Document Version
Final published version

Licence
CC BY

Citation (APA)
Bianchini, A., Ferreira, C. S., Paraschivoiu, I., & Melani, P. F. (2026). Are vertical-axis wind turbines a scientific mirage or the future of offshore wind energy? A critical perspective a century after Darrieus' patent. *Renewable and Sustainable Energy Reviews*, *234*, Article 116915. https://doi.org/10.1016/j.rser.2026.116915

Renewable and Sustainable Energy Reviews 234 (2026) 116915

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Are vertical-axis wind turbines a scientific mirage or the future of offshore wind energy? A critical perspective a century after Darrieus' patent

Alessandro Bianchini [a,*], Carlos Simao Ferreira [b], Ion Paraschivoiu [c], Pier Francesco Melani [a]

[a] Department of Industrial Engineering, Università degli Studi di Firenze, Via di Santa Marta 3, 50139, Firenze, Italy
[b] Delft University of Technology, Wind Energy, Kluyverweg 1, 2629HS, Delft, the Netherlands
[c] IOPARA Inc. - Wind Turbines and Aeronautics Consulting, 1595 Norway, Ville Mont Royal, QC, H4P 1Y3, Canada

ARTICLE INFO

Keywords:
Vertical-axis
Wind turbine
VAWT
Darrieus
Offshore
Review

ABSTRACT

After one century from the original patent of J.M. Darrieus on a lift-driven "turbine having its rotating shaft transverse to the flow of the current", vertical-axis wind turbines (VAWTs) are stuck in a dichotomy between being the most fertile field of research for aerodynamicists and a technology that still fails in turning into an industrial reality, with many companies going in and out of the market. After the research on VAWTs restarted in the early 2000s, significant progress was made in understanding their complex aerodynamics and modeling them with simulations of different fidelity, leading in turn to the definition of design guidelines able to reduce the performance gap with respect to horizontal-axis wind turbines (HAWTs) to less than ten percentage points. This did not persuade the consolidated HAWT industry to leave the most efficient and reliable horizontal-axis archetype, especially after the rush towards diffused onshore energy production by VAWT started in the 2010s failed. However, recent discoveries are putting again Darrieus VAWTs in the spotlight as a possible game changer in offshore wind energy, where their faster wake recovery could bring to farms with unprecedented energy density in a market where competition for marine space is strong. Different to other reviews made to date, the present study not only presents the evolution of VAWTs over the last decades, but also critically analyses the lessons learnt made along the way and highlights the recent discoveries that are opening after a century new prospects for VAWT technology.

1. Background and motivation

Vertical-axis wind turbines (VAWTs) are to date one of those cases in science where the amount of research published does not go hand-in-hand with investments and interest from industry [1].

Academia has been fascinated for decades by the complexity of the aerodynamics of airfoils in cycloidal motion, similar to what happened for helicopters in comparison to planes.

The continuous variation of the angle of attack (AoA) during the revolution, due to the different relative orientation of the peripheral and relative speeds, makes in fact VAWT aerodynamics much more complex, with a massive presence of dynamic stall [2] and other unsteady interactions between the flow structures detached upwind and the blades passing downwind, and in turn make them have aerodynamic efficiencies lower than those of horizontal-axis wind turbines (HAWTs). Historically, the performance difference between VAWTs and conventional HAWTs was quite large (in the order of 20% less, with a target power coefficient of 0.40-0.42 for VAWTs vs. 0.48-0.50 for HATWs) [3]. Recently, the innovations that will be described in this study have reduced the difference to less than 10% [4], with VAWTs able to overcome the reference threshold of 0.45. On top of these undeniable differences in efficiency, the architecture of lift-driven VAWTs also offers some very interesting advantages, including the lack of a yawing system, lower aerodynamic noise production with respect to HAWTs [5,6], and, mostly, the possibility to place the generator on the ground thus massively reducing the weight suspended on top of the tower, with tremendous advantages in terms of stability [7].

Despite these advantages, industry quite often still looks at VAWTs with distrust. On the one hand, this may be due to a sort of "emotional" diffidence towards a new and unproven technology where consolidated technology exists. While this is understandable, claimed reasons for not pursuing VAWT as an alternative technology are often partially

---

* Corresponding author.
E-mail address: alessandro.bianchini@unifi.it (A. Bianchini).

https://doi.org/10.1016/j.rser.2026.116915
Received 20 November 2025; Received in revised form 15 March 2026; Accepted 16 March 2026
Available online 23 March 2026

exacerbated, especially regarding the need for a new supply chain since basic components could be directly borrowed from existing HAWT industry. On the other hand, it is acknowledged that VAWTs have not received the same level of industrialization and applied research as HAWTs [8], thus lacking experience and benchmarking data in many aspects. Finally, it is sadly seen by VAWT experts that the wind industry is still not aware of all the innovations and progress made over the last 20 years, which can potentially shed new light on the future of the technology.

Moving from this background, the ambition of the present study is to go beyond the review papers published to date by not only providing a critical overview on this last century of research and development in VAWTs, as seen by the authors, who have been among the most active researchers in the field in the last 20 years, but also examining the very last discoveries on VAWT technology that emerged in the last two-three years. More specifically, while the prospects in offshore installations were already suggested by Ref. [8] as one of the possible key drivers for future development, very recent studies by TU Delft [9–11] and other researchers have shown that the known faster wake recovery of Darrieus VAWT can be further magnified in offshore installations by triggering a more intense vertical flow advection from the upper layers of the atmosphere, giving rise to the so-called *regenerative wind farming* that could potentially lead to unprecedented power density for future offshore wind farms. This possibility is put into context in a particular moment of wind energy history, in which wake losses in offshore wind farms are casting a shadow on the actual Levelized Cost of Energy (LCoE) of offshore wind and on the future maritime planning [12].

It is important to note that this article is structured not as a simple review study, but mostly as a perspective one. As such, rather than employing systematic database search protocols, the literature discussed herein has been critically selected based on the authors' long-standing, direct experience in the field to highlight foundational shifts, current bottlenecks, and future technological trajectories. As such, the referenced studies were selected primarily to exemplify key technological milestones and broader trends, rather than to serve as subjects for individual methodological critique.

The study is organized as follows. Section 2 presents an historical perspective on the development of VAWTs; in particular, we identified three main phases of VAWT development, i.e., the generation of large, Troposkien-blade machines in North America, the rush to small VAWTs in the early 2000s, and the present attempt to develop offshore VAWTs. Section 3 instead discusses the new discoveries and design paradigms that have emerged after a significant restart of the research, which took place at the beginning of the new millennium; particular focus is given to new perspectives in modeling unsteady flows and their effects on performance. Section 4 is dedicated to new scientific understandings of vertical flow advection in VAWTs and how these could potentially represent the true catalyst for the technology in offshore applications. Conclusions and recommendations are finally proposed in Section 5.

2. VAWTs over history: a retrospective analysis

Both the very first windmill [13] and the first wind turbine from Prof. James Blyth in 1887 were indeed based on a vertical-axis concept [14], probably due to the similarity with other devices humans made to exploit the wind force, such as sails, or with natural elements like trees. The first patent of a lift-driven *"turbine having its rotating shaft transverse to the flow of the current"* [15] was presented for the first time by the French engineer J.M. Darrieus exactly one century ago in 1925 in France and was then granted also in the US in 1931. Exploiting the wind through blades moving around an axis orthogonal to the wind is therefore neither new nor revolutionary. However, the development of vertical-axis wind technology parallel to conventional horizontal-axis one has seen alternate fortune over the years, relegating it often to be one of the most challenging research areas for aerodynamicists rather than a real industrial alternative.

Some very interesting papers/books have been published already focusing on the evolution of Darrieus VAWTs throughout history [3,8,16]. They presented in detail the different projects and demonstrators produced, and the reader is invited to refer to them for this information. This section instead aspires to present the evolution of Darrieus technology from a more critical perspective. Three main phases are distinguished, for each of which the main lesson learnt, in terms of both scientific progress and industrialization challenges, are identified and critically discussed in order to highlight how they could potentially contribute to the future development of the technology.

2.1. From the first patent to big demonstrators in North America

As most of renewable energy concepts proposed at the beginning of the 20th century, VAWT technology did not actually progress until the late 1960s, when engineers at the National Aeronautical Establishment of the National Research Council of Canada (NRC) started investigating the concept presented in Darrieus' patent [17,18], realized the very first experimental campaign on this type of rotors, shown in the left hand side of (Fig. 1), and then constructed in 1977 the first grid-connected large-scale Darrieus turbine (230 kW) in Magdalen Islands (Canada) [19]. The Canadian research program culminated with the world's largest VAWT ever built in 1988, the 110 m tall, 64 m diameter (swept area of 4000 m^2) 3.8 MW Éole at Cap-Chat, Québec [3]. In the years of the rise of VAWTs, however, the Canadian program was not alone. In Great Britain, for example, the H-type or Musgrove rotor was introduced [20], having for the first time straight blades and allowing to be reefed to provide speed control. In the US, VAWT research was initially undertaken at the National Aeronautics and Space Administration (NASA) in the early 1970s [21]. After these pioneering studies, the US Department of Energy (DOE) funded research programs at Sandia National Laboratories (SNL) [22]. The experience of the SNL wind energy research division represented a milestone in VAWT research up to the end of the 20th century [23] and culminated with the installation of a 34-m 500 kW turbine, show on the right hand side of (Fig. 1) [24,25]. This prototype was heavily instrumented and introduced many technological innovations, such as tailored airfoils, variable-speed control, and regenerative braking. Many other relevant examples of this pioneering phase could be mentioned, both from academia and research institutions; again, the reader is referred to the detailed historical reviews presented in Refs. [3] and [8].

Following the spirit of the present study, however, an annotated analysis of the heritage of this first historic phase is given. It is indeed undisputed that the pioneering studies in North America marked the beginning of VAWT technology. Experimental test at full scale not only proven the feasibility of the technology but also allowed a progressively increasing understanding of the complex physics past blades in cycloidal motion. However, the lack of computational fluid dynamics (CFD) resources and the need of relying on engineering methods only prevented scientists to delve properly into some complex phenomena connected to unsteady aerodynamics, like flow curvature effects, dynamic stall of spanwise flow components. This was particularly relevant in some cases for airfoil aerodynamics, where panel methods were able to provide partially reliable estimations of the behaviour near stall conditions, which is, however, of capital importance in VAWT. An iconic case is represented by the airfoil polars of the NACA0021 airfoil. For more than 30 years, the reference source for all the studies on VAWT was the report by Sheldahl & Klimas [26], who first tested in the wind tunnel symmetric airfoils and proposed extrapolation over the entire range of angles of attack, as needed in VAWT simulation. Several studies used such a report as a reference for the NACA0021 airfoil, but they all forgot that only few, low thickness-to-chord ratio airfoils were tested in reality by Sheldahl & Klimas, while many of the data commonly used (as those of the NACA0021 airfoil) come from a theoretical extrapolation, which has recently proven several times to be inaccurate [27] and thus led to systematic errors in most of the studies.

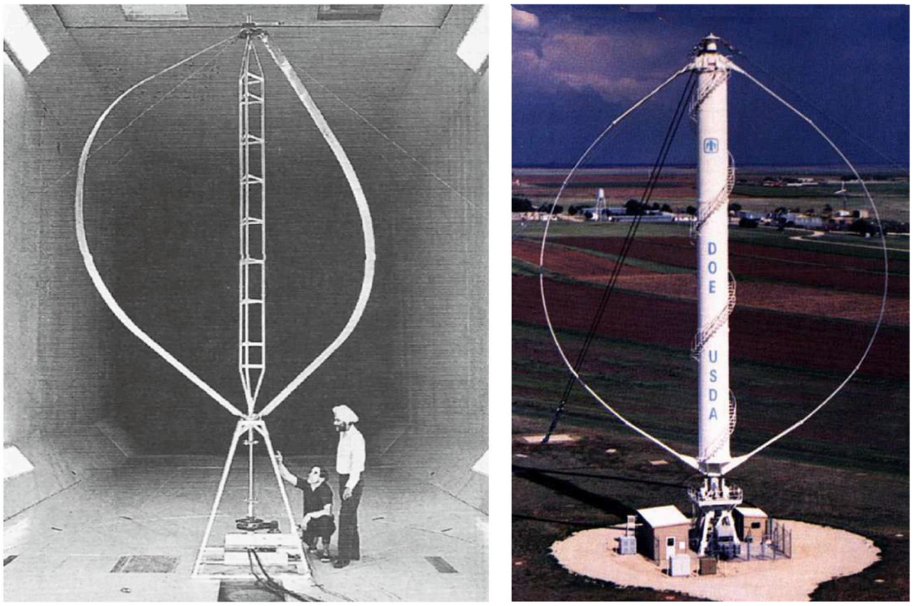


Fig. 1. First VAWTs demonstrators. (left) First experimental prototype at NRC; (right) SNL/DOE 34-m test rig. Figures from Ref. [8].

