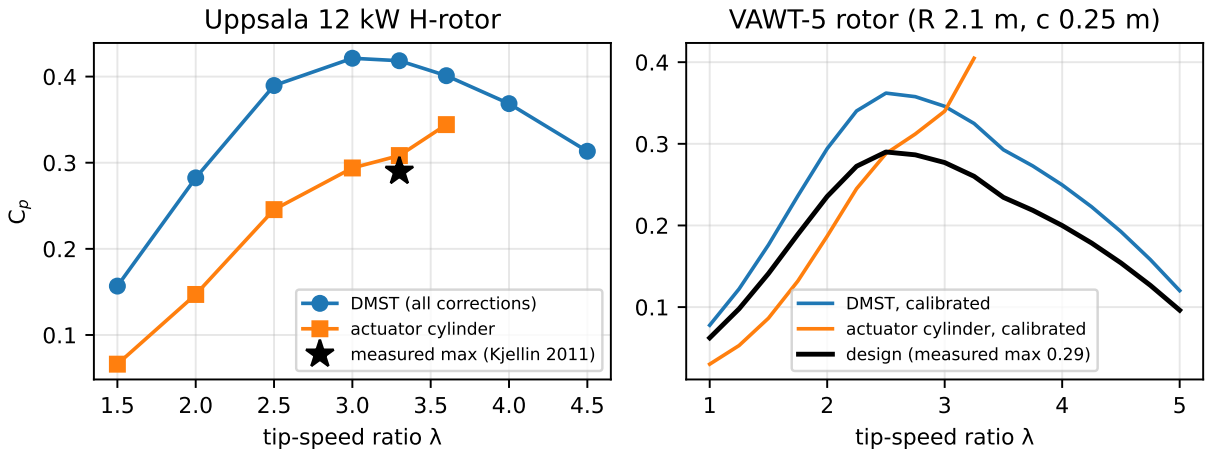


Figure 2: Left: the two models against the measured maximum of the Uppsala rotor. Right: VAWT-5's calibrated curves and the design curve.

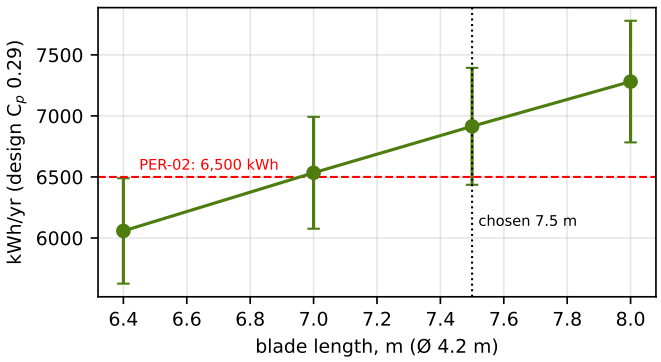


Figure 3: Energy against blade length with the measured C_p.

4 Structure, joints and drawings

Load cases written for the H-rotor (overspeed 1.3×, parked in the 50-year gust 52.5 m/s, braking, 20-year fatigue over the site's wind with blade loads from the DMST) chose the parts from standard sizes: a 6082-T6 blade extrusion with a 4 mm skin (6.2 kg/m, utilisation 0.82, fatigue damage 0.47), struts with a 3 mm wall, a 457.0 x 12.5 mm shaft and a 610→406 mm tower with a 16.0 mm wall. The natural frequencies, not strength, set the tower and the shaft (Fig. 4): the rotor sits 4 m above the tower top, and its rocking mode must stay above the three-per-revolution excitation; the tower's first mode crosses the once-per-revolution speed, so the controller never holds the rotor between 68 and 83 rpm. Our beam model and CalculiX agree within 1 % (1.24, 6.78 against 1.25, 6.82 Hz) once we found that CalculiX stiffens tapered beams by about 8 % (rigid joints at each section change; shown on a cantilever with an exact solution). The joints (blade clamps 4 x M12 A4-80, tower flange 16 x M30 10.9 HV, 12 x M30 8.8 anchors) and eleven drawing sheets follow. The drawn parts weighed about four times what the frequency model had assumed at the tower top; the drawings now export their masses back to the model, iterated to convergence (about 5.5 t above the foundation).

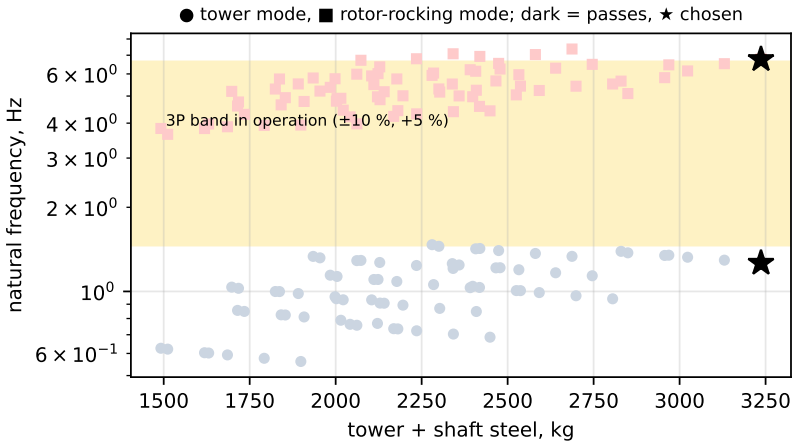


Figure 4: Tower and shaft candidates: both modes against the excitation band; the chosen design (⋆).

