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Apparent-Wind Aerodynamics of High-Performance Sailing: Speed Ratio, VMG, and Comparison with VAWT Kinematics

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Abstract

This study develops a compact apparent-wind framework for high-performance sailing craft and uses vertical-axis wind-turbine (VAWT) kinematics as a bounded comparison. By establishing closed-form equations, the model connects key variables: sailing angle, lift-to-drag ratio, resistance, speed ratio, apparent-wind angle, and velocity made good (VMG). The model is formulated as an upper-bound framework limited to established, approximately steady foil-borne operation; it is not intended to replace a complete velocity-prediction program or dynamic model of takeoff, maneuvers, touchdown, and recovery. A constant loss factor is used only as a transparent sensitivity parameter, while a velocity-dependent formulation is identified as the appropriate iterative extension for class-specific prediction. Predictions are compared with representative published ranges for iQFOiL, SailGP F50, and racing iceboats. Differences between ideal and observed performance are interpreted through aerodynamic and hydrodynamic drag, foiling-transition nonlinearities, cavitation, ventilation, structural loading, and control limitations. The VAWT–sailing analogy is restricted to relative-flow kinematics and lifting-surface control because the systems have different optimization objectives and flow physics. Finally, an exploratory energy-harvesting analysis distinguishes the unloaded zero-driving-force speed limit from a generator-loaded operating point governed by a coupled force–energy balance. The resulting framework provides clear, practical relationships while identifying the additional class-specific and dynamic physics required for predictive performance modeling.

Keywords: apparent wind; high-performance sailing; hydrofoil sailcraft; iceboat; speed ratio; velocity made good; loss-factor sensitivity; VAWT kinematics; energy harvesting

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1. Introduction

1.1. Background

Modern high-performance sailing has evolved rapidly since the 2013 America's Cup, when fully foiling AC72 catamarans demonstrated the potential of rigid wing sails and lift-based propulsion while reducing reliance on traditional downwind spinnakers. The AC50 technology introduced in the 2017 America's Cup subsequently provided the foundation for SailGP, established in 2018 as a separate international racing league using standardized F50 foiling catamarans. This technological evolution extended to the Paris 2024 Olympics, which replaced RS:X windsurfing with iQFOiL and introduced Formula Kite. Under favorable conditions, high-performance foiling craft can reach approximately

30–45 knots (56–83 km/h), with Formula Kite capable of attaining speed ratios approaching three times the true wind speed [1–4].

The performance of these sailing vessels depends on apparent-wind geometry. Increasing boat speed strengthens and shifts the apparent wind, enhancing forces and creating positive feedback to further increase speed. Sailing craft motion determines the apparent-wind magnitude and direction; together with sail trim, these determine the angle of attack and the aerodynamic lift and drag for propulsion. Sail trim adjusts angle, twist, and camber to maximize forward drive, while hydrofoils and righting systems balance lateral force and heeling moment. Foil-borne flight reduces hull resistance but introduces drag, cavitation, ventilation, stability, and control constraints. Velocity prediction programs (VPPs) determine speed and velocity made good (VMG) by balancing aerodynamic drive against hydrodynamic and parasitic resistance.

Wind turbines extract energy through rotor rotation, whereas sailing craft convert aerodynamic force into translational motion. Both share a useful aerodynamic framework: blade or craft motion modifies the wind experienced by a lifting surface. The vector difference between free-stream wind and surface velocity defines apparent, or relative, wind. Its direction and surface orientation determine AoA; lift and drag resolve into driving or tangential forces and reaction components. This framework connects sail trim with turbine blade-pitch control, although their performance objectives remain fundamentally different.

The comparison is especially informative for lift-type vertical-axis wind turbines (VAWTs). As a blade travels around the rotor, its motion produces cyclic variations in relative-wind magnitude, inflow angle, and AoA. Fixed-pitch blades may consequently experience dynamic stall, torque ripple, and fatigue-producing loads [5,6]. Active or prescribed pitch can orient the blade relative to the instantaneous apparent wind, redistribute tangential force, improve starting, and increase cycle-averaged torque or power coefficient [7–10]. Refined AoA reconstruction further shows that kinematic inflow alone cannot represent dynamic-force hysteresis throughout the rotor cycle [11]. The optimum is therefore a rotor-level compromise between energy extraction, stall avoidance, actuator demand, and structural durability—not simply the AoA corresponding to the maximum isolated-airfoil L/D.

A horizontal-axis wind turbine (HAWT) provides a simpler limiting comparison: relative wind combines axial inflow with blade tangential velocity, and lift and drag resolve into thrust and torque-producing components. The tangential component is geometrically analogous to sailcraft driving force. However, a turbine extracts kinetic energy and experiences rotor-disk induction, whereas a sailcraft accelerates until aerodynamic drive balances hydrodynamic and parasitic resistance. Accordingly, turbine power optimization and sailcraft speed or VMG optimization must remain distinct.

Literature Gap

Apparent-wind triangles, lift and drag decomposition, and VMG are established concepts, but the literature does not provide the present closed-form sequence linking sailing angle, effective lift-to-drag ratio, a transparent resistance penalty, speed ratio, and upwind and downwind VMG within one compact framework. Existing VPP studies generally emphasize class-specific numerical prediction, while VAWT studies emphasize cyclic torque and power. The unresolved need is therefore not another textbook velocity triangle, but a clearly bounded analytical bridge that exposes the governing trends, identifies where the bridge fails, and can be checked against representative high-performance craft.

1.2. Research Questions

This study asks four questions: (1) How do apparent-wind geometry and force balance constrain U/V and VMG? (2) How do L/D , sailing angle, and resistance losses change the ideal polars? (3) How do the closed-form trends compare with representative iQFOiL, SailGP F50, and iceboat performance? (4) Which parts of VAWT relative-flow and pitch-control reasoning transfer usefully to sail trim, and which do not?

1.3. Specific Contributions

The paper makes three specific contributions. First, it derives a transparent closed-form set of speed-ratio and VMG relations and states their force-balance assumptions. Second, it separates constant- K sensitivity analysis from a velocity-dependent loss formulation and quantifies the gap between ideal predictions and representative performance. Third, it defines a limited VAWT–sailing comparison based on apparent-flow kinematics and aerodynamic control, distinguishes turbine power optimization from sailing speed or VMG optimization, and clarifies the limits of the steady framework when cyclic blade pitching or sail pumping introduces flow-history effects.

2. Methodology and Assumptions

2.1. Coordinate System and Definitions

In Figure 1, let U denote boat speed, V true wind speed, θ the true wind angle measured from the upwind direction, and β the apparent-wind angle. For a straight leg toward an upwind mark, the idealized velocity made good (VMG) is

$$\text{VMG} = U \cos \theta \quad (1)$$

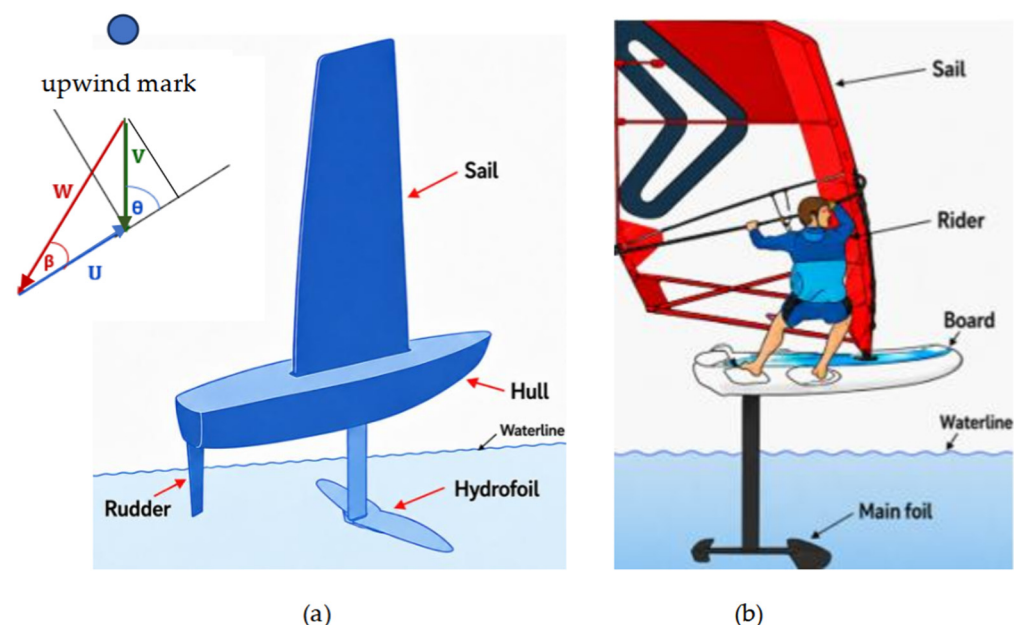


Figure 1. (a) Hydrofoil sailing craft with one sail and one primary submerged hydrofoil. (b) iQFOiL with a sail, board, front hydrofoil wing, and rear stabilizer; sail and foil pumping in this configuration are discussed in Section 7.4.3.

For a downwind mark, the positive downwind component may be written $\text{VMG}_d = -U \cos \theta$. The apparent-wind velocity vector is $\mathbf{W} = \mathbf{V} - \mathbf{U}$, where bold symbols denote vectors and W , V , and U denote their magnitudes. The apparent-wind magnitude and angle follow from the velocity triangle:

$$W = \sqrt{U^2 + V^2 + 2UV\cos\theta}, \quad \beta = \tan^{-1} \left(\frac{\sin\theta}{\cos\theta + U/V} \right) \quad (2)$$

These relations explain why a fast foiler experiences strong apparent wind rotated toward the bow. A purely drag-driven craft running directly downwind cannot reach the true wind speed because its relative wind and thrust vanish as U approaches V . Lift-based sailing avoids this limit by operating across the wind, allowing $U/V > 1$ when aerodynamic efficiency is high and total resistance is low. Aerodynamic lift L and drag D are given as

$$L = \frac{1}{2} \rho_a A_s W^2 C_L \quad (3)$$

$$D = \frac{1}{2} \rho_a A_s W^2 C_{D,s} \quad (4)$$

Here, ρ_a is air density, A_s is sail reference area, and C_L and $C_{D,s}$ are the sail-system lift and drag coefficients, respectively.

2.2. Aerodynamic and Hydrodynamic Force Boundaries

At steady speed, aerodynamic driving force equals total resistance and heeling moment equals righting moment. Classic VPPs iterate these balances; foiling VPPs must additionally satisfy vertical-force and pitch equilibrium. The Offshore Racing Congress describes the standard VPP logic as a search for equilibrium and optimum trim at each wind speed and angle [12]. Cella et al. [13] extended this logic by coupling high-fidelity aerodynamic and hydrodynamic analyses to a performance model. Patterson [14] developed static and dynamic six-degree-of-freedom VPPs for America's Cup foilers, emphasizing time to flight, fixed foil angle of attack, and peak speed. These studies show that maximum speed is an equilibrium ceiling, not a kinematic multiple of wind speed. Parametric AC75 hydrofoil studies likewise demonstrate that performance prediction requires coupled design and equilibrium constraints [15].

Hydrofoil sailing reduces hull wave-making and frictional resistance, but foil and strut profile and induced drag, spray, free-surface, rudder, and aerodynamic losses remain. As speed increases, the weight-supporting lift coefficient decreases approximately as U^{-2} , potentially reducing induced drag, while skin-friction and form drag rise with dynamic pressure. Optimal foils therefore become thinner, smaller, and higher in aspect ratio, subject to takeoff, structural, control, cavitation, and class constraints. The vehicle boundary includes the sail or wing, platform, foils, rudder, struts, and wetted hull. Aerodynamic drive acts along craft velocity; submerged surfaces balance lateral force, and righting moment opposes heel. The steady solution assumes zero longitudinal acceleration and excludes transient takeoff, pumping, tacking, gybing, and recovery.

2.3. Energy and Control-Volume Boundaries

The force model uses the moving craft as the system boundary. Air supplies aerodynamic work, while the water supplies the reaction force and receives momentum through the foils. Because the sail continually enters fresh air, its energy flux cannot be equated directly to that of a stationary turbine having the same geometric area. Turbine swept-area power is therefore used only as a reference scale, not as an identical control volume or air-mass flow rate.

2.4. Treatment of the Loss Factor K

Two treatments of K are distinguished. Fixed values such as $K = 0, 1$, and 3 are dimensionless sensitivity cases used to show how losses contract an ideal polar; they are not class-specific constants. For prediction, K must be obtained from the velocity-dependent aerodynamic and hydrodynamic resistance terms in Equation (9), including regime-dependent coefficients. Because K then depends on U , the speed ratio and K must be solved iteratively. Discontinuities near takeoff and changes associated with ventilation or cavitation lie outside the compact closed form.

2.5. Solution and Optimization Procedures

For the sensitivity solution, L/D , θ , and a prescribed K are supplied to the closed-form speed relation; the apparent-wind angle and the upwind or downwind VMG are then evaluated. Optima are obtained by differentiating the relevant speed or VMG expression with respect to θ . In the velocity-dependent formulation, a trial U determines W and the resistance term, K , is updated, and the longitudinal force balance is iterated to convergence. The analytical solution is interpreted as an upper-bound benchmark rather than a substitute for a six-degree-of-freedom VPP.

3. Apparent-Wind and Force-Balance Model

3.1. Apparent-Wind Velocity and Force Decomposition

Figure 2a defines the velocity vectors, sailing directions, and wind-angle notation used in the governing relationships presented in Section 3. Panel (b) shows the true-wind, boat-velocity, and apparent-wind triangle using the notation defined in Section 2.1. In panel (c), aerodynamic lift L and drag D resolve into forward driving and lateral components:

$$F_{\text{drive}} = L \sin \beta - D \cos \beta, \quad F_{\text{lat}} = L \cos \beta + D \sin \beta \quad (5)$$

The lateral component is balanced primarily by the side force generated by the hydrofoil and rudder, together with any residual hull contribution. It also produces a heeling moment that must be opposed by righting moment. In the direction of motion, the real steady-state balance is

$$\Sigma F_x = F_{\text{drive}} - R_h - R_a = L \sin \beta - D \cos \beta - R_h - R_a = 0 \quad (6)$$

where R_h is hydrodynamic resistance of the foils, struts, rudder, and any immersed hull area, and R_a is aerodynamic resistance of the platform, rigging, and crew not already included in the sail-force decomposition. For the idealized zero-residual-resistance limit used to establish a theoretical speed ceiling ($K = 0$ and $R_h + R_a \rightarrow 0$), the available driving-force margin approaches zero: $L \sin \beta - D \cos \beta = 0$. Defining $\gamma = L/D$ (lift-to-drag ratio) gives $\tan \beta = D/L = 1/\gamma$. Combining this with the apparent-wind relation Equation (2) gives

$$\tan \beta = \frac{D}{L} = \frac{1}{\gamma} = \frac{V \sin \theta}{V \cos \theta + U} \quad (7)$$

Solving for the ideal steady-state speed ratio U/V yields an ideal upper-bound relationship

$$\frac{U}{V} = \gamma \sin \theta - \cos \theta, \quad \gamma = \frac{L}{D} \quad (8)$$

This expression is an ideal upper bound. It shows how L/D and true-wind angle set the attainable speed ratio when hydrodynamic, aerodynamic, structural, and control losses are neglected. Introducing the nondimensional loss term K gives Equation (9).

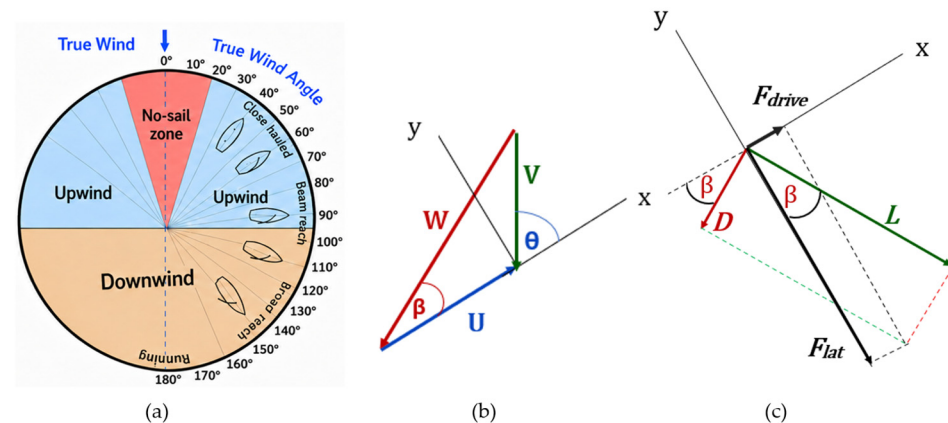


Figure 2. Velocity and force diagrams for hydrofoil sailing: (a) sailing upwind (close-hauled) and downwind (broad reach) at steady state. (b) U , V , W , θ , and β . (c) Driving force balances in the direction of motion, aerodynamic lift L and drag D resolve into forward driving force and lateral force.

3.2. Steady-State Speed Ratio and Apparent-Wind Angle

Closed-Form Speed Relation

The compact relation follows directly from the longitudinal force balance in Equation (6). Substituting the apparent-wind geometry gives

$$\sin\beta = \frac{V\sin\theta}{W}, \quad \cos\beta = \frac{U + V\cos\theta}{W}$$

$$0 = \frac{LV\sin\theta - D(U + V\cos\theta)}{W} - (R_h + R_a)$$

Multiplying by $W/(DV)$ and rearranging yields Equation (9), with $K = (R_h + R_a)W/(DV)$. Thus K is the dimensionless resistance penalty in the speed-ratio relation.

$$\frac{U}{V} = \frac{L}{D}\sin\theta - \cos\theta - K, \quad K = \frac{(R_h + R_a)W}{DV} \quad (9)$$

$$K(U, \theta) = \frac{\frac{1}{2}\rho_w C_{D,w} A_w U^2 + \frac{1}{2}\rho_a C_{D,a} A_a W^2}{\frac{1}{2}\rho_a C_{D,s} A_s W V}$$

$$K(U, \theta) = \frac{\rho_w A_w C_{D,w}}{\rho_a A_s C_{D,s}} \frac{(U/V)^2}{W/V} + \frac{A_a C_{D,a}}{A_s C_{D,s}} \frac{W}{V}$$

In the expanded expression for K above, water-side resistance is approximated by $\frac{1}{2}\rho_w C_{D,w} A_w U^2$ and additional air-side resistance by $\frac{1}{2}\rho_a C_{D,a} A_a W^2$. Sail drag is $D = \frac{1}{2}\rho_a C_{D,s} A_s W^2$, giving the denominator DV/W required by Equation (9). Here ρ_w and ρ_a are water and air densities; A_w and A_a are the corresponding resistance reference areas; and $C_{D,w}$, $C_{D,a}$, and $C_{D,s}$ are water-side, additional air-side, and sail drag coefficients. Coefficients may depend on loading and operating regime. $K(U, \theta)$ must therefore be updated with U and W ; prescribed constant K values are sensitivity cases, not measured craft constants. A complete VPP must additionally satisfy lateral, vertical, and moment equilibrium.

3.3. Maximum Straight-Line Speed

Analytical Condition for Maximum Straight-Line Speed

Maximum straight-line speed occurs where the derivative of U/V with respect to θ vanishes. Because $K(\theta)$ depends on sailing angle and speed, its variation can shift the optimum heading as well as reduce the attainable speed ratio. For the ideal $K = 0$ model, differentiation gives

$$\frac{d}{d\theta} \left(\frac{U}{V} \right) = \gamma \cos \theta + \sin \theta = 0 \Rightarrow \tan \theta = -\gamma \quad (10)$$

$$\left(\frac{U}{V} \right)_{\max} = \sqrt{1 + \gamma^2} \quad (11)$$

$$\theta_{\text{speed}}^* = 180^\circ - \tan^{-1} \gamma = 90^\circ + \tan^{-1} \left(\frac{1}{\gamma} \right) \quad (12)$$

For $\gamma = 10$, the ideal result is $\theta^* \approx 95.7^\circ$ and $(U/V)_{\max} \approx 10.05$. Thus, the maximum-speed heading is a near beam reach, slightly on the downwind side. In practice, cavitation, ventilation, structural loading, control authority, and sea state impose a lower operational ceiling than the aerodynamic expression alone. The SailGP F50 generally reaches maximum speed on a crosswind or slightly downwind course, typically between a beam reach and a broad reach ($\text{TWA} = 90\text{--}110^\circ$), where favorable apparent-wind geometry supports strong aerodynamic drive during sustained foiling.

3.4. VMG Formulation and Optimization

3.4.1. Maximum Upwind VMG

Upwind velocity made good is the projection of boat velocity toward the windward mark. A fast but wide course can lose to a slower course sailed closer to the wind, so the optimum maximizes the product of the speed ratio and $\cos \theta$. For the ideal $K = 0$ model,

$$\frac{d}{d\theta} \left(\frac{\text{VMG}}{V} \right) = \frac{d}{d\theta} [(\gamma \sin \theta - \cos \theta) \cos \theta] = 0 \Rightarrow \tan 2\theta = -\gamma \quad (13)$$

$$\text{maximum: } \theta_u^* = 90^\circ - \frac{1}{2} \tan^{-1} \gamma = 45^\circ + \frac{1}{2} \tan^{-1} \left(\frac{1}{\gamma} \right) \quad (14)$$

$$\left(\frac{\text{VMG}_u}{V} \right)_{\max} = \frac{\sqrt{1 + \gamma^2} - 1}{2} \quad (15)$$

With $\gamma = 10$, $\theta_u^* \approx 47.9^\circ$ and $(\text{VMG}_u/V)_{\max} \approx 4.52$. A nonzero K penalizes VMG and can shift the optimum because its projected contribution varies with $\cos \theta$; therefore, the closed-form result is best treated as an aerodynamic upper bound.

3.4.2. Maximum Downwind VMG

For a downwind mark, positive progress is $-U \cos \theta$ when θ is measured from the upwind direction. The optimum balances a deeper course against the speed retained by the apparent-wind system. For $K = 0$, the corresponding results are

$$\text{minimum: } \theta_d^* = 180^\circ - \frac{1}{2} \tan^{-1} \gamma = 135^\circ + \frac{1}{2} \tan^{-1} \left(\frac{1}{\gamma} \right) \quad (16)$$

$$\left(\frac{\text{VMG}}{V} \right)_{\min} = -\frac{\sqrt{1 + \gamma^2} + 1}{2} \text{ or } \left(\frac{\text{VMG}_d}{V} \right)_{\max} = \frac{\sqrt{1 + \gamma^2} + 1}{2} \quad (17)$$

With $\gamma = 10$, $\theta_d^* \approx 137.9^\circ$ and $(\text{VMG}_d/V)_{\max} \approx 5.52$. The idealized downwind optimum exceeds the upwind value because true wind contributes favorably to the apparent-wind geometry. In Figure 3, the red point marks maximum speed and the green and purple points mark maximum upwind and downwind VMG; increasing K from 0 to 1 and 3 contracts the polar.

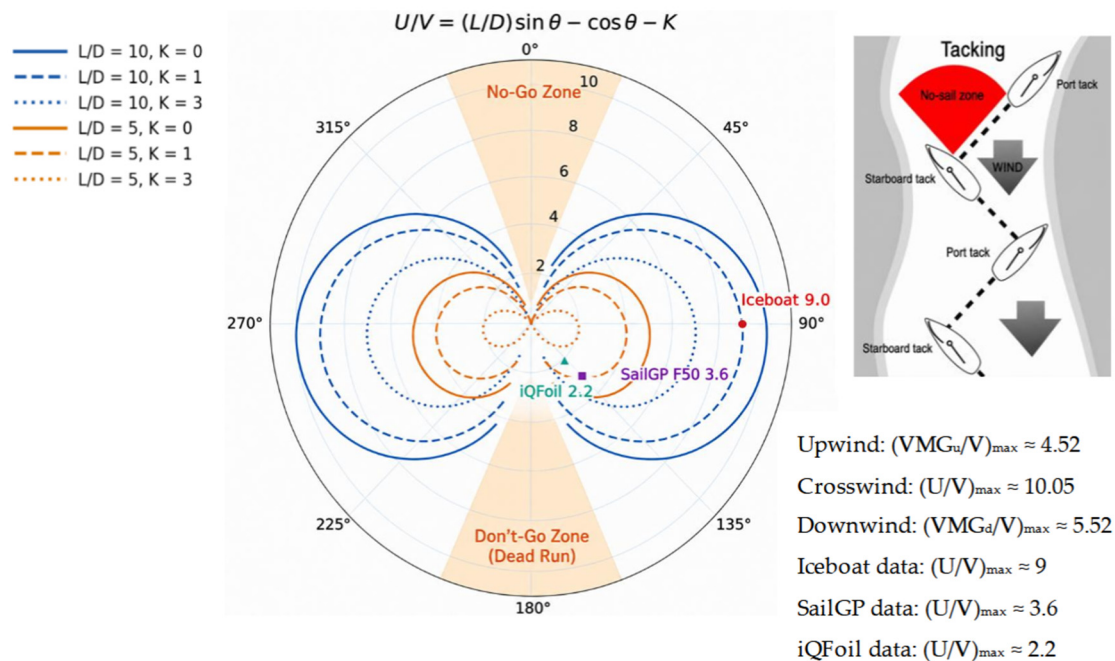


Figure 3. Predicted U/V polar diagram for $L/D = 10$ and 5 ; $K = 0, 1, 3$. Increasing K contracts the polar while retaining its basic shape. Only non-negative forward-speed ratios (U/V) are shown.

4. Model Results and Sensitivity Analysis

This section evaluates the predicted polar, optimum headings, and the influence of prescribed resistance penalties.

4.1. Ideal Performance Polars and Effects of L/D , K , and Sailing Angle

Polar Diagram and Representative Performance

Figure 3 presents the predicted polars for effective sail- L/D values of 10 and 5 with nondimensional loss factors $K = 0, 1$, and 3, representing ideal-, moderate-, and high-loss sensitivity cases. The sectors $\theta = 340$ – 360° and 0 – 20° , the No-Go Zone, form the upwind no-sail zone, where the sail cannot generate sufficient forward drive. Near $\theta = 160$ – 200° , in the Do-not-Go Zone (Dead Run), high-speed hydrofoil sailcraft generally gybe between broad-reaching headings rather than sail directly downwind, where the apparent wind weakens and stable foiling becomes more difficult to maintain. Although gybing covers a longer distance, the stronger apparent wind and sustained foiling on broad reaches generally produce a higher downwind VMG, as indicated by Equations (16) and (17), and faster race-course performance.

Representative race-performance data for iQFOiL ($U/V \approx 2$), the SailGP F50 ($U/V \approx 3$), and a racing iceboat ($U/V \approx 9$) are superimposed to compare the idealized predictions with observed operating points. In particular, the measured iceboat speed ratio is consistent with an effective sail-system L/D of approximately 10, reflecting exceptionally low runner resistance under favorable light-wind and smooth-ice conditions [16]. The representative iQFOiL and F50 speed ratios are based on published GPS and race-performance analyses [17,18].

The craft markers show representative published operating points. Table 1 uses selected illustrative effective sail lift-to-drag ratios, headings, and prescribed K values, rather than independently measured synchronized inputs. Effective L/D is the ratio of sail- or wing-system lift to drag, including finite-span effects, trim, and deformation. Crew, platform, and rigging drag excluded from that sail-force boundary enters R_a ; water-side

resistance enters R_h . Each contribution is assigned once. If a source ratio includes whole-craft aerodynamic drag, the overlapping contribution must be excluded from R_a .

Table 1. Illustrative finite-loss consistency check using selected sail-system L/D , headings, and prescribed resistance penalties [16–18].

Craft	$(L/D)_{eff}$	θ	K	Predicted U/V	Published U/V
iQFOiL	6	145°	2	2.26	2.20
SailGP F50	10	140°	3	4.19	3.60
Racing iceboat	10	90°	1	9.00	9.00

Note. Calculated U/V uses Equation (9). Inputs are illustrative, not independently measured operating conditions; exact agreement is not independent validation.

The selected inputs reproduce the approximate performance scale, with the F50 calculation remaining higher than the published value. The iceboat equality follows from the selected parameter combination and does not demonstrate predictive accuracy. Independent assessment requires synchronized wind, heading, craft speed, sail-force, and resistance measurements, with inputs established independently of the comparison speed.

4.2. Optimum Sailing Angle and VMG

For $\gamma = 10$ and $K = 0$, the maximum-speed angle is 95.7°, and the optimum upwind and downwind VMG angles are 47.9° and 137.9°. The corresponding normalized values are 10.05, 4.52, and 5.52. A constant K lowers speed, whereas velocity-dependent resistance can also shift these angles.

4.3. Sensitivity to Nonlinear and Velocity-Dependent Losses

The fixed-K curves represent sensitivity envelopes for approximately steady foil-borne operation. In practice, profile and parasitic drag scale approximately with dynamic pressure, whereas induced drag depends on the required vertical lift and lateral force. Below the minimum foiling speed, hull contact sharply increases wetted area, frictional drag, and wave-making resistance; this nonlinear transition is outside the closed-form model. During sustained foiling, Equation (9) requires iterative updating of U, W, and K until force balance converges. Such coupling may contract the ideal polar nonuniformly and shift the optimum sailing angles, improving the representation of class-specific losses.

5. Comparison with Published Performance Data

Table 2 compares the ideal $\gamma = 10$, $K = 0$ speed ratio evaluated across the published heading ranges with representative published U/V. The observations are not synchronized by wind, trim, foil, and control state; this is an ideal-reference comparison, not validation of a calibrated VPP. Upwind and downwind maximum VMG values from Section 3.4 are distinct from U/V and are not used as speed references here.

Table 2. Ideal speed-ratio reference evaluated at published heading ranges and compared with representative craft performance [1–4,12–18].

Craft/Course	Observed TWA	Representative Peak Speed		Published U/V
		Knots (km/h)	Ideal U/V at Reported TWA	
SailGP F50 upwind	38–45°	≈43 (≈80)	5.37–6.36	2.5–3.0
SailGP F50 downwind	135–150°	≈55 (≈102)	5.87–7.78	3.0–3.6
iQFOiL upwind	35–42°	≈22 (≈40)	4.92–5.95	1.5–2.0
iQFOiL downwind	140–155°	≈30 (≈56)	5.13–7.19	1.8–2.2
Racing iceboat (maximum speed)	~90°	≈59 (≈109)	10.00	8–10

The ideal reference exceeds the representative hydrofoil speed ratios, illustrating resistance and operating constraints omitted from the zero-loss model. Because the inputs and observations are unmatched ranges, percentage prediction errors are not inferred. Water-side and additional air-side resistance reduce the force margin, while foil loading, control, and environmental effects constrain attainable operation. Iceboats approach the low-resistance ideal more closely under favorable ice conditions [16].

A speed ratio $U/V > 1$ does not violate conservation laws because V is a reference velocity, not a speed limit. The craft extracts energy from the air while the foils, hull, or runners exchange momentum with water or ice and supply the lateral reaction needed to convert aerodynamic lift into forward drive. As U increases, apparent-wind loading and resistance rise until force and power balance establish a finite equilibrium speed. Racing iceboats can reach $U/V \approx 8$ – 10 in steady light wind on smooth, warm ice, but increased aerodynamic and runner drag reduce the ratio to roughly 2–3 in strong winds [16].

The comparison in Table 2 further illustrates the differences between ideal and practical optimum sailing angles. The ideal upwind angle of 47.9° is 2.9 – 9.9° wider than the F50 range and 5.9 – 12.9° wider than the iQFOiL range. The ideal downwind angle of 137.9° lies within the reported F50 range and is 2.1 – 17.1° shallower than the iQFOiL range [17,18]. These deviations identify the scale of missing class-specific resistance, control, and environmental physics.

6. Comparison with VAWT Kinematics and Control

6.1. Relative-Flow Equations and Conventions

Shared Angle-of-Attack Framework

VAWT blade pitch and sail trim orient lifting surfaces relative to motion-modified apparent wind. VAWT pitch control regulates azimuth-dependent tangential force and cyclic loading to improve cycle-averaged torque and power; sail trim regulates forward drive within heel and flight-stability constraints. Their different optimization objectives are discussed in Section 6.3.

The governing nondimensional speed ratios are the VAWT tip-speed ratio λ and the sailing speed ratio S :

$$\lambda = \frac{\omega R}{V_\infty}, \quad S = \frac{U}{V} \quad (18)$$

Here, ω is rotor angular speed, R is rotor radius, where ωR is blade tangential speed, V_∞ is free-stream wind speed, U is boat speed, and V is true wind speed. For an idealized zero-pitch Darrieus blade, the relative-flow angle is $\beta(\theta, \lambda) = \tan^{-1}[\sin \theta / (\lambda + \cos \theta)]$. Blade pitch δ_p changes the aerodynamic angle of attack, $\alpha_{VAWT} = \beta - \delta_p$. In sailing, $\alpha_{sail} \approx \beta - \delta_s$, where β is apparent-wind angle and δ_s is sail trim angle.

For the VAWT comparison, azimuth is measured from the upwind rotor position and increases in the direction of rotation; positive blade pitch rotates the chord toward the local relative wind, and angle of attack is the signed angle from chord to relative velocity. These conventions must accompany the kinematic equation because reversing the azimuth or rotation convention changes the signs. The relation remains idealized because it neglects axial and tangential induction, wake interaction, blade–vortex encounters, three-dimensional flow effects, and dynamic-stall behavior. More refined VAWT analyses show that the inferred angle of attack, dynamic-force hysteresis, and resulting blade loads depend strongly on pitch, rotor solidity, and unsteady flow development [11].

6.2. Similarities in Lifting-Surface Control and Response Time

Control Time Scale and Dynamic Stall

A VAWT blade traverses every azimuth once per revolution, so its relative velocity and angle of attack (AoA) are intrinsically periodic. The available pitch-control window is only a fraction of the rotor period. Active control must therefore provide adequate actuator bandwidth, phase accuracy, stroke, and durability while operating repeatedly under centrifugal and aerodynamic loading. At low-to-moderate λ , large AoA excursions can cause dynamic-stall vortex formation, shedding, hysteresis, torque ripple, and severe transient structural loads. Experiments and analyses identify this cyclic interaction among AoA, dynamic stall, and fatigue as a central VAWT design problem [5,6,10,11].

Sailing usually offers a longer response time than VAWT pitch control. Along a steady course, sail angle, twist, and camber can be adjusted quasi-steadily, although gusts, acceleration, maneuvers, waves, and ride-height disturbances demand rapid corrections.

The idealized VAWT geometry in Figure 4b omits induction, wake interaction, and dynamic stall. Leu et al. [19] used flexible MEMS thermal flow sensors on a pitching airfoil to identify frequency-dependent boundary-layer transition and re-laminarization, demonstrating hysteresis between increasing and decreasing angles of attack. This flow-history-dependent behavior shows why instantaneous angle-of-attack geometry alone cannot fully describe the unsteady response of a pitching blade. It also suggests that cyclic pitching can delay separation during part of the pitching cycle while producing phase-dependent aerodynamic loading. Figure 4 compares a historical sail-windmill configuration [20] along with cyclic VAWT blade pitch and quasi-steady sail trim.

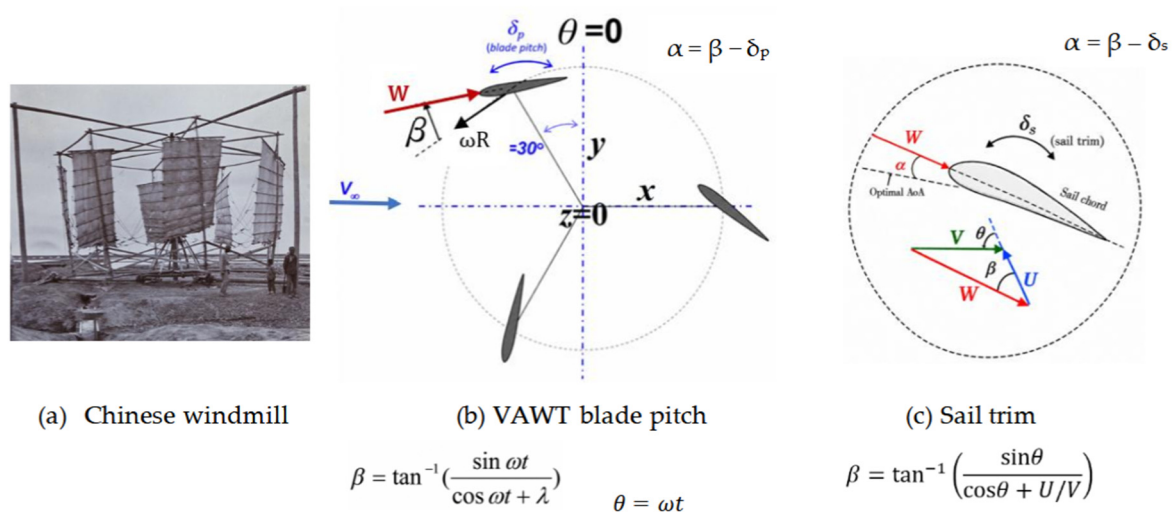


Figure 4. Shared angle-of-attack (AoA or α) and apparent-wind-angle (AWA or β) geometry for (a) a sail windmill used for pumping brine at the Taku Government salt fields near Tientsin, 1912–1914 (William Cooper Collection, WC01-042, Historical Photographs of China Project, University of Bristol; cropped and reproduced with permission); (b) a pitch-controlled lift-type VAWT, adapted from Miao et al. [8]; and (c) a trimmed sail.

6.3. Different Optimization Objectives and Limits of the Analogy

6.3.1. Different System-Level Objectives

VAWT pitch control and sail trim share the regulation of lifting-surface incidence, but their system-level objectives differ. Pitch control can shift the azimuthal region of positive tangential force, reduce dynamic stall, and redistribute cyclic loads. A fixed pitch improved power coefficient by 6.6% at $\lambda = 4$ in one H-Darrieus configuration [7,10]. Miao et al. [8] found that variable pitch improved starting torque and performance at low tip-

speed ratios, while Chen et al. [9] optimized azimuth-dependent schedules to improve torque and power coefficients. The rotor-level optimum therefore balances cycle-averaged energy capture, self-starting, cyclic loads, fatigue, and actuator requirements; maximizing isolated-airfoil lift-to-drag ratio alone does not establish maximum rotor power.

For a sailing craft, sail trim regulates incidence and aerodynamic loading to produce forward drive while limiting heeling moment and maintaining lateral-force balance and foil-borne stability. Measured sail loading depends strongly on trim and apparent-wind angle [21]. The appropriate objective is sustainable speed or effective race-course VMG, accounting for maneuvers and changing wind conditions. For iQFOiL pumping, athlete mechanical work is an additional energy input, whereas active VAWT pitch actuation consumes energy that must be included when assessing net shaft output.

The analogy is limited to relative-flow geometry and selected unsteady mechanisms. Tacking and rotor cycling differ in trajectories and wake interactions; the drag-driven analogy applies near directly downwind sailing, rather than at the lift-driven broad-reach VMG optimum. Sailing's water-side reaction is also distinct from turbine induction.

6.3.2. Characteristic Time Scales and Unsteady Response

Table 3 compares illustrative VAWT rotor periods, iQFOiL pumping periods, and sail-trim adjustment times. Because these time scales describe different processes, similar instantaneous angles of attack do not imply comparable flow histories or aerodynamic responses.

Table 3. Comparison of VAWT pitch control and sail trim in high-performance sailing.

Feature	Lift-Type VAWT	Lift-Based Modern Hydrofoil Sailing and iQFoil
Apparent wind velocity and angle β	Cyclic with blade azimuth and λ , Figure 4b,	Set by true wind, boat velocity, and heading, Figure 4c, Equation (2)
Tip speed ratio or U/V	Tip speed ratio $\lambda = 3$ to 7	Sailing speed ratio $U/V = S \approx 1.5$ to 4 for sailcraft, $U/V \approx 8$ to 10 for iceboat
AoA (α) control	Blade pitch control δ_p , $\alpha = \beta - \delta_p$	Sail trim δ_s , $\alpha = \beta - \delta_s$, twist, and camber
Peak lift-to-drag ratio	Peak 2-D blade-section $L/D \approx 30$ –50, under steady attached flow	Effective sail or wing $L/D \approx 10$ –15, depending on trim and operating conditions
Useful force	Tangential force producing torque	Forward driving force, Equation (5)
Characteristic time	Illustrative rotor period: 0.2 s at 300 rpm; substantial loading changes occur within each cycle.	SailGP: illustrative trim-adjustment time of a few seconds. iQFoil: illustrative pumping period of 0.5 s at 2 Hz.
Unsteady limitation	Dynamic stall, phase lag, torque ripple	Gust response, maneuver loss, foil/ride-height coupling
Cyclic pitching and pumping	Controlled blade pitch varies with rotor azimuth to regulate aerodynamic torque and cyclic loads.	In iQFoil, sail pumping changes sail incidence and local apparent-wind loading to generate transient drive; see Section 7.4.3.
Control energy input	Active pitch actuation requires energy, which must be included when assessing net power output.	The athlete performs mechanical work during pumping; propulsion reflects both wind-energy input and athlete input.
System objective	Maximum cycle-averaged C_p while limiting cyclic and fatigue load	Maximum speed or effective VMG while maintaining stability and control

Note. Author's synthesis based on the references cited in Sections 6 and 7.4.3. Times are illustrative and depend on operating conditions. VAWT and pumping values are cycle periods; the SailGP value is an estimated trim-adjustment time.

7. Practical Constraints and Discussion

7.1. Foiling Transition and Operating Envelope

Below the class-dependent minimum foil-borne speed, the hydrofoils cannot generate sufficient vertical lift to support the craft fully. Partial or complete hull contact then causes a sharp increase in wetted area, frictional drag, and wave-making resistance. Because this displacement-to-foiling transition is nonlinear and may be discontinuous, the present steady closed-form model is not valid in this regime and should be applied only after stable foil-borne operation has been established.

Foiling thresholds depend on class, foil area, loading, athlete or crew mass, course, pumping, waves, and wind. Representative foil-borne onset speeds are about 8–17 knots (4.1–8.7 m/s), with efficient racing commonly at 15–30 knots (7.7–15.4 m/s). Olympic foiling classes may take off in roughly 5–10 knots of true wind; their effective operating range is often approximately 8–25 knots. At stronger winds, aerodynamic loading, ventilation, cavitation, and reduced control margins constrain operation. These ranges are illustrative envelopes, not universal limits.

The high-speed SailGP F50 catamaran achieves stable hydrofoiling at a takeoff threshold of roughly 13–15 knots (6.7–7.7 m/s) of wind speed, translating to a safe operating speed envelope spanning from 25 knots (12.9 m/s) up to an absolute cavitation-limited peak near 56 knots (28.8 m/s or 103.9 km/h).

7.2. Cavitation and Ventilation

Cavitation occurs when local pressure on the foil falls to the water vapor pressure. A useful nondimensional measure is the cavitation number

$$\sigma = \frac{p_{\infty} - p_v}{1/2 \rho_w U^2} \quad (19)$$

Here, p_{∞} is the undisturbed water pressure at foil depth, and p_v is the water vapor pressure. For fixed ambient pressure and water temperature, σ falls approximately as $1/U^2$. Thus, increasing speed makes a given suction peak progressively more vulnerable to vapor formation. Cavitation can reduce lift, increase drag, generate unsteady loading, vibration, noise, and erosion, and ultimately prevent further acceleration. Conventional hydrofoils encounter increasingly restrictive cavitation limits as speed rises, although onset depends on foil geometry, loading, immersion, and operating conditions [22]. The onset and severity of cavitation depend on hydrofoil immersion, hydrodynamic loading, section pressure distribution, surface roughness and condition, dissolved gas content, water temperature, and transient variations in angle of attack.

Ventilation is a distinct free-surface phenomenon in which atmospheric air is drawn downward along a surface-piercing strut, tip vortex, or separated-flow region and spreads over the foil. Mackenzie's [22] numerical and full-scale experiments using an International Moth hydrofoil sailboat found that reduced foil submergence enlarged the ventilated cavity, while interaction between the foil tip and free surface could sustain its development. Because sailing hydrofoils operate close to the air–water interface and frequently pierce it through their struts or tips, ventilation may develop before the onset of classical vapor cavitation. Both mechanisms can abruptly reduce lift and increase drag, disrupting force and moment equilibrium, destabilizing foil-borne flight, and potentially causing sudden touchdown or loss of control.

7.3. Structural, Fatigue, Control, and Sea-State Constraints

Light, slender foils deform under high load. Marimon Giovannetti et al. [23] demonstrated that fluid–structure interaction materially changes hydrofoil response, while Knudsen et al. [24] found that Nacra 17 foil deformation can profoundly affect foil and

whole-boat behavior. Hydroelastic deformation changes effective camber, twist, angle of attack, load distribution, and cavitation margin. A foil optimized as rigid may therefore operate away from its intended shape at racing load. Control authority provides another practical ceiling. Ride-height, pitch, heel, and leeway disturbances grow more consequential as dynamic pressure increases. Waves change immersion and local incidence; crew or automatic systems must respond without exciting oscillations or breaching the foil. The fastest steady VPP point may be unsailable if it has insufficient control margin. Accordingly, the operational speed limit is typically below the hydrodynamic failure boundary and varies with sea state and gustiness.

7.4. Race-Course VMG and Transient Maneuvers

7.4.1. From Steady Polars to Effective VMG

A polar diagram gives U as a function of true-wind angle and speed. For each leg, the optimum VMG is found by maximizing the appropriate projected velocity. Upwind, sailing closer to the wind raises $\cos \theta$ but generally lowers U ; footing faster increases U but lengthens the route. Downwind, very deep sailing shortens distance but may reduce apparent wind, foil loading, and flight stability. The VMG optimum lies at the tangency between the polar and a line of constant progress toward the mark. Empirical work supports treating VMG as a combined technical and tactical variable.

Caraballo et al. [3] used GPS data from elite Formula Kite competitors and defined VMG as the best combination of speed and sailing angle. Their approach is important because race performance depends not only on peak speed but also on sailing distance, maneuver frequency, and time spent in different course sectors. These factors are especially significant for hydrofoil craft, as a tack or gybe can trigger cavitation, ventilation, touchdown, or loss of foil-borne flight, followed by a substantial performance penalty during deceleration, recovery, and re-acceleration.

Hydrofoil races combine straight legs with tacks, gybes, and gate roundings. An illustrative maneuver-intensive SailGP model assigns 80–85% of elapsed time to straight sailing and 15–20% to maneuvers and immediate recovery. These are modeling assumptions, not measured race statistics. Tacks cross the low-drive head-to-wind region; gybes and roundings require coordinated steering, sail trim, and foil control. Class- and course-specific telemetry should determine interval durations and speed losses. iQFOiL formats include differing combinations of upwind, downwind, reaching, and sprint legs [25].

When maneuver intervals include immediate recovery, this time must not be counted again as a separate component. Gate roundings should likewise be assigned distinct intervals unless their durations are already included in tack or gybe measurements. Reaching time may be incorporated into straight-line sailing or treated separately when substantial. Although steady VPP predictions provide a baseline, they can overestimate race performance by neglecting maneuvers, unstable flight, and recovery losses. Separating these time intervals gives the course-level effective VMG:

$$VMG_{eff} = \frac{D_{mark}}{t_{upwind} + t_{downwind} + \sum t_{tack} + \sum t_{gybe} + \sum t_{gate} + \sum t_{recovery} + \sum t_{disp.}} \quad (20)$$

where the numerator is net distance gained toward the mark and the denominator is total elapsed time. Frequent maneuvers, prolonged recovery, touchdowns, and displacement-mode operation can reduce effective VMG despite high steady-state performance. Craft- and course-specific telemetry is therefore needed to determine the time allocation and associated loss terms.

Dynamic velocity prediction programs (VPPs) are particularly valuable for hydrofoil sailcraft because they capture transient takeoff, tacks, gybes, gate roundings, touchdowns, recovery, and re-acceleration losses omitted from steady-state models. Patterson [14]

demonstrated the importance of transient modeling for predicting time to flight and configuration selection, while Melis [26] incorporated displacement, transition, and foiling modes within a unified framework. However, the latter excluded cavitation, ventilation, wave effects, and added resistance, illustrating the need to incorporate additional physical constraints for realistic performance prediction.

7.4.2. Takeoff, Maneuvers, and Flight Recovery

The transition from displacement or skimming operation to stable foil-borne flight is a transient optimization and dynamic-control problem involving sail power, foil loading, pitch, ride height, and trajectory. Rodriguez et al. [27] formulated an adaptive takeoff-maneuver optimization for an America's Cup sailboat, demonstrating that coordinated control inputs and trajectory selection can reduce the time and energy required to establish stable, high-speed foil-borne operation. An effective tack must coordinate heading, rudder or foil control, sail trim, heel, pitch, and ride height to minimize speed loss and avoid touchdown while passing through the low-drive head-to-wind region. Race performance therefore depends not only on maximum steady-state speed but also on the ability to achieve, maintain, and rapidly recover the foiling equilibrium after maneuvers, wave disturbances, ventilation, or touchdown.

7.4.3. Sail and Foil Pumping in iQFOiL

In iQFOiL, athlete-generated pumping couples sail motion with board-foil motion. Sail pumping varies incidence, camber, and apparent-wind loading to generate transient drive, helping acceleration toward takeoff in marginal wind and recovery after a maneuver or touchdown. Olympic-windsurfing measurements document its high physiological demand [28], while iQFOiL testing indicates that footstraps support larger hip and knee movements and coordinated whole-body pumping [29]. Foil pumping is distinct: cyclic body motion heaves and pitches the board-foil system, changing hydrodynamic incidence and loading. Its contribution to lift and propulsion requires separate hydrodynamic analysis.

Section 6.3 and Table 3 compare the relevant time scales. Windsurf-inspired pitching-foil experiments demonstrate unsteady aerodynamic propulsion under specified conditions [30]; performance depends on frequency, amplitude, mean incidence, and phase rather than a universal optimum frequency parameter. The pitching-airfoil hysteresis discussed in Section 6.2 [19] further illustrates the importance of flow history, without directly demonstrating iQFOiL pumping performance. A dynamic VPP should couple aerodynamic sail forces and hydrodynamic foil forces through craft motion while accounting for athlete mechanical power and transient acceleration. The present steady-speed ratio and VMG relations remain a baseline for sustained sailing.

7.5. Sources of Theoretical–Measured Performance Gaps

The gap between ideal and observed speed ratios reflects combined resistance and operating constraints. Foil, strut, and residual hull drag reduce the driving-force margin; takeoff and changing immersion make resistance nonlinear. Cavitation, ventilation, structural loading, sea state, and control limits further restrict steady performance, while maneuver and recovery losses reduce course-average VMG. Thus, the $\gamma = 10$ zero-loss reference is an ideal benchmark rather than a class-specific prediction.

7.6. Practical Applications and Model Limitations

The model supports trend interpretation, parameter screening, and comparison of ideal benchmarks during established, approximately steady foiling. Class-specific

prediction requires independently determined aerodynamic and resistance inputs; operation outside this regime requires a coupled dynamic VPP.

8. Exploratory Energy-Harvesting Application

8.1. Unloaded Speed Limit and Loaded Power Extraction

High-speed sailing couples aerodynamic drive with water-side reaction and resistance [31]. Platzter and Sarigul-Klijn [32] showed that vessel speed, ordinary vessel resistance, and hydrokinetic-turbine drag must be considered together when assessing energy-ship power production. Building on this coupled force-balance concept, the present study introduces a bookkeeping distinction between aerodynamic propulsion power, load-associated mechanical power, gross electrical output, auxiliary consumption, and net electrical output.

Without a generator, steady operation satisfies $F_{drive} = R_{craft}$, where $R_{craft} = R_a + R_h$. Adding generator resistance R_g requires a new loaded equilibrium and recalculated apparent wind. Propulsion power is $P_{prop} = F_{drive} U$; the part associated with the added load is $F_{drive} = R_{craft} + R_g$, $P_{load} = R_g U = P_{prop} - R_{craft} U$; $P_{net,elec} = \eta_{overall} R_g U - P_{aux}$. Here, P_{load} is the mechanical power associated with the added generator resistance. It is not automatically turbine shaft power. The overall efficiency $\eta_{overall}$ accounts for extraction, drivetrain, generator, and other conversion losses, while P_{aux} denotes auxiliary electrical consumption. Quantitative prediction of net electrical output therefore requires independently specified generator-load and conversion-efficiency models.

8.2. Wind-Power Reference and Ideal Propulsion-Power Scaling

A useful aerodynamic parallel exists between a drag-based wind turbine and a sailboat running directly downwind with a drag-dominated spinnaker, as illustrated in Figure 5a,b. In both idealized systems, the relative wind and useful driving force diminish as the moving surface approaches the true wind speed. For an ideal drag turbine, the maximum power coefficient is $C_p = 4C_D/27$, approximately 20% for a representative drag coefficient, under the simplified assumptions of the model [33].

A drag-propelled sailboat likewise cannot exceed true wind speed when sailing dead downwind. Consequently, conventional spinnakers have largely been abandoned in high-performance foiling classes, which sail faster by using lift-based sails on broad reaches and gybing toward the destination. Lift-based turbines operate at tip-speed ratios of approximately 3–7, while lift-based foilers reach $\frac{U}{V} \approx 1.5$ –4 [1,2,12,17,18]. The Betz limit (59.3%) applies to a stationary turbine control volume and cannot be compared directly with a sailcraft speed ratio.

The kinetic-power reference for a stationary wind stream scales with the cube of true wind speed:

$$P = \frac{1}{2} \rho_a A_{rot} V^3 \quad (21)$$

where A_{rot} is rotor swept area. A stationary turbine extracts only a fraction of this flux, whereas a moving lifting surface encounters a different apparent-wind magnitude and control volume.

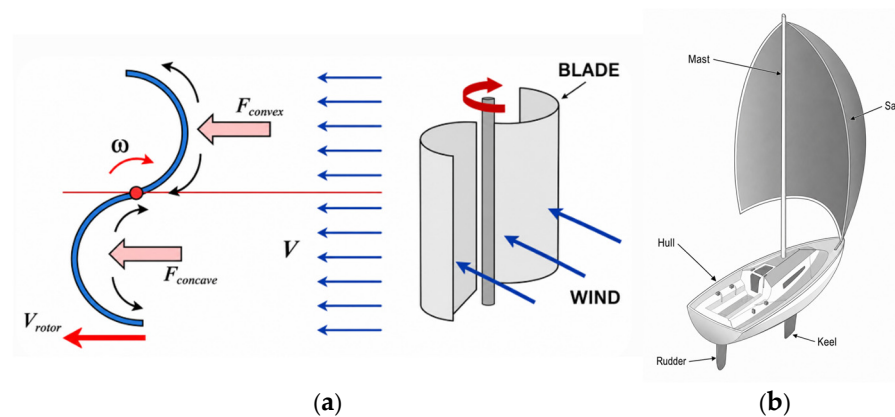


Figure 5. Drag-based comparison: (a) a vertical-axis wind turbine and (b) a sailboat running directly downwind under a spinnaker, for which the boat speed remains bounded by the wind speed.

Figure 6 compares lift-based wind-turbine regulation with the operating wind-speed envelope of hydrofoil sailing. For crosswind motion ($\theta = 90^\circ$), Equations (2)–(5) give $W = \sqrt{U^2 + V^2}$, $L = \frac{1}{2}\rho_a A_s W^2 C_L$, $D = \frac{1}{2}\rho_a A_s W^2 C_D$, $F_{\text{drive}} = L \sin \beta - D \cos \beta$, $\sin \beta = V/W$, and $\cos \beta = U/W$.

$$P_{\text{prop}} = F_{\text{drive}} U = \frac{1}{2} \rho_a A_s W^2 \left(C_L \frac{V}{W} - C_{D,s} \frac{U}{W} \right) U \quad (22)$$

Equation (22) describes aerodynamic propulsion power under the stated crosswind assumptions. With $S = U/V$, its dimensionless form is

$$\frac{P_{\text{prop}}}{\frac{1}{2} \rho_a A_s V^3} = C_L S \sqrt{1 + S^2} \left(1 - S \frac{D}{L} \right) \quad (23)$$

For a large lift-to-drag ratio, optimization gives approximately

$$S_{\text{opt}} \approx \frac{2}{3} \frac{L}{D}$$

and therefore

$$P_{\text{prop,max}} \approx \frac{1}{2} \rho_a A_s V^3 \frac{4}{27} C_L \left(\frac{L}{D} \right)^2 \quad (24)$$

For approximately constant C_L and large L/D , the optimized ideal propulsion-power scale is proportional to $(L/D)^2$. Omitting the numerical coefficient gives

$$P_{\text{prop,max}} \sim \frac{1}{2} \rho_a A_s V^3 C_L \left(\frac{L}{D} \right)^2 \quad (25)$$

Equations (22)–(25) describe ideal aerodynamic propulsion-power scaling, not generator shaft or electrical output. Equal stationary capture areas and Betz limits do not apply to this moving-surface comparison. Craft resistance and extraction losses must be deducted at the loaded equilibrium.

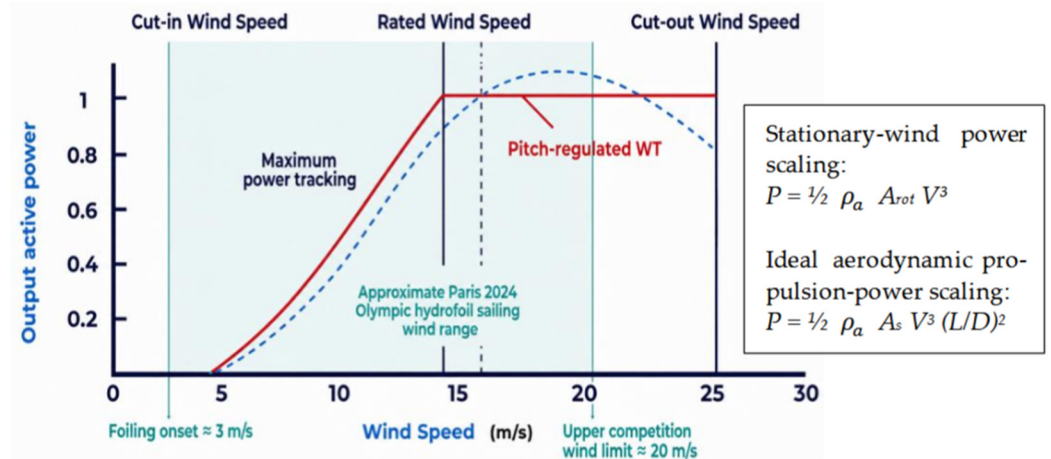


Figure 6. Comparison of lift-based wind-turbine power regulation and the operating wind-speed envelope of high-performance hydrofoil sailing [1,2,4,16–18]. The vertical axis shows power normalized by a reference value; the curves illustrate schematic operating trends.

8.3. Coupled Generator Load and Scope of the Estimate

Predicting net output requires a coupled solution for U , W , sail loading, craft resistance, generator resistance, and conversion efficiency. The load–speed tradeoff is operating-point dependent; no universal maximum electrical output follows from the ideal $(L/D)^2$ propulsion scaling. Cavitation, ventilation, structural limits, and trim changes further restrict operation. Without an independently specified load and efficiency model, the present section makes no quantitative net-generation prediction.

9. Conclusions

The closed-form apparent-wind framework connects sailing angle, effective sail-system L/D , resistance, speed ratio, apparent-wind angle, and upwind and downwind VMG. Prescribed constant K values provide sensitivity comparisons; class-specific prediction requires iterative evaluation of velocity-dependent resistance. Comparisons with representative iceboat, iQFOiL, and SailGP F50 performance illustrate the gap between the ideal reference and practical operation, rather than independently validating the model. The VAWT comparison identifies shared relative-flow geometry and lifting-surface control while distinguishing rotor power optimization from sailing speed or VMG optimization.

The energy-harvesting application remains exploratory: aerodynamic propulsion power is distinct from net electrical output, which requires a coupled, loaded equilibrium and explicit extraction, conversion, and auxiliary losses. Future work should determine model inputs independently, quantify uncertainty, and extend the framework to dynamic sailing and generator-loaded operation.

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Abbreviations

The following abbreviations are used in this manuscript:

AoA	Angle of attack, α
AWA	Apparent-wind angle, β
AWV	Apparent-wind velocity, W
C _p	Power coefficient
L/D	Lift-to-drag ratio, γ
TSR	Tip-speed ratio, λ
TWA	True wind angle, θ
TWS	True wind speed, V
VAWT	Vertical-axis wind turbine
VMG	Velocity made good
VPP	Velocity prediction program

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