Notwithstanding this, it was not the lack of research interest that made the emphasis on VAWT beginning to shift in favour of HAWTs. First, superior power coefficients (more than 10% higher) made industry deem HAWTs to be more competitive than VAWTs. In addition, a sort of “emotional” diffidence also arose from a series of early accidents [28]. Possibly the most famous accident was the crash of the NRC Magdalen Islands VAWT in 1978, where during unscheduled maintenance the turbine unexpectedly self-started by itself with no brakes and eventually corkscrewed into the ground after reaching the run-away condition [29]. At that time, researchers were indeed convinced that VAWT technology was inherently not self-starting (hence the decision to remove the mechanical brakes), while it is now known the VAWT can self-start if gusty wind conditions exist [30,31]. In these regards, the attempt to quickly reach large-size applications (prior to a complete understanding of the underlying physics), while valuable for speeding up industrial development, can be probably deemed to have also represented a big risk. This is somehow similar to what happened in the same years for the large, megawatt-scale, two-blade HAWTs that were developed in the US [14] and came to a standstill in favour to the lighter, smaller, three-blade rotors developed in Denmark that did represent the forefathers of modern HAWTs.

2.2. *The urban dream: rushing towards small turbines in the early 2000s*

After large-scale VAWT research came to a standstill in the 90s, leaving the stage to the more efficient HAWT technology, a restart of the research was seen at the beginning of the new millennium, when a change of paradigm was hypothesized. Interest was indeed paid by architects, project developers, and local governments to understand whether small wind turbines can effectively be exploited to provide delocalized power in the built environment [32–34]. In this scenario, VAWTs were put again in the spotlight, as they were supposed to work more effectively in the case of low-speed, turbulent, and gusty flows [35]. In particular, the ability, proven by experiments and numerical models [2,36,37], of Darrieus rotors to even enhance their performance if invested by skewed flows was seen as a possible game changer for rooftop installations [38]. Moreover, Darrieus turbines have lower noise emission than HAWTs [39] and can be designed with various architectures [40], some of which are seen as more aesthetically pleasant and easy to integrate into buildings [41]. As a result, a huge number of industrial products and prototypes were presented in the early 2000s, some of them are reported in Fig. 2(b).

Despite the interesting prospects on paper, several factors hampered the real industrial diffusion of small VAWTs [42], as illustrated in Fig. 2.

From a tecno-economic point of view, the capital cost per installed kW was very high [43], as it is known that several cost items do not scale linearly with rated power [44]. More than this, the actual Annual Energy Production (AEP) measured in most of the pilot installations was significantly lower than expected, contributing to a bad reputation for the technology. The root causes of almost all wind turbines underperforming in the built environment were indeed many, the most relevant being the discrepancy between numerical predictions and the actual wind seen by the rotors [45], generally slower and gustier. Velocity variations and turbulence affected the aerodynamic performance and lead to higher fatigue loading on the components, shortening the lifespan of both turbines and supporting structures on the rooftops [46]. While these findings were common for both HAWTs and VAWTs [47], VAWTs, which were theoretically supposed to be less sensitive to turbulence and flow misalignment, showed poor performance. First, it is known that Darrieus VAWT may have problems with self-starting, especially at the low Reynolds numbers typical of Small Wind Turbines (SWTs) [30,31]. The reason for this is twofold. On one hand, blades can momentarily be in a position with respect to oncoming wind in which the actual angles of attack are very high and not able to provide sufficient torque to start spinning the rotor. This problem has been shown to be quite theoretical, as wind direction changes are likely sufficient to allow for first turbine rotation if the wind is sufficient. On the other hand, the time needed to accelerate to the design tip-speed ratio is in the order of minutes for small VAWTs [30], which is particularly critical for low-speed flows characterized by gusts in the order of few seconds. This effect is more pronounced in the H-shape configuration usually employed in small-scale installations; while this blade arrangement maximizes the rotor swept area and aerodynamic performance, it also increases its moment of inertia, hampering acceleration. Reports proved that this resulted in poor performance for long periods of time in the case of low wind speeds [48]. Building upon this experience, more advanced control strategies have been proposed lately [49,50], without having, however, the chance to be tested extensively. Even when self-starting was ensured, actual energy conversion was lower than expected. Small dimensions and lower wind speeds led to low Reynolds numbers [51], impacting airfoil performance and, mostly, resistance to stall, which in turn led to massive dynamic stall effects [52]. Moreover,

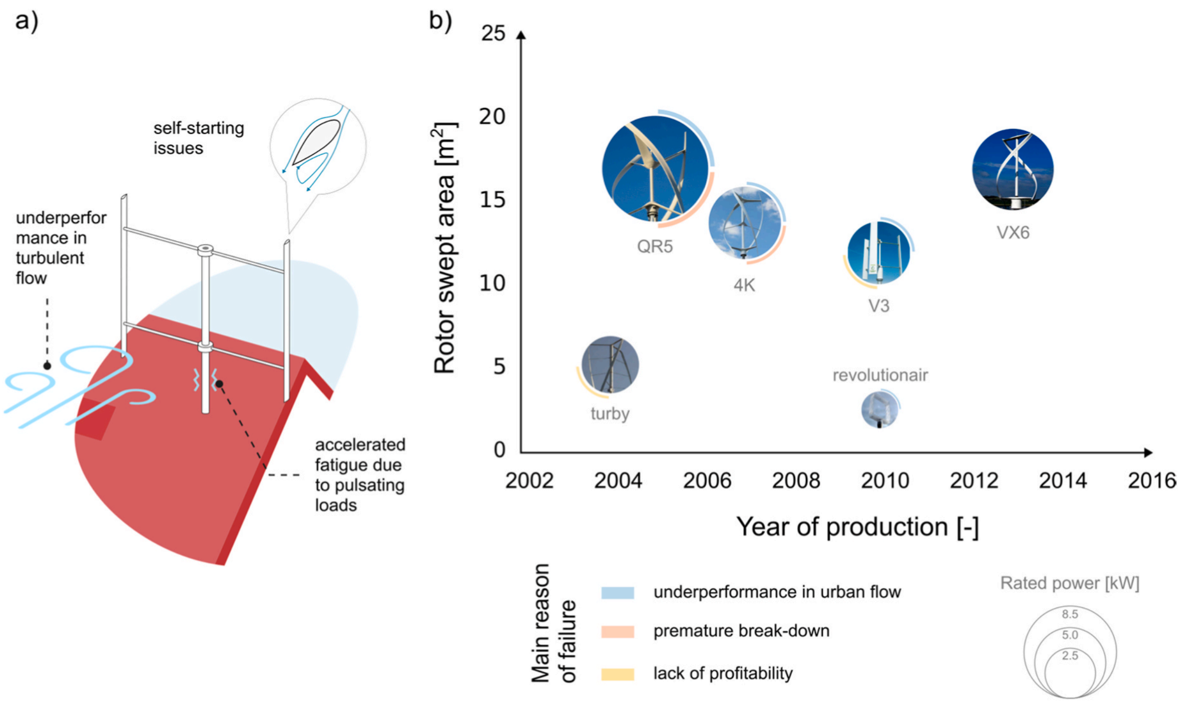


Fig. 2. Overview of the small VAWTs developed in the first 2000s: (a) Schematic illustration of the main issues hampering the industrial diffusion of VAWT in the early 2000s. Turbines faced a combination of problems ranging from inflow (turbulent and gusty winds in small applications close to the built environment) to lack of proper design guidelines (like flow curvature effects); (b) Some commercial small turbines available at the time, classified in terms of rotor size and reason of failure. Underperformance was a main issue for most of the rotors, especially up to 2010. Premature breakdown also affected significantly the first models.

in both H-shaped or Gorlov configurations, the impact of struts' resistant torque was massive, cutting up to 30% of the actual torque available [51]. Finally, small turbines often made use of inverters borrowed from the solar field (as dedicated ones were not available or very costly to develop), leading often to suboptimal power control.

Despite the negative results from an industrial point of view, the experience of small rotors has presented a milestone in VAWT history from several perspectives:

- It prompted the restart of research on VAWTs in many countries, creating for the first time a global community on the topic, after most of the research had been conducted in North America only.
- Small wind turbines could be tested in the wind tunnel at scale (or close to it) [53,54], expanding significantly the number of data available for benchmarking of simulations. Pioneering studies, for example, provided data for complex phenomena like dynamic stall (through PIV measurements [55]) or wake dissipation mechanisms [56,57]. Moreover, inconsistencies found in experiments with respect to theoretical expectations pushed scientists into studying more in depth some physical phenomena taking place past blades in cycloidal motion; these new understandings are now at the basis of new design choices discussed in Section 3. This was due to the fact that scaling down turbine dimensions forced designers to increase the overall solidity of the machines (in order to recover suitable Reynolds numbers through larger blade chords), resulting in designs that triggered flow curvature and unsteady flow effects to an unprecedented magnitude.
- The complexity of VAWTs aerodynamics pushed researchers into further developing engineering simulation methods and introducing higher fidelity ones. Regarding the first aspect, the Double Multiple Streamtubes Model (DMST) developed by Paraschivoiu [58] was further developed adding sub-models and corrections that made it able to handle correctly also higher-solidity designs [59]. Regarding the use of higher-fidelity methods, the increase in computational resources allowed for the first time the use of Computational Fluid Dynamics (CFD) to VAWTs. This has led to the definition of reference guidelines for CFD applied to VAWTs (e.g., Refs. [60,61]), as well as to unprecedented studies on three-dimensional flow structures [62]. While the accuracy of some CFD studies is still a topic of discussion (due to the scarcity of experimental benchmarking, mostly referring to small-scale models, as well as to the very high demanding calculation cost of three-dimensional models), the advent of blade-resolved studies marked a cornerstone in VAWT development. More broadly, studies on VAWTs in this period have triggered further investigation into airfoil unsteady aerodynamics after the relevant experience made on helicopters.

2.3. *Large-size offshore designs*

After a period of absence from industrial research agendas, which was, however, characterized by an impressive scientific production [8] (whose main outcomes are better discussed in the following Section 3), VAWTs emerged again in the last 10 years with a completely new perspective, i.e., the idea of going towards very large rotors [63], especially for offshore applications [64]. In particular, in Ref. [61] Prof. Paraschivoiu and others claimed that large VAWTs might be able in theory to recover the performance gap with respect to HAWTs, providing on the other hand system architectures that are theoretically cheaper and simpler. The industrialization of the technology is, however, not sufficient to verify these prospects yet.

Focusing particularly on offshore applications, if small rotors failed in exploiting some of intrinsic advantages of VAWT architecture like omni-directionality or better handling of turbulent flows, another advantage, i.e., the possibility of lowering the center of gravity of the turbine by putting the generator at the bottom of the tower, could represent a game-changer in the new floating wind industry. Upscaling conventional HAWTs in the floating configuration is indeed hindered by the fact that most of the turbine weight is concentrated in the rotor-nacelle assembly: increasing tower height and generator weight along with the turbine's rated power indeed increases inertial and gravitational loads, and thus the overall loads that must be compensated with the floating foundation [65]. Moreover, an additional underlying assumption is that the oscillating aerodynamic loads of VAWTs could have a less constrained scaling compared to those affecting HAWT blades [66]. Finally, operation and maintenance could be less critical [67]. As a result, many have been the proposals done so far both at industrial and research level [8], including Troposkien, H-type, or Gorlov turbines, e.g., Refs. [68–70]. Focusing on offshore applications, also twin-VAWT concepts were proposed (Fig. 3) [71]. The vast majority of such designs unfortunately remained at conceptual or pre-design level, facing resistance from investors, often motivated by the fact that the offshore supply chain for HAWT technology is already at a level of maturity that discourages radical changes. Moreover, the unfavorable economic situation, which started after the end of the restrictions connected to the Covid19 pandemics in 2021 and drove up prices for rare-earth materials, steel, and other key components of the offshore industry, is currently somehow pushing toward consolidation of existing technologies rather than to the introduction of new ones. A partial exception to this at the time of writing is the Swedish company SeaTwirl [72], which received a massive funding from the European Commission to push forward the development of a H-type Darrieus turbine on a spar floater (right hand side of Fig. 3). Section 4 will discuss, however, some limitations in the design of large offshore VAWTs that currently seem underestimated by analysts and designers.

3. New discoveries and design paradigms

Research on small scale prototypes described in Section 2 had the major merit of giving new impulse to research in VAWTs. In particular, the advent of CFD analyses allowed investigating phenomena not explored so far or shedding new light into some of those who were hypothesized in the first phase of big Troposkien turbines but not proven or completely characterized. Innovations were indeed many, and some review studies have been published already, especially on power augmentation devices described in Section 3.3. Again, the present study does not intend to repeat such reviews, but instead to critically analyze which was the impact that these innovations had on VAWT technology in terms of technical advancement, increase in technology readiness, and economic viability. Such innovations are suggested as key enablers for the attempt to design the new generation of offshore rotors described in Section 2.3.

To enable a more effective discussion, three main areas of innovation are proposed in the following.

3.1. Flow curvature effects

The functioning principle of Darrieus VAWTs implies that the airfoils rotate around an axis orthogonal to the flow direction, while immersed into a linear main flow stream. This condition is sometimes referred to as “cycloidal motion” and is known by aerodynamicists for long. The macro-effect of such a combination of motions is the continuous variation of the angle of attack and the resulting dynamic effects that will be discussed in Section 3.2. However, additional complex phenomena are triggered, among which a series of “flow curvature effects” which impact the aerodynamic performance of the airfoils. In particular, whenever the chord length of the airfoil is large in comparison to the revolution radius of its trajectory (i.e., the turbine radius), the airfoil itself cannot be assimilated anymore to a point in the space to which lumped quantities can be referred to, such as in conventional 1D aerodynamics. More specifically, the points along the airfoil surface are characterized by a different peripheral speed (both in direction and in modulus, since the local revolution radius is different), which in turn makes the local velocity triangle different (see Fig. 4). As a result, the pressure profile that is generated around the airfoil, and in turn the aerodynamic forces that are produced, are different from those expected for the same airfoil in the case it is exposed to a straight flow field having the same relative speed and incidence referred to its aerodynamic center. The first who theorized and mathematically demonstrated flow curvature effects were Migliore et al. [73]. They proposed modeling them as the superposition of a *virtual camber* [74] and a *virtual incidence* [75]. To model the first effect, one should consider that an airfoil in cycloidal motion behaves aerodynamically as if it is conformally transformed into a virtually cambered one having the same thickness distribution along the chord, but the camber line curved along the revolution trajectory [76]. Moreover, this virtual airfoil is expected to work with an average incidence different from the one calculated with conventional velocity triangles (Fig. 4).

After the first theorization by Migliore, who only made theoretical analyses based on panel methods, combined experimental and numerical studies by Bianchini et al. [74,75] have quantified more in detail such effects and have shown the actual dependency on the tip-speed ratio, the turbine chord-to-radius ratio (c/R), and the azimuthal position. In particular, the use of CFD allowed analyzing also high angle of attack that are not captured well by panel methods. These studies also confirmed that, while flow curvature effects are theoretically present in every cycloidal motion, they become relevant for the design only when $c/R > 0.1$. More interestingly, this new phase of the research led to three important design guidelines:

- If one wants to simulate correctly Darrieus VAWTs using engineering methods, such as the BEM or lifting line one, it is mandatory to use as an input the polars of the virtual airfoil [59,77,78], including also a virtual incidence that can be treated as a virtual pitch [75];

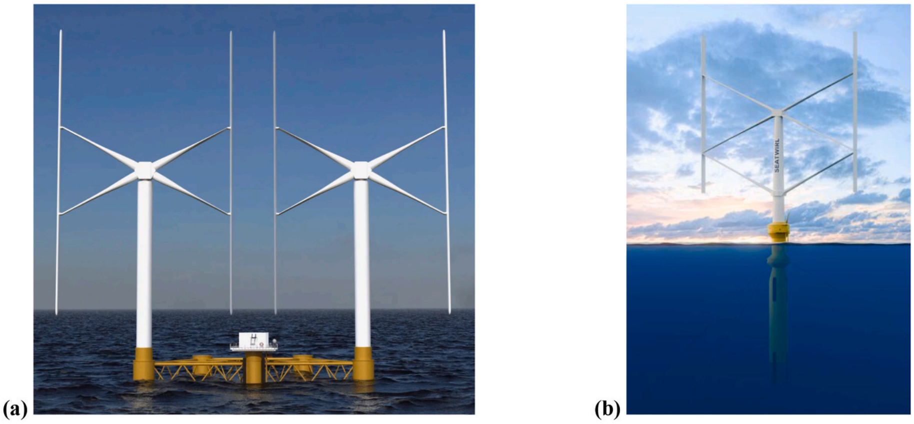


Fig. 3. (a) Concept design of the Nenuphar TwinFloat turbine (render openly available in the web); (b) Render of the SeaTwirl floating turbine concept [72].

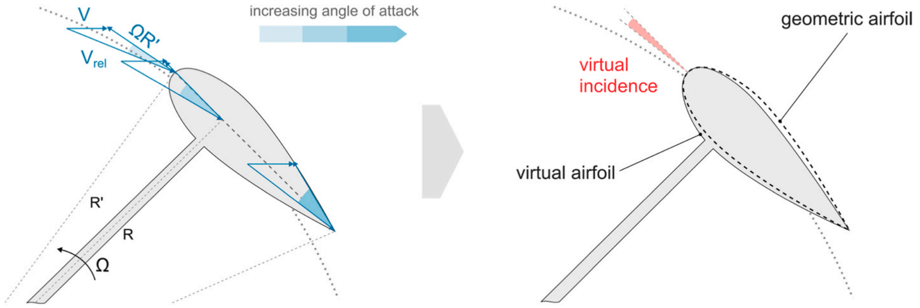


Fig. 4. Flow curvature effects. (a) Variation of the local angle of attack along the airfoil; (b) Virtually transformed airfoil subject to virtual incidence.

- Looking at the problem from a different perspective, if one wants to reproduce with the physical model the target performance defined at simulation level, the turbine should be made with physical airfoils different from those used during the design, i.e., the virtually-transformed ones mounted with the additional camber point outwards as shown in Fig. 4.
- Overall, the suggested guideline for the design is to use symmetric airfoils at the design level, which show overall the best performance [79]. In practice, the turbine will be constructed with virtually cambered ones. These airfoils will perform at rated speed (high TSR, when flow curvature effects are prominent) as symmetric ones, while they will work as cambered airfoils (which they physically are) at low TSR, i.e., during start-up and acceleration phases, maximizing the benefits of such airfoils as lower Reynolds numbers and larger AoAs [31,80–82].

As a corollary of the above, it can be also observed that high-solidity wind turbine design, which are known to help in the case of small rotors and to provide lower revolution speed beneficial for centrifugal stresses, are subject to massive flow curvature effects, whose impact must be carefully assessed during the design phase. These studies on flow curvature effects have impacted significantly the research on VAWTs with high solidity and are now at the basis of all relevant studies involving high-solidity rotors, e.g., Refs. [83–85].

Another important design aspect connected to the cycloidal motion, and often neglected in the past, is the impact of airfoil pitching moment [86] and its impact on performance in relationship to the blade-spoke connection [87]. In particular, in Ref. [88] it was shown that, due to variation of the aerodynamic center of the airfoils at the different incidence angles experienced in VAWT motion, a mismatch is created between the aerodynamic center and the blade-spoke connection point, which in turn generates a moment that directly contribute to torque (Fig. 5).

In particular, it was demonstrated that at very low revolution speeds, the contribution of such moment becomes significant due to the very high angles of attack experienced by the blade. In case of a straight-camber or an inward-concavity airfoil, the effect of the pitching moment is to reduce the starting torque upwind, increasing on the other side the downwind performance. This is of particular importance for airfoils compensated for virtual camber (with respect to a symmetric one), whose increased torque output and flatter torque profile could improve their starting characteristics with respect to common literature indications. Then, the influence of the pitching moment was studied in combination with the selection of the blade-spoke connection point. In particular, it was shown that, when the blade is attached far from its aerodynamic center (e.g., at middle chord), the contribution of the pitching moment to torque can become extremely relevant. By doing so, however, alternate loads on the connection point also become larger, making the structural design of the rotor more challenging. As a final design guideline, it is suggested that the selected airfoil must be connected at quarter chord, or as close as possible to its aerodynamic center, in order to limit the stresses on the connection, and only then properly pitched to achieve maximum efficiency.

3.2. Dynamic effects on airfoil performance

Due to their cycloidal motion, VAWT blades operate in a highly unsteady environment characterized by large oscillations in both angle of attack and relative inflow velocity. These unsteady effects influence blade performance and loads not only in limited the post-stall region, where dynamic stall dominates, but also under nominal operating conditions at relatively high tip-speed ratios. In such conditions, rapid inflow variations alter the temporal response of aerodynamic forces and introduce additional loads associated with local flow acceleration around the blade (impulsive loads) [89]. Unsteadiness is therefore intrinsic to all VAWT configurations to a much larger extent with respect to what previously hypothesized [58]. Fig. 6 revisits VAWT historical evolution focusing on the relationship between rotor design and unsteady operation. To the purpose, the definition of reduced frequency proposed by Laneville and Villecoq [90] is adopted, as in Eq. (1):

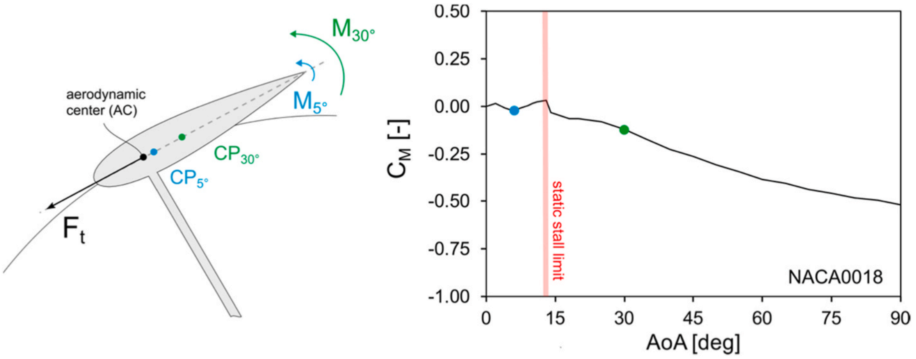


Fig. 5. Some examples of small VAWTs developed in the first 2000s.

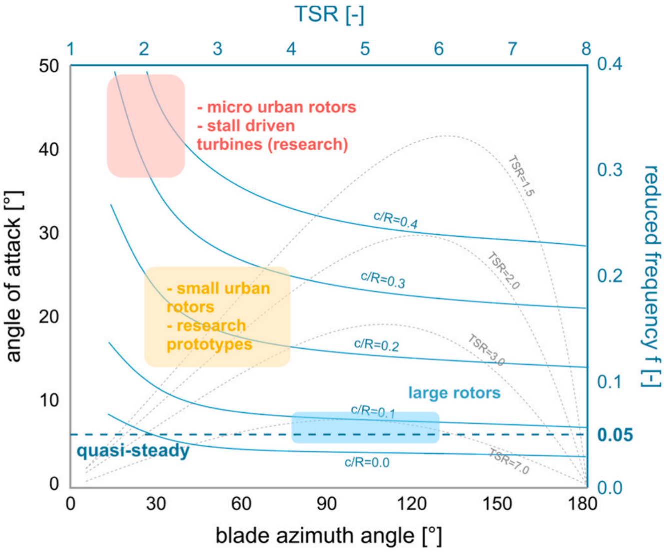


Fig. 6. Average reduced frequency as a function of the turbine design and tip-speed ratio. Adapted from Ref. [91].

$$f = \frac{c\dot{\alpha}_{max}}{2\Omega R\alpha_{max}} \tag{1}$$

where c is the chord length, Ω the rotational speed, R the rotor radius, and α the instantaneous angle of attack. This formulation conveniently links unsteadiness to rotor geometry, specifically the chord-to-radius ratio c/R, and its nominal tip-speed ratio (TSR). The quasi-steady limit, below which unsteady effects are negligible, is established at $f = 0.05$.

According to this map, early large-scale demonstrators developed in North America (see Section 2.1), designed for high-speed operation at low angles of attack, with small chords $(0.05 < c/R < 0.1)$ and high TSRs $(4 < TSR < 6)$, still operated near the quasi-steady limit, thus experiencing moderate unsteady effects. Theoretically, the same applies to recent offshore concepts (see Section 2.3), although their more flexible composite blades exhibit lower natural frequencies, often approaching the rotor blade-passing frequency.

This amplifies vibration amplitudes and increases the effective reduced frequency, introducing aeroelastic stability concerns that remain an active research frontier [92].

Downscaling for urban applications (see Section 2.2) led to higher c/R and lower TSRs, driven by the need to maintain higher Reynolds numbers on smaller rotors. This shift moved the nominal operating point to a region with high unsteadiness $(0.1 < f < 0.2)$ and larger angles of attack, where unsteady boundary layer evolution and separation dominate blade aerodynamics and determines both performance and load fluctuations. Depending on airfoil selection and operating parameters, dynamic stall might also occur. Recently, researchers have tried to exploit, rather than mitigate, these unsteady effects. "Stall-driven" VAWTs employ large chords (up to $c/R \sim 0.4$) to intentionally promote unsteady flow and take advantage of the transient lift enhancement given by unsteady boundary layer growth and roll-up, without incurring in the drag penalty given by vortex shedding and unsteady separation [93]. Due to the limitations of current Unsteady Aerodynamic Models (UAMs), most of these studies rely on experiments or high-fidelity simulations.

Despite the intrinsic relationship between VAWT operation and unsteady aerodynamics, the development of UAMs for turbine design and verification has remained stagnant for decades. The main models, developed in the '80s by Strickland [89] and Berg [94], only accounted for the observed stall delay during boundary-layer growth and roll-up via a lag in the effective angle of attack. At the time, the influence of other unsteady phenomena (attached flow dynamics, vortex convection and detachment) on VAWT performance was not yet understood. Since then, only limited progress has been achieved. Attempts to adapt the Beddoes-Leishman dynamic stall model (e.g., Ref. [95]), still one of the most comprehensive physics-based formulation, faced challenges in calibration and adaptation to VAWT kinematics. This is also the reason why many small-scale commercial prototypes (see Section 2.2) suffered from accelerated fatigue and poor aerodynamic performance under turbulent flow.

To enable the successful deployment of VAWTs in the future, it is therefore essential to identify the key phenomena governing their unsteady behaviour and include them into a robust UAM. Fig. 7 summarizes recent research efforts in this direction [96,97], mapping the main flow regimes to their dominant unsteady mechanisms and corresponding turbine operating conditions. and the turbine operating points where they have the most relevance. Following Le Fouest et al. [96], four flow regimes can be distinguished:

- *Attached flow*: unsteady effects under attached flow conditions are relevant for very small turbines, operating at high reduced frequencies, and large offshore rotors, where aero-elastic coupling might arise. Current understanding of wake lag and impulsive loading remains limited, though both significantly affect load phasing at moderate to high TSRs (see Fig. 7). Pirrung and Gaunaa [98] made an early attempt to include these effects, but it never went beyond theoretical considerations. Among quasi-steady effects, flow curvature has received the most attention. Studies by Strickland [89] and later Ferreira [99] pointed out that this is a quasi-steady effect and can be thus handled in a UAM framework. Current formulations, nonetheless, are still based on the virtual transformations or simplified models described in Section 3.1;
- *Shear layer growth*: unsteady boundary layer development and roll-up virtually affect all VAWT designs, as flow separation is rarely absent. The main open question concerns the boundary layer dynamics of thick airfoils used on modern designs. Kim et al. [100] highlighted that the progressive trailing edge stall characterizing these airfoils does not follow the classical assumptions behind dynamic stall modelling, which originated from observations on leading edge stall. In this case, there is no significant difference between an airfoil in pitching and VAWT motion, provided that the pitch rate in the stall region is consistent [97];
- *Dynamic stall*: dynamic stall, i.e., the formation and shedding of a leading-edge vortex (LEV) and sometimes a trailing edge vortex (TEV), dominates blade aerodynamics at low TSRs and high angles of attack, leading to severe load fluctuations after LEV detachment. In VAWTs, LEV-blade interaction is more complex than in the pitching airfoil case because of the mismatch between the circular blade trajectory and the LEV path in the freestream (see Fig. 7). More in detail, the phasing between LEV detachment and the start of the blade pitch-down motion, strongly influences magnitude and frequency of the following load fluctuations [97];
- *Flow re-attachment*: at the angle of attack ranges and reduced frequencies typical of VAWT operation (see Fig. 6), deep stall and flow re-attachment play a central role in determining cyclic load variations. A phenomenon which still requires extensive investigation is the interaction between the passing blade and the LEV shed by a preceding blade [97]. Implementing this interaction within low-order UAM frameworks remains a major challenge, as it related to the flow field at the rotor level.

The discussion above focuses on the upwind region for brevity, but similar mechanisms occur also in the downwind one, where lower inflow velocities, and thus higher reduced frequencies, amplify unsteady effects.

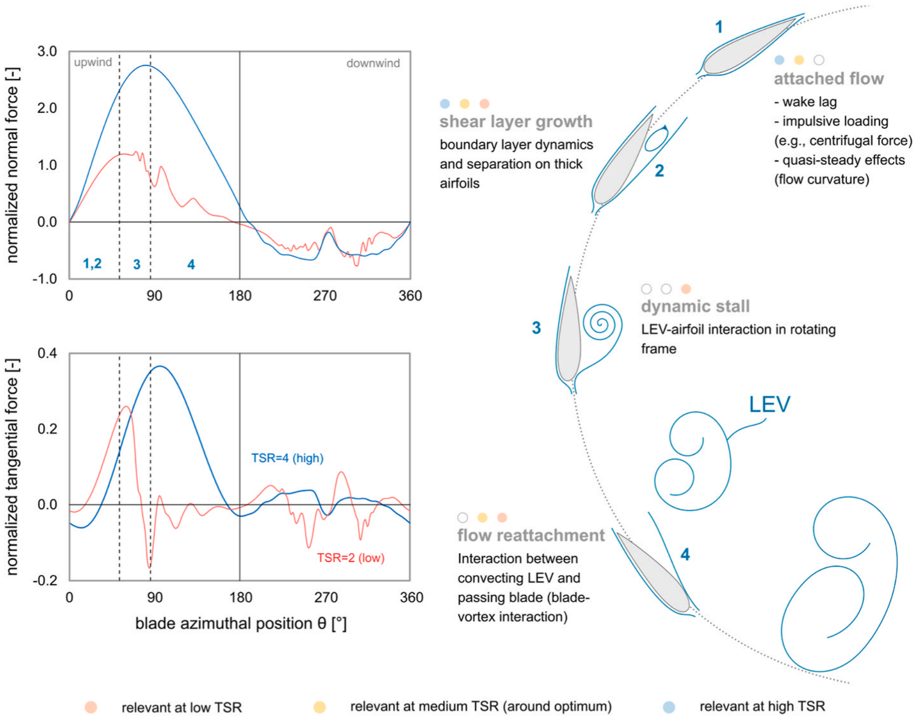


Fig. 7. Main dynamic effects on VAWTs requiring investigation. Load curves are adapted from Ref. [52].

3.3. Variable pitch and performance augmentation devices

Research on Power Augmentation Devices (PADs), i.e., passive or active devices to enhance turbine performance, emerged alongside the rush towards small VAWTs for urban applications in the 2000s [101, 102]. These devices were and, to some extent still are, considered promising solutions VAWTs core problems: poor self-starting capability, low-efficiency, and load fluctuations (see Section 2.2). Their deployment, however, has faced obstacles similar to those that hindered small VAWTs themselves.

Passive devices, e.g., Gurney Flaps [103–106], Vortex Generators [107–109], or even a combination of the two [110] gained attention due to their simplicity, ease of implementation, and potential for retrofitting existing machines. Numerical studies reported efficiency increase of 20%-50% and torque fluctuations reductions up to 20% [111,112]. Yet, these benefits were typically confined to the design point. Off-design, passive devices often fail to cope with the complex aerodynamics of VAWTs, leading to significant performance degradation.

Moreover, as shown in Fig. 8 for the Gurney Flap case, the aerodynamic coupling between the *upwind* and *downwind* halves of the rotor further limits their effectiveness: unloading the blades upwind tends to increase loading downwind, and vice versa, making it difficult to achieve a net gain in overall performance. This is a key concept in VAWTs, too often overlooked or not completely captured by theoretical studies and needs special consideration whenever the performance of an airfoil for a specific range of angles of attack is changed (either with passive or active devices). Moreover, combined with their limited technological maturity (most remain at Technology Readiness Levels (TRL) 3–5 [111]) and uncertainty regarding their effectiveness under highly turbulent conditions, these factors have so far prevented spread commercial adoption of PADs.

Active devices, in particular active pitch [114–118] and intracycle rotational speed control [119], face the opposite issue. In principle, they can improve performance across the entire operating envelope, but their feasibility is limited by the complexity of the actuation and control systems [111]. On top of that, they struggle with rapid directional changes typical of real wind environments, undermining one of the key advantages of VAWTs: omni-directionality. For large, offshore machines (see Section 2.3), implementation of active PADs, especially variable pitch, is complicated by the large high structural loads and large lever arms involved.

A notable exception is found in hydrokinetic turbines. Operating in controlled water channels or similar environments, they experience relatively steady inflows with constant direction and low turbulence.

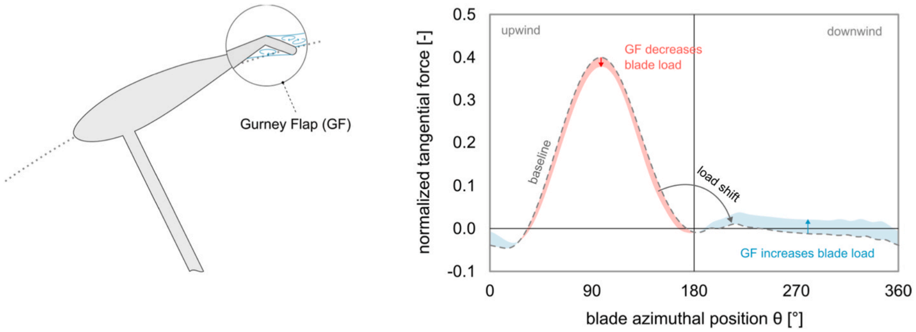


Fig. 8. Example of Gurney Flaps application to a small VAWT and effect on the load profile. Adapted from Ref. [113].

This removes the main barrier to PAD deployment, allowing for device optimization around one or two operating conditions. Numerical and experimental studies have demonstrated that Gurney flaps [113], vortex generators [120], variable pitch [121], and intracycle speed control [119] can significantly enhance the performance and mechanical stability of prototype and commercial hydrokinetic turbines, thus showing the potential of PADs for this application.

3.4. Power augmentation in closely-spaced rotors

On top of individual turbine design studies, a number of theoretical [122,123] and experimental [124,125] studies have recently demonstrated that the aero/hydrodynamic efficiency of Darrieus turbines can be improved if two or more rotors are deployed in close proximity. Such multi-rotor configurations can provide a higher power generation compared to a standalone turbine. In particular, the recent study from Mohamed et al. [122] identified the different mechanisms taking place when two counter-rotating Darrieus rotors are deployed in a closely-spaced inline configuration (Fig. 9). This layout indeed creates a blockage region in the area between the rotors, straightening the local inflow and suppressing streamtube expansion. In turn, this allows more momentum flux to enter the rotor domain. The change in the inflow direction creates a favorable increase in the angle of attack in the region of interaction, enhancing lift and thus torque generation. The azimuthal sector where this happens depends on the specific rotor arrangement [126].

While this effect is extremely attractive for all applications having a constant inflow direction, e.g., hydrokinetic VAWTs in rivers or channels, its application to VAWT-based farms is more critical. In fact, the power augmentation effect is strongly dependent on the alignment of the array with the wind. When the inflow deviates beyond a critical misalignment angle, which depends on rotor spacing (approximately 60° for typical layouts), the two rotors start operating in each other wake, lowering efficiency way below that of an isolated rotor [127]. However, recent analyses suggest that, under favorable alignment conditions, the potential performance gains in array configurations could be massive [128].

On the other hand, the concept of pairs of Darrieus rotors may find interesting application in the design of single units for floating applications, as proposed by the former French company Nenuphar in 2006 (Fig. 3) [71]. In these conditions, innovative mooring systems could be studies so as to self-orientate the entire floating unit towards the wind and thus constantly exploit the power augmentation effect. However, no such concept is currently in a phase of industrial development.

4. New prospects: the game changer for offshore applications?

Upon examination of Sections 2 and 3, a critical observer not involved in VAWT research directly would likely draw two main conclusions: 1) the levels of efficiency and industrialization reached by HAWTs likely do not leave room for another technology to compete; 2) VAWTs may have potential in some niche applications due to ancillary benefits like lower noise or more pleasant aesthetic apparel, especially when integrated with existing structures. However, recent theoretical investigations and experimental evidence at laboratory scale suggested that – if proven true – VAWTs could represent an interesting alternative to HAWTs in offshore installations. Such evidence came as the culmination of both the improved understanding of inner physics past blades in cycloidal motion and the enhanced simulation capabilities presented in previous sections; indeed, it is only once a more detailed aerodynamic modeling (especially for flow curvature effects and dynamic aerodynamic properties) and reliable CFD methods (to explicitly model turbulence and complex, three-dimensional flows) become available that VAWTs have been looked from a different perspective, i.e., not only as competitors with HAWTs at individual turbine level, but rather as an interesting solution for more efficient wind farm clustering. This new research scenario will be described in this Section 4.

4.1. HAWTs' benefits and drawbacks in offshore conditions

While HAWTs are and will remain irreplaceable in onshore applications, thanks to better energy conversion and cost-effectiveness, doubts have been raised recently on the possible negative impacts (ranging from higher LCOE, to excessive use of marine space, impact on sea life, visual impact, and other detrimental effects on human activities) of massive HAWT-based offshore deployment into multi-GW offshore wind farms [129]. These impacts are intrinsic to HAWT architecture. Indeed, it is known that, for a single wind turbine, energy is harvested directly from the oncoming wind at hub height. However, within extensive wind farms or clusters, the energy available in the horizontal airflow is rapidly exhausted by the front rows of turbines, necessitating the vertical entrainment of wind from above the farm to maintain energy production. As shown in Fig. 10(a), in HAWTs such exchange of momentum between the wind flow and the turbine occurs primarily in the direction of the wind, and it is achieved only by using turbulent mixing at the wake boundaries as the mechanism to draw the fresh air required for wake dissipation from the upper layers of the Atmospheric Boundary Layer (ABL) [130]. As a result, it is necessary to increase the spacing between turbines to allow for a sufficient recovery of the wake, limiting in turn the achievable power density of current installations to 5-7 MW/km^2 [129]. To address power losses caused by wake interference in HAWTs, various solutions are being explored, shifting the perspective from individual turbines to the wind farm as a whole [131–133]. One of the most used and effective approaches is "wake steering", which involves operating rotors at high yaw angles (greater than 20°) to redirect their wakes away from downstream turbines [131]. This strategy effectively increases the energy density of the wind farm, also by activating, although at small scale, the generation of counter-rotating vortexes able to draw fresh air from outside the wake [134,135]. Moreover, this control technology has been efficiently complemented with farm-level management, actually improving the overall energy conversion of modern farms. On the other hand, its potential is limited by

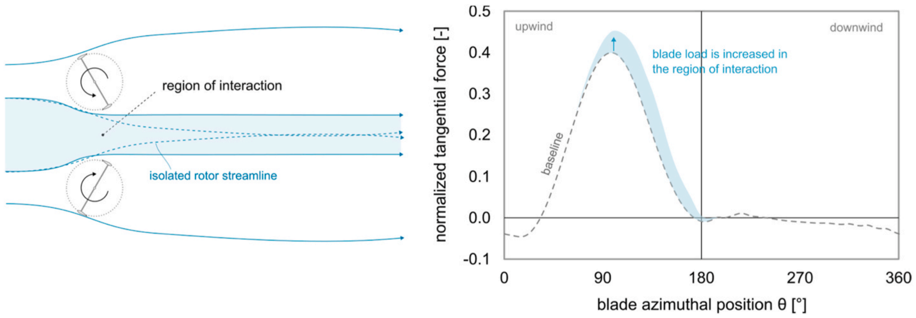
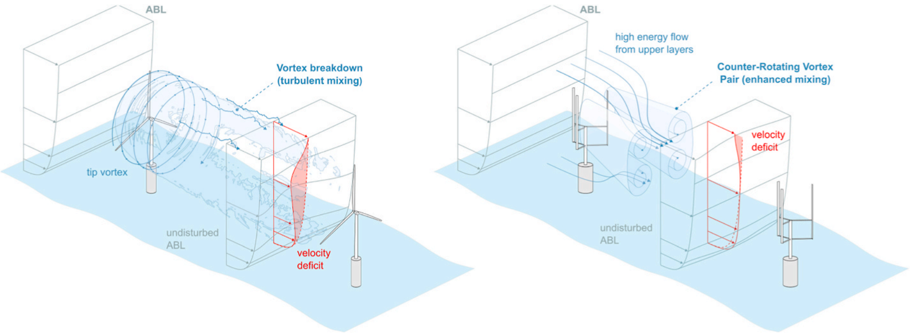


Fig. 9. Power augmentation mechanism in closely-spaced VAWTs. Adapted from Ref. [122].



a)

b)

Fig. 10. Underlying physics of wake recovery in HAWTs (left) or VAWTs (right). In HAWTs wake dissipation is achieved only by using turbulent mixing at the wake boundaries. VAWTs are instead able to provide forces also in a plane perpendicular to the wind direction, thus can in theory create vertical flow structures that could bring “fresh” air from the upper levels of the ABL down to wind farm level, thus promoting mixing and wake dissipation.

efficiency losses and increased loads experienced by individual HAWTs when operated in yaw [136]. Other proposals have been made about tilting the turbines to advect the wake vertically [137,138], but they are even more critical in terms of increased loads. In addition, modern horizontal-axis rotors are generally very large and mounted on tall towers, thus exploiting higher and more energized section of the wind shear profile and generating complex interaction with the atmospheric boundary layer. Overall, it should be noted that discussed limitations are architectural for HAWTs and not technological failures, with these machines often nearly reaching the aerodynamic efficiency limits. Despite all challenges, however, wake losses are seen today as the main obstacle tothe economic competitiveness of future offshore wind farms [139–141]. As suitable offshore locations for wind farms become scarce, there is a growing push towards higher power densities, potentially exceeding 10 MW/km^2. This trend risks reducing wind farm efficiencies to below 60% relative to isolated wind turbines as per [142,143]. The expected large-scale expansion of offshore wind energy, if reliant on current HAWT-based farms, could lead to intensive marine space usage with possible adverse environmental and societal impacts.

4.2. *Vertical flow advection in VAWTs for increased energy density: the concept*

From a large-scale aerodynamic perspective, the only way to reduce wake losses, i.e., to have a more energized flow within dense farms, is to achieve a higher vertical entrainment of energy and momentum from the upper layers of the ABL into the farm [144], which has been recently called “regenerative wind farming” [10]. This cannot be accomplished solely through turbulent mixing at the wake boundaries, as in HAWTs, but would require actively promoting the exchange of momentum by generating rotor forces perpendicular to the wind stream without compromising the axial thrust. Recent studies have tried therefore to determine if a different turbine architecture, namely the VAWT concept, can enable such a mechanism.

What is proven to date? - Recent studies [10,11,145,146], in fact, have proven that the only architecture able to intrinsically promote this force system is the vertical-axis turbine [147], while the concept of “regenerative wind farming” can be addressed also with additional appendices like proposed for example by Refs. [148,149]. As qualitatively shown in Fig. 10(b), VAWT rotors indeed act as a 3D actuator cylinder that simultaneously generates thrust aligned and perpendicular to the wind, extracts energy, and creates a pressure field and a trailing vorticity system that advect the wake vertically within the wind farm. Several mechanisms intrinsic to VAWT aerodynamics can be exploited to achieve this enhanced mixing.

A first mechanism consists in the generation of a crosswise/radial force, which triggers the formation of a counter-rotating vortex pair (CRVP) in the turbine near-wake (x/D $<$ 5). This force naturally arises from the blade-flow interaction in the plane perpendicular to the axis of rotation and can be magnified by applying a positive collective pitch to the rotor blades. The presence of CRVPs, experimentally demonstrated for the first time at TU Delft [11], induces vertical momentum entrainment from the undisturbed flow above the rotor as well as deflection of the wake in the lateral direction, due to the combined effect of the rotor crosswise force and CRVP roll-up. A theoretical interpretation of the process is illustrated by Fig. 11. A following experimental study [145] quantified the advantage in wake recovery given by the CRVP structure, reporting a +55% increase in the momentum available to a second turbine placed 5D downstream of the first one. The same work also revealed that the CRVPs generated by the two closely aligned turbines merge downstream, creating a stronger turbulent mixing region that further accelerates wake recovery and re-energizes the flow further downstream.

Evidence described above has been corroborated by laboratory-scale experiments and this actually represented a big step forward with respect to mere theoretical speculations. On the other hand, it should be acknowledged that the reduced scale of the models and the necessarily

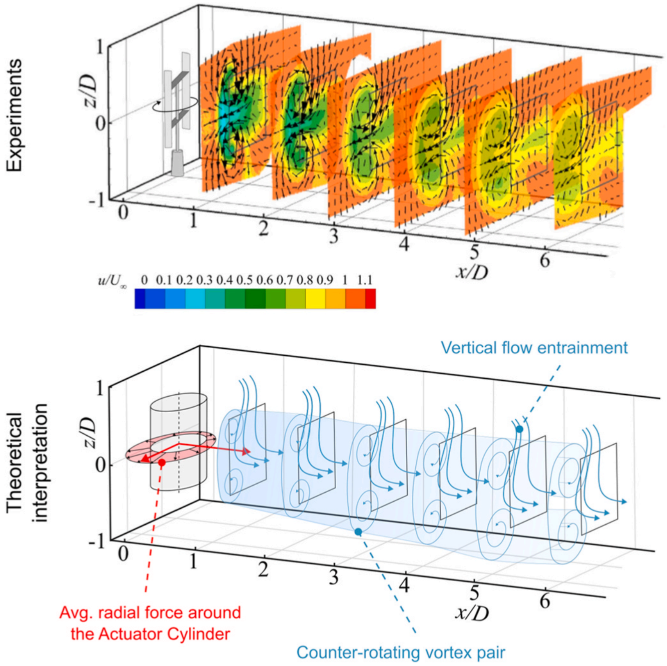


Fig. 11. Experimental demonstration of vertical flow advection in VAWTs wake [11] (top) and its theoretical interpretation (bottom).

simplified inflows reproduced in the tunnel require additional work before the magnitude of these effects can be claimed also for VAWT turbines in real-life working conditions.

A second mechanism, proposed by Mendoza and Goude [146] through numerical simulation, involves pitching the struts connecting the rotor blades to the tower to generate a vertical force and deflect the wake in the vertical direction. Their simulations showed authors that full wake recovery could be achieved within 5D downstream of the turbine, although this concept has not yet been extended to the wind farm scale. Similar results have been also presented by Ribeiro et al. [150]. Similar principles are also at the basis of different turbine architectures, like for example the X-Rotor [151–153].

Farm scale effects have instead been investigated for the CRVP-based mechanism. Measurements on a 3 x 3 layout (small scale turbines) by Bensason et al. [10] confirmed the existence of CRVPs and their superposition across multiple turbines, consistent with the single rotor observations. The progressive accumulation of these vortices throughout the array generates persistent, large-scale entrainment cells that continuously draw high-momentum air from the atmospheric layers above the turbine canopy. Collectively, the turbine array thus acts as a momentum mixing region rather than a momentum sink, achieving wake recovery rates in the central region of the farm up to six times larger than the baseline case.

The concept of regenerative wind farming is so interesting that – at the time of writing of this study – is being further expanded by incorporating the concept of “multi-rotor” systems, in which static wings are also introduced to maximize the vertical exchange of momentum [154–156].

What still requires demonstration? – The latest results about the theoretical ability of the VAWT architecture to advect fresh air from the upper levels of the atmospheric boundary layer down to the wind far level are undeniably interesting. However, it should be remembered that to date significant uncertainties are still present: a) the impact of realistic inflows: inflows for wind tunnel small-scale turbines cannot reproduce the complexity of a real atmospheric flows; b) turbulence: atmospheric turbulence has scales and spectra that cannot be reproduced exactly in the tunnel; c) scales: to date, as proven in Section 2, only few VAWT demonstrators of relevant size have been produced. Actual performance at scale has then to be proven yet, alongside with the magnitude that flow advection can have in reality. On the other hand, in the ideal case in which such magnitude was in real life similar to the one argued from preliminary analyses, the new technology (VAWTs for vertical flow advection + improved wind farm layouts) could be entitled of achieving power densities up to 15 MW/km^2, compared to the 3.6-6.0 MW/km^2 typical of HAWT-based farms. This would correspond to potential capacity factors around 56%, comparable with current HAWT installations, but with far more efficient use of marine space. Alternatively, given the same power density, the capacity factor of HAWT-based farms would go down to 45-47% due to wake losses.

4.3. Challenges in designing large VAWTs for offshore applications

Although the prospects highlighted in Sect. 4.1 suggest that the Darrieus architecture could in theory represent a potentially disruptive technology, it is true that not only such a scenario has to be proven at utility scale and with realistic inflows, but also that designing large offshore VAWT rotors could be a task much more complicated than preliminary theoretical studies hypothesized.

The first limitation regards maximum physical dimensions. In fact, while some literature has identified a limit around 30 MW for the rated power of offshore VAWTs [66], some practical design calculations suggest that such limit is quite unrealistic. Indeed, if one assumes a realistic power coefficient of 0.45 (quite high for VAWTs, but at hand for a H-VAWT based on the innovations discussed in Sect. 3) and a rated wind speed of 10 m/s (comparable to state-of-the-art offshore HAWTs for windy installations), this would led to a swept area of about 109,000 m^2; assuming again a turbine height-over-diameter ratio of 2 and the H-type configuration (for the sake of simplicity, but also to be compliant with the hypothesized power coefficient), turbine’s blades would span for more than 460 m, i.e., a value that is out of any reasonable range at the moment in terms of blade manufacturability, transportation, and installation. Repeating again this very simple pre-design exercise, fixing now the blade tip height to 300 m, i.e., a value in line with current cutting-edge offshore HAWT designs (especially in terms of installation constraints), one will find that a rated power of approximately 10 MW is currently a reasonable maximum figure for offshore VAWTs.

Even if these dimensions are met, they will impose additional design constraints in terms of relative inflow that are unprecedented for VAWT technology. The first element of discussion is turbine architecture. Some studies pointed out that the Troposkien shape is the most favorable one for upscaling VAWTs [69]. While this is perfectly understandable from a load perspective, since the Troposkien blades allow for the best load distribution spanwise [157,158] and the resistant torque of the struts is minimized, the efficiency of such concept would likely be lower than the reference power coefficient value of 0.45 that was hypothesized before, leading to even worse specific power values. This is due to the fact that the revolution radius is not constant, and thus the operating conditions of large portions of the blade. Moving to the H-type configuration brings notable increases in efficiency [70], at the cost of increased loads, especially gravitational ones on the struts, which becomes not only long (as long as the revolution radius), but also thick enough to ensure a good resistance area; this in turn increases the parasitic drag, penalizing efficiency [51].

Assuming now that an H-type configuration is in fact selected, a problem that has been strongly underestimated to date is the impact of wind shear on VAWTs. As apparent from Fig. 12, when VAWT dimensions reach the multi-MW scales discussed before, the wind shear profile, although favorable in offshore conditions, creates a non-negligible variation in the actual tip-speed ratio at different span heights, and in turn different ranges of the angle of attack and resulting efficiency.

It should be remembered in fact that, while the effect of wind shear can potentially be compensated in HAWTs with variable pitch actuation along the revolution [159], in VAWTs the only way to correct the effects of wind shear would be to act with blade design. This concept was one of the those at the basis of recent innovative rotor designs such as the X-Rotor [160], but has not been quantified so far in more conventional designs. In particular, assuming that a Darrieus turbine is optimized for the TSR at midspan, the upper half of the rotor would work with an equivalent tip-speed ratio that reduced progressively toward the tip (see Fig. 11). However, the variation is likely to be small, as large rotors will exploit a portion of the wind profile in which vertical gradients are moderate. On the other hand, in the lower part of the revolution, the tip-speed ratio will progressively increase, leading potentially to performance reduction in virtue of a narrowing of the optimal range of angles of attack. In the future, optimized designs could be developed to account for these effects, either with blades with curved blades or with local blade twisting. In both cases, however, the manufacturing of the blade would be more complex and costly, hampering one of the main benefits of the H-Darrieus configuration.

These are only high-level design problems, but they already give a hint of how far the current VAWT industry is in comparison to the level of maturity of the HAWT one. Additional aspects would include optimized control [161,162], moorings (if floating) [67], and – most importantly – the maximization of vertical flow advection introduced in Section 4.1. Moreover, experimental data about the actual reliability and failure rates of large VAWTs are extremely scarce, since very few test models (especially in the H-type configurations) have been produced and tested for a significant time. Only few simulations have been provided to date (e.g., Ref. [163]). Notwithstanding this, the opportunities presented earlier in this study still clearly point out at least big room for research to prove if VAWTs could represent an alternative with

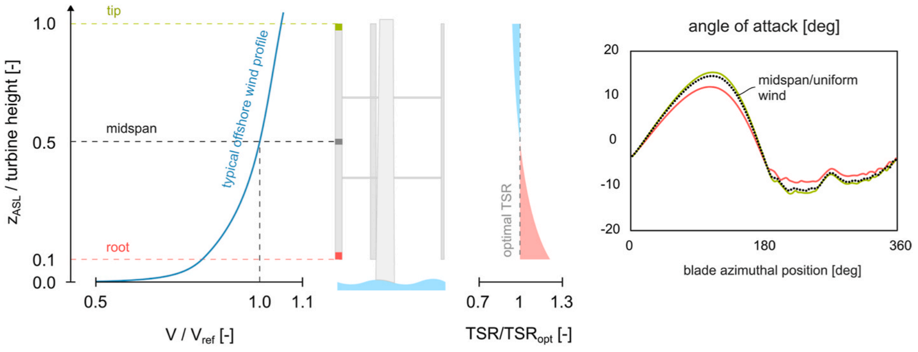


Fig. 12. Effect of wind shear on the local angle of attack along the blade span in a large size VAWT.

respect to HAWTs in offshore conditions.

4.4. HAWTs vs. VAWTs in offshore applications: a critical comparison

Despite the theoretical possibility outlined in Section 4.2 of potentially having faster wake recovery and then allow for high energy density wind farm layouts, it is undisputed that VAWTs still lag behind their horizontal-axis counterparts in terms of technological development and readiness for industrial-scale deployment [67,164]. As discussed, while part of this gap can be attributed to the limited interest from both industry and academia over recent decades, technological challenges are inherently associated with the VAWT architecture, which become even more pronounced in offshore applications [4]. In such an environment, where potential benefits could be maxima, the relatively low Technology Readiness Level of VAWT technology represents a major barrier to investment, as offshore wind projects already involve high capital expenditures and financial risk [164].

To provide the reader with a broader overview of the aspects discussed so far, Table 1 presents a concise comparison between VAWTs and HAWTs in offshore conditions. It is evident from the comparison how one of the primary obstacles preventing VAWTs from competing with HAWTs is the absence of a mature industrial ecosystem comparable

Table 1
VAWTs potential advantages and open challenges for offshore applications in comparison with HAWTs.

KPI	VAWT		HAWT	
	potential advantage	open challenge	current advantage	open challenge
Scalability	- cost-effective blade scaling due to reduced gravitational loading [66]	- current prototypes limited to 10 MW - limited industrial experience with large-scale designs [164] - need for massive support structures when dimensions increase	- scalability to 15–22 MW [166] - mature supply chain	- further scaling constrained by gravitational loads and installation constraints
Wake recovery	- faster wake recovery (∼5D spacing) [145,168]	- limited validation data - lack of mature wake interaction models [169]	- extensive reference datasets [170] - validated tools for wake interaction prediction [171]	- larger turbine spacing (7–10D) due to slow wake recovery [129] - mitigation strategies provide limited improvements [136]
Fatigue life	- fatigue benefits due to reduced loading from yaw and platform motion[a] [164]	– 2 x cycle loading[b] - fatigue-critical components (e. g., struts) [172]	- lower cyclic loading in normal operation - mature aeroelastic modelling tools [166]	- fatigue prediction for frontier applications[a] remains uncertain
Farm-scale operation	- easier maintenance and lower downtime due to simplified drivetrain and absence of yaw system [164]	- lack of operational VAWT wind farms limits operational data and maintenance experience	- established monitoring, maintenance procedures, and operational expertise	- offshore drivetrain and nacelle maintenance remain costly - farm costs scale with inter-array cabling [173]
Farm-scale power density	- higher farm power density (up to ∼15 MW km^{-2}) [10] - reduced marine footprint	- farm-level performance to be demonstrated at commercial scale - lack of established layout optimization tools [169]	- farm power density well characterized for conventional layouts	- lower power density (3–6 MW km^{-2}) [129] - large spatial footprint, especially for floating [174]
Certification	- simplified drivetrain and lack of yaw system may streamline certification pathways	- absence of dedicated standards and DLCs[c] - uncertain load prediction due to complex aerodynamics [167]	- comprehensive certification standards and DLC frameworks widely accepted by industry and financial institutions	- certification procedures may require adaptation for emerging applications[a]
Bankability	- LCOE reductions through rotor scaling and increased farm density - reduced platform mass and cost[a] [175]	- limited operational and performance data increase investment risk	- long operational track record and well-established financing framework	- financing costs increase for higher-risk or first-of-a-kind projects[a]
Technology Readiness Level (TRL)	- rapid development due to simpler prototyping and modular concepts	- current TRL ∼ 4–5, limited to isolated demonstrators [67,164] - no supply chain	- TRL 9 for fixed-bottom turbines - TRL 7–8 for floating applications	-

[a] Floating applications.
[b] H-rotor.
[c] Design Load Cases.

to that which has developed around HAWTs after decades of technological development and operational experience [165]. This long development history has also enabled the creation of the advanced aeroelastic tools currently used for HAWT design and certification [166]. In contrast, the complex aerodynamics of VAWTs (see Section 3.2) make the prediction of unsteady loads and the rigorous definition of certification Design Load Cases (DLCs) a particularly challenging task [167].

5. Conclusions and future perspectives

The history of wind turbines has been to a large extent a history of success. From the forefather Vestas V10 up to the 20 MW and larger rotors under study today, horizontal axis wind turbines have been providing an increased amount of clean and affordable energy. HAWTs have proven to be efficient, reliable, and environmentally friendly in the installations made to date. On the other hand, the history of VAWTs has known alternate fortune, oscillating between some first attempts of industrialization and sound claims from academia. Upon examination of the critical review provided in this paper, it is apparent that, despite the significant amount of research done over the last twenty years that has reduced the efficiency gap with respect to HAWTs to less than 10%, VAWTs cannot compete with HAWTs in onshore installations or whenever the turbines can operate in a sufficiently free flow, since HAWTs represent a technologically mature, reliable, and simply more efficient technology; under these preconditions, industry has not have interest in try filling the gap in terms of industrialization of VAWT technology. Borrowing an image presented by Prof. Ferreira during the WESC Conference 2023, HAWTs are the "Formula 1 cars" of renewables and have no rivals when racing on track, i.e., with good wind resource, low turbulence, and no obstacles. However, when we need to go off track, rally cars are much better suited. Theoretically speaking, this could be the case of new offshore installations, in which the needs of reducing use of marine space, cost of cables and infrastructures, and the request for massive installed power are pushing towards farms so dense that HAWTs are unable to exploit their potential completely. Under this perspective, the unique possibility provided by VAWT architecture to create forces perpendicular to the wind direction without penalizing thrust (apparent from a theoretical point of view, and recently proven at laboratory scale) could be exploited to entrain momentum and energy from the higher levels of the ABL down to the farm level, so to achieve faster wake dissipation and then more energy-dense wind farms. To achieve this, however, significant effort is needed first from scientists to demonstrate if this technology is actually able to provide such a positive interaction with the atmosphere in real-life cases (actual scales, realistic inflow, turbulence, etc.); to this end, financed projects at low technology readiness level could represent a key catalyst of research in a phase where many unknowns still exist, especially providing support for the realization of demonstration prototypes at larger scales, which could provide the experimental benchmark that is mandatory to validate theoretical speculations and simulation models. If proven feasible, industry could then need to leave the diffused aversion to VAWTs and invest money to re-adapt the existing supply chain to promote VAWTs in offshore applications. Only in this scenario, vertical-axis wind turbines could turn from a "scientific mirage" to a significant contributor to future wind energy conversion.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

References

[1] Salvador-Gutierrez B, Sanchez-Cortez L, Hinojosa-Manrique M, Lozada-Pedraza A, Ninaquispe-Soto M, Montaño-Pisfil J, et al. Vertical-axis wind turbines in emerging energy applications (1979–2025): global trends and technological gaps revealed by a bibliometric analysis and review. Energies 2025;18. https://doi.org/10.3390/en18143810.

[2] Simão Ferreira CJ, Van Bussel G, Van Kuik G. An analytical method to predict the variation in performance of a H-Darrieus in skewed flow and its experimental validation. Proc Euro Wind Energy Conf 2006;2:988–93.

[3] Paraschivoiu I. Wind turbine design: with emphasis on darrieus concept. Reprinted. Montreal: Presses Internat. Polytechnique; 2009.

[4] Griffith DT, Barone MF, Paquette J, Owens BC, Bull DL, Simao-Ferriera C, et al. Design studies for deep-water floating offshore vertical axis wind turbines. Albuquerque, NM (United States): Sandia National Lab. (SNL-NM); 2018. https://doi.org/10.2172/1459118.

[5] Aihara A, Bolin K, Goude A, Bernhoff H. Aeroacoustic noise prediction of a vertical axis wind turbine using large eddy simulation. Int J Aeroacoustics 2021;20:959–78. https://doi.org/10.1177/1475472X211055179.

[6] Wang W-Y, Ferng Y-M. Numerical model for noise reduction of small vertical-axis wind turbines. Wind Energy Sci 2024;9:651–64. https://doi.org/10.5194/wes-9-651-2024.

[7] Collu M, Kolios AJ, Chahardehi A, Brennan F. A comparison between the preliminary design studies of a fixed and a floating support structure for a 5 MW offshore wind turbine in the north sea: marine renewable and offshore wind energy. In: RINA R. Inst. Nav. Archit. - mar. Renew. Offshore wind energy - pap. Royal Institution of Naval Architects; 2010. p. 63–74.

[8] Hand B, Cashman A. A review on the historical development of the lift-type vertical axis wind turbine: from onshore to offshore floating application. Sustain Energy Technol Assessments 2020;38:100646. https://doi.org/10.1016/j.seta.2020.100646.

[9] Broertjes TJ, Bensason D, Sciacchitano A, Ferreira C. Lift-induced wake Re-Energization for a VAWT-based multi-rotor system. J Phys, Conf Ser 2024;2767:072012. https://doi.org/10.1088/1742-6596/2767/7/072012.

[10] Bensason D, Mulay J, Sciacchitano A, Ferreira C. Experimental demonstration of regenerative wind farming using a high-density layout of vertical-axis wind turbines. Wind Energy Sci 2025;10:1499–528. https://doi.org/10.5194/wes-10-1499-2025.

[11] Huang M, Sciacchitano A, Ferreira C. On the wake deflection of vertical axis wind turbines by pitched blades. Wind Energy 2023;26:365–87. https://doi.org/10.1002/we.2803.

[12] EUR-Lex - 52020DC0741 - EN - EUR-Lex n.d. https://eur-lex.europa.eu/legal-content/EN/PIN/?uri=celex:52020DC0741 (accessed October 15, 2025).

[13] See the 1,000-Year-Old windmills still in use today n.d.

[14] Owens B. The wind power story: a century of innovation that reshaped the global energy landscape. 2019.

[15] Marie DGJ. Turbine having its rotating shaft transverse to the flow of the current. US1835018A. 1931.

[16] Möllerström E, Gipe P, Beurskens J, Ottermo F. A historical review of vertical axis wind turbines rated 100 kW and above. Renew Sustain Energy Rev 2019;105:1–13. https://doi.org/10.1016/j.rser.2018.12.022.

[17] Templin RJ, Rangi RS. Vertical-axis wind turbine development in Canada. IEE Proc Phys Sci Meas Instrum Manag Educ Rev 1983;130:555–61. https://doi.org/10.1049/ip-a-1.1983.0085.

[18] Blackwell BF, Sullivan WN, Reuter RC, Banas JF. Engineering development status of the darrieus wind turbine. J Energy 1977;1:50–64. https://doi.org/10.2514/3.47929.

[19] Templin RJ, McConnell RD. Summary report on the collapse of the magdalen islands wind turbine. 1979. p. 353–65.

[20] Price TJ. UK large-scale wind power programme from 1970 to 1990: the carmarthen Bay experiments and the musgrove vertical-axis turbines. Wind Eng 2006;30:225–42. https://doi.org/10.1260/030952406778606214.

[21] Muraca RJ, Stephens MV, Dagenhart JR. Theoretical performance of cross-wind axis turbines with results for a catenary vertical axis configuration. 1975.

[22] American Wind Energy Association and others. Vertical axis wind turbine: the history of the DOE program. 1986.

[23] Sutherland HJ, Berg DE, Ashwill TD. A retrospective of VAWT technology. Albuquerque, NM (United States): Sandia National Laboratories (SNL-NM); 2011. https://doi.org/10.2172/1035336.

[24] Berg DE. Structural design of the sandia 34-meter vertical-axis wind turbine. Albuquerque, NM (USA): Sandia National Labs.; 1985.

[25] Ashwill TD. Measured data for the Sandia 34-meter vertical axis wind turbine. Albuquerque, NM (United States): Sandia National Labs.; 1992.

[26] Sheldahl RE, Klimas PC. Aerodynamic characteristics of seven symmetrical airfoil sections through 180-degree angle of attack for use in aerodynamic analysis of vertical axis wind turbines. Albuquerque, NM (USA): Sandia National Labs.; 1981. https://doi.org/10.2172/6548367.

[27] Melani PF, Balduzzi F, Ferrara G, Bianchini A. An annotated database of low reynolds aerodynamic coefficients for the NACA0021 airfoil. AIP Conf Proc 2019;2191:020111. https://doi.org/10.1063/1.5138844.

[28] Tjiu W, Marnoto T, Mat S, Ruslan MH, Sopian K. Darrieus vertical axis wind turbine for power generation I: assessment of darrieus VAWT configurations. Renew Energy 2015;75:50–67. https://doi.org/10.1016/j.renene.2014.09.038.

[29] South P, Watts A. Magdalen islands VAWT field test. 1979. p. 334–51.

[30] Dominy RG, Lunt P, Bickerdyke A, Dominy J. Self-starting capability of a darrieus turbine. Proc Inst Mech Eng Part J Power Energy 2007;221:111–20. https://doi.org/10.1243/09576509JPE340.

[31] Bianchini A, Ferrari L, Magnani S. Start-up behavior of a three-bladed H-darrieus vawt: experimental and numerical analysis, vol. 1; 2011. p. 811–20. https://doi.org/10.1115/GT2011-45882.

[32] Dayan E. Wind energy in buildings. Power generation from wind in the urban environment - where it is needed most. Refocus 2006;7:33–4. https://doi.org/10.1016/S1471-0846(06)70545-5. 36,38.

[33] Beller C. Urban wind energy - state of the art 2009. Danmarks Tekniske universitet. Risø Nationallaboratoriet for Bæredygtig Energi; 2009.

[34] Balduzzi F, Bianchini A, Ferrari L. Microeolic turbines in the built environment: influence of the installation site on the potential energy yield. Renew Energy 2012;45:163–74. https://doi.org/10.1016/j.renene.2012.02.022.

[35] Balduzzi F, Zini M, Molina AC, Bartoli G, De Troyer T, Runacres MC, et al. Understanding the aerodynamic behavior and energy conversion capability of small darrieus vertical axis wind turbines in turbulent flows. Energies 2020;13. https://doi.org/10.3390/en13112936.

[36] Mertens S, Van Kuik G, Van Bussel G. Performance of an H-Darrieus in the skewed flow on a roof. J Sol Energy Eng Trans ASME 2003;125:433–40. https://doi.org/10.1115/1.1629309.

[37] Bianchini A, Ferrara G, Ferrari L, Magnani S. An improved model for the performance estimation of an H-darrieus wind turbine in skewed flow. Wind Eng 2012;36:667–86. https://doi.org/10.1260/0309-524X.36.6.667.

[38] Balduzzi F, Bianchini A, Carnevale EA, Ferrari L, Magnani S. Feasibility analysis of a Darrieus vertical-axis wind turbine installation in the rooftop of a building. Appl Energy 2012;97:921–9. https://doi.org/10.1016/j.apenergy.2011.12.008.

[39] Möllerström E, Ottermo F, Hylander J, Bernhoff H. Noise emission of a 200 kW vertical axis wind turbine. Energies 2016;9:19. https://doi.org/10.3390/en9010019.

[40] Aslam Bhutta MM, Hayat N, Farooq AU, Ali Z, Jamil ShR, Hussain Z. Vertical axis wind turbine - a review of various configurations and design techniques. Renew Sustain Energy Rev 2012;16:1926–39. https://doi.org/10.1016/j.rser.2011.12.004.

[41] Sharpe T, Proven G. Crossflex: concept and early development of a true building integrated wind turbine. Energy Build 2010;42:2365–75. https://doi.org/10.1016/j.enbuild.2010.07.032.

[42] Kumar R, Raahemifar K, Fung AS. A critical review of vertical axis wind turbines for urban applications. Renew Sustain Energy Rev 2018;89:281–91. https://doi.org/10.1016/j.rser.2018.03.033.

[43] Chagas CCM, Pereira MG, Rosa LP, da Silva NF, Freitas MAV, Hunt JD. From megawatts to Kilowatts: a review of small wind turbine applications, lessons from the US to Brazil. Sustainability 2020;12:2760. https://doi.org/10.3390/su12072760.

[44] Bianchini A, Bangga G, Baring-Gould I, Croce A, Cruz JI, Damiani R, et al. Current status and grand challenges for small wind turbine technology. Wind Energ Sci Discuss 2022;2022:1–54. https://doi.org/10.5194/wes-2022-34.

[45] Kc A, Whale J, Urmee T. Urban wind conditions and small wind turbines in the built environment: a review. Renew Energy 2019;131:268–83. https://doi.org/10.1016/j.renene.2018.07.050.

[46] Malliotakis GE, Nikolaidis TN, Baniotopoulos CC. Small wind turbines: sustainability criteria related to the local built environment. IOP Conf Ser Earth Environ Sci 2020;410:012046. https://doi.org/10.1088/1755-1315/410/1/012046.

[47] Fields J, Oteri F, Preus R, Baring-Gould I. Deployment of wind turbines in the built environment: risks, lessons, and recommended practices. Golden, CO (United States): National Renewable Energy Lab. (NREL); 2016. https://doi.org/10.2172/1260340.

[48] Battisti L. Design options to improve the dynamic behavior and the control of small H-Darrieus VAWTs. Appl Sci 2021;11:9222. https://doi.org/10.3390/app11199222.

[49] Battisti L, Benini E, Brighenti A, Dell'Anna S, Raciti Castelli M. Small wind turbine effectiveness in the urban environment. Renew Energy 2018;129:102–13. https://doi.org/10.1016/j.renene.2018.05.062.

[50] Brandetti L, Mulders SP, Merino-Martinez R, Watson S, Van Wingerden J-W. Multi-objective calibration of vertical-axis wind turbine controllers: balancing aero-servo-elastic performance and noise. Wind Energy Sci 2024;9:471–93. https://doi.org/10.5194/wes-9-471-2024.

[51] Bianchini A, Ferrara G, Ferrari L. Design guidelines for H-Darrieus wind turbines: optimization of the annual energy yield. Energy Convers Manag 2015;89:690–707. https://doi.org/10.1016/j.enconman.2014.10.038.

[52] Melani PF, Balduzzi F, Brandetti L, Ferreira CS, Bianchini A. An experimental and numerical analysis of the dynamic variation of the angle of attack in a vertical-axis wind turbine. J Phys, Conf Ser 2020;1618:052064. https://doi.org/10.1088/1742-6596/1618/5/052064.

[53] Battisti L, Zanne L, Dell'Anna S, Dossena V, Persico G, Paradiso B. Aerodynamic measurements on a vertical axis wind turbine in a large scale wind tunnel. J Energy Resour Technol Trans ASME 2011;133. https://doi.org/10.1115/1.4004360.

[54] Dossena V, Persico G, Paradiso B, Battisti L, Dell'Anna S, Brighenti A, et al. An experimental study of the aerodynamics and performance of a vertical axis wind turbine in a confined and unconfined environment. J Energy Resour Technol Trans ASME 2015;137. https://doi.org/10.1115/1.4030448.

[55] Ferreira CS, Van Bussel G, Van Kuik G. 2D CFD simulation of dynamic stall on a vertical axis wind turbine. Verif Val PIV Measure 2007;23:16191–201. https://doi.org/10.2514/6.2007-1367. Reno, Nevada.

[56] Persico G, Dossena V, Paradiso B, Battisti L, Brighenti A, Benini E. Time-resolved experimental characterization of the wakes shed by H-Shaped and troposkien vertical axis wind turbines. J Energy Resour Technol 2017;139:031203. https://doi.org/10.1115/1.4035907.

[57] Bianchini A, Balduzzi F, Ferrara G, Ferrari L, Persico G, Dossena V, et al. Detailed analysis of the wake structure of a straight-blade H-Darrieus wind turbine by means of wind tunnel experiments and computational fluid dynamics simulations. J Eng Gas Turbines Power 2018;140. https://doi.org/10.1115/1.4037906.

[58] Paraschivoiu I. Wind turbine design: with emphasis on Darrieus concept. Reprinted. Montreal: Presses Internat. Polytechnique; 2009.

[59] Bianchini A, Balduzzi F, Ferrara G, Persico G, Dossena V, Ferrari L. A critical analysis on low-order simulation models for darrieus vawts: how much do they pertain to the real flow? J Eng Gas Turbines Power 2019;141. https://doi.org/10.1115/1.4040851.

[60] Balduzzi F, Bianchini A, Maleci R, Ferrara G, Ferrari L. Critical issues in the CFD simulation of Darrieus wind turbines. Renew Energy 2016;85:419–35. https://doi.org/10.1016/j.renene.2015.06.048.

[61] Rezaeiha A, Montazeri H, Blocken B. Towards accurate CFD simulations of vertical axis wind turbines at different tip speed ratios and solidities: guidelines for azimuthal increment, domain size and convergence. Energy Convers Manag 2018;156:301–16. https://doi.org/10.1016/j.enconman.2017.11.026.

[62] Balduzzi F, Drofelnik J, Bianchini A, Ferrara G, Ferrari L, Campobasso MS. Darrieus wind turbine blade unsteady aerodynamics: a three-dimensional Navier-Stokes CFD assessment. Energy 2017;128:550–63. https://doi.org/10.1016/j.energy.2017.04.017.

[63] Paraschivoiu I, Ammar S, Saeed F. VAWT versus HAWT: a comparative performance study of 2–6 MW rated capacity turbines. Trans Can Soc Mech Eng 2018;42:393–403. https://doi.org/10.1139/tcsme-2017-0137.

[64] Griffith DT, Paquette J, Barone M, Goupee AJ, Fowler MJ, Bull D, et al. A study of rotor and platform design trade-offs for large-scale floating vertical axis wind turbines. J Phys, Conf Ser 2016;753:102003. https://doi.org/10.1088/1742-6596/753/10/102003.

[65] Papi F, Bianchini A. Technical challenges in floating offshore wind turbine upscaling: a critical analysis based on the NREL 5 MW and IEA 15 MW Reference Turbines. Renew Sustain Energy Rev 2022;162:112489. https://doi.org/10.1016/j.rser.2022.112489.

[66] Ottermo F, Bernhoff H. An upper size of vertical axis wind turbines. Wind Energy 2014;17:1623–9. https://doi.org/10.1002/we.1655.

[67] Ghigo A, Faraggiana E, Giorgi G, Mattiazzo G, Bracco G. Floating vertical axis wind turbines for offshore applications among potentialities and challenges: a review. Renew Sustain Energy Rev 2024;193:114302. https://doi.org/10.1016/j.rser.2024.114302.

[68] Cahay M, Luquiau E, Smadja C, Silvert F. Use of a vertical wind turbine in an offshore floating wind farm. OnePetro; 2011. https://doi.org/10.4043/21705-MS.

[69] Borg M, Shires A, Collu M. Offshore floating vertical axis wind turbines, dynamics modelling state of the art. part I: aerodynamics. Renew Sustain Energy Rev 2014;39:1214–25. https://doi.org/10.1016/j.rser.2014.07.096.

[70] Hand B, Cashman A. Conceptual design of a large-scale floating offshore vertical axis wind turbine. Energy Proc 2017;142:83–8. https://doi.org/10.1016/j.egypro.2017.12.014.

[71] Floating Wind Power. KIRT X THOMSEN n.d. https://www.kirt-thomsen.com/floatingwindpowerpage (accessed November 18, 2025).

[72] Seatwirl. 2025. https://seatwirl.com/.

[73] Migliore PG, Wolfe WP, Fanucci JB. Flow curvature effects on darrieus turbine blade aerodynamics. J Energy 1980;4:49–55. https://doi.org/10.2514/3.62459.

[74] Bianchini A, Balduzzi F, Rainbird JM, Peiró J, Graham JMR, Ferrara G, et al. On the influence of virtual camber effect on airfoil polars for use in simulations of Darrieus wind turbines. Energy Convers Manag 2015;106:373–84. https://doi.org/10.1016/j.enconman.2015.09.053.

[75] Bianchini A, Balduzzi F, Ferrara G, Ferrari L. Virtual incidence effect on rotating airfoils in Darrieus wind turbines. Energy Convers Manag 2016;111:329–38. https://doi.org/10.1016/j.enconman.2015.12.056.

[76] Bianchini A, Carnevale E, Ferrari L. A model to account for the virtual camber effect in the performance prediction of an H-darrieus VAWT using the momentum models. Wind Eng 2011;35:465–82. https://doi.org/10.1260/0309-524X.35.4.465.

[77] Bianchini A, Ferrara G, Ferrari L, Magnani S. An improved model for the performance estimation of an H-darrieus wind turbine in skewed flow. Wind Eng 2012;36:667–86. https://doi.org/10.1260/0309-524X.36.6.667.

[78] Bianchini A, Balduzzi F, Rainbird JM, Peiro J, Michael J, Graham R, et al. An experimental and numerical assessment of airfoil polars for use in darrieus wind turbines-part I: flow curvature effects. J Eng Gas Turbines Power 2016;138. https://doi.org/10.1115/1.4031269.

[79] Bianchini A, Ferrari L, Magnani S. Energy-yield-based optimization of an H-Darrieus wind turbine. In: ASME Turbo Expo 2012 Turbine Tech. Conf. Expo; 2012. p. 997–1006. https://doi.org/10.1115/GT2012-69892.

[80] Du L. Numerical and experimental investigations of darrieus wind turbine Start-up and operation. Durham University; 2016. Ph.D Thesis.

[81] Dominy RG, Lunt P, Bickerdyke A, Dominy J. Self-starting capability of a Darrieus turbine. Proc Inst Mech Eng Part J Power Energy 2007;221:111–20. https://doi.org/10.1243/09576509JPE340.

[82] Beri H, Yao Y. Effect of camber airfoil on self starting of vertical axis wind turbine. J Environ Sci Technol 2011;4:302–12. https://doi.org/10.3923/jest.2011.302.312.

[83] Reingewirtz Y, Greenblatt D. Dynamic stall and virtual camber on high-solidity vertical axis wind turbines. Renew Energy 2026:125578. https://doi.org/10.1016/j.renene.2026.125578.

[84] Jain P, Abhishek A. Performance prediction and fundamental understanding of small scale vertical axis wind turbine with variable amplitude blade pitching. Renew Energy 2016;97:97–113. https://doi.org/10.1016/j.renene.2016.05.056.

[85] Impacts of blade camber on cross-flow turbine performance and loading. alphaXivn.d. https://www.alphaxiv.org/abs/2509.14416 (accessed March 14, 2026).

[86] Bianchini A, Balduzzi F, Ferrara G, Ferrari L. Aerodynamics of darrieus wind turbines airfoils during start-UP. Turbo Expo: Power for Land, Sea Air 2016;9. https://doi.org/10.1115/GT2016-57679.

[87] Bianchini A, Balduzzi F, Ferrara G, Ferrari L. Influence of the blade-spoke connection point on the aerodynamic performance of darrieus wind turbines. Turbo Expo: Power for Land, Sea, and Air 2016;9. https://doi.org/10.1115/GT2016-57667.

[88] Bianchini A, Balduzzi F, Ferrara G, Ferrari L. Aerodynamics of darrieus wind turbines airfoils: the impact of pitching moment. J Eng Gas Turbines Power 2017;139. https://doi.org/10.1115/1.4034940.

[89] Strickland JH, Webster BT, Nguyen T. A vortex model of the darrieus turbine: an analytical and experimental study. J Fluid Eng 1979;101:500–5. https://doi.org/10.1115/1.3449018.

[90] Laneville A, Vittecoq P. Dynamic stall: the case of the vertical axis wind turbine. J Sol Energy Eng 1986;108:140–5. https://doi.org/10.1115/1.3268081.

[91] Amet E, Maître T, Pellone C, Achard J-L. 2D numerical simulations of blade-vortex interaction in a darrieus turbine. J Fluid Eng 2009;131. https://doi.org/10.1115/1.4000258.

[92] Griffith DT, Barone M, Paquette J, Owens B, Bull D, Simao-Ferriera C, et al. Design studies for deep-water floating offshore vertical axis wind turbines. https://doi.org/10.2172/1459118; 2018.

[93] Keisar D, Arava I, Greenblatt D. Dynamic-stall-driven vertical axis wind turbine: an experimental parametric study. Appl Energy 2024;365:123199. https://doi.org/10.1016/j.apenergy.2024.123199.

[94] Berg DE. Improved double-multiple streamtube model for the Darrieus-type vertical axis wind turbine. 1983.

[95] Dyachuk E, Goude A, Bernhoff H. Dynamic stall modeling for the conditions of vertical axis wind turbines. AIAA J 2014;52:72–81. https://doi.org/10.2514/1.J052633.

[96] Fouest SL, Fernex D, Mulleners K. Time scales of dynamic stall development on a vertical-axis wind turbine blade. Flow 2023;3:E11. https://doi.org/10.1017/flo.2023.5.

[97] Le Fouest S, Mulleners K. The dynamic stall dilemma for vertical-axis wind turbines. Renew Energy 2022;198:505–20. https://doi.org/10.1016/j.renene.2022.07.071.

[98] Pirrung G, Gaunaa M. Dynamic stall model modifications to improve the modeling of vertical axis wind turbines. 2018.

[99] Ferreira CS. The near wake of the VAWT - 2D and 3D views of the VAWT aerodynamics. Delft University of Technology; 2009. Ph.D Thesis.

[100] Kim HR, Printezis JA, Ahrens JD, Seume JR, Wein L. Characterization of dynamic stall of a wind turbine airfoil with a high reynolds number. Wind Energy Sci 2025;10:161–75. https://doi.org/10.5194/wes-10-161-2025.

[101] Das Karmakar S, Chattopadhyay H. A review of augmentation methods to enhance the performance of vertical axis wind turbine. Sustain Energy Technol Assessments 2022;53:102469. https://doi.org/10.1016/j.seta.2022.102469.

[102] Zhao Z, Wang D, Wang T, Shen W, Liu H, Chen M. A review: approaches for aerodynamic performance improvement of lift-type vertical axis wind turbine. Sustain Energy Technol Assessments 2022;49:101789. https://doi.org/10.1016/j.seta.2021.101789.

[103] Bianchini A, Balduzzi F, Di Rosa D, Ferrara G. On the use of gurney flaps for the aerodynamic performance augmentation of darrieus wind turbines. Energy Convers Manag 2019;184:402–15. https://doi.org/10.1016/j.enconman.2019.01.068.

[104] Syawitri TP, Yao Y, Yao J, Chandra B. Geometry optimisation of vertical axis wind turbine with gurney flap for performance enhancement at low, medium and high ranges of tip speed ratios. Sustain Energy Technol Assessments 2022;49:101779. https://doi.org/10.1016/j.seta.2021.101779.

[105] Yang P, Chen L, Zhang BX, He CC. Performance improvements of vertical axis wind turbines with modified gurney flaps. J Phys, Conf Ser 2024;2707:012077. https://doi.org/10.1088/1742-6596/2707/1/012077.

[106] Yu H, Zheng Z, Yang P. Effect of gurney flaps on the performance of a vertical axis wind turbine under icing condition. Int J Renew Energy Dev 2026;15:122–34. https://doi.org/10.61435/ijred.2026.61538.

[107] De Tavernier D, Ferreira C, Viré A, LeBlanc B, Bernardy S. Controlling dynamic stall using vortex generators on a wind turbine airfoil. Renew Energy 2021;172:1194–211. https://doi.org/10.1016/j.renene.2021.03.019.

[108] Rajendran KM, Premkumar PS, Nadaraja Pillai S. Enhancing vertical axis wind turbine efficiency through Vortex generator integration: a performance analysis study. In: G V, Selvirajan KMP, Gupta A, Cao S, editors. Recent dev. Wind Eng. Singapore: Springer Nature; 2025. p. 87–98. https://doi.org/10.1007/978-981-97-9947-3_8.

[109] Mouaikel P, Haddad AE, Eid P, Bou-Mosleh C. Aerodynamic optimization of a helical vertical axis wind turbine using trapezoidal vortex generators. In: 2025 sixth int. Conf. Adv. Comput. Tools Eng. Appl. ACTEA; 2025. p. 1–7. https://doi.org/10.1109/ACTEA66485.2025.11189964.

[110] Ivanković M, Manolesos M, Jentzsch M, Kozmar H, Nayeri CN. Dynamic stall of vertical-axis-wind-turbine rotor blades equipped with Gurney flaps and vortex generators. J Phys, Conf Ser 2024;2767:072023. https://doi.org/10.1088/1742-6596/2767/7/072023.

[111] Abdolahifar A, Zanj A. A review of available solutions for enhancing aerodynamic performance in Darrieus vertical-axis wind turbines: a comparative discussion. Energy Convers Manag 2025;327:119575. https://doi.org/10.1016/j.enconman.2025.119575.

[112] Shen Z, Gong S, Zuo Z, Chen Y, Guo W. Darrieus vertical-axis wind turbine performance enhancement approach and optimized design: a review. Ocean Eng 2024;311:118965. https://doi.org/10.1016/j.oceaneng.2024.118965.

[113] Balduzzi F, Melani PF, Soraperra G, Brighenti A, Battisti L, Bianchini A. Some design guidelines to adapt a Darrieus vertical axis turbine for use in hydrokinetic applications. E3S Web Conf 2021;312:08017. https://doi.org/10.1051/e3sconf/202131208017.

[114] Sagharichi A, Maghrebi MJ, ArabGolarcheh A. Variable pitch blades: an approach for improving performance of Darrieus wind turbine. J Renew Sustain Energy 2016;8:053305. https://doi.org/10.1063/1.4964310.

[115] Huang H, Huang Z, Li G. Improving vertical axis wind turbine starting performance by active control blade pitching to combined using lift-drag force. J Braz Soc Mech Sci Eng 2025;48:71. https://doi.org/10.1007/s40430-025-06103-w.

[116] Le Fouest S, Mulleners K. Optimal blade pitch control for enhanced vertical-axis wind turbine performance. Nat Commun 2024;15:2770. https://doi.org/10.1038/s41467-024-46988-0.

[117] de Souza LF, Miotto RF, Wolf WR. Active flow control of vertical-axis wind turbines: insights from large-eddy simulation and finite-time resolvent analysis. J Fluid Struct 2025;139:104410. https://doi.org/10.1016/j.jfluidstructs.2025.104410.

[118] Guevara P, Rochester P, Vijayaraghavan K. Optimization of active blade pitching of a vertical axis wind turbine using analytical and CFD based metamodel. J Renew Sustain Energy 2021;13:023305. https://doi.org/10.1063/5.0026591.

[119] Strom B, Brunton SL, Polagye B. Intracycle angular velocity control of cross-flow turbines. Nat Energy 2017;2:1–9. https://doi.org/10.1038/nenergy.2017.103.

[120] Satrio D, Erwandi Rahuna D. Investigation of enhanced peak lift performance and stall angle delay by attachment of Vortex Generators on blade surfaces of vertical Axis Ocean current turbine. Ocean Eng 2025;326:120762. https://doi.org/10.1016/j.oceaneng.2025.120762.

[121] Melani PF, Balduzzi F, Ferrara G, Bianchini A. Development of a desmodromic variable pitch system for hydrokinetic turbines. Energy Convers Manag 2021;250:114890. https://doi.org/10.1016/j.enconman.2021.114890.

[122] Mohamed OS, Melani PF, Balduzzi F, Ferrara G, Bianchini A. An insight on the physical mechanisms responsible of power augmentation in a pair of counter-rotating Darrieus turbines. Energy Convers Manag 2023;284:116991. https://doi.org/10.1016/j.enconman.2023.116991.

[123] Alexander AS, Santhanakrishnan A. Mechanisms of power augmentation in two side-by-side vertical axis wind turbines. Renew Energy 2020;148:600–10. https://doi.org/10.1016/j.renene.2019.10.149.

[124] Dabiri JO. Potