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Vertical-Axis Wind Turbines: A Technical Case Study of a Small-Scale Savonius Rotor and Permanent-Magnet Generator System

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ABSTRACT

This paper presents a technical case study of a small-scale vertical-axis wind turbine (VAWT) based on a paired two-bucket Savonius rotor arrangement and permanent-magnet electrical conversion. The objective is to provide a reproducible engineering description of the system-level calculations while separating theoretical estimates, baseline generator simulation outputs and product-level information. The calculation geometry uses a rotor height of 1.234 m and a characteristic diameter of 0.435 m, giving 0.53679 m² swept area per rotor and 1.07358 m² for the paired two-rotor unit. At the principal design calculation point of 18 m/s, the total available wind power across the paired swept area is approximately 3.835 kW. The electrical system target is 1000 W, represented as 500 W per generator channel. This corresponds to 26.1% of the available wind power at 18 m/s; this value is reported only as a system-level consistency ratio and is not presented as a measured aerodynamic power coefficient. The electromagnetic baseline was evaluated using a supplied generator simulation dataset. The baseline simulation reports 27.66 W at 300 rpm, 65.14 W at 474 rpm, 113.98 W at 600 rpm and 295.39 W at 1000 rpm. A supplied physical reference point for a baseline generator was 240 W at 1000 rpm. The simulation is therefore used as a baseline electrical-conversion reference rather than as proof of complete-turbine performance. The paper also compares Savonius, Darrieus/H-rotor, helical and hybrid VAWT concepts, discusses the operating limits of drag-driven rotors and identifies the measurements required for independent performance verification.

Keywords: *vertical-axis wind turbine; Savonius rotor; distributed wind energy; permanent-magnet generator; baseline electromagnetic simulation; tip-speed ratio; power coefficient; system-level analysis.*

INTRODUCTION

Distributed wind systems can be useful where compact equipment, changing wind direction, limited land availability, and local electrical loads influence the selection of a generation technology. Vertical-axis wind turbines differ from conventional horizontal-axis wind turbines (HAWTs) in that the rotor axis is

vertical and the aerodynamic response is not tied to a yawing nacelle. Savonius rotors are particularly attractive for small-scale applications because of their simple construction, relatively high starting torque and ability to accept wind from changing directions. Their principal limitation is aerodynamic efficiency: the returning blade experiences opposing drag and the flow around the rotor is strongly unsteady. Published reviews report substantial variation in Savonius power coefficient with rotor geometry, overlap, aspect ratio, blade shape, end plates, operating tip-speed ratio and flow conditions [1–3].

The present work is intentionally framed as a technical case study rather than a systematic literature review. The literature is used to establish the aerodynamic context and reasonable performance ranges; the numerical calculations are performed for the specific paired-rotor configuration considered here. Product-level statements are identified as supplied or manufacturer-reported information where applicable, and they are not treated as independent certification. The main quantitative contribution is the transparent calculation of swept area, wind power, tip-speed ratio and system-level power requirements, supplemented by a baseline permanent-magnet generator simulation.

The paper also separates three evidence levels: (i) analytical calculations derived from stated dimensions and physical constants; (ii) baseline electromagnetic simulation results supplied for the generator; and (iii) product or design information supplied by the manufacturer or project documentation. This separation is important because a generator simulation is not equivalent to a complete wind-turbine test, and a commercial specification is not equivalent to independently measured performance.



Figure 1. Supplied project image of the paired vertical-axis wind-turbine configuration. The frame contains two helical Savonius rotor units with generator assemblies located near the lower portion of the structure. Source: supplied project material.

VAWT ARCHITECTURES AND OPERATING PRINCIPLES

Savonius rotor

The Savonius rotor is a drag-dominated VAWT. Wind acting on the concave surface of the advancing bucket produces a larger aerodynamic drag force than the force acting on the returning convex surface, producing a net torque. The basic configuration is mechanically simple and can self-start under suitable conditions. Its disadvantages include returning-blade negative torque, cyclic loading, wake interaction and a comparatively low power coefficient. Experimental and review literature shows that reported performance varies widely with geometry and test conditions [1,2].

Helical or twisted bucket arrangements are commonly studied as a means of distributing torque production over azimuth angle. The intent is not to claim a universal performance improvement for every helical rotor, but to explain why a twisted geometry can alter instantaneous torque and reduce periodic loading compared with a straight two-bucket arrangement.



Figure 2. Supplied image illustrating the twisted/helical Savonius blade form used in the project configuration. Source: supplied project material.

Comparison with other VAWT architectures

A meaningful comparison should distinguish drag-driven Savonius machines from lift-driven Darrieus-family rotors. Recent reviews place typical Savonius operation at lower TSR than Darrieus machines and report substantially different achievable power coefficients [2,4]. The following table is therefore intended as a qualitative engineering comparison; the ranges are literature context rather than performance guarantees for the present system.

Architecture	Primary mechanism	Typical TSR range	Representative Cp range	Self-starting tendency	Structural complexity
Savonius	Drag-dominated	≈0.6–1.2	≈0.15–0.30	Generally good	Low–moderate
H-Darrieus / H-rotor	Lift-dominated	≈2.0–5.0	≈0.35–0.45 in optimized studies	Often weak at low TSR	Moderate–high
Troposkein Darrieus	Lift-dominated	≈2.5–5.0	≈0.30–0.45	Often weak	High
Gorlov / helical Darrieus	Lift-dominated	≈2–5	≈0.25–0.48 reported	Variable	Moderate–high
Savonius–Darrieus hybrid	Combined drag/lift	≈1–4+	Configuration-dependent	Improved relative to pure Darrieus in some designs	High

Table 1. Literature-context comparison of common VAWT architectures. Values are broad reported ranges and should not be interpreted as guaranteed performance for a particular design [1–4].

SYSTEM CONFIGURATION AND GEOMETRY

The system considered in this case study consists of two Savonius rotor units coupled to two permanent-magnet generator channels within a common structural arrangement. The two-rotor interpretation is important for reconciling the 1 kW-class electrical target with the swept area. Calculations are therefore reported both per rotor and for the paired unit.

Parameter	Symbol	Per rotor	Paired unit / note
Rotor height	H	1.234 m	Same design height for both rotors
Characteristic rotor diameter	D	0.435 m	Used for TSR calculation
Rotor radius	R	0.2175 m	D/2
Swept area	A = D H	0.53679 m²	1.07358 m² for two rotors
Rotor arrangement	—	Two-bucket Savonius	Two rotor units
Blade material	—	GFRP	Supplied project configuration
Generator architecture	—	1 generator/rotor; 2 PCB units/generator	4 PCB units total in paired system
Electrical design target	—	≈500 W/generator	≈1000 W combined
Principal calculation point	—	18 m/s	1100 rpm reference speed
Air density	ρ	1.225 kg/m³	Nominal sea-level reference

Table 2. System geometry and calculation inputs. Only geometry needed for the system-level analysis is reported; internal generator construction details are outside the scope of this paper.

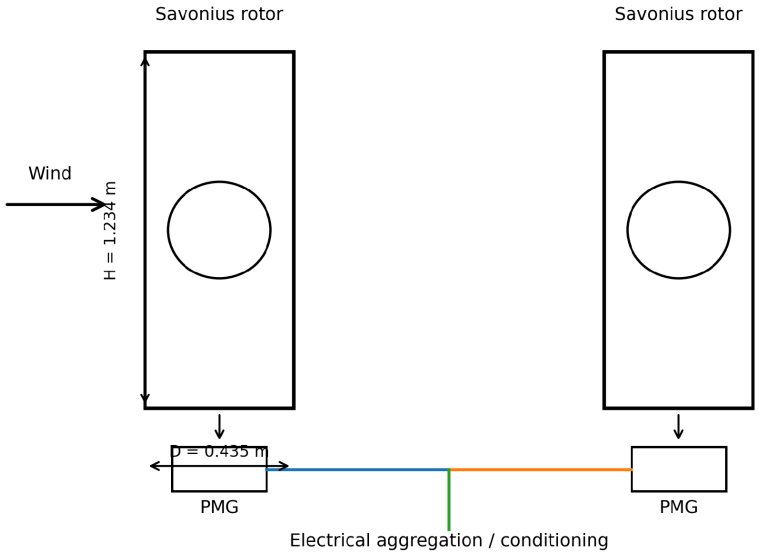


Figure 3. Simplified architecture used in the system-level analysis. Two Savonius rotor units are represented with one permanent-magnet generator channel per rotor; the electrical outputs are subsequently aggregated or conditioned.

Geometry details and reproducibility

The reported rotor height and diameter are sufficient to reproduce the swept-area and first-order wind-power calculations. The supplied project images indicate a twisted/helical bucket form and a two-bucket rotor arrangement. Exact overlap ratio, twist angle, end-plate diameter ratio and detailed internal blade-profile coordinates are not numerically specified here because those parameters are part of the detailed design definition rather than required inputs for the system-level calculations. This distinction prevents unsupported geometric values from being inferred from a render or photograph.

ANALYTICAL PERFORMANCE MODEL

Swept area and wind power

For a vertical-axis rotor, the projected swept area used for the first-order power calculation is the product of characteristic diameter and rotor height:

$$A = D\,H$$

For the present rotor, $A = 0.435 \times 1.234 = 0.53679\ m^2$. For the paired two-rotor unit, the aggregate swept area is $2A = 1.07358\ m^2$.

$$P_w = \tfrac{1}{2}\,\rho\,A\,V^3$$

Using $\rho = 1.225\ kg/m^3$, the available wind power at 18 m/s is approximately 1.917 kW per rotor and 3.835 kW for the paired unit.

Tip-speed ratio

$$\lambda = \omega R / V, \qquad \omega = 2\pi N / 60$$

At $N = 1100$ rpm, $\omega = 115.19$ rad/s. With $R = 0.2175$ m and $V = 18$ m/s, the tip speed is 25.05 m/s and $\lambda = 1.392$. This value is reported as a kinematic operating point of the system; it is not used to assert that 1.392 is the optimum power-coefficient TSR of a Savonius rotor. Literature generally places peak Savonius performance at lower TSR values, although geometry and operating conditions shift the optimum [1,2,4].

Power coefficient and system-level consistency

$$C_p = P_{mech} / (\tfrac{1}{2}\rho A V^3)$$

The power coefficient is an aerodynamic quantity and should be based on rotor shaft power when it is used as a measured performance metric. Because the present paper does not contain a complete aerodynamic shaft-power measurement, the 1000 W electrical target is not converted directly into Cp.

$$\eta_{sys,target} = P_{e,target} / P_{w,total}$$

For the paired unit at 18 m/s, η_sys,target = 1000 / 3834.94 = 0.261. This 26.1% value is a system-level consistency ratio only. If an electrical conversion efficiency η_e is assumed for sensitivity analysis, the aerodynamic Cp required to reach the target is Cp,req = 0.261/η_e. For example, η_e = 0.90, 0.92 and 0.95 correspond to required Cp values of approximately 0.292, 0.286 and 0.277, respectively. No single constant generator efficiency is adopted as a measured fact.

Wind-power envelope

Wind speed (m/s)	Available wind power, paired unit (W)	Rotor power at Cp=0.15 (W)	Rotor power at Cp=0.25 (W)	Rotor power at Cp=0.30 (W)
2.0	5.3	0.8	1.3	1.6
3.0	17.8	2.7	4.4	5.3
4.0	42.1	6.3	10.5	12.6
5.0	82.2	12.3	20.5	24.7
6.0	142.0	21.3	35.5	42.6
7.0	225.5	33.8	56.4	67.7
8.0	336.7	50.5	84.2	101.0
9.0	479.4	71.9	119.8	143.8
10.0	657.6	98.6	164.4	197.3
12.0	1,136.3	170.4	284.1	340.9
15.0	2,219.3	332.9	554.8	665.8
17.5	3,524.2	528.6	881.0	1,057.2
18.0	3,834.9	575.2	958.7	1,150.5

Table 3. Analytical wind-power envelope for the paired swept area. Cp columns are mechanical-power sensitivity cases, not measured outputs.

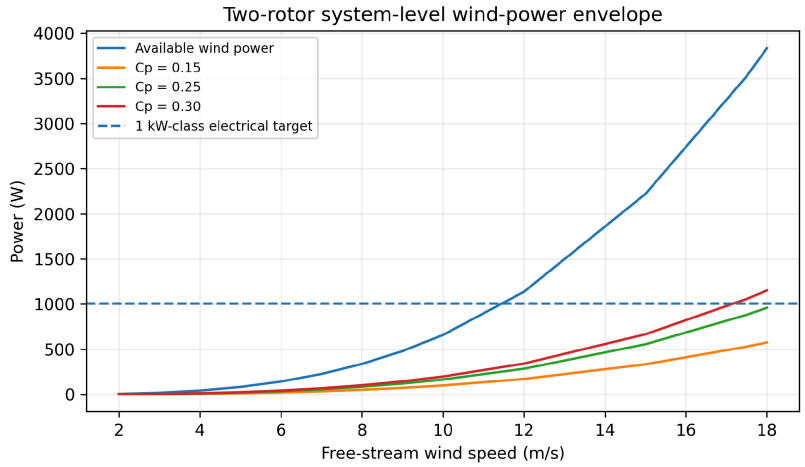


Figure 4. Analytical wind-power envelope for the paired rotor unit. The 1000 W line denotes the electrical design target; the Cp curves represent mechanical-power sensitivity cases.

BASELINE ELECTROMAGNETIC GENERATOR SIMULATION

A separate electromagnetic simulation dataset was used as the baseline electrical-conversion reference. The simulation workflow comprised magnetostatic and transient electromagnetic analyses of the permanent-magnet generator, with voltage, current and power evaluated over several rotational speeds. The documentation identifies ANSYS Maxwell 2024 R1 as the simulation environment for the baseline magnetostatic analysis. The present paper reports only aggregate baseline outputs needed to understand the generator-level behavior and does not disclose detailed magnet geometry, material grade, pole arrangement, PCB construction, conductor routing, internal air-gap definition or other design-enabling parameters.

The simulation should be interpreted as a generator-level model rather than a complete wind-turbine simulation. In particular, the results do not include aerodynamic torque generation, wind-tunnel boundary conditions, tower interaction, rotor structural dynamics or the full electrical conditioning chain. The supplied simulation documentation also notes that theoretical simulation results can differ from physical results and that simplified representations may be used in parts of a parametric study.

Baseline simulation results

Speed (rpm)	Phase voltage (V)	Line voltage (V)	Phase current (A)	Simulated power (W)
300	43.0	74.476	0.3036	27.66
474	66.0	114.315	0.4659	65.14
600	87.4	151.381	0.6163	113.98
1000	140.7	243.699	0.9922	295.39

Table 4. Baseline generator simulation outputs from the supplied electromagnetic dataset. Torque is not reproduced because the aggregate electrical-power values are sufficient for the present baseline comparison and do not require the use of model-specific torque reporting.

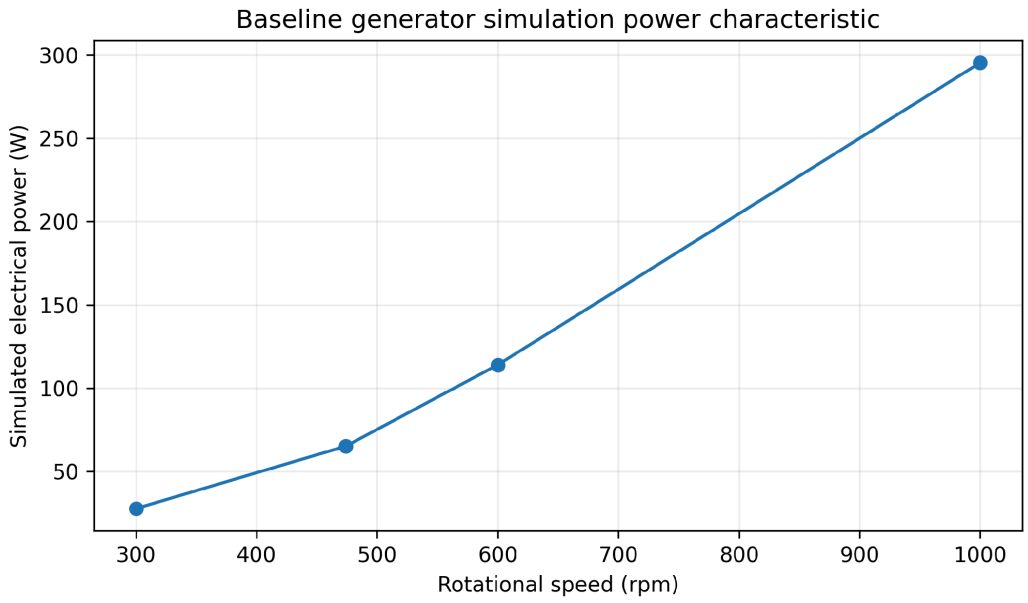


Figure 5. Baseline generator simulation power characteristic. The curve describes the simulated generator channel, not the complete VAWT.

Physical baseline reference

The same project documentation provides a physical forced-jig reference for a baseline regular generator: 154.24 V, 1.556 A and 240.0 W at 1000 rpm. This point is included only as a supplied generator-level reference. It is not presented as a wind-turbine measurement because the generator was driven under a forced-jig condition rather than by a calibrated aerodynamic rotor operating in a wind field.

Reference	Speed	Voltage	Current	Power
Physical baseline reference	1000 rpm	154.24 V	1.556 A	240.0 W
Electromagnetic simulation baseline	1000 rpm	140.70 V phase	0.9922 A phase	295.39 W

Table 5. Generator-level baseline comparison at approximately 1000 rpm. The two rows represent different test/model conditions and should not be interpreted as a formal simulation error metric.

GENERATOR INTEGRATION AND 1 KW-CLASS SYSTEM TARGET

PCB-level power architecture

For system accounting, each generator is defined as two parallel PCB-based generator units, each assigned a nominal 250 Wp design point. Therefore: 2 PCB units × 250 Wp ≈ 500 W per generator; 2 generators × 500 W ≈ 1000 W for the paired turbine. The notation Wp is used here to denote the specified

peak/design electrical power of each PCB unit, not an independently measured output at every operating condition.

The paired rotor arrangement uses two permanent-magnet generator units, one associated with each Savonius rotor. Each generator unit is electrically configured from two PCB generator units, with a nominal design target of approximately 250 Wp per PCB. Thus, one complete generator is treated as approximately 500 W (2 × 250 Wp), and the paired two-generator system has an approximately 1 kW aggregate electrical design target (2 × 500 W). These are system design targets used for the engineering calculation; the baseline electromagnetic simulation reported earlier is retained as a separate generator-level reference and is not presented as proof of the 250 Wp-per-PCB target.

$$T_eq = P / \omega$$

The principal 1 kW-class point can therefore be summarized as follows:

Quantity	Per rotor/channel	Paired unit
Swept area	0.53679 m²	1.07358 m²
Wind speed	18 m/s	18 m/s
Rotor speed reference	1100 rpm	1100 rpm
Available wind power	1.917 kW	3.835 kW
Electrical design target	≈500 W per generator (2 × 250 Wp PCB units)	≈1000 W combined (2 generators)
Target / available wind power	26.1%	26.1%
Power-equivalent torque at 1100 rpm	4.34 N·m	8.68 N·m
Tip-speed ratio	1.392	1.392

Table 6. System-level consistency calculations for the paired 1 kW-class configuration.

The arithmetic above resolves the apparent discrepancy between a 1 kW-class unit and the wind power available to a single rotor: the electrical target is associated with two rotor-generator channels, so the relevant aggregate swept area is twice the single-rotor area. Even so, 1000 W should be regarded as a design target rather than a demonstrated output. Independent validation would require simultaneous measurement of wind speed, rotor speed, shaft torque, generator electrical output and relevant electrical losses.

BLADE, STRUCTURAL AND MANUFACTURING CONSIDERATIONS

The supplied project configuration uses a twisted/helical Savonius blade form and glass-fiber-reinforced polymer (GFRP) blades. Helical geometry is relevant to torque distribution because the local aerodynamic phase varies continuously along the rotor height rather than all blade sections reaching the same azimuthal condition simultaneously. This can alter cyclic torque and structural loading, but the present paper does not quantify the reduction because no independent torque-ripple measurement is included.

The project documentation reports that detailed blade development involved computational modeling and iterative design work. Those underlying CFD datasets are not reproduced here, and no solver setup, turbulence model, mesh-independence study, convergence history or pressure-field result is claimed. Accordingly, CFD is treated as a design-development activity reported in project documentation, not as an independently reproduced result of this paper.

Rotor balance, shaft alignment and structural stiffness are important because a VAWT experiences cyclic aerodynamic loading. Manufacturing precision can reduce geometric imbalance and assembly variation, but a numerical tolerance should not be converted into a quantified energy gain without experimental evidence. The analysis therefore treats manufacturing control as an engineering quality factor rather than as a directly measured efficiency improvement.

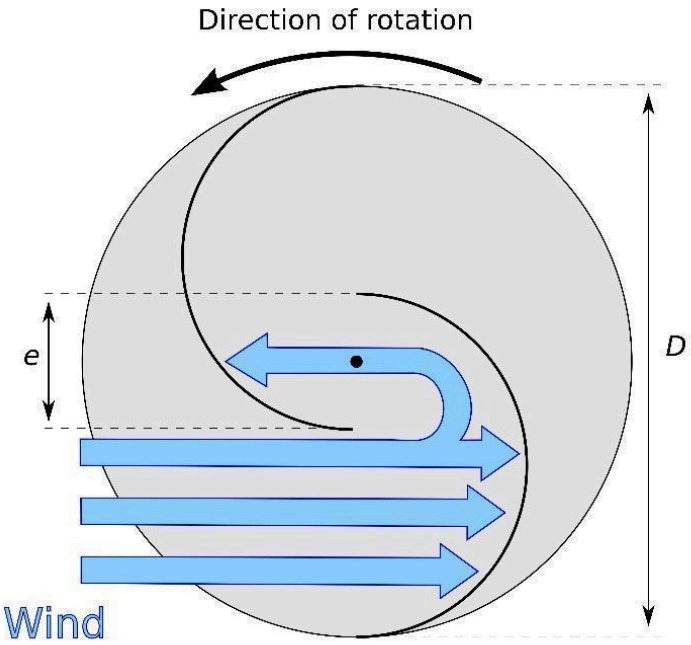


Figure 6. Generic Savonius rotor cross-section illustrating diameter D, blade overlap e and the differential drag mechanism. This figure is used for geometric explanation; the drawing is not a dimensional representation of the project rotor.

OPERATING ENVELOPE AND LOW-WIND INTERPRETATION

A wind-speed threshold for rotor rotation should not be confused with the onset of useful electrical generation. Product literature associated with the project has reported a cut-in value of approximately 2 m/s; this is treated here only as a manufacturer-reported specification rather than an independently verified result. For the paired swept area, the total kinetic wind power at 2 m/s is only about 5.3 W, illustrating why a rotor may rotate at low wind speed while producing little useful electrical power.

The present analysis uses 18 m/s as the principal high-speed calculation point and 1100 rpm as the corresponding rotational reference. No independent cut-out or braking test is included in this paper. Therefore, 18 m/s should be interpreted as the upper calculation point rather than as a certified operating or survival limit.

Figure 4 provides the available-wind-power envelope and mechanical sensitivity bands. Because speed-dependent generator efficiency and complete rotor shaft-power measurements are not available, a measured electrical power curve is not claimed. This avoids converting a theoretical Cp assumption into a false experimental power curve.

DISCUSSION

What the calculations establish

- The paired rotor geometry gives an aggregate swept area of 1.07358 m².
- At 18 m/s, the nominal available wind power across that area is approximately 3.835 kW using $\rho = 1.225$ kg/m³.
- The 1000 W electrical target corresponds to 26.1% of the nominal available wind power at that point.
- The 1100 rpm reference produces a TSR of 1.392 for the 0.435 m diameter rotor; this is a kinematic design point, not a claimed optimum TSR.
- The supplied generator simulation reaches 295.39 W at 1000 rpm for the modeled generator channel.
- The supplied physical forced-jig baseline reaches 240.0 W at 1000 rpm, but this is not a complete wind-turbine measurement.

Interpretation of efficiency

The paper does not adopt the previously quoted commercial efficiency figures as established performance values. Instead, it distinguishes aerodynamic Cp from electrical system efficiency. Published Savonius studies report broad Cp ranges, with many conventional configurations in the lower part of the range and optimized configurations reaching higher values depending on geometry and test method [1,2]. The 26.1% system-level ratio obtained here is therefore best interpreted as a consistency requirement for the paired 1 kW-class target. It is not evidence that the rotor has achieved a measured Cp of 0.261.

Betz-limit context

The Betz coefficient of $16/27 \approx 0.593$ is a classical ideal-flow benchmark for wind-energy extraction and should not be used as the sole performance reference for a Savonius rotor. Drag-dominated VAWTs have substantially lower practical power coefficients because of returning-blade drag, wake interaction and unsteady separation. Modern reviews place many Savonius configurations around $Cp \approx 0.15–0.25$, with higher values reported for optimized configurations under specific conditions [1,2,4]. The relevant engineering comparison is therefore between the measured or simulated rotor Cp under defined conditions

and the literature for comparable Savonius geometries, rather than simply comparing a Savonius machine with the Betz limit.

SCOPE AND LIMITATIONS

- No wind-tunnel or field measurement of complete-turbine shaft torque and electrical power is included.
- The generator simulation is a baseline electromagnetic study and does not model the complete aerodynamic rotor.
- The 1000 W electrical value is a design target, not an independently demonstrated output.
- No speed-dependent generator/controller efficiency map is assumed.
- The 18 m/s calculation point is not a certified operating or survival limit.
- Detailed blade-profile coordinates and internal generator construction parameters are not necessary for the calculations presented and are not reported.
- The air density of 1.225 kg/m³ is a nominal sea-level reference. At altitude or under different temperature and pressure conditions, available wind power scales directly with air density.
- The literature comparison uses broad reported ranges; Cp depends strongly on swept-area definition, test section blockage, Reynolds number, TSR, rotor geometry and measurement method.

DECLARATIONS

Conflict of interest

The author is affiliated with Necon Renewable Energy, the organization associated with the turbine configuration examined in this case study. This employment relationship is a potential source of bias and is disclosed explicitly. The paper is not presented as independent product certification. Manufacturer- or project-supplied performance information is identified as such, while the analytical calculations and the baseline generator simulation are separately described.

Funding and company involvement

No separate external research grant is reported for preparation of this student paper. The engineering configuration and project data were available to the author through the associated technical work. No claim of independent third-party certification is made. Any institutional or product-development relationship should therefore be considered when interpreting the case-study results.

Figure-use statement

Project photographs/renders included in this paper are identified as supplied project material. The author is responsible for ensuring that any required reproduction permission is held for the final journal submission.

Data availability

The aggregate baseline generator simulation outputs and all equations needed to reproduce the system-level calculations are reported in this paper. Detailed electromagnetic model files, internal generator construction parameters and proprietary geometric definitions are not part of the publicly reported dataset.

CONCLUSION

This technical case study provides a consistent system-level analysis of a paired small-scale Savonius VAWT and permanent-magnet generator arrangement. The configuration uses a 1.234 m rotor height and 0.435 m characteristic diameter, producing 0.53679 m² swept area per rotor and 1.07358 m² for the paired unit. At 18 m/s, the nominal available wind power is approximately 3.835 kW. The 1000 W electrical design target therefore corresponds to a 26.1% system-level wind-power ratio for the paired unit. The associated TSR at 1100 rpm is 1.392.

The baseline electromagnetic simulation provides an independent layer of evidence at the generator level, with simulated power increasing from 27.66 W at 300 rpm to 295.39 W at 1000 rpm. A supplied physical forced-jig reference of 240 W at 1000 rpm provides a second generator-level benchmark, but neither dataset demonstrates complete wind-turbine performance. The principal value of the analysis is therefore the transparent separation of aerodynamic theory, generator simulation and system target calculations.

For a complete performance claim, the next measurement stage would require a calibrated wind field, simultaneous rotor speed and shaft-torque measurement, generator voltage and current measurement, electrical loss accounting, repeated runs and uncertainty estimates. Until those measurements are available, the 1 kW-class designation should be interpreted as a system design target rather than as a verified field output.

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APPENDIX A. REPRODUCIBLE CALCULATION SUMMARY

Calculation	Expression	Result
Single-rotor swept area	0.435 × 1.234	0.53679 m²
Paired swept area	2 × 0.53679	1.07358 m²
Angular speed at 1100 rpm	2π × 1100 / 60	115.19 rad/s
Tip speed at 1100 rpm	115.19 × 0.2175	25.05 m/s
TSR at 18 m/s	25.05 / 18	1.392
Wind power per rotor at 18 m/s	0.5 × 1.225 × 0.53679 × 18³	1.917 kW
Wind power for two rotors at 18 m/s	2 × 1.917	3.835 kW
Target ratio	1000 / 3834.94	1000 / 3834.94 = 0.261 (26.1%)
Torque-equivalent per 500 W generator	500 / 115.19	4.34 N·m
Combined torque-equivalent	2 × 4.34	8.68 N·m