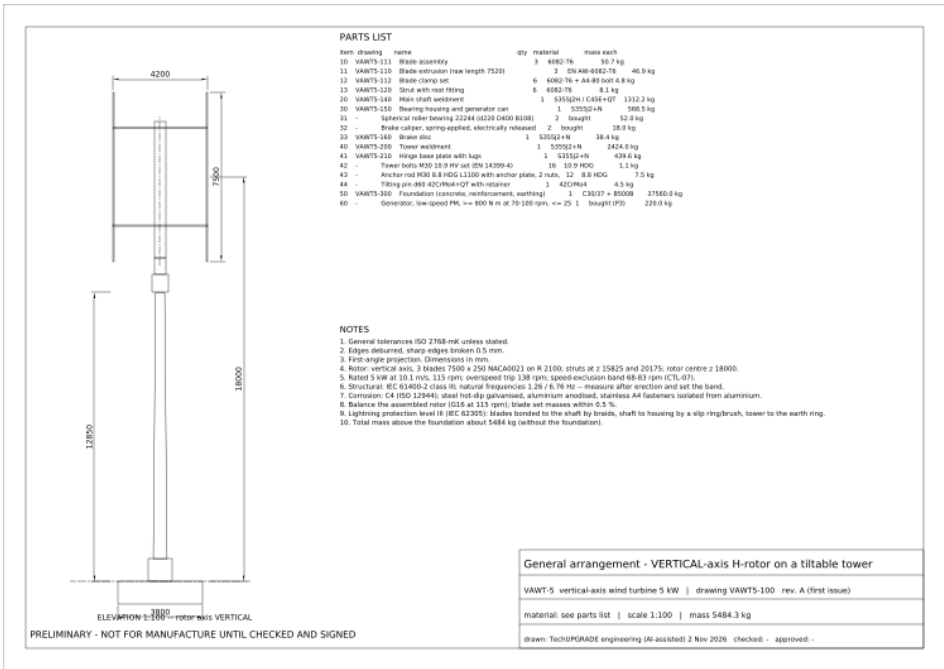


Figure 5: General arrangement (sheet VAWT5-100): the vertical-axis rotor on the tiltable tower.

5 Detailed design: 3D model, assembly and joints

At the client's request the free-standing tower was compared with a guyed one (273.0 × 8.0 mm, three guys of 14 mm strand at 10 m): its modes 1.18 / 3.56 Hz move the speed band to 64–78 rpm and cost 43 kWh a year instead of 150, and the tower weighs 620 kg instead of 2,301 kg; but it needs three anchors, a 20 m circle kept clear and yearly re-tensioning. The free-standing tower was kept (the client agreed). A second CAD model of 97 parts, including every fastener group, was rendered with physical materials (Fig. 6) and is the platform's 3D view. Sheet VAWT5-130 (Fig. 7) is a section through the tower top with 22 ballooned items: the upper 22244 bearing locates the shaft and carries the rotor's weight, the lower one floats for thermal growth; the brake disc sits on the journal between two spring-applied calipers; the generator is coupled by a flange below; the encoder, the vibration sensor and the winding sensors are placed; fits, torques and the assembly order are given. Sheet VAWT5-101 details the four bolted joints: the blade clamp (4 x M12 A4-80, 71 N m), the strut root in double shear (2 x M16 8.8 HDG (ISO 4014)), the tower base (16 x M30 10.9 HV, 2,033 N m) on 12 x M30 8.8 anchors, and the tilting hinge, which lets the tower be erected by winch.

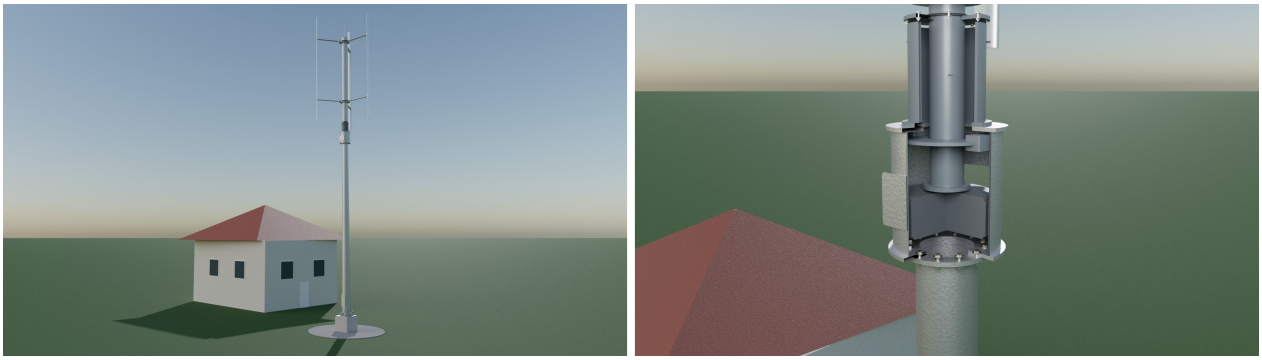


Figure 6: The detailed model (Blender/Cycles): the turbine at the house, and a cut-away of the tower top (bearing housing, brake, generator can).

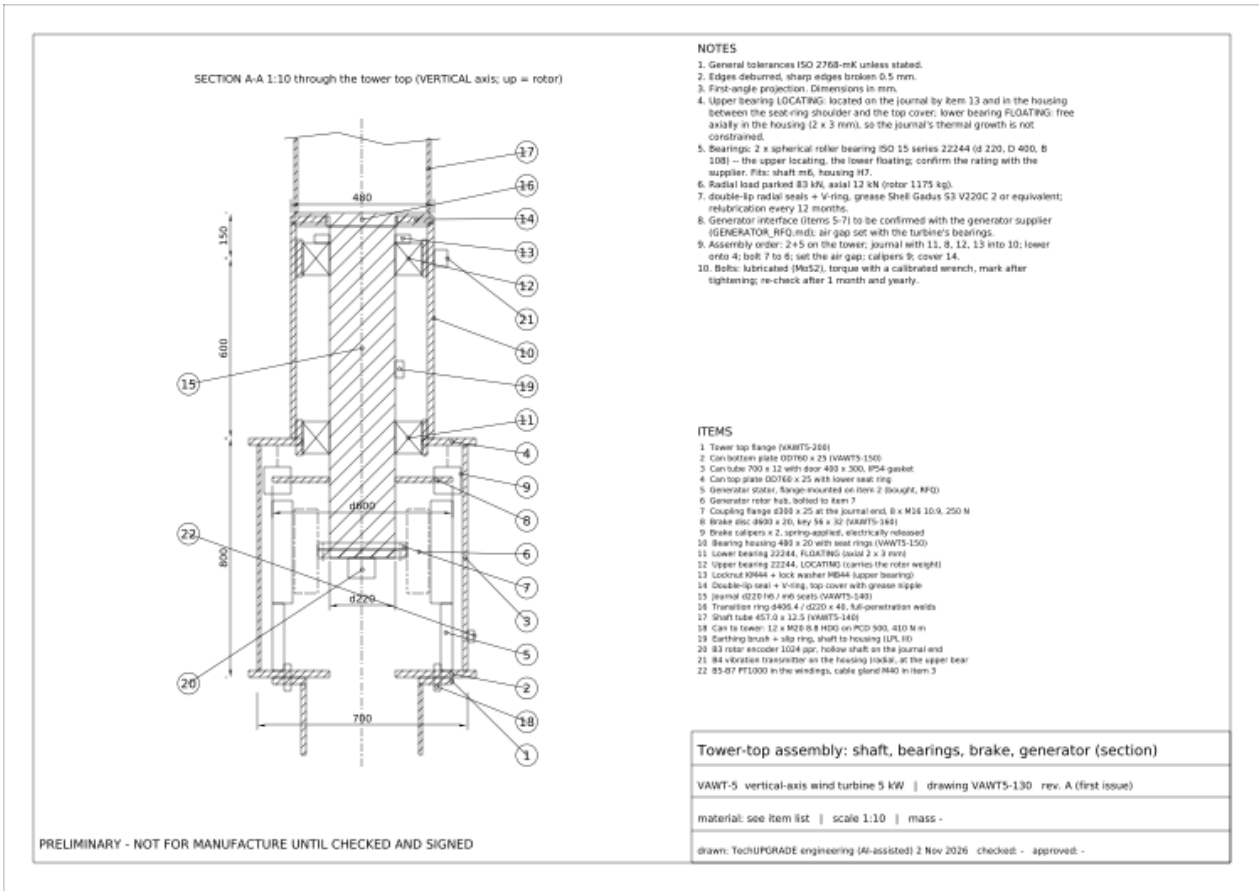


Figure 7: Sheet VAWT5-130: the tower-top assembly in section, with the item list.

6 The production package and the platform's 3D board

The 3D model was carried to revision C (133 parts plus the two boards): the drive train in its parts (both 22244 bearings with races and rollers, the KM44 locknut, the generator as stator, windings, magnet rotor and rotor hub, the hub bolted to the journal's coupling flange by 8 × M16, so the path of the torque from the rotor to the generator is visible), the sensors (encoder on the journal, vibration transmitter on the housing, anemometer and vane on a 3 m boom below the rotor, outside the blades' circle), the cables in the tower and the trench, and the controller cabinet with its switchgear, the rectifier and the two boards placed from their KiCad models (Fig. 8). The boards were rendered from their layouts with every part's 3D model, with and without the solder mask (Fig. 9).

On the platform the same model is the tenant's *3D Turbine* board (Fig. 10): lit by a real sky, every part pickable with its drawing, material and mass, a parts tree by assembly group, X-ray of the tower top, isolate, explode, views of each element, and the sensors' live values pinned to the sensors. Two lessons from its release: the platform's Content-Security-Policy allows no WebAssembly, so a Draco-compressed model never loaded on production although it did in a preview without the policy; the model is now plain glTF, decimated, simplified and quantised (8.9 MB), and the preview applies production's policy. And the tenant's users had no menu entry for the Simulation Manager at all; it was added with the 3D board. The single-line diagram was redrawn with every line computed from the edges of the equipment it joins (Fig. 11).

The drawing set (Table 1) is **issued for the prototype build**: every sheet dimensioned, toleranced and specified, with the boards' manufacturing files, the bill of materials, the I/O list and cable schedule, and the firmware. Before the first cut, four items close it: a qualified engineer's check and signature on every sheet (each is marked preliminary until then), the blade clamp's machining sheets VAWT5-112-1/-2/-3, the generator supplier's interface, and a geotechnical survey with a review of the power board's layout.

Table 1: The drawing set rev. A.

Sheet	Title	Scale	Material	Mass (kg)
VAWT5-100	General arrangement - VERTICAL-axis H-rotor on	1:100	see parts list	5484.3
VAWT5-101	Joint details: blade clamp, strut root, tower	1:4	see VAWT5-100 parts list	–
VAWT5-110	Blade extrusion profile NACA0021 c250	1:1	EN AW-6082-T6 (EN 755-2)	6.2
VAWT5-111	Blade, machined, with inserts and end caps	1:20	EN AW-6082-T6	50.7
VAWT5-112	Blade clamp set (saddle plates, insert, strut	1:2	EN AW-6082-T6	4.8
VAWT5-120	Strut, NACA0018 c180, with root fitting	1:5	EN AW-6082-T6	8.1
VAWT5-130	Tower-top assembly: shaft, bearings, brake, ge	1:10	see item list	–
VAWT5-140	Main shaft weldment (tube, journal, hub flange	1:40	tube S355J2H 457.0 x 12.5 (EN 10210); jo	1312.2
VAWT5-150	Bearing housing and generator can	1:10	S355J2+N; housing machined from hollow b	568.5
VAWT5-160	Brake disc d600 x 20	1:5	S355J2+N (or C45E), friction faces groun	38.4
VAWT5-200	Tower weldment, tapered, tiltable	1:75	S355J2+N plate 16 mm (EN 10025-2)	2424.0
VAWT5-210	Hinge base plate (tilting)	1:10	S355J2+N 50 mm plate	439.6
VAWT5-300	Foundation, gravity block with pedestal	1:50	concrete C30/37, exposure XS1/XC4 (EN 20	37560.0
VAWT5-400	Power single-line diagram	–	IEC 60617	–
VAWT5-401	Control wiring	–	IEC 60617	–

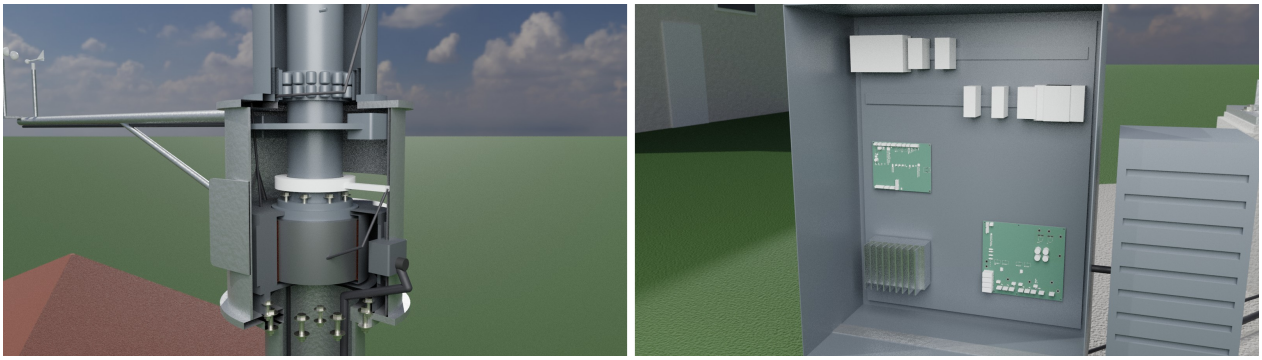


Figure 8: Revision C: the drive train cut open (coupling to the generator, bearings, brake, encoder, sensor boom) and the controller cabinet with the two boards.

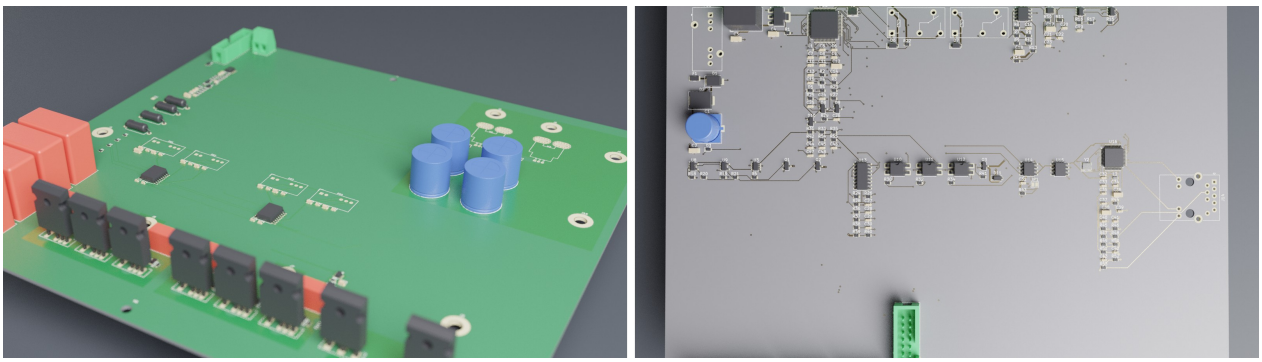


Figure 9: The boards from their KiCad layouts: VAWT5-PWR assembled, and VAWT5-CTL without the solder mask (the tracks between the parts).

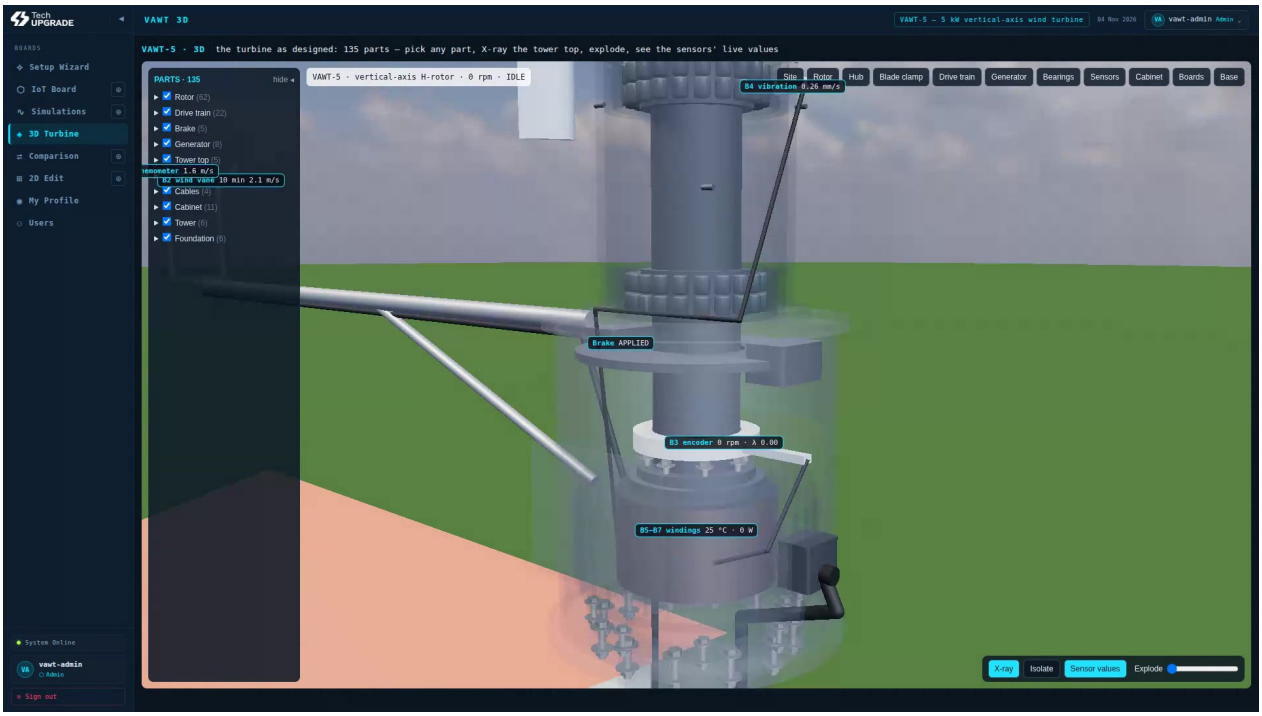


Figure 10: The tenant's 3D Turbine board on production: the drive train in X-ray, with the encoder's, the windings' and the brake's live values.

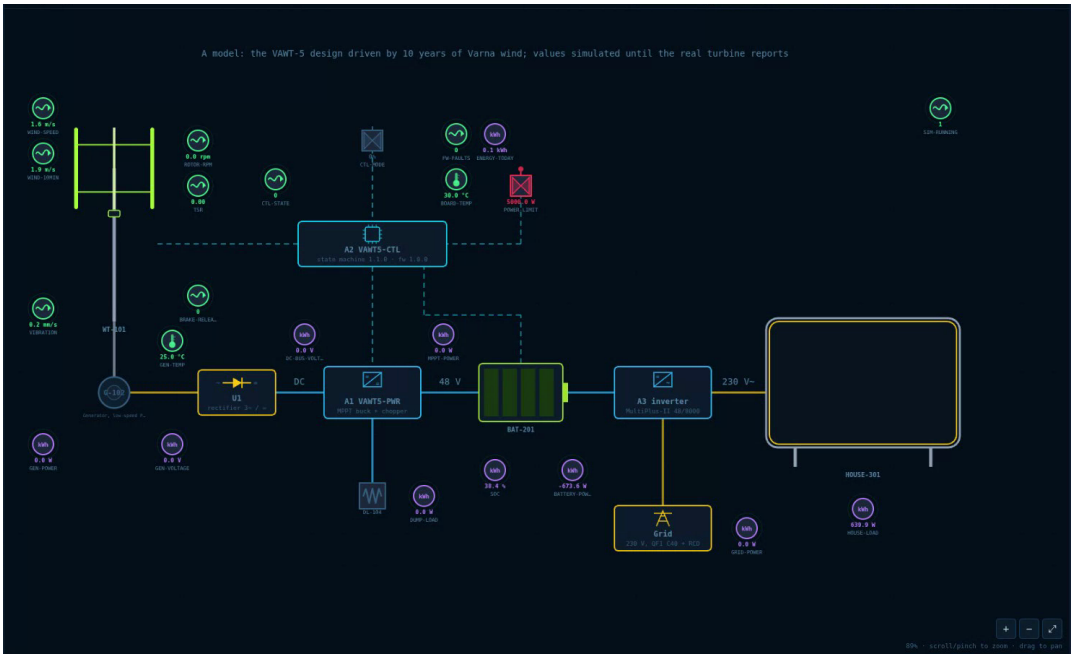


Figure 11: The Control Board: the single-line diagram with every line joined to its equipment and the readings live.

7 Electrical system and electronics

The inverter (Victron MultiPlus-II 48/8000, certified to EN 50549-1 and IEC 62109-1) and the battery (3 × Pylontech US5000) are bought; no generator maker publishes the torque this rotor needs at low speed, so the generator is a purchase specification with acceptance tests. The designed chain is a diode rectifier and a two-phase interleaved SiC buck converter to the 48 V bus: 87.8 % from rotor to battery at rated, the converter 96.7 %; a switching simulation in ngspice gave 97.6 % against the averaged model's 97.4 % (conduction only) (Fig. 14). Holding 5 kW above rated wind by slowing the rotor raises the generator current to 35.8 A at 20 m/s (efficiency 68 %); the engineering manager lowered the cut-out to 15 m/s: 16 h a year parked, 67 kWh a year lost, current 28.5 A. Two boards were generated

from Python descriptions (KiCad 9, Freerouting): a controller with a safety chain that does not depend on the firmware (watchdog, hardware overspeed monitor, E-stop, relays that only release the brake when all agree), and the power board (129 parts): schematic checks with no finding, design-rule check 0 errors, 0 unconnected, schematic parity 0, with 2.5 mm between high- and low-voltage copper (Fig. 15). Sheet VAWT5-400 is the power single-line diagram (Fig. 12): generator, lockable isolator, surge protection, the normally closed short-circuit contactor that brakes the generator when control power is lost, rectifier, converter, battery, inverter, grid and house circuits, and the earthing; VAWT5-401 wires every sensor and actuator to the controller's terminals. An I/O list (22 signals with range, terminal and cable) and a cable schedule (17 cables) complete it. A fabrication specification gives the board house the stack-ups, copper weights, a CTI 600 laminate for the 450 V nets, IPC class 2 and a conformal coating for the coastal site; the layer plots showed signal tracks across the controller's inner ground layers, to be removed in revision B. Revision B also halves the dump load to 12 Ω (two 24 Ω/7 kW resistors in parallel) with a 75 A chopper IGBT, after the firmware tests (Section 8).

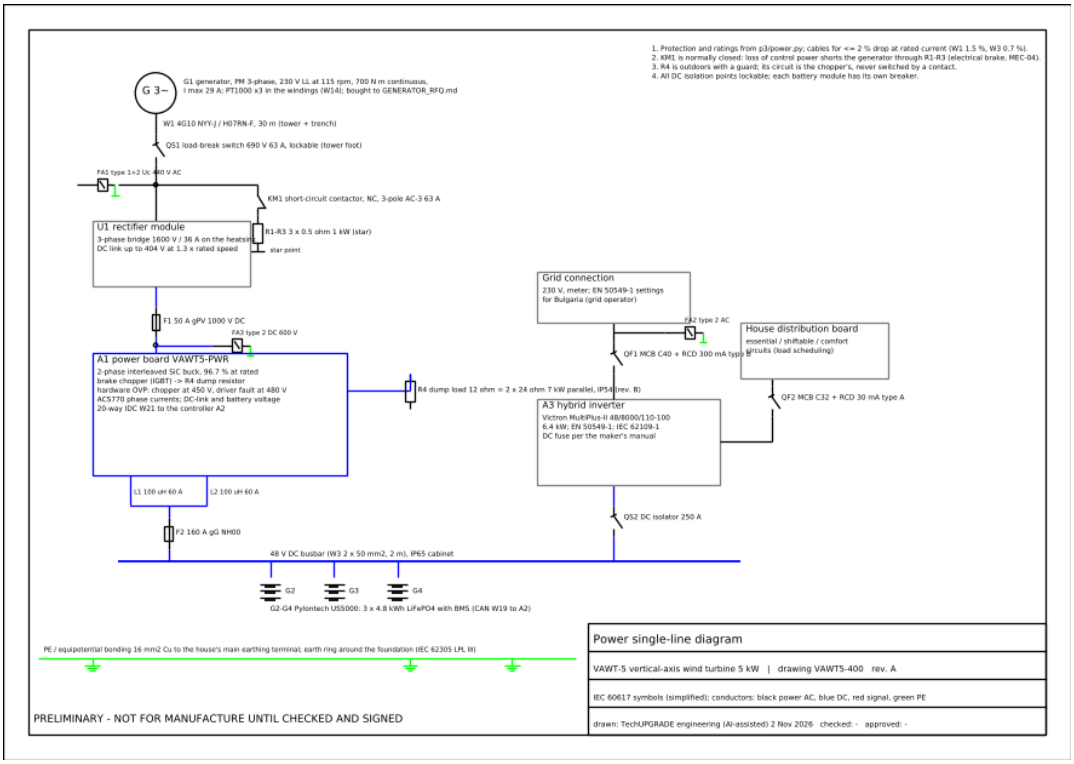


Figure 12: Sheet VAWT5-400: power single-line diagram.

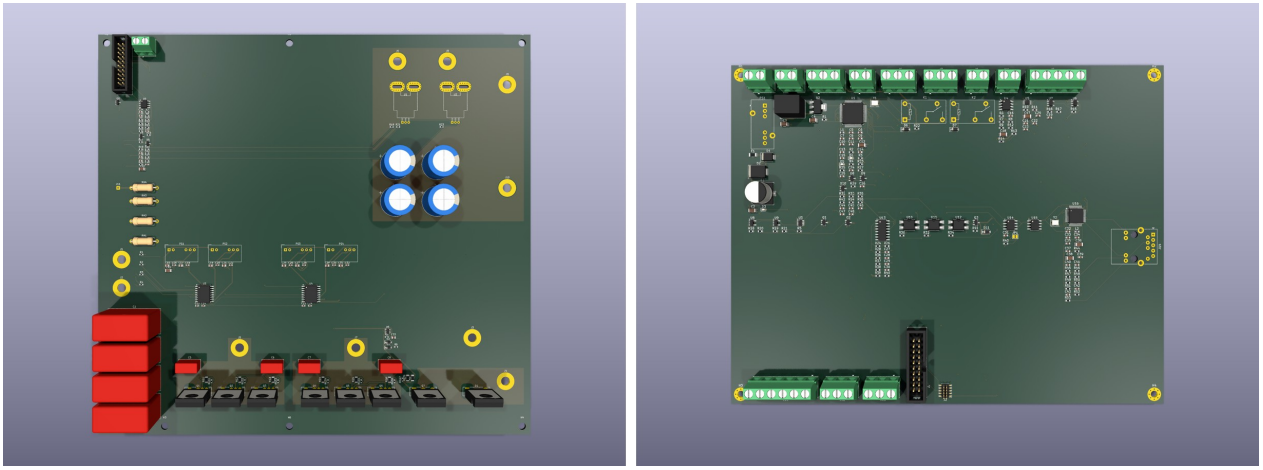


Figure 13: The power board VAWT5-PWR and the controller VAWT5-CTL in 3D (KiCad).

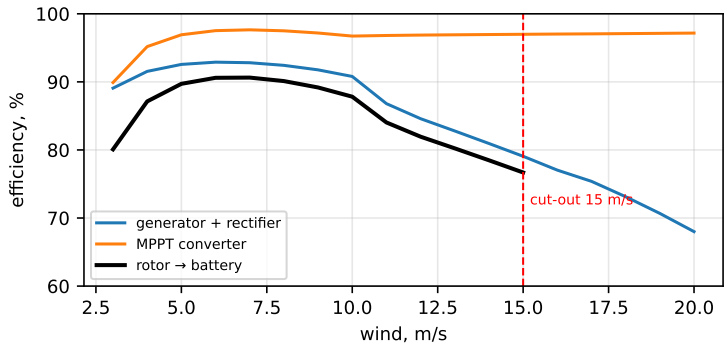


Figure 14: Efficiencies of the electrical chain by wind speed.

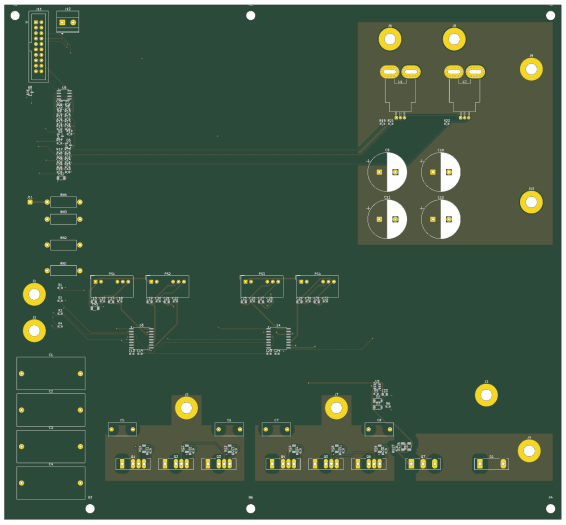


Figure 15: The power board VAWT5-PWR rev. A: switch-node copper over the heatsink row of SiC MOSFETs, gate resistors at the gates.

8 Controller: state machine, firmware and the storm

The controller's state machine (9 states, 21 transitions, version 1.1.0) is written once as data; the firmware's transition table, its diagram (Fig. 16) and the platform's connector profile are generated from it, so they cannot disagree. A plant model built from the design (rotor $C_p(\lambda)$, inertia, generator, rectifier, converter, battery, brake) found the most important result of the project: in a gust from 12 to 25 m/s, electrical braking alone could not hold the rotor, which ran to 500 rpm; the storm state therefore applies the mechanical brake at once above 120 rpm or while the speed still rises (peak 124 rpm, Fig. 17).

The firmware went as an approved proposal to the platform's local development team. Twelve of its thirteen tasks were completed, but each rebuilt the whole project on its own branch, and the integration failed; such work must be built in sequence on one base. The engineering manager then wrote it: a portable C core called at 1 kHz (state machine, MPPT at λ 2.5, the stall power limit, the speed band, storm and fault braking, battery and temperature limits, sensor plausibility, commands, the BMS decoder), 95/95 unit checks, and the software-in-the-loop scenarios of the specification, all passing (Table 2). They changed the design twice. A step from 10 to 12 m/s near rated speed could not be braked into stall with the 24 Ω dump load (battery 5.1 kW and dump 2.4 kW at 230 V against about 8 kW of wind) and ran to the overspeed trip; with 12 Ω it peaks at 118 rpm and settles at 5 kW. And the speed band cannot be crossed upward in 3 s: only the wind accelerates the unloaded rotor (about 5 s), so the specification now requires $\leq$ 6 s upward (5 s is about six cycles of the 1.26 Hz tower mode, well short of the $\sim$16 a resonance needs at 1 % damping) and $\leq$ 3 s downward (measured 1.7 s). A stop command for a running turbine was missing; it became state machine 1.1.0.

Table 2: Software-in-the-loop scenarios (the C core driving the plant model at 1 kHz).

Scenario	Result	Criterion
Wind ramp 3–15 m/s	pass	$\lambda_{opt} \pm 10\,\%$; P $\leq$ 5.1 kW (max 5,075 W); band up in 5.2 s ($\leq$ 6)
Wind 9–4 m/s	pass	band down in 1.7 s ($\leq$ 3)
Gust 12–25 m/s	pass	STORM; peak 120 rpm ($\leq$ 130); standstill after 6.1 s ($\leq$ 60)
Battery full, 10 m/s	pass	dump 5,052 W; DC link max 246 V ($\leq$ 450)
BMS silent	pass	charge current 10.0 A after 5 s ($\leq$ 10)
Encoder lost, 8 m/s	pass	runs on the generator frequency, flag set
Converter fault, 12 m/s	pass	BRAKING; peak 96 rpm ($\leq$ 138)
Energy over the wind bins	pass	7,390 vs 7,419 kWh/yr (-0.38 %; $\leq$ 3)

Around the core, a Zephyr 3.7 LTS application for the VAWT5-CTL board (HRTIM current loops at 40 kHz, encoder and anemometer timers, safety I/O with two watchdogs fed only when the core allows, PT1000s, the BMS over CAN, MQTT telemetry and commands, parameters in flash with a CRC, MCUboot with signed images and roll-back) builds in 126 kB of flash and 52 kB of RAM, also for a Nucleo bench kit. Image 1.0.0 is released in the tenant's firmware library for state machine ^1.1.0, signed (SHA-256 954a94de1794…); the turbine's connector on the platform runs that state machine version. Not yet done: the bench test on real boards.

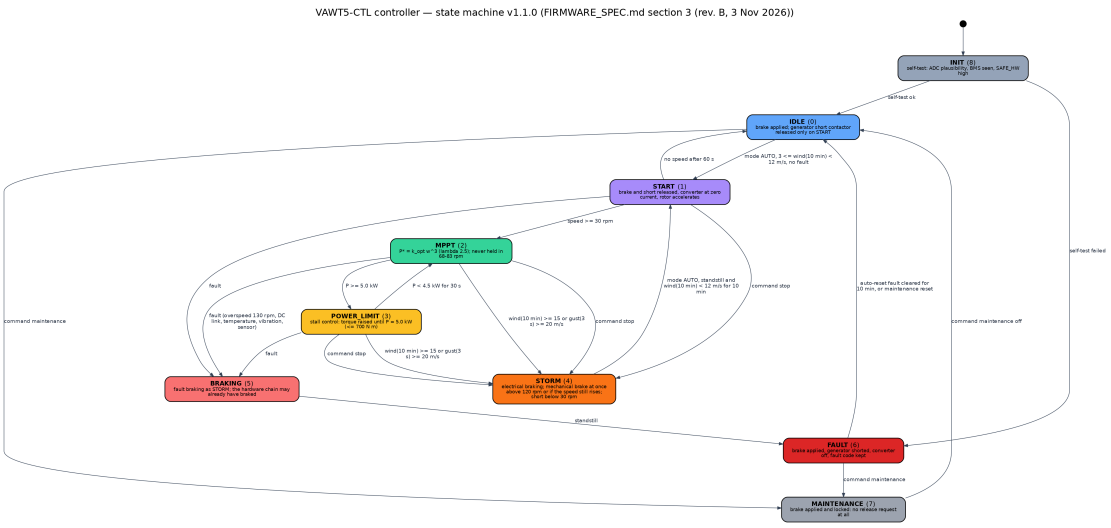


Figure 16: The controller's state machine v1.1.0, drawn from the same file as the firmware's table and the connector profile.

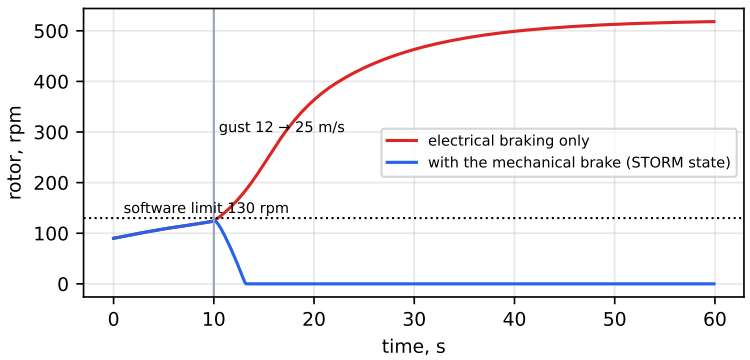


Figure 17: A 25 m/s gust: electrical braking only, and with the mechanical brake.

9 The digital twin

The tenant `vawt` carries the design's numbers (copied from the result files), a live simulated turbine publishing the readings the component owners read, a single-line diagram as the platform's Control Board (with a vertical-axis symbol added: the platform's existing one drew a horizontal-axis turbine), a 3D view, alarm rules and scenarios. Over ten years with an assumed 5,000 kWh smart home, the turbine gives 7,185 ± 466 kWh a year and the house is 74.9 % self-sufficient (Fig. 18). Hourly wind hides turbulence: the live simulator's turbine with 10 s steps gave 5.3 % less over three months, so about 6,805 kWh a year, 5 % above the requirement. In a 48-hour grid outage in January the battery alone leaves 15.3 kWh unmet; with load scheduling (essential 35 %, shiftable 45 %, comfort 20 % of the load; the battery kept for the essential loads) no essential load goes unpowered (0.0 kWh), 7.6 kWh of comfort loads are shed and 12.3 kWh of tasks wait for the wind. The connector `vawt1_` of the turbine runs the controller's profile (state machine 1.1.0) and will mirror the real controller's state; the IoT Board shows the turbine on its single-line diagram.

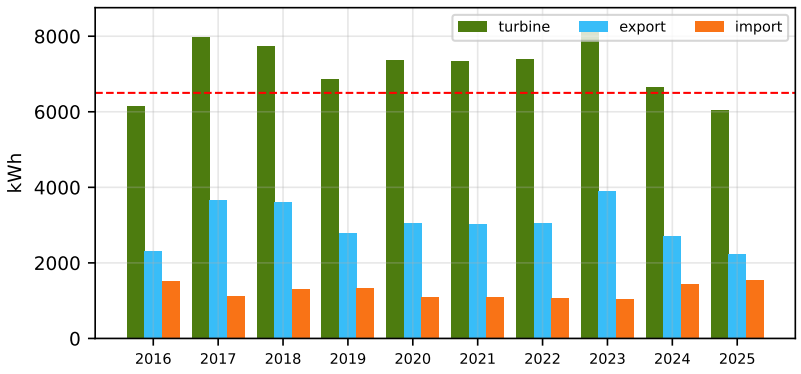


Figure 18: The twin over ten years of Varna wind: turbine energy, export and import.

10 Verification

A traceability matrix maps all 42 requirements to evidence: 6 met, 22 met by design, 12 partial, 2 open (noise; firmware updates). A system FMEA (19 items) puts the foundation's soil (no survey yet), the tilting procedure, lightning and blade separation first; every severity-9 or -10 item has a measure that does not depend on the firmware. A compliance matrix lists the Machinery Regulation (EU) 2023/1230, the Low Voltage and EMC Directives and the standards; a test plan (T0–T9) turns "met by design" into "verified" on the prototype.

11 Errors found and corrected during the work

The process is part of the result. Found by the checks the work built in, and corrected: a factor-two streamtube width (by the validation); the first energy estimate, which mixed two efficiency assumptions (by the twin); the house load at 59 % of the stated value and an interpolated power curve that overstated energy (by the twin's own numbers); CalculiX's stiffening of tapered beams (by an exact benchmark); a rotary inertia counted twice; the drawn masses four times the assumed ones (by exporting them); a microcontroller without an Ethernet controller (while choosing parts); net classes lost on saving and in the router's export, which made a first "zero errors" on the power board invalid (withdrawn); a storm runaway (by the plant model); a dump load too small to brake a gust into stall and a missing stop command (by the firmware's tests); an animation whose tower left its hinge (a parenting error); the guyed tower's saving first stated as its mass (in the process log and the film, corrected); a 3D model that never loaded on production (WebAssembly refused by the CSP) and a tenant without a menu entry for its Simulation Manager (both found after the release, fixed); and, from the client, a horizontal-axis picture where the turbine must be vertical.

Contributions

What this report adds: (i) a complete, scripted design chain for a small vertical-axis turbine in which drawings, boards, the controller specification and the twin read the calculations' results, so a change re-issues them; (ii) a design calibrated on a measured vertical-axis rotor rather than on model output, with two independent models and an explicit statement of where they disagree with the measurement; (iii) the finding that this rotor's tower and shaft are sized by dynamics and that its 1P crossing must be handled by the controller; (iv) a simulated demonstration that electrical braking alone is

insufficient in strong gusts for a small direct-drive VAWT, and the controller rule that fixes it; (v) a controller whose state machine is one source for the firmware, its diagram and the platform connector, and whose software-in-the-loop tests changed the hardware design; (vi) an account of the errors that the built-in checks caught, as evidence of how far such checks carry and where human review remains necessary.

Limitations

No part has been built or measured. The design C_p rests on one measured maximum of a similar rotor; the load model is not IEC 61400-2's simplified model and its partial factor 1.35 must be justified by load measurement; soil, the generator's mass and the bolted joints' details are assumed; the house's consumption is assumed; the power board's layout needs an expert review; the firmware is tested only in simulation, not yet on the boards, and the plant model has no starting torque (the rotor's self-start must be shown on the prototype). The package is preliminary: not for manufacture until checked and signed.

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**: 6 of 8 requirements are met and 1 partly; the open items are listed.

requirement	status	evidence
R1 Reproducibility	met	Every number from scripts in docs/projects/vawt-5kw (p0 site_and_sizing.py, p2 aero/structure/joints/drawings, p3 power.py and spice, p5 sil/plant.py, p7 checks) and sim-manager/vawt, branch vawt-5kw; tools image tools/vawt-eng (pinned versions); data: ERA5 + Varna airport (antarctic_hut/data); report: make_results.py, make_figures.py, gen_tex.py
R2 Baseline comparison	met	Rotor: DMST and Madsen's actuator cylinder (independent); structure: own beam FE and CalculiX; converter: averaged loss model and an ngspice switching simulation
R3 Validation	met	Measured power coefficient of the Uppsala 12 kW H-rotor (Kjellin et al. 2011); the design uses the measured value because both models over-predict it
R4 Statistical analysis	met	Annual energy over ten weather years with 95 % confidence intervals (t-based); the turbulence check over three months in three seasons
R5 Sensitivity analysis	met	Blade length 6.4-8.0 m; chord/solidity 0.18-0.34 m; tower and shaft geometry (24 candidates); cut-out 13-20 m/s; turbulence vs hourly wind
R6 Generalisation	partial	The calibration (one measured rotor, solidity 0.25) is applied to a rotor of solidity 0.36 and not tested there; the plant model reproduces the chain at operating points not used to build it (within 1.6 %) *Open:* power-curve measurement on the prototype (TEST_PLAN T3)
R7 Scientific contribution	met	Contributions section
R8 Independent review	missing	– *Open:* review by an independent wind-turbine engineer (and a power-electronics engineer for the boards)

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