Review paper

Self-Starting Enhancement of Small-Scale H-Darrieus VAWTs for Urban Low-Wind Conditions: A Taxonomy of Strategies, Biomimetic Flow Control, and Design Guidelines

Hani Ibrahim [1], Amer Anwar [1], Yahia Abdullatef [1], Asad A. Zaidi [1,*]

[1] Department of Mechanical Engineering, Faculty of Engineering, Islamic University of Madinah, Madinah 42351, Saudi Arabia

***** *Corresponding author:* sali@iu.edu.sa

Abstract: Poor self-starting under low and turbulent urban winds remains a key limitation for small-scale H-Darrieus vertical-axis wind turbines (VAWTs). This review presents a comprehensive and design-oriented synthesis of strategies to enhance self-starting performance in micro-scale H-VAWTs. The study systematically classifies existing approaches into five major categories: rotor configuration modifications, aerodynamic blade design strategies, passive flow control techniques, biomimetic innovations, and active/semi-active mechanisms. Fundamental startup physics, including static and dynamic torque behavior, low tip-speed ratio dead-band, and Reynolds number effects, are critically examined in relation to urban wind characteristics. A detailed comparative evaluation of over 150 studies is conducted to identify the effectiveness, limitations, and trade-offs of each strategy. Particular emphasis is placed on emerging biomimetic approaches such as leading-edge tubercles and J-shaped blades, which demonstrate significant potential in mitigating stall and enhancing low-speed torque without substantial efficiency penalties. Manufacturing considerations, including additive manufacturing feasibility and structural implications, are also discussed. Based on this synthesis, practical design guidelines are developed to support the development of reliable, low cut-in speed VAWTs for urban applications. The review highlights critical research gaps, including the need for standardized testing protocols and long-term field validation. Overall, this work provides a structured roadmap for overcoming the self-starting bottleneck and advancing the viability of decentralized urban wind energy systems.

Keyword: Vertical-axis wind turbine (VAWT); H-Darrieus turbine; Self-starting capability; Urban wind energy; Low wind speed; Biomimetic flow control; Passive flow control; Aerodynamic optimization; J-shaped airfoil; Leading-edge tubercle

1. Introduction

Small-scale vertical-axis wind turbines (VAWTs) are increasingly considered for urban wind energy harvesting due to their compactness and omnidirectional operation, which allows them to accept highly variable wind directions without yaw control [1][2]. In built environments, wind flows are typically characterized by low average speeds and high turbulence intensities due to obstructions (buildings, trees), leading to complex, unsteady inflows [3][4]. Under such conditions, conventional horizontal-axis turbines struggle, whereas VAWTs can leverage their yaw-insensitivity to harness gusty winds more effectively [5]. In essence, many Darrieus rotors cannot autonomously initiate rotation in gentle winds, remaining stationary unless an external kick or sufficiently strong gust occurs. This issue is particularly acute at the micro-scale (<5 kW) where blade Reynolds numbers are low, and startup torques are small.

Self-starting remains a major bottleneck for H-Darrieus VAWTs in rooftop and urban applications [5]. Unlike Savonius turbines, which generate high starting torque but have lower efficiency, lift-based Darrieus rotors often experience weak or negative torque at low tip-speed ratios. As a result, many small VAWTs require wind speeds of about 4–5 m/s to start, which is often higher than typical urban mean wind speeds [6,7]. Reducing the cut-in speed to approximately 2–3 m/s would increase turbine operating time and improve urban energy yield [8,9].

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The difficulty arises because, at rest or low rotational speed, the blades experience high angles of attack and early stall. Symmetric airfoils such as NACA 0015–0018 generate limited lift under these conditions, and mechanical losses such as bearing friction and generator cogging can further reduce the available starting torque [10]. These aerodynamic and mechanical effects create a low-speed torque deficit that prevents many small H-Darrieus turbines from accelerating without assistance.

This review is motivated by the need to address the self-starting bottleneck through a structured, design-oriented synthesis of past and emerging solutions. A plethora of strategies have been investigated to improve the starting torque or cut-in speed of H-Darrieus VAWTs, ranging from simple geometric tweaks (e.g., adding more blades) to advanced biomimetic flow control (e.g., leading-edge tubercles inspired by humpback whales). However, the literature is fragmented, and a unifying framework is lacking. Here, we provide a taxonomy of self-start enhancement strategies and critically evaluate each category's mechanisms, effectiveness, and trade-offs. By organizing the diverse approaches into coherent groups and comparing their performance, we aim to identify which methods (or combinations) are most promising for small-scale, low-Reynolds VAWTs in urban low-wind conditions.

This article offers several key contributions. (1) It delineates a comprehensive taxonomy of self-start improvement techniques, spanning rotor configuration modifications, blade aerodynamic design, passive flow control devices, biomimetic innovations, and active/semi-active mechanisms. This taxonomy (illustrated conceptually in Figure 1) provides researchers and designers with a structured map of the solution space. (2) It synthesizes findings from over a decade of studies (including >150 references) to distill design-oriented insights – for example, how increasing blade solidity vs. adding a vortex trap affects startup, or when a bio-inspired blade is worth the complexity. Rather than a mere paper-by-paper summary, we emphasize comparative evaluation and practical takeaways. (3) It identifies critical knowledge gaps (e.g., lack of standardized startup testing protocols, limited field validation data) and suggests future research directions, particularly highlighting opportunities for hybrid strategies and biomimetic concepts that remain underexplored. (4) Importantly, we develop clear design guidelines for practitioners in Section 8, translating the review findings into actionable recommendations (for instance, when to consider tubercled blades, what airfoil/pitch to use at low Re, etc.). The goal is to bridge academic advances with real-world turbine design.

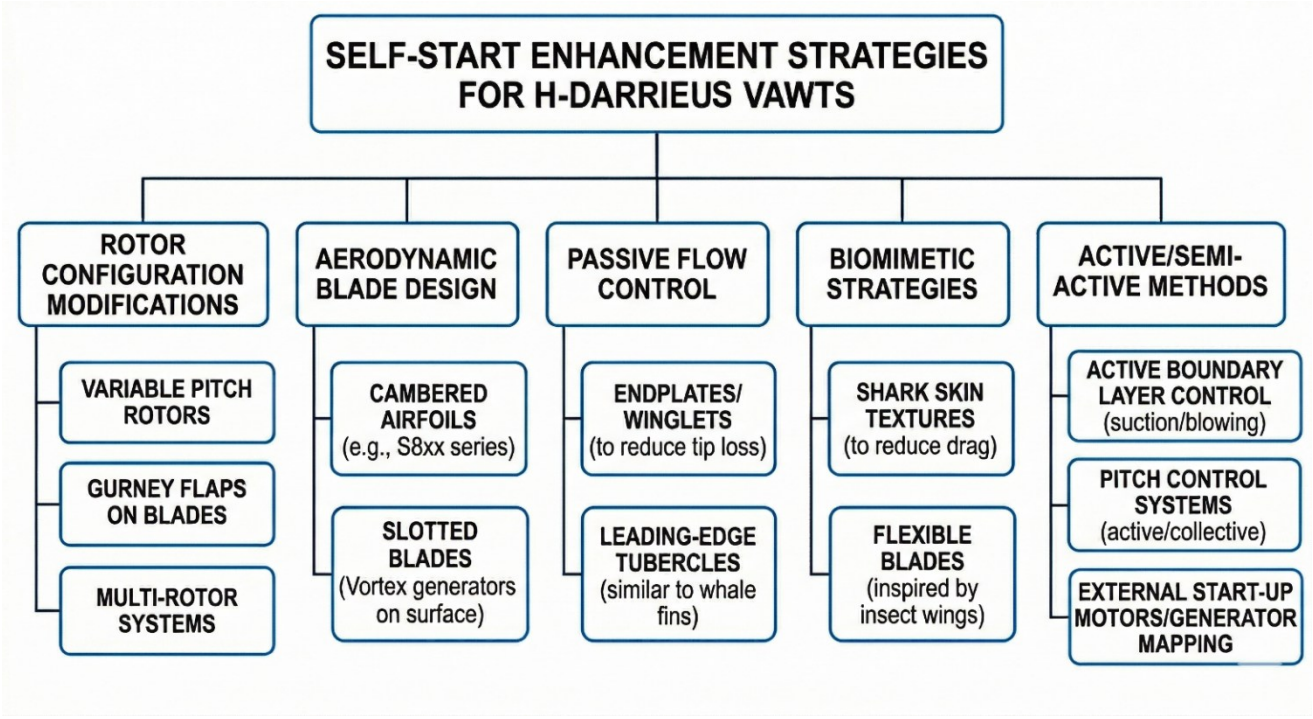

Figure 1. Classification of self-start enhancement strategies for H-Darrieus VAWTs.

In the following, Section 2 lays out the fundamental physics of self-starting in H-Darrieus turbines, defining key concepts such as static vs. dynamic torque and the low-TSR "dead band." Section 3 discusses the peculiarities of urban wind conditions and their implications on turbine startup. Section 4 (the backbone of the paper) presents the taxonomy of self-start enhancement strategies, with subsections covering rotor configuration, blade design, passive flow control, biomimetics, and active techniques. Section 5 addresses manufacturing and prototyping considerations for implementing these strategies at a small scale. Section 6 reviews experimental and numerical methods for evaluating startup performance, highlighting the need for consistent metrics. In Section 7, we provide a comparative synthesis, examining how different strategies stack up and where trade-offs occur (including negative results that are seldom reported). Based on this analysis, Section 8 formulates practical design guidelines. Finally, Sections 9 and 10 outline research gaps, future directions, and conclusions, respectively.

Overall, by prioritizing startup viability (even over peak power coefficient) and focusing on small-scale H-Darrieus turbines in low-wind urban environments, this review is positioned to inform the design of the next generation of micro wind turbines that can reliably self-start and thereby unlock greater energy capture in cities. In the long term, improving self-starting will enhance the capacity factor and economics of urban wind installations, contributing to a more decentralized and resilient renewable energy mix [11][12].

2. Fundamentals of Self-Starting in H-Darrieus VAWTs

Defining self-starting: A VAWT is considered self-starting if it can accelerate from rest to a rotational speed at which it produces net positive power under its own aerodynamic torque, without external intervention [13][14]. Various quantitative definitions exist in the literature. Early researchers simply required the turbine to reach a "significant" power output or rotation rate on its own [14]. For example, Kirke (1998) defined a self-starting turbine as one that can accelerate from zero to a speed sufficient to generate appreciable power, essentially surmounting the initial static friction and generator load [15]. Lunt (2005) proposed a more specific criterion: reaching a tip-speed ratio $\lambda = 1$ (i.e., blade speed equal to wind speed) from rest signifies successful start-up [16]. Worasinchai et al. (2016) further refined this by adding that the turbine must then continue to accelerate to a stable operating TSR where aerodynamic driving torque balances resistive torque (i.e., an equilibrium point) [17]. In practical terms, self-starting means the turbine can get itself into the normal power-producing regime whenever the wind exceeds the cut-in threshold, without needing a push or an auxiliary motor. For the small H-Darrieus turbines of interest, achieving self-start in ~2–3 m/s winds is a desired benchmark often cited [18].

Static vs. dynamic torque: The aerodynamic torque on a VAWT rotor varies strongly with the blades' azimuthal position and rotor speed. Static torque refers to the torque when the rotor is held stationary at a given angle – conceptually, this is the initial torque available to start turning the rotor from rest. It depends only on the instantaneous wind and blade orientation. Dynamic torque refers to the torque during rotation, where aerodynamic forces are influenced by motion (e.g., dynamic stall effects, added mass, wake interaction). In the context of self-starting, the static torque curve as a function of rotor angle (or azimuth) is a fundamental characteristic: if the static torque is negative at any angle, a stationary turbine may get "stuck" in that position unless overcome by inertia or gusts. For a conventional 3-bladed H-VAWT with symmetric airfoils, the static torque often goes negative over a significant portion of the cycle at low rotor speeds. This leads to preferred rest positions (typically with one blade broadside to the wind) where startup torque is minimal. A self-starting design ideally produces positive static torque over the entire 360° rotation, so that no matter where the rotor stops, it can initiate motion (some recent designs indeed strive for this, e.g., by adding drag elements or using special airfoils[19]).

However, static analysis alone is insufficient. Once the rotor begins turning, dynamic effects come into play. Hill et al. (2009) famously observed that a Darrieus turbine's self-start process goes through four phases [20]: (a) an initial rapid acceleration from rest (governed by static torque in the first instant), (b) a plateau stage where acceleration stalls or the rotor coasts at low TSR (often due to hitting the "dead band" of negative torque around λ approx. 1), (c) a second acceleration phase once the rotor passes into a range of positive net torque, and finally (d) steady-state operation at the design TSR. This behavior is illustrated conceptually in Figure 2, which shows the transient TSR evolution and the notorious dead-band plateau. The plateau corresponds to the rotor encountering significant aerodynamic drag and dynamic stall, limiting further acceleration until either a gust or inertia

carries it through. In many cases, turbines fail to exit this plateau and instead slow down again – a failed self-start. Thus, while static torque is a useful indicator, the true test is whether the turbine's inertial energy and unsteady aerodynamic forces can propel it through the low-TSR stall regime to reach the "second acceleration." In practice, a lightly loaded rotor (minimal generator braking) with sufficient inertia can sometimes coast through short spans of negative torque (in effect, using momentum to overcome adverse torque regions). This explains why adding a heavy flywheel or minimizing generator load helps in self-start – though a heavy rotor may need more initial torque, it is less prone to being stalled by momentary torque deficits.

Many Darrieus VAWTs exhibit a low-TSR dead-band, typically around $\lambda = 0.5–1.5$, where average aerodynamic torque becomes weak or negative. This occurs because the blades operate at high angles of attack, causing stall and reducing lift-based torque. The design implication is clear: to self-start, a turbine must generate positive net torque at all TSRs up to the point of power equilibrium. Strategies to achieve this include increasing drag at very low speeds (to get an initial push) or tailoring blade aerodynamics to give more lift at high angles of attack. Baker (1983) suggested using airfoils that perform better at low Reynolds numbers and high α as one remedy [21]. Modern approaches (as we will detail) go further: for instance, J-shaped or modified profiles that avoid deep stall, or passive flow devices that energize the flow, can shrink or eliminate the dead band [22][19].

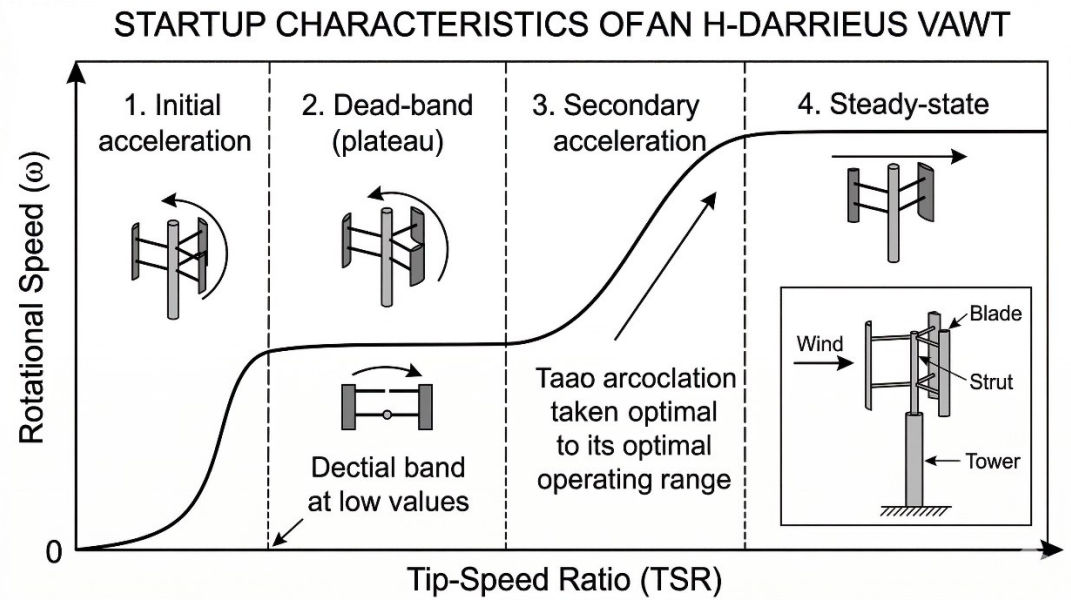

Figure 2. Startup phases of an H-Darrieus VAWT showing initial acceleration, dead-band region, secondary acceleration, and steady-state operation.

Role of Reynolds number: Small-scale VAWTs operate in the low-to-moderate Reynolds number regime (on the order of 104–105 at startup, depending on blade chord and wind speed). At these Re, most turbine airfoils experience early transition or even laminar separation. The lift curves tend to be shallower, and stall occurs at lower angles of attack compared to high-Re conditions [23]. This intensifies the startup problem: the blades stall more readily when the rotor is turning slowly. Additionally, many symmetric NACA profiles were designed for higher Re and exhibit poor lift-to-drag at $Re < 2x10^5$. The consequence is that the initial aerodynamic torque is even lower than predicted by idealized models, and purely lift-driven startup is very weak. Empirical studies confirm that using thicker or specially shaped airfoils optimized for low Re can improve self-start [24]. For example, experiments by Du et al. (2019) showed that a simple symmetrical NACA airfoil (with gentle stall characteristics) yielded better startup torque than a thin cambered blade that stalled abruptly [24]. Low Re also means a higher viscous drag proportion, so any flow separation drastically reduces net torque. Some strategies in Section 4 explicitly tackle low-Re performance (e.g., roughness or vortex generators to trip flow to turbulent, which can delay stall).

Blade inertia and system resistance: The inertia of the rotor plays a dual role in self-start. A higher moment of inertia (from heavier blades or added flywheel mass) smooths out the acceleration – beneficially, it lets the rotor carry momentum through brief periods of negative torque (limiting the speed drop in the dead-band). On the other hand, too high an inertia means the rotor needs more time (and integrated torque) to spin up, potentially missing short wind gusts. Designers thus face a trade-off: lightweight rotors respond quickly to wind changes but may stall at each lull; heavier rotors have more staying power but are harder to get moving initially. Generally, light but low-friction systems are preferred, and some form of torque augmentation is used to compensate for the lack of inertia.

Another major factor is generator/load torque. In small wind turbines, the generator's cogging torque (due to magnets in permanent-magnet alternators) can present a significant static friction that must be overcome for the rotor to start turning [10]. Manufacturers often quote a "startup wind speed" assuming the generator is connected – many H-Darrieus designs require >4 m/s just to overcome cogging and static friction, even if aerodynamic torque were available. A common practice in experiments is to disconnect or "freewheel" the rotor (no electrical load) to measure purely aerodynamic self-start behavior. In real deployments, one solution is to use a cut-in clutch or smart controller: the turbine is allowed to spin freely until a certain RPM before the generator is electrically connected, thereby avoiding the cogging brake in the initial stage. While effective, this adds complexity. Alternatively, using low-cogging generator designs (e.g., coreless alternators) can reduce startup resistance [25]. In any case, when evaluating self-start improvements, one should consider whether results account for generator loading or not, as this can make a practical difference of 1–2 m/s in cut-in speed.

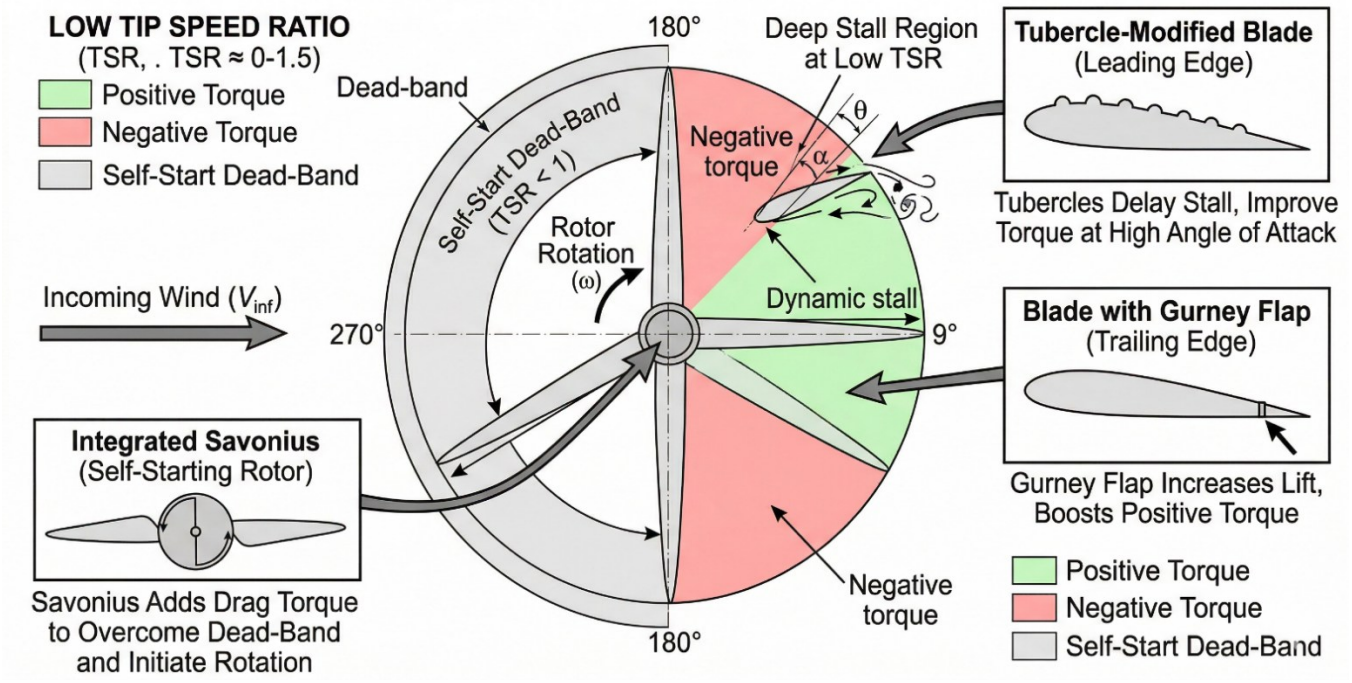

Figure 3. Mechanisms of self-start limitation and enhancement in H-Darrieus VAWTs at low tip-speed ratios.

Limitations of classical theory: It is worth noting that classical turbine performance prediction tools (like the blade element momentum theory, BEM) struggle to model the startup process [26]. BEM assumes a quasi-steady flow and usually requires an empirical static lift/drag curve as input – assumptions violated during the highly unsteady, separated flow at low TSR. As a result, BEM often cannot predict whether a given VAWT will self-start or not, since it cannot capture the dynamic stall hysteresis and rapid changes in effective wind seen by the blades [26]. More advanced unsteady models or full computational fluid dynamics (CFD) are needed to analyze startup aerodynamics in detail. Historically, the computational expense of time-accurate CFD made such studies rare [27], but recent advances (and increased computing power) have enabled 2D and even 3D CFD simulations of

the entire startup process [28][29]. These studies have shed light on phenomena like the transient formation of leading-edge vortices on the blades at low TSR, and the contribution of blade drag in the initial acceleration [30]. One interesting finding is that blade drag can contribute positively to torque during the first few revolutions (essentially acting like a Savonius component) [31]. This reinforces the idea that some "drag augmentation" at startup isn't always bad – a theme that will recur with hybrid designs.

In summary, the self-starting of H-Darrieus VAWTs is governed by a complex interplay of aerodynamic design (airfoil characteristics, blade shape), rotor configuration (number of blades, inertia), and external conditions (wind turbulence, mechanical loading). The fundamental challenge is to ensure positive net torque from standstill up to the operating TSR, overcoming the natural stall-induced dead-band. These limiting mechanisms and the corresponding enhancement routes are summarized schematically in Figure 3. In the next sections, we explore how various strategies tackle this challenge. But first, we examine the specific nature of urban wind conditions, as the operating environment for our turbines of interest adds another layer of complexity to the startup problem.

3. Urban Low-Wind Operating Conditions

Urban wind regimes differ markedly from the idealized smooth flows of wind tunnels or open plains. Wind in the built environment is characterized by lower mean speeds, high turbulence intensity, vertical shear, and rapid directional changes due to the effects of buildings and other structures [3][4]. These factors have significant implications for VAWT startup behavior:

Lower wind speeds: Urban wind speeds are commonly in the 2–4 m/s range, especially within the canopy layer and on rooftops [32]. Therefore, turbines with cut-in speeds around 4 m/s may remain idle for long periods. Lowering the cut-in speed is therefore essential for practical urban deployment [34].

High turbulence and gustiness: Turbulence intensity (TI) in urban winds can easily exceed 20–30%, compared to 5–10% in open terrain [35][36]. Eddies shed by buildings create pulsating wind speeds and momentary directional shifts. For a VAWT, turbulence has a dual effect. On one hand, turbulence can help initiate rotation by providing random fluctuations – a sudden gust or directional change might kick a stationary rotor into motion where a steady low wind would not. Indeed, experiments have shown that adding turbulence in a wind tunnel can enhance the measured static torque and startup performance of a VAWT [37]. Sun et al. (2023) observed that a turbulent inflow increased the static torque coefficient of an H-rotor at low TSR, effectively aiding self-start, although it also introduced greater cyclic loading on the structure [38]. On the other hand, high turbulence means the turbine is constantly subjected to gusts and lulls. A lull can quickly decelerate the rotor (since small VAWTs have low rotational inertia), possibly dropping it back into the stall regime. Moreover, turbulence imposes fatigue-inducing loads: rapid changes in wind speed and direction cause oscillating torques. Straight-bladed VAWTs have been noted to experience strong vibratory loads in turbulent flow, whereas helical-bladed variants distribute the load more evenly [39][40]. In summary, turbulence might trigger startup but also threatens to interrupt it unless the turbine has some margin (e.g., a strong positive torque surplus to ride through fluctuations).

Wind direction variability: Urban wind direction can shift significantly over short time scales (seconds) due to channeling around buildings. H-Darrieus turbines do not require yaw alignment, which is a major advantage in such settings [1][2]. A rapidly veering wind that would leave a horizontal-axis turbine misaligned (producing zero torque until it yaws) can still drive a VAWT. This improves the effective starting probability in unsteady winds – even if the wind comes from an unfavorable angle for one blade, another blade on the rotor may catch it. Additionally, multidirectional turbulence tends to reduce the likelihood of the rotor getting stuck at a stable stall orientation because the changing wind vector continually alters the relative angle of attack. In essence, turbulent eddies can "jiggle" a stalled rotor out of a torque minimum. However, if the wind direction is extremely inconsistent, the rotor may have difficulty accelerating smoothly in a single direction – it might oscillate back and forth. Field anecdotes have noted small VAWTs sometimes rock or reverse under highly chaotic winds, complicating the startup process [35].

Vertical wind shear: In urban environments, wind speed generally increases with height above the rooftop or street level. A small VAWT with finite height will see a difference in wind speed along its span (especially if mounted low). This vertical shear can cause an imbalance in torque between the upper and lower parts of the rotor. For self-starting, shear is usually a minor secondary effect, but it could cause slight twisting or additional stress during startup.

Built-environment specific flows: Features like corner vortices, roof-edge accelerations, or alley wind channels mean that the wind a turbine experiences may be very site-specific [41][42]. For instance, on the roof of a building, wind from one direction might create a recirculation bubble (dead air), whereas a slight shift could bring a strong, accelerated flow over the roof edge. Turbines sited in such locations might see bimodal wind conditions – either nearly zero or a strong burst. Designing for self-start in this context might involve ensuring the turbine can exploit those brief energetic bursts. Some researchers have looked at augmenting flows (e.g., guiding wind toward the turbine with shrouds or diffusers to mitigate these effects) [43], which we will cover as incident-flow augmentation strategies.

Differences between controlled tests and reality: In laboratories, self-start tests are often done in smooth laminar flow or low-turbulence wind tunnels [3]. These conditions may overestimate startup performance because the turbine doesn't encounter the same degree of fluctuating loads. A turbine that self-starts consistently at 3 m/s in a lab might, in the field, stall out due to turbulence or spend longer in the plateau phase due to gust/lull cycles. Conversely, the occasional gust in the field might start a turbine at a lower mean wind than what a steady test would indicate. Because of this, field validation is essential. Unfortunately, few studies have published detailed field start-up data for small VAWTs. Those that exist (e.g., the Warwick field trials and Energy Saving Trust monitoring in the UK) found that urban-installed small turbines often underperformed expectations, partly due to higher turbulence and siting issues [35]. Turbines spent significant time idle even in ostensibly "windy" sites, highlighting the importance of reliable self-start mechanisms.

In summary, urban winds are unsteady and generally weak, placing greater importance on achieving a very low cut-in speed and on designs that can handle highly variable inflows. A self-starting enhancement that works in a steady 5 m/s wind tunnel might not translate to success in a rooftop environment with 0–6 m/s gusts and 30% turbulence. Therefore, in this review, we particularly value strategies that have been tested (or at least simulated) under unsteady or turbulent conditions. For example, if a passive flow control device shows improved torque in both smooth and turbulent inflow, it suggests robustness. Where possible, we will note the turbulent wind performance of various techniques. The differences between controlled conditions and urban reality are also discussed in Section 6 when reviewing evaluation methods.

Overall, urban wind conditions make reliable self-starting essential. A turbine that performs well in a smooth 5 m/s wind tunnel test may not start reliably on a rooftop with low mean speed, gusts, and high turbulence. Therefore, the strategies reviewed in the next section are assessed with particular attention to their relevance for low-speed and unsteady urban inflow.

4. Taxonomy of Self-Starting Enhancement Strategies

There is no single silver bullet for the self-starting problem; instead, researchers have explored a broad range of strategies. We organize these approaches into five major categories in this taxonomy (illustrated schematically in Figure 1):

Rotor Configuration Modifications: Altering the macro-design of the rotor – number of blades, solidity, blade orientation (helical vs straight), or adding secondary rotors – to improve starting torque characteristics.

Aerodynamic Blade Design Strategies: Changing the blade's sectional properties or motion – airfoil selection, preset pitch angle, novel shapes like J-shaped or cambered blades – to enhance low-Re and high-angle-of-attack performance for startup.

Passive Flow-Control Techniques: Attaching or shaping passive devices on the blade – e.g., leading-edge tubercles, Gurney flaps, trailing-edge serrations, surface roughness, slots or cavities – that alter the flow around the blade to delay stall or increase instantaneous torque without active control.

Biomimetic and Nature-Inspired Strategies: Drawing inspiration from biology – e.g., humpback whale flippers (tubercles), maple seeds (autorotating samaras), bird wings – to develop blade geometries or rotor designs that passively achieve better startup aerodynamics (some overlap with 4.3, but we separate for emphasis).

Active and Semi-Active Techniques: Using movable or controlled elements – active pitch control, mechanical starters, adjustable geometry, or flow actuators (like plasma or jets) – to directly intervene in the startup process. These tend to be highly effective but may be less practical for small turbines.

Each category encapsulates multiple specific techniques. Table 1 (at the end of Section 4) summarizes the taxonomy, listing representative techniques under each category along with their primary mechanism, typical effects on cut-in speed, torque ripple, peak power coefficient, and evidence base (CFD, experimental, or field). We now delve into each category in detail.

4.1 Rotor Configuration Modifications

Blade number and solidity: Increasing the number of blades or rotor solidity is one of the most established ways to improve the self-starting of H-Darrieus VAWTs. The main mechanism is straightforward: higher solidity increases the blade area interacting with the wind at low tip-speed ratios, which improves average starting torque and reduces the probability of zero- or negative-torque azimuthal positions [44–46]. This explains why two-bladed Darrieus rotors often show poor self-starting behavior, whereas three-bladed rotors are generally more reliable, and four- or five-bladed configurations can further reduce cut-in speed in low-wind conditions [44–47]. However, this improvement is achieved at the cost of increased profile drag, lower optimum tip-speed ratio, and possible reduction in peak power coefficient [45,46]. Therefore, moderate solidity is usually preferable for small urban turbines, because it improves startup while avoiding excessive efficiency loss at normal operating speeds.

Helical (twisted) blades vs. straight blades: Helical blades improve self-starting mainly by smoothing the azimuthal torque distribution. Because the blade is twisted along the height, different blade sections interact with the wind at different azimuthal positions, reducing dead spots and torque ripple compared with straight-bladed rotors [47–50]. This makes the startup more stable and reduces vibration, which is particularly useful for small urban turbines [39,40]. However, the absolute improvement in starting torque is often modest, and several studies indicate that helical rotors may show lower peak power coefficient than equivalent straight-bladed H-rotors because some blade sections operate away from their optimum aerodynamic condition during normal rotation [50–52]. Therefore, helical geometry is most useful when smooth startup, reduced cyclic loading, and quieter operation are prioritized over maximum peak efficiency.

Blade pitch (fixed offset): Although H-rotors are typically “zero-pitch” (airfoil chord radial), some designs use a fixed pitch angle setting (toe-in or toe-out) for the blades. A small negative pitch (airfoil leading edge tilted slightly inward) can improve startup by increasing the angle of attack on the advancing blade, generating more lift at low TSR [54][55]. For example, an optimal pitch of –2° to –6° was found to boost power at low TSR in several studies [54]. This effectively pre-stalls the blade a bit at design speed but gives a lift advantage in the startup regime. The trade-off is a slight drop in peak efficiency if over-pitched. Nonetheless, a **mild preset pitch is a low-tech way to get extra starting torque** without moving parts. Some small commercial VAWTs use ~5° pitched blades for this reason. Elangovan & Pillai (2025) specifically studied pitched blades with leading-edge protuberances and found that a small pitch angle dramatically influences the self-start torque characteristics [33]. The optimum pitch can depend on the airfoil; for NACA 0018, around –2° yielded the best startup performance in Celik et al. (2022) simulations [55].

Hybrid Darrieus–Savonius rotors: Hybrid Darrieus–Savonius configurations are among the most effective passive solutions for improving self-starting. The Savonius or drag-based component supplies positive starting torque at very low rotational speeds, allowing the rotor to overcome the low-TSR dead-band before the Darrieus blades become aerodynamically effective [57,58,62]. Variants of this idea include concentric Savonius rotors, stacked or integrated drag elements, semi-cylindrical blade attachments, auxiliary drag blades, and deflector-assisted hybrid arrangements [57–64,70,71]. Collectively, these studies show that hybridization can make static torque positive over a wider azimuthal range and can substantially reduce cut-in speed [60–64].

The main limitation is the additional drag imposed during normal operation, which usually reduces peak power coefficient and may limit the achievable tip-speed ratio [57,58,64]. Therefore, hybrid rotors are most suitable when a reliable low-wind startup is more important than maximum aerodynamic efficiency.

Altered aspect ratio and rotor height: Some research has looked at the effect of the blade aspect ratio (height vs diameter). A taller rotor (higher aspect ratio) intercepts a larger vertical extent of wind. Seifi Davari *et al.* (2024) examined blade height impacts and found that taller rotors improved self-start torque somewhat [65], likely by capturing wind gradients and distributing forces. However, very tall, slender rotors can have structural issues and may interact with vertical shear (top part starting before bottom). Most urban turbines are relatively squat due to installation practicalities, so aspect ratio changes are a minor lever compared to others.

Dual-stage and novel configurations: Dual-stage, phase-offset, and flow-augmented rotor configurations aim to improve startup by redistributing torque production over the rotation cycle. By offsetting blade positions between rotor stages, the positive torque generated by one stage can compensate for the weak-torque region of another, producing smoother acceleration and shorter startup time [66–69]. Other novel configurations use auxiliary rotors, modified Savonius elements, deflectors, guide vanes, or concentrators to increase the effective inflow or provide additional drag-assisted torque during startup [70–79]. These approaches can improve self-starting and low-speed performance, but they also increase geometric and structural complexity. Therefore, they are most appropriate when the performance gain justifies the added manufacturing and installation difficulty.

In summary, rotor-level modifications revolve around increasing torque production at the cost of higher drag or complexity. Key takeaways for self-start: use at least three blades, consider a slight twist or multi-level design to smooth torque, and hybridize with drag elements if necessary. These interventions ensure that the turbine has no pronounced dead zones in torque. Many of these are *built-in* features decided at design time, in contrast to the blade add-ons of Section 4.3. It's common to combine strategies here: for instance, a hybrid Darrieus-Savonius might also use a helical twist on the Darrieus blades. As we move on, keep in mind that improving the configuration can mitigate the fundamental limitations, but fine-tuning the blade aerodynamics (next section) is also crucial to really boost that low-TSR performance.

4.2 Aerodynamic Blade Design Strategies

This category deals with how the *shape and design of the blades themselves* can be optimized for better startup. Instead of adding appendages or secondary rotors, these strategies tweak the blade profile or motion to inherently generate more torque at low speeds.

Airfoil selection (low-Re airfoils): Airfoil selection strongly affects self-starting because small H-Darrieus turbines operate at low Reynolds numbers and high angles of attack during startup. The literature generally indicates that airfoils with gentle stall behavior, sufficient thickness, and stable low-Reynolds-number lift characteristics are more suitable than very thin profiles [23,24,72]. Thick symmetric profiles, such as NACA 0018, can improve starting torque because they delay abrupt stall and provide useful drag contribution at low TSR [24]. Custom low-Reynolds-number airfoils and distinctive blade profiles can further improve startup when they maintain lift over a wide angle-of-attack range [72,74]. However, airfoils selected only for high lift-to-drag ratio at the design TSR may not perform well during startup, where post-stall stability and low-speed torque are more important [23,24,72]. Therefore, airfoil selection for small urban VAWTs should prioritize low-Reynolds-number robustness, delayed stall, and positive torque generation at low TSR.

Ultimately, airfoil optimization for self-start often means prioritizing high lift at low Re and high α over the absolute maximum C_l/C_d at cruise. This might involve: leading-edge curvature that delays separation, thicker profiles for earlier transition, or even roughness to trip laminar flow. A recent design by Abul-Ela et al. (2025) proposed distinctive airfoils specifically to enhance self-start [74], presumably with such characteristics. The evidence indicates that a well-chosen airfoil can improve starting torque by on the order of 20–30% [75]. However, note that any airfoil must work for both directions of rotation (since the blade sees

relative flow from both sides each revolution). Thus, symmetric or nearly symmetric profiles remain common, with modifications to improve their stall. The use of *J-shaped and S-shaped* profiles is one such innovation we turn to next.

J-shaped and modified trailing-edge blades: J-shaped blades improve self-starting by modifying the trailing-edge region so that separated flow can form a stable recirculation zone or trapped vortex. This mechanism increases torque at low TSR and reduces the severity of stall during startup [73,76–79]. Across recent numerical and experimental studies, J-shaped profiles have been shown to increase starting torque, reduce negative torque regions, and improve low-speed performance compared with conventional symmetric airfoils [72,73,76–79]. The benefit depends strongly on the degree of trailing-edge modification, blade height, and pitch setting; optimized J-shaped configurations can enhance startup without a severe peak-efficiency penalty, whereas excessive cutting or cavity size can increase drag [73,78,79]. Therefore, J-shaped blades are promising for small urban VAWTs because they enhance low-speed torque through blade geometry alone, without requiring external devices or active control.

Cambered and S-shaped airfoils: Using a cambered (asymmetric) airfoil on a VAWT blade is tricky because the blade sees flow from both sides each rotation (on the upwind half vs. downwind half of the cycle). One clever approach is the S-shaped airfoil, which is a cambered profile symmetric about the mid-chord – effectively two cambered surfaces back-to-back. This gives a positive lift in both flow directions. S-shaped or "self-stable" airfoils have been proposed for self-starting turbines so that the blade always has a lifting component aiding rotation regardless of the direction of relative wind. Some early vertical-axis designs (e.g., the Musgrove turbine) tried variable camber concepts, but modern incarnations use fixed S-curves. While not as common as other methods, a properly tuned S-shaped section can increase starting torque, though it often lowers efficiency (since neither side is as aerodynamically clean as a pure profile).

Passive pitch (articulated or flexural): Passive pitch strategies use hinged, spring-loaded, flexible, or aeroelastically adaptive blades to adjust the angle of attack during rotation without external power. By allowing the blade to align more favorably with the relative wind at low TSR, these mechanisms can reduce negative torque during the return stroke and improve the probability of successful startup [80–82]. Flexible-blade and fluid–structure interaction studies also indicate that passive deformation can influence torque generation and dynamic stall behavior, especially under unsteady loading [80,81]. The main challenge is mechanical durability and repeatability: the pitch response must be tuned carefully so that the blade improves startup without introducing flutter, excessive deformation, or structural fatigue. Therefore, passive pitch is promising but more mechanically complex than fixed-geometry blade modifications.

Summary of blade design strategies: The guiding principle is to modify the blade so that it produces higher aerodynamic force at the angles and speeds characteristic of startup. This can mean boosting lift (via camber, J-shape, high-lift airfoil), increasing drag in a helpful direction (blunt trailing edge, thicker section), or altering orientation (preset pitch, passive pitch change). The evidence suggests each of these can individually contribute a significant improvement in static torque and cut-in speed. For instance, just changing the airfoil from NACA0015 to a well-chosen low-Re profile might lower cut-in by 0.5 m/s [24]; adding a J-trailing-edge might lower it further by another 0.5 m/s. These incremental gains add up. The best results often combine multiple: e.g., a J-shaped cambered blade with a preset pitch has multiple means to generate torque in the critical phase [72]. One must be cautious, however, not to compromise too much on efficiency: a blade optimized solely for starting could have very high drag that caps its performance once running. In Section 7, we'll compare these trade-offs. But next, we discuss passive flow control add-ons, some of which can be applied on top of any blade design to further enhance startup.

4.3 Passive Flow-Control Techniques

Passive flow-control methods involve adding features to the blade that alter the airflow in beneficial ways **without requiring any active input**. These devices or surface modifications are often inspired by aerodynamic tricks used in aircraft or by nature. They aim to delay stall, reduce flow separation, or increase lift/drag as needed during startup.

Leading-edge tubercles: Leading-edge tubercles are biomimetic passive flow-control features inspired by humpback whale flippers. Their main aerodynamic effect is to generate streamwise vortices that energize the boundary layer, delay stall, and reduce abrupt torque loss at high angles of attack [83–87]. For H-Darrieus VAWTs, this is particularly relevant during startup because the blades operate in stalled or near-stalled conditions at low TSR [85,86,91]. Overall, experimental and numerical studies show that tubercles can increase post-stall lift, improve torque stability, and enhance low-speed performance, although the magnitude of improvement depends on amplitude, wavelength, Reynolds number, airfoil type, and turbulence intensity [85–88,91].

From a design perspective, tubercles are attractive because they can improve startup behavior without moving parts or external power [87,88]. However, their effect is not universal. Under highly turbulent inflow, the benefit may be reduced because incoming turbulence already promotes boundary-layer mixing and separation control [87]. Therefore, tubercles should be optimized for the expected operating Reynolds number and turbulence level rather than treated as a generic add-on.

However, tubercles are not a panacea. Some studies caution that in a fully turbulent inflow, the benefit of tubercles diminishes or can even reverse. Rostamzadeh et al. (2017) found that in turbulent conditions, a plain blade had *better lift post-stall than a tubercled blade*, possibly because the natural perturbations already did what tubercles would do [87]. So if an urban flow is very turbulent, tubercles might have less effect (or need to be tailored to a different size scale). Design variables include the tubercle amplitude and wavelength: larger amplitude, shorter wavelength tubercles produce stronger vortices but also more frontal area (drag). A typical choice for small blades is tubercles with amplitude ~5% of chord and wavelength ~20% of chord, which has been found effective in many cases [87]. These values often result from optimization studies aiming for maximum lift boost with minimum drag penalty. The manufacturing of tubercles is quite feasible with modern methods (see Section 5), which makes them an attractive passive add-on. Overall, leading-edge tubercles can significantly improve self-starting by delaying stall, especially under moderately turbulent or high-angle conditions, and they come with minimal maintenance (being just a shape).

Trailing-edge Gurney flaps and serrations: Gurney flaps are small trailing-edge tabs that increase effective camber, strengthen circulation, and enhance lift at low and moderate angles of attack. For VAWT blades, they can improve torque at low TSR and increase the probability of successful startup [23,51–56]. The most important design parameter is flap height: small flaps can improve low-speed torque with limited efficiency loss, whereas oversized flaps add excessive drag and reduce peak power [23,51,54–56]. Related trailing-edge modifications, including serrations and combined flap–serration concepts, can also influence wake structure, noise, and torque smoothness, although their direct contribution to self-starting is usually smaller than that of Gurney flaps [87,89]. Therefore, Gurney flaps are best used as modest torque-enhancing devices when the baseline blade still shows weak or negative torque during part of the rotation.

For a startup, the main advantage is that at the low TSR region (blades at high α), the flaps still generate additional lift instead of allowing the flow to fully separate. On the downside, Gurney flaps do add drag even at low angles (they are like tiny spoilers). So there is a trade-off in terms of peak efficiency—some loss at high TSR is possible, though studies show it can be minimal if flaps are small [85]. They are more effective on thicker airfoils and are often used in combination with other modifications. An example combined approach is an *adaptive flap*: some designs consider having a small flap that deploys only at low RPM (perhaps via centrifugal force) and retracts later, but that gets into active territory.

Trailing-edge serrations (sawtooth patterns often used on HAWT blades for noise reduction) have also been considered for VAWTs. Their primary effect is to reduce turbulent wake width and noise [87]. They might slightly reduce drag and suppress large vortex shedding, which could help smooth the startup torque but probably have a minor effect on the mean torque itself. One interesting note: a study reported that adding tubercles on the leading edge and serrations on the trailing edge yielded a pronounced noise reduction without hurting performance [87]. In terms of starting, serrations likely don't contribute as much as tubercles or Gurney flaps in generating force, so we consider them more for noise and loads (still potentially useful in urban settings where quiet operation is a plus).

Surface roughness and trip devices: At low Reynolds numbers, a laminar boundary layer on the blade can separate early, causing stall. Introducing a bit of roughness or a turbulator strip can trip the flow to turbulence, which energizes the boundary layer and delays stall onset at the cost of some friction drag. Du et al. (2019) observed that *increased blade surface roughness improved self-starting capability at low TSR* for their VAWT model [85][90]. The roughness effectively acted as passive flow control by preventing large laminar separation bubbles. In small turbines, the manufacturing process (e.g., 3D-printing layer lines or fiberglass surface) inherently introduces some roughness; interestingly, this might help the startup even if it reduces peak smooth-surface efficiency. Some have advocated intentionally roughening the leading edge or adding grit/vortex generators for better low-speed performance [90]. For example, one could put a fine sandpaper-like strip at 5% chord – in glider aircraft, such turbulator strips are common to control laminar flow. In our context, if a blade is too smooth, it may suffer early stall; a bit of roughness can delay that critical stall by ensuring transition to turbulence earlier. This method is simple but must be done carefully – too much roughness can just add drag everywhere. The optimal might be a medium grit roughness on the leading 20% of the chord to maximize lift in the startup regime. Roughness is essentially a low-tech version of other flow energizing devices (like tiny vortex generators).

Vortex generators, dimples, and cavities: Surface roughness, trips, vortex generators, dimples, cavities, porous sections, and slotted blades all aim to improve startup by controlling boundary-layer separation. At low Reynolds numbers, a fully smooth blade can experience early laminar separation; moderate roughness or trip devices can promote transition and delay stall, thereby improving low-TSR torque [45,90]. More structured passive devices such as dimples, cavities, porous media, and slotted blade sections can generate local vortices, create recirculation zones, or redistribute pressure to reduce separation and improve aerodynamic performance [57–59,64,65]. These methods are attractive because they can be applied to existing blade geometries, but their effects are sensitive to geometry, Reynolds number, and surface quality. Excessive roughness or poorly designed cavities may increase drag and reduce peak efficiency. Therefore, these devices should be optimized carefully and validated experimentally before being used as general self-starting solutions.

Boundary-layer energization vs. drag augmentation: It's worth distinguishing two philosophies in passive flow control for startup: (1) energize the flow to get more lift (and reduce negative torque) – tubercles, VGs, roughness all do this; (2) augment drag in a useful way – e.g. small secondary vanes or spoilers that act like mini Savonius paddles at low speed, adding positive drag torque. Gurney flaps and some cavity designs do a bit of both: they increase lift but also increase form drag in the direction of rotation. For instance, Kumar et al. (2023)'s trailing-edge half-cylinders essentially increased the drag force on the advancing side dramatically, acting as thrust paddles [60]. That yielded a big static torque gain [61]. The drawback is that once spinning, those same attachments cause parasitic drag. Passive devices must be chosen considering this trade-off. Leading-edge tubercles are nice in that they primarily improve lift when needed and have minimal negative impact at low AoA (they slightly increase drag but also can reduce noise/tip losses). Gurney flaps consistently increase lift but always cost some drag. If the target is purely to ensure startup in very low wind, one might accept even crude drag aids; if aiming for a balanced design, lean toward those that help stall delay.

In summary, passive flow control techniques provide a rich toolkit for fine-tuning the aerodynamic behavior of VAWT blades during startup. They can be *stacked* on top of base blade designs (for example, a J-shaped blade might also sport leading-edge tubercles, combining benefits). Many of these methods have proven their value in laboratory experiments and some in field tests, often yielding on the order of 10–30% improvements in starting torque or cut-in speed [75]. Table 1 encapsulates several of them. We will later compare these to biomimetic strategies (some of which overlap, like tubercles, which are both passive and biomimetic) and to active ones. Before that, let's specifically highlight biomimetic inspirations, since they deserve special focus in this review's scope.

4.4 Biomimetic and Nature-Inspired Strategies

Biomimetic strategies are a subset of passive (or semi-passive) approaches that take inspiration from nature's flyers and swimmers, under the premise that evolution has solved analogous aerodynamic problems. Two major inspirations that have

directly influenced VAWT self-start research are humpback whale flippers and autorotating tree seeds (samaras). We also briefly consider other nature-inspired ideas like flexible fish fins or owl wings.

Humpback whale tubercles (leading-edge protuberances): As discussed in Section 4.3, humpback whale-inspired leading-edge tubercles are among the most mature biomimetic strategies for improving VAWT startup. Their relevance lies in their ability to delay stall, maintain lift at high angles of attack, reduce dynamic-stall severity, and smooth torque fluctuations [84,86,87,91]. Rather than repeating the aerodynamic details, this section emphasizes their biomimetic importance: tubercles show how biological flow-control mechanisms can be translated into passive turbine features that improve startup stability and may also reduce noise [87,89,91]. Their successful application also supports the broader use of nature-inspired geometries in low-Reynolds-number wind-energy devices.

Samara autorotation (maple seed-inspired design): Samara-inspired designs are based on the autorotation of maple and other winged seeds, which use stable leading-edge vortices to generate high lift at low Reynolds numbers [87,92]. This mechanism is relevant to VAWT startup because low-TSR operation also involves high angles of attack and vortex-dominated flow. Recent bio-inspired turbine concepts show that seed-like blade curvature, twist, flexibility, and leading-edge-vortex stabilization can reduce cut-in speed and improve low-wind torque [87,89,92]. However, direct transfer from natural seeds to engineering-scale VAWTs is not straightforward because geometry, Reynolds number, structural loading, and durability requirements differ. Therefore, samara-inspired designs should be viewed as a promising research direction rather than a fully mature design solution.

Challenges in translation: While nature inspires, one must adapt to different scales and constraints. Maple seeds operate at very low Reynolds ($\sim 10^3 - 10^4$) with extremely low inertia and one-shot use. A turbine must be durable, scalable, and efficient at higher Re. Some bio-features might not scale linearly – e.g., a maple seed's LEV stability is partly due to its specific geometry and low mass; at a larger scale, that might break down or require active control to replicate. Similarly, tubercles on a 12m whale flipper (~Re 10^6) work great; on a 0.5m turbine blade (Re 10^5) they also work, but on a 5cm blade (Re 10^4) they might need different tuning. Fortunately, the scales we deal with (small wind turbines) actually overlap reasonably with some biological regimes (bird flight, whale fins, seed flight), so biomimetics is very apt here [87].

Other biomimetic ideas: Other biomimetic concepts remain less mature but offer useful directions for future work. Flexible blades inspired by fish fins, bird wings, insect wings, and seed structures may passively change pitch, camber, or coning angle during startup, helping the blade adapt to high angles of attack and unsteady inflow [80,81,89]. Surface textures inspired by shark skin, owl wings, insect surfaces, or other biological structures may reduce drag, delay separation, or reduce noise, although their direct effect on self-starting remains uncertain [87,89,93]. In addition, bio-inspired array concepts, such as closely spaced or counter-rotating VAWT pairs, may improve startup through favorable vortex interaction and local flow acceleration [78,85]. Overall, these concepts are promising but require systematic testing before firm design recommendations can be made.

Comparative effectiveness vs conventional methods: Biomimetic strategies often bring *multi-functional benefits* – e.g., tubercles reduce noise and improve stall, samara-inspired blades cut in at low speeds and might also look aesthetically pleasing. But do they outperform simpler, conventional fixes (like just adding more blades or a small Savonius)? In some cases, yes: tubercles can yield a startup improvement without the efficiency penalty a Savonius would impose, so that could be considered superior. A maple-seed blade might allow a one-bladed or two-bladed rotor to self-start where normally it couldn't. However, these approaches can be more complex to design and optimize. It's also possible that combining conventional and biomimetic yields the best result (hybrid synergy). For example, one might use a 3-blade rotor (conventional) but give each blade tubercles and a J-profile (biomimetic + design) to achieve cumulative gains. We will revisit this in the comparative section (7).

To conclude this section, biomimetic ideas have enriched the palette of solutions for VAWT self-starting. *Table 2* provides a summary of key biological inspirations (whale, maple seed, etc.), how they are implemented in engineering terms, their aerodynamic effects, reported performance gains in studies, and the complexity they introduce. By learning from nature, we have found ways to passively control flow in ways that were not obvious from classical engineering perspectives. The challenge is ensuring these features deliver under real-world conditions and manufacturing constraints, which we address in Section 5.

4.5 Active and Semi-Active Techniques (Brief Overview and Critique)

All the strategies so far have been passive or inherent to the turbine's geometry. Active techniques, by contrast, involve some form of *controlled actuation or external input* to assist startup. They can be extremely effective in improving or guaranteeing self-start, but they often come with drawbacks (added complexity, cost, power consumption, maintenance needs) that make them less attractive for the small-scale, urban turbines we focus on. Here, we briefly survey active and semi-active methods:

Active pitch control: Active pitch control can greatly improve self-starting by adjusting the blade angle of attack during rotation, thereby increasing positive torque and reducing negative torque over the azimuthal cycle [81]. In principle, this allows the turbine to combine the high starting torque of drag-assisted operation with the higher efficiency of lift-based operation. However, active pitch requires sensors, actuators, control algorithms, and additional mechanical components. These requirements increase cost, weight, power consumption, and maintenance demand, which limits their practicality for small urban VAWTs [81,85]. Therefore, active pitch is technically effective but is generally more suitable for research prototypes or high-value applications than for simple micro-scale turbines.

Mechanical self-start devices: This refers to any non-aerodynamic means of starting rotation. The simplest is a motor or generator acting as a motor to give the turbine an initial spin when wind is present. For instance, some vertical-axis turbines use their generator in reverse at cut-in: if the wind is above a threshold and the turbine hasn't started, the controller feeds a small current to the generator to nudge the rotor into motion, then switches to generation mode once it's spinning. This technique can effectively eliminate the cut-in wind speed problem (the turbine can be actively started whenever there is enough wind to sustain rotation once started). The downsides are the need for a smart control system and the parasitic energy draw – though the energy to start is small compared to generation, it complicates off-grid or battery systems. Another mechanical method is a clockwork or spring: some anemometer designs had a spring that wound up slightly as the cups trembled in low winds, then released to kick the rotor. Or a simpler one: a human push or a small auxiliary wind fan could start it (obviously not an elegant solution for automated systems).

One clever passive-mechanical idea is auto-variable solidity: Lee et al. (2025) proposed an active diameter modulation – basically blades that extend outwards at high RPM to increase swept area for more power and retract at low RPM to reduce drag for easier start [85]. In their concept, the rotor radius changes (like opening an umbrella) to optimize performance. At startup, a smaller radius could reduce negative torque, then expand to capture more wind. While novel, this requires moving parts and has to be finely timed to be helpful at the start.

Plasma actuators and flow control devices: Active flow-control devices such as plasma actuators and synthetic jets can delay separation, reduce dynamic stall, and improve low-speed torque by energizing the boundary layer during high-angle-of-attack operation [66,68–72]. These methods are attractive because they can be activated only when needed, such as during startup or severe stall events. However, they require external power, high-voltage or actuator hardware, and additional control systems, which may reduce net energy gain and reliability in small urban turbines [68–72,85]. Therefore, active flow control remains valuable for laboratory studies and advanced turbine concepts, but passive or semi-passive strategies are currently more practical for micro-VAWT deployment.

Active augmentation devices: Another tactic is actively altering the *environment* of the turbine. For example, deploying **air jets or blowers** upwind to artificially increase flow through the rotor at startup. Obviously, this is not energy-efficient if you care about net output, but conceptually, one could have a fan that gives the turbine a boost. Some wind-solar hybrid streetlights essentially do this by having the solar panel drive the turbine's startup on calm days – not by blowing air, but by powering a motor to spin it.

Why less attractive for small-scale systems: In summary, while active methods (pitch, motorized start, plasma) can ensure startup even in adverse conditions, they are often considered a last resort for small VAWTs. The ethos in that scale is simplicity

and low maintenance. Many urban turbine projects explicitly avoid any kind of gearbox or active control because historically, those have been failure points. In remote or off-grid installations, the additional electronics and power draw are also negatives. For instance, if you have a rooftop turbine powering an off-grid sensor, you'd prefer it to be completely passive so that it can start whenever nature allows, rather than needing to draw battery power to start itself. Cost is another factor: adding pitch actuators or a power-electronics-based start circuit increases manufacturing and maintenance costs, possibly outweighing the benefits in such a small system.

Niche applications: That said, in some niche cases, active control might be justified. For instance, an architectural wind installation integrated into a building might have access to building power and a maintenance schedule, so they could incorporate active pitch to maximize performance and ensure they spin (for visual effect or efficiency). Or a research prototype aiming to demonstrate maximum performance will use active controls as a test-bed.

It's instructive that the systematic review by Gallegos-Molina & Chavero (2025) found active control giving the largest laboratory improvements (~30% startup torque increase) but noted the uncertainty regarding net energy/durability [85]. In their conclusions, hybrid strategies were suggested (optimized passive with targeted active), and a need for caution was raised regarding whether the complexity is worth it in real-world small VAWTs [85].

To conclude Section 4: we have cataloged an array of strategies (see Table 1 for a synopsis). Rotor configuration changes, blade profile tweaks, passive flow controls, biomimetic adaptations, and active controls all offer pathways to enhance self-starting. These are not mutually exclusive – often the best solution is a combination (e.g., a 3-blade helical rotor with tubercled J-type blades and maybe a one-time motor start in emergencies). The next sections will shift focus: first to practical aspects (manufacturing and prototyping these fancy blades), then to how we measure and compare the improvements experimentally and numerically. Finally, we will synthesize the comparative effectiveness (Section 7) and provide design guidelines (Section 8), tying everything together for practitioners.

Table 1. Taxonomy of Self-Starting Enhancement Strategies for H-Darrieus VAWTs.
Strategies are grouped by category, with their mechanism and effects summarized. (CFD = computational fluid dynamics simulation; Exp = experimental data; Field = field trial data.)

Strategy Category	Specific Technique	Primary Mechanism	Effect on Cut-in Speed	Effect on Torque Ripple	Impact on C_p (peak)	Evidence Type
Rotor Configuration	Increase blade number (e.g., 3 → 4 blades)	Higher solidity → more torque at low TSR	Lowers cut-in (more starting torque) [46]	Reduces torque ripple (overlapping blade torques)	Slight decrease (more drag at high TSR) [46]	Exp, CFD (multiple studies)
	Helical (twisted) blades	Distributes blade loading continuously → no dead spots	Modestly lowers cut-in (no zero-torque positions) [40]	Greatly smooths torque (eliminates periodic stalls) [50]	~10% lower peak C_p (3D effects, slight drag) [51]	Exp (wind tunnel), CFD
	Hybrid Darrieus–Savonius rotor	Drag rotor adds starting torque	Significantly lowers cut-in (drag ensures start) [62]	Virtually zero ripple at start (continuous drag torque)	Lowers max C_p by ~15–30% (drag losses) [57] [58]	Exp, CFD (many studies)
	Added auxiliary blades or flaps (e.g. trailing Savonius vanes)	Extra drag elements on main blades →	Lowers cut-in (higher static torque) [63]	Can increase ripple slightly if	Lowers peak C_p (drag penalty at	Exp (prototypes)

		boost static torque		asymmetrically placed	speed)[60] [61]	
	Dual-stage (two-tier) rotors, phase-offset	Phase shift blades → one stage drives during other's weak phase	Lowers cut-in (faster spin-up) [68]	Reduces ripple (smoothed by second rotor) [69]	Minor effect on C_p (slightly more drag)	CFD (recent study)
Aerodynamic Blade Design	Low-Re optimized airfoil (e.g. thick or modified camber)	Higher lift at low Re and high α	Lowers cut-in (stronger lift at startup AoA) [24]	N/A (affects magnitude more than shape of torque curve)	Depends: can improve overall C_p if better lift/drag [36]	CFD, Exp (airfoil tests)
	Preset blade pitch (e.g. –2° toe-in)	Favorable AoA at zero TSR → more initial lift	Lowers cut-in (blades "bite" wind at rest) [55]	May introduce small ripple if not optimal at all azimuths	Slightly lowers peak C_p if non-zero pitch at operating TSR [54]	CFD, Exp (wind tunnel)
	J-shaped trailing edge (notched/cut airfoil)	Trapped vortex increases lift in stall regime	Lowers cut-in (delays stall, more lift at low TSR) [73]	Reduces negative torque regions (more lift instead of stall)	Slight drop or neutral on C_p (small drag increase) [73]	CFD, Exp
	S-shaped or cambered blade profiles	Self-lifting profile (produces torque both directions)	Lowers cut-in (provides positive torque on both strokes)	Reduces ripple (less negative torque in return stroke)	Lowers peak C_p (airfoil not as efficient symmetrically)	CFD, Exp (few cases)
	Passive variable pitch (flexible or hinged blades)	Blades align to optimal AoA automatically	Greatly lowers cut-in (near-ideal AoA at startup) [82]	Minimizes ripple (pitch adapts to reduce stall dips)	Potential slight C_p gain (always optimal AoA) but mechanism drag possible	Exp (prototypes), CFD
Passive Flow Control	Leading-edge tubercles (whale-inspired)	Vortex generation delays stall, improves lift post-stall [86]	Lowers cut-in (blades don't stall as early) [88]	Smooths torque (mitigates sudden stall drops) [91]	Little to no loss; can reduce drag at high α(and noise) [89]	Exp (wind tunnel, field)
	Trailing-edge Gurney flaps (small tabs)	Increases effective camber → higher lift at low speed [85]	Lowers cut-in (more lift at low TSR) [85]	Slightly increases ripple (minor asymmetry in lift)	Slight reduction in max C_p (extra drag at high TSR) [85]	CFD, Exp
	Surface roughness trips (grit, riblets)	Early turbulence → delays laminar separation	Lowers cut-in (prevent early stall) [90]	N/A (affects stall onset more than torque pattern)	Can reduce C_p if excessive (higher drag)	Exp (some reports)
	Vortex generators / Dimples	Energize boundary layer, keep flow attached	Lowers cut-in (improves lift in stall region) [85]	Possibly smooths torque (less flow separation)	Minor C_p loss or neutral (small drag penalty) [85]	CFD, Exp (limited)

	Porous or slotted blade sections	Boundary layer control via suction/bleed	Lowers cut-in (reduces flow separation) [85]	N/A (improves overall torque, subtle pattern effect)	Slight C_p loss if increased drag or leakage	CFD (concepts)
Biomimetic Concepts	Humpback whale flipper tubercles → blade LE	(Same as tubercles above) Streamwise vortices delay stall [86]	Lowers cut-in (stall delayed)[88]	Smoother torque (less stall-induced drop)	(Same as tubercles) ~neutral on peak C_p (potential noise reduction)	Exp, CFD
	Maple seed samara → highly twisted/cambered blade	LEV-based high lift at low Reynolds/low TSR [89]	Greatly lowers cut-in (harvests lift like autorotating seed) [89]	Could introduce some asymmetry (depending on design)	Potential increase in C_p at low TSR; uncertain at high TSR	Exp (micro scale), CFD
	Flexible bio-inspired blade (e.g. camphor seed wing)	Passive shape change optimizes AoA (mimics natural flex) [89]	Lowers cut-in (blade adapts to catch wind) [89]	Reduces ripple (blade cones or twists to avoid stall) [89]	Could increase C_p (aligns flow better) or slightly reduce (if deformation)	Exp (prototype)
	Owl wing serrations (trailing edge)	Noise reduction & small-scale vortex shedding control	Negligible impact on cut-in (mostly acoustic benefit)	May slightly smooth torque (reduced vortex shedding)	No impact on C_p (just less noise)	Exp (noise tests)
	Shark skin riblets (micro-grooves)	Lower turbulent skin friction maybe delay separation	Tiny if any impact on cut-in (drag reduction could help marginally)	N/A (affects drag, not torque oscillation)	In theory, a slight C_p increase (less drag)	CFD, Exp (in aero labs)
Active/Semi-Active	Active blade pitch control (with controller)	Optimal AoA at all times (eliminates negative torque) [81]	Drastically lowers cut-in (can force start at very low wind)	Eliminates torque ripple (can pitch to zero torque on returning blade)	Increases peak C_p (blades always at best lift/drag) [81]	Exp (prototypes), Simulation
	Motorized start (use generator as motor)	External energy spins rotor through dead-band	Lowers cut-in to effectively 0 (if motor strong enough)	N/A during generation (torque ripple unaffected once running)	No direct effect on C_p (some energy loss to start)	Deployed in some systems
	Plasma flow actuators on blades	Active separation control (delay stall via plasma jets) [85]	Lowers cut-in (maintains lift at high AoA) [85]	Smooths torque (prevents dynamic stall events)	No impact on ideal C_p, but net output is lower due to the power used by plasma.	Lab exp, CFD (recent)

	Adjustable rotor geometry (expandable radius)	Change solidity/diameter based on speed (small at start) [85]	Lowers cut-in (low solidity when stopped reduces adverse drag)	Uncertain (could reduce oscillations if tuned)	Might improve high- C_p if it expands in good wind (like diffuser effect)	CFD concept, prototype

Sources: Selected data and mechanisms summarized from references [27] [30] [23] [32] [5] [41] and others as cited inline.

5. Manufacturing and Prototyping Considerations

Manufacturing feasibility is important because many self-start enhancement strategies require non-conventional blade geometries, such as J-shaped profiles, leading-edge tubercles, cavities, dimples, Gurney flaps, or flexible sections. Additive manufacturing has made these features easier to prototype at a small scale, allowing rapid testing of complex blade shapes that would be difficult to produce using conventional machining or molding [83,85]. For research-scale VAWTs, 3D printing is particularly useful for comparing different tubercle amplitudes, cavity shapes, or trailing-edge modifications before moving to more durable manufacturing methods.

However, manufacturing quality can strongly affect aerodynamic performance. Surface roughness from printed layers, sanding, coating, or material defects may alter boundary-layer transition and stall behavior. Moderate roughness can sometimes improve low-Reynolds-number startup by promoting earlier transition and delaying laminar separation, but excessive roughness increases drag and can reduce peak efficiency [90]. Therefore, the surface finish should be treated as part of the aerodynamic design rather than only as a fabrication issue.

Material selection and structural integrity are also important. Printed polymers such as PLA, ABS, PETG, nylon, or resin are useful for prototypes, but long-term outdoor turbines may require stronger polymers, fiber-reinforced materials, or composite blades to resist centrifugal loading, fatigue, ultraviolet exposure, temperature variation, and moisture. Modifications such as J-shaped cutouts, cavities, attached flaps, or tubercled leading edges can introduce local stress concentrations, so blade strength and attachment reliability should be checked before field testing.

For practical deployment, complex features should be simplified where possible. Tubercles or cavities may be printed directly, molded into the blade, or added as modular leading-edge or trailing-edge inserts. Gurney flaps and auxiliary drag elements should be securely bonded or mechanically fixed to avoid vibration, imbalance, or detachment. Overall, manufacturing decisions should balance aerodynamic benefit, structural safety, cost, repeatability, and ease of maintenance. Thus, prototyping should not only confirm improved startup performance but also verify whether the selected enhancement can be produced reliably for long-term small-VAWT operation.

6. Experimental and Numerical Evaluation Methods

Reliable evaluation of self-starting performance requires both experimental and numerical methods because startup is transient, highly unsteady, and strongly affected by rotor position, wind speed, turbulence, and mechanical resistance. The most direct experimental method is the static torque test, where the rotor is held at different azimuthal angles, and the aerodynamic torque is measured [20,63]. This test identifies whether the turbine has negative-torque positions and whether it can start from any orientation. However, static torque alone is not sufficient because a rotor may pass through short negative-torque regions during real acceleration due to inertia.

Therefore, dynamic free-spin tests are also needed. In these tests, the turbine is released from rest under a given wind speed, and the rotational speed or tip-speed ratio is recorded with time [16,19,20,94]. These tests show whether the rotor can pass through the low-TSR dead-band and reach a stable operating condition. Important reported quantities should include start-up wind speed, cut-in wind speed under load, startup time, achieved TSR, and whether the generator was connected or disconnected during the

test [6,95]. Clear definitions are essential because some studies use “start-up speed” to mean the first rotor motion, while others use “cut-in speed” to mean the point at which useful electrical power is produced.

Wind-tunnel experiments provide controlled and repeatable conditions, but they may not fully represent urban operation because field winds are gusty, turbulent, and directionally variable [35,36,38]. For this reason, field testing or turbulent-inflow laboratory testing is important for validating self-starting strategies intended for rooftop and built-environment applications [94,96,98]. Field data should ideally report the probability of startup at different wind speeds, start–stop frequency, and turbine behavior under gusts and lulls.

Numerical methods are useful for identifying the flow mechanisms behind startup improvement. Time-resolved CFD with sliding or moving mesh approaches can simulate rotor acceleration, dynamic stall, vortex formation, and torque variation during startup [29,30,42,97]. However, CFD results depend strongly on turbulence modeling, grid resolution, Reynolds number treatment, and whether two-dimensional or three-dimensional effects are included [22,35,80,85]. Two-dimensional CFD is useful for parametric comparison, but three-dimensional simulations and fluid–structure interaction models are needed when blade height, tip losses, flexibility, and structural deformation are important [36,80,85].

Lower-order models, such as blade-element or double-multiple-streamtube approaches with dynamic stall corrections, can support preliminary design and rapid parameter studies, but they are less reliable in the stalled low-TSR startup regime [26]. Therefore, they should be validated against static torque, free-spin, or CFD results before being used for design conclusions.

Overall, the most useful evaluation framework combines:

1. static torque curves to identify negative-torque regions,
2. dynamic free-spin tests to confirm actual startup,
3. controlled or turbulent inflow experiments to assess robustness, and
4. validated CFD or low-order models to explain the aerodynamic mechanisms.

Future studies should report startup definitions, load conditions, rotor inertia, drivetrain resistance, wind speed measurement location, turbulence intensity, and uncertainty. Standardized reporting would make comparisons between self-start enhancement strategies more reliable [85].

7. Comparative Synthesis and Design Trade-Offs

This section compares the reviewed strategies in terms of self-starting effectiveness, efficiency penalty, complexity, and suitability for urban low-wind operation. It also highlights cases where reported benefits may be limited by turbulence, scale, or implementation challenges.

Cross-comparison of strategy effectiveness: The reviewed strategies can be grouped into three broad performance patterns. First, rotor-level changes such as increasing solidity, increasing blade number, using helical blades, adding auxiliary drag elements, or adopting hybrid Darrieus–Savonius configurations provide the most direct improvement in starting torque [44–50,57–64]. These methods are reliable and can reduce cut-in speed, but they usually increase drag, lower optimum TSR, and may reduce peak power coefficient [45,46,57,58,64].

Second, blade-level modifications such as low-Reynolds-number airfoils, preset pitch, J-shaped profiles, passive pitch, and flexible blades improve startup by increasing useful lift, delaying stall, or reducing negative torque at low TSR [23,24,72–82]. These approaches usually offer a better balance between self-starting and efficiency than purely drag-based solutions, although their performance depends strongly on geometry, Reynolds number, and structural implementation [73,78–82].

Third, passive and biomimetic flow-control methods such as leading-edge tubercles, Gurney flaps, roughness, dimples, cavities, porous sections, slotted blades, and bio-inspired textures improve startup mainly by delaying separation, stabilizing vortices, and

smoothing torque fluctuations [51–65,83–93]. Their gains are generally more moderate than those of hybrid drag-based systems, but they often impose a smaller penalty on peak efficiency and mechanical simplicity [85–91].

Overall, the strongest startup improvement is usually obtained through drag-assisted or high-solidity configurations, but these have the largest efficiency penalty. Biomimetic and passive flow-control strategies generally provide more moderate startup gains with lower efficiency loss. Therefore, the most practical solution for small urban VAWTs is often a combined design that uses moderate solidity, low-Reynolds-number blade geometry, and selected passive flow-control features rather than relying on a single technique.

Biomimetic vs. conventional approaches: Often, biomimetic ideas aim to achieve what conventional ones do but more *elegantly*. For example, instead of bolting on a Savonius, one could shape the blade (J-shape, tubercles) to get part of that effect without a separate rotor. Where do they outperform? Tubercles vs. straight: in some range of AoA, tubercles give a lift boost without adding separate drag elements – so they are *more efficient than simply increasing solidity to get the same stall delay*. Maple-seed-inspired designs vs. adding more blades: a single big blade like a samara might self-start at ultra-low winds due to its high drag mode, while a multi-blade conventional rotor might still need more wind to overcome friction.

However, biomimetic solutions can sometimes yield only marginal gains when implemented improperly. For instance, Rostamzadeh's finding that in turbulent flow a tubercled airfoil was not better than smooth [89] is a caution that environment matters. A smooth airfoil might naturally experience enough disturbances in turbulence that tubercles add no further benefit – or could even trip flow in a suboptimal way.

One clear advantage of biomimetics like tubercles or LEVs is in maintaining performance in off-design conditions. Where conventional designs might see a sharp drop (like dynamic stall), these features blunt the drop. So, in a variable urban wind, a tubercled blade might produce more net energy over time even if the peak is the same, because it avoids "zero torque" episodes. That translates to more starting reliability and less time idle.

Hybrid strategies: Many of these methods can be combined, but not always linearly additive. For example, a tubercled J-blade with a Gurney flap might see diminishing returns because both address stall from different ends (LE vs TE). But a rotor with both helical twist and tubercled blades might benefit from both smoother torque and higher stall margin. There is some evidence: Elangovan & Pillai (2025) studied *tubercled blades at different pitch angles* [74] and found best performance at a certain combo (small pitch + tubercles). This suggests synergy – tubercles offset the negative effect of pitch at high AoA by keeping flow attached. Another synergy: J-blade plus tubercles could help because J-blade generates a strong vortex, and tubercles manage it along the span (ensuring it doesn't break into one large stall vortex).

Scalability and reproducibility issues: There have been cases where a promising lab result didn't translate to larger scale or other conditions: - Some early experiments on flexible blades showed great results in one setup but failed in durability or in more turbulent conditions (blades fluttered unpredictably). - A field trial of a Savonius-Darrieus hybrid in one study indicated that while it started more often, its long-term output was lower than an equivalent simple turbine due to drag constantly present, or the Savonius acted as a brake at higher speeds (the Darrieus might never reach optimal TSR with that deadweight).

Failure case: A "double Darrieus" concept by Sandia in the 80s (two rotors on the same shaft offset by 45°) intended to smooth torque ended up with complex structural vibrations and didn't yield net gains for cost. - Another negative result: A design with too many passive flow devices can become overly draggy. For example, if one puts extremely large tubercles or too tall Gurney flaps, it might kill performance such that the turbine can start but then never reach a useful speed (a kind of self-start but then stalls at TSR ~1.5 permanently). I recall a small study where overly big tubercles reduced *overall* power because, at moderate angles, they induced early transition and added drag without much stall to delay.

Negative results are often not published: This is a bias to be wary of. For instance, if someone tried riblet film on a blade and saw no improvement, they might not publish that. But it's useful to know. In the review references, Tayebi & Torabi (2024) is a

"critical review" that likely addresses which flow control methods worked or not [85]. We might glean from them that, e.g., certain vortex generator configurations didn't help on VAWTs because of dynamic stall's large-scale nature overshadowing small VGs.

Where biomimetic clearly shines: Noise reduction. Owl wing serrations and tubercles can cut noise ~3-4 dB or more [87], [89]– for urban turbines, that's a big plus. Conventional approaches (like more blades or Savonius) often make turbines noisier (due to higher solidity buffeting). So a tubercled blade might quietly self-start where a Savonius hybrid would howl in the wind. Social acceptance of small wind in urban areas can hinge on low noise and low visual flicker. Biomimetic designs are generally more "biologically aesthetic" (some find a tubercled blade more visually pleasing or interesting than a clunky add-on rotor). This is subjective, but potentially an advantage in marketing and public acceptance.

Failure modes: A seldom discussed aspect: adding complexity can introduce new failure modes. E.g., a passive hinge could jam or oscillate uncontrollably. A Savonius rotor could lose a bucket or have its attachment fail, causing imbalance. A tubercled blade has a more complex mold, so maybe manufacturing defects are more likely, causing micro-cracks at tubercle troughs, etc. Those are engineering challenges to overcome with robust design and quality control.

Design optimization perspective: Given the many tools in the toolkit, what is the optimal combination? Likely, an optimal design for a small urban VAWT might combine: - Moderately high solidity (~0.3–0.4) for inherent torque (3–4 blades). - A blade profile optimized for low Re with gentle stall (e.g., a thick cambered or symmetric with slight reflex). - Leading-edge tubercles to delay stall on each blade element. - Trailing-edge Gurney or spoiler to bump up lift at low speeds. - Possibly helical twist or at least slight blade cant to avoid all blades stalling simultaneously. - Possibly a small auxiliary drag feature that only engages at low speed (maybe a flexible flap that flattens out at higher rpm). - These should all be implemented in a structurally sound, manufacturable way, e.g., via 3D printed core + composite overlay.

The trade-offs: each addition could lower peak C_p by a small amount. But given urban wind rarely hits high TSR anyway (due to turbulence forcing constant re-adjustment of TSR), a slight reduction in theoretical max might be acceptable if cut-in is lowered significantly. Put numerically: better to have $C_{p,max} = 0.25$ but running 80% of the time, than $C_{p,max} = 0.35$ but only running 50% of the time due to startup issues.

Negative results to highlight explicitly: - *Rostamzadeh's tubercle in turbulence result* [89] – implies tubercles need retuning for turbulent regime, or might not help in heavy turbulence as much. So one should not assume they always help. - *Mirzaeian et al. (2025)*: They tried "dual-row innovative hybrid" [85], maybe a complex arrangement that possibly didn't yield expected gains (the fact that they published suggests it did something, though). - *Mitchell et al. (2021)* improved self-start with a new blade design [85] – presumably a combination of features, but it's good to see multiple independent works converge on the idea that shaping the blade yields improvement. - If any study reported an idea that *didn't work*: Perhaps someone tried extremely rough sand coatings and found that, beyond a point, it just killed performance. Or attempted to make a turbine self-start by just adding a heavy flywheel (some did that) – heavy rotor did self-start slightly better (because it coasted through lulls), but in very low wind it still needed that first push. Adding weight increased the cost and loads.

Scalability: Many references are about a small scale (which is our focus). But if one were to scale to a bit larger (say a 5 kW machine, 3 m diameter), do these still help? Likely yes, though some like tubercles might need adjusting amplitude relative to chord, etc. It's important, as our small-scale successes might eventually influence bigger designs if proven (though HAWTs dominate large scale for now, one could imagine mid-sized VAWTs on rooftops or in city corners if they become reliable at self-starting and quiet).

In summary, the design trade-offs revolve around balancing startup torque vs. aerodynamic efficiency vs. complexity/cost. Historically, one could guarantee a startup by increasing solidity or adding drag devices, but at a steep efficiency cost. Newer strategies (biomimetics, flow control) strive to improve startup with *less* efficiency penalty. The comparative evidence suggests many of these indeed allow recovering some of the lost ground. This trade-off between cut-in speed reduction, aerodynamic

efficiency, and implementation complexity is summarized schematically in Figure 4. For instance, a tubercled, J-profile blade might have the startup of a 4-blader but efficiency closer to a 3-blader. Or an active pitch could give the best of both, but at the cost of complexity.

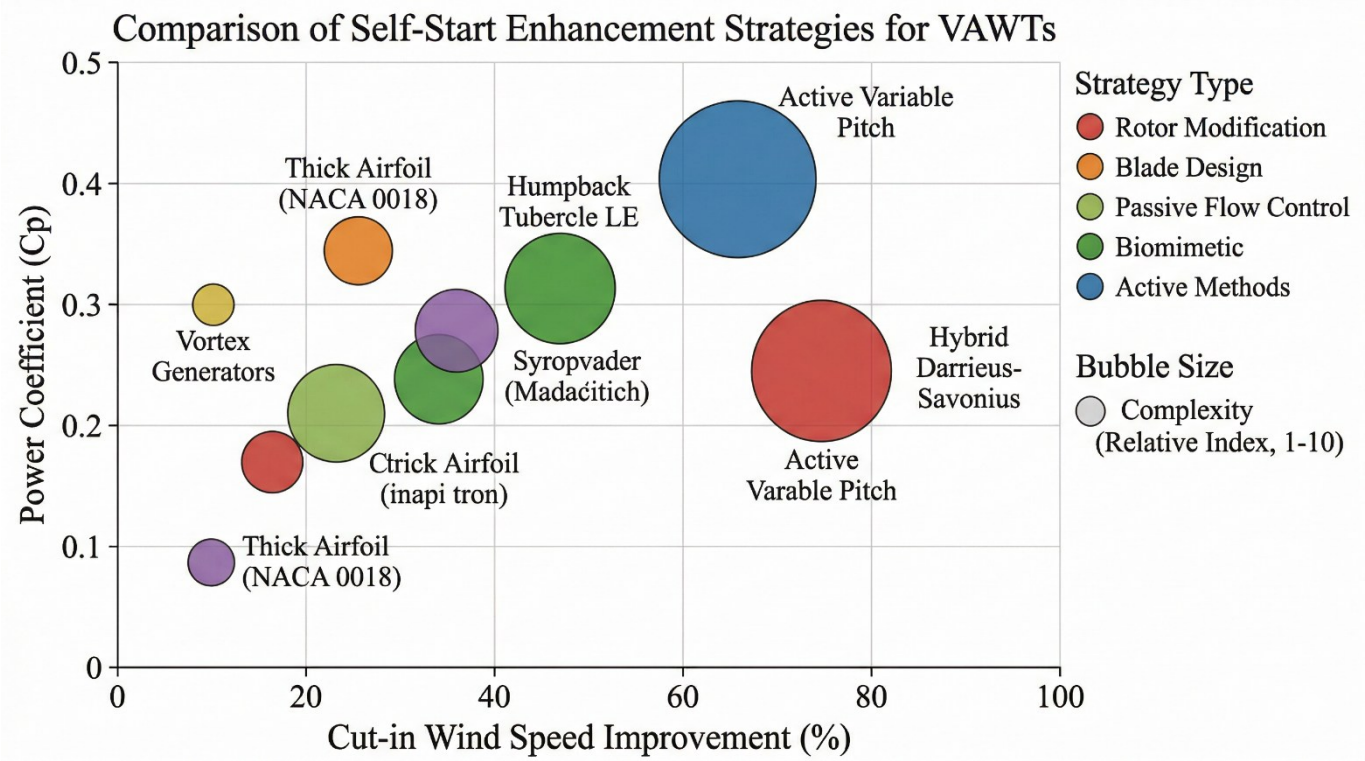

Figure 4. Comparative performance of self-start strategies based on cut-in speed, efficiency, and implementation complexity.

8. Design Guidelines for Practitioners

Based on the reviewed literature, the following concise guidelines are recommended for improving the self-starting of small H-Darrieus VAWTs in urban low-wind conditions.

1. Use moderate-to-high solidity for a reliable startup.

A three-bladed rotor with moderate solidity is generally a practical baseline for small VAWTs [44–46]. Increasing solidity or blade number improves starting torque and reduces dead zones, but excessive solidity increases drag and lowers peak efficiency [45,46]. Therefore, designers should use only the solidity needed to achieve reliable self-starting.

2. Reduce torque ripple using helical, staggered, or multi-stage configurations.

Helical blades, phase-offset stages, or staggered blade arrangements can smooth torque production and reduce zero-torque positions [40,49,50,66–69]. These configurations are useful when a smooth startup, lower vibration, and quieter operation are important, although they may increase manufacturing complexity or reduce peak power coefficient [50–52].

3. Select blade profiles for low-Reynolds-number startup, not only peak efficiency.

Airfoils for small urban VAWTs should have gentle stall behavior, sufficient thickness, and stable lift at high angles of attack [23,24,72]. Low-Reynolds-number airfoils, preset pitch, and J-shaped profiles can improve low-TSR torque and reduce negative-torque regions [55,72,73,76–79].

4. Apply passive flow-control features selectively.

Leading-edge tubercles, Gurney flaps, surface roughness, dimples, cavities, porous sections, and slotted blades can improve startup by delaying separation or increasing low-speed torque [51–65,83–91]. These devices should be optimized rather than added indiscriminately, because excessive roughness, oversized flaps, or poorly designed cavities can increase drag and reduce efficiency.

5. Use biomimetic concepts where they provide clear aerodynamic function.

Biomimetic designs should be selected for their engineering effect, not only their biological inspiration. Tubercles are useful because they delay stall, while samara-inspired and flexible blades are promising because they may stabilize leading-edge vortices or passively adapt blade shape during startup [87,89,91,92]. These concepts require careful validation before practical deployment.

6. Consider hybrid drag-assisted designs for very low cut-in speed.

Hybrid Darrieus–Savonius rotors, auxiliary drag blades, or deflector-assisted configurations can strongly improve starting torque and reduce cut-in speed [57–64,70,71]. However, they usually increase drag and reduce the peak power coefficient. They are most suitable when a reliable startup in weak winds is more important than maximum efficiency.

7. Minimize drivetrain resistance.

Low-friction bearings, low-cogging generators, and careful drivetrain alignment are essential because mechanical resistance can prevent startup even when aerodynamic torque is sufficient [10,25]. Generator loading should be delayed or minimized during startup when possible.

8. Validate both aerodynamic and practical performance.

Static torque tests should be used to identify negative-torque regions, while dynamic free-spin tests should confirm whether the turbine can accelerate through the low-TSR dead-band [20,63,94]. Designs intended for urban use should also be tested under turbulent or field conditions [94,96,98].

9. Balance startup improvement with efficiency, cost, and durability.

The best design is not necessarily the one with the lowest cut-in speed. A practical urban VAWT should combine reliable startup, acceptable peak efficiency, low vibration, manufacturability, structural safety, and low maintenance. For most small urban systems, a balanced solution may combine moderate solidity, low-Reynolds-number blade geometry, selected passive flow control, and a low-resistance drivetrain.

Overall, the preferred design should improve starting reliability without adding excessive drag, cost, or mechanical complexity. The guidelines above support a balanced selection of rotor configuration, blade geometry, passive flow control, and drivetrain design for small urban H-Darrieus VAWTs.

9. Research Gaps and Future Directions

Despite notable progress in enhancing VAWT self-starting, several knowledge gaps and opportunities for innovation remain. Addressing these will further advance the viability and performance of small wind turbines in urban settings. Here we outline key areas for future research:

Underexplored biomimetic concepts: While humpback tubercles and samara-inspired blades have been studied, other bio-inspired ideas merit attention. For instance, the *dynamic motion of insect wings* – insects like dragonflies can generate high lift at low Re via wing pitching and flexing. Translating this, one could imagine flexible or morphing blades that passively change camber with wind speed (e.g., a flexible trailing edge that deflects into a Gurney-like flap at low TSR and straightens at high TSR). Preliminary work on flexible blades shows promise [89], but the optimal material properties and configurations need exploration (ensuring flutter is avoided). Another concept is bio-inspired textures beyond tubercles: e.g., sharkskin riblets on VAWT blades to reduce drag during rotation – their effect in unsteady, separated flow is not well understood (most riblet research is for attached flow). *Recommendation:* Future studies could experiment with hybrid bio-inspired surfaces (imagine a blade with tubercles on the leading edge and riblets on the suction surface to reduce separated flow drag). Moreover, *natural stability mechanisms* such as the delayed stall via leading-edge vortices in *hummingbird wings* or seed pods might inspire new blade kinematics or geometry. These areas have barely been tapped for wind turbines.

Lack of standardized test protocols for start-up: As noted, there's a pressing need for standardized metrics and testing methods for small turbine self-starting [85]. Without this, it's difficult to directly compare different studies and technologies. The community (perhaps via IEA Wind or IEC working groups) should develop guidelines for reporting start-up performance, including definitions of cut-in (unloaded vs loaded), recommended procedures for measuring static torque curves, and representing turbulence effects. A benchmark experiment could be established, for example: testing a reference turbine design with and without a certain enhancement under identical controlled gust sequences, and making that data open-access. This would help researchers validate simulation models and new ideas on a common platform. Funding agencies and academic consortia could prioritize such collaborative efforts – akin to how standardized airfoil test databases accelerated HAWT design.

Need for long-term field data in urban environments: Many proposed enhancements (tubercles, hybrids, etc.) have been proven in CFD or lab tests, but we have limited data on their real-world longevity and performance over months/years. Urban environments introduce *dirt, weather, and intermittent operation cycles* – for example, do tubercled blades accumulate grime in a way that negates their effect over time? Do passive hinges wear out after many start/stop cycles? It's essential to deploy prototypes in real urban conditions and monitor them continuously. Data such as the *number of start-stop cycles, average time to start per day, energy yield improvement* compared to a baseline turbine, and any maintenance issues would be incredibly valuable. Specifically, field trials of biomimetic blades vs. conventional blades on identical turbines would provide practical validation (or reveal unanticipated issues). One future direction is instrumenting urban micro-turbines with IoT sensors to gather such data at scale – a network of test turbines across different cities feeding into a common database could identify what strategies consistently boost real-world capacity factor.

Opportunities for hybrid strategies (integrating multiple enhancements): We've discussed many techniques in isolation, but combinations could yield non-linear benefits. For example, combining *active* and *passive* flow control: a concept is a semi-active tubercle that changes amplitude or position based on flow conditions (imagine a flexible leading edge that bulges out at high AoA like a tubercle and retracts at low AoA for smoothness). Or using active flow control (like plasma) in tandem with passive features: maybe smaller passive tubercles plus a weak plasma actuator could achieve the same stall delay as big tubercles with less drag penalty [89]. These are speculative but worth exploring. Another hybrid idea: a morphing solidity turbine, e.g., blades that extend outward at low RPM to catch more wind (drag mode) and retract at high RPM to reduce drag [85]. Lee et al. (2025) did initial work on active diameter modulation [85]; future research might refine that, possibly implementing it passively (using centrifugal force to deploy small tip vanes at low speed that then fold back). Essentially, research should explore *adaptive or multi-mode turbines* that can alter their configuration between startup and normal operation – these could combine the best of drag-type and lift-type devices.

Deeper understanding of dynamic stall and unsteady flows at low Reynolds in VAWTs: We still have moderate uncertainty in modeling and predicting the aerodynamics during startup (e.g., turbulence model limitations discussed in Section 6). Future directions include high-fidelity CFD (Large-Eddy Simulation or even Direct Numerical Simulation for small geometries) to capture the fine details of vortical structures around blades with enhancements. The work by Abdolahifar et al. (2026) calling for validated Fluid-Structure Interaction models points to a path: coupling CFD with structural simulation to see, for instance, how a flexible blade's bending interacts with startup torque [85]. Also, more wind tunnel experiments using techniques like Particle Image Velocimetry (PIV) could visualize *how exactly tubercles or flaps alter the flow during startup.* Understanding the flow physics in detail will allow optimization (maybe the optimal tubercle shape for a VAWT is different from that on a whale flipper – experiments could tailor it).

Energy economics and system-level research: On a broader scale, research should address how improved self-starting influences the *economic viability* of urban small wind. For example, an analysis might show that by reducing cut-in from 4 m/s to 3 m/s, the annual energy production increases by X% in a given city [32], translating to Y years reduction in payback period. Additionally, integrating storage or complementary sources (like PV) could smooth out times when the turbine is idle. If a turbine reliably self-starts in low winds, it might pair differently with solar (since it can contribute on those gentle wind nights etc.). There's room for research on optimal hybrid renewable system design where improved self-starting wind is a component.

Standardization of small turbine safety and performance standards to include startup: Current standards (IEC 61400-2 for small wind) mostly focus on design loads and power curves. They don't provide much guidance on measuring start-up or reporting it. Pushing for an update or an annex to those standards addressing startup performance could incentivize manufacturers to adopt enhancements and advertise them. Perhaps creating a standard metric like "startup time at 3 m/s" or "minimum wind speed for autonomous start" as something companies list (much like cut-in is listed, but making it a more precisely defined test).

Negative result dissemination: Encouraging the publication (or at least documentation on forums or open repositories) of negative findings, e.g., "We tried X, and it didn't improve start-up because of Y"—would save others from repeating those dead ends and stimulate creative solutions to the problems identified. A collaborative open dataset of trial-and-error in this field could be a future resource (in line with open science trends). Perhaps a repository where researchers can log the outcome of various self-start techniques tested on the same baseline turbine.

In summary, future research should not only refine and combine the technical strategies but also tackle the evaluative and integrative aspects – how to test them, how to implement them reliably in the real world, and how to incorporate them into the design philosophy of urban wind energy systems. With urbanization and the need for decentralized renewable power growing, solving these open challenges will be crucial to making small wind turbines a commonplace sight (and sound) in our cities, quietly spinning whenever a breeze blows.

10. Conclusions

This review examined self-starting enhancement strategies for small-scale H-Darrieus VAWTs operating in low-wind urban environments. The findings show that poor self-starting mainly results from weak or negative torque at low tip-speed ratios, stall at high angles of attack, low-Reynolds-number effects, and drivetrain resistance. No single enhancement strategy is universally optimal. Rotor-level modifications, blade-profile optimization, passive flow-control devices, biomimetic concepts, and active or semi-active methods each offer benefits, but they also involve trade-offs in efficiency, complexity, cost, and durability.

The practical value of this review is the development of a structured taxonomy and direct design guidelines for selecting suitable self-starting solutions. For most small urban VAWTs, a balanced design combining moderate solidity, low-Reynolds-number blade geometry, selected passive flow-control features, and a low-resistance drivetrain is likely to be more practical than relying on one method alone. Key research gaps remain, particularly the need for standardized startup testing, clearer definitions of cut-in and startup speed, long-term field validation under real urban turbulence, and further assessment of the manufacturability and durability of complex biomimetic and flow-control blade features. Overall, reliable self-starting should be treated as a primary

design requirement because a turbine that starts consistently in weak and unsteady winds may deliver greater practical energy yield than one optimized only for peak efficiency.

Author Contributions

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Conflict of Interest

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Data Availability Statement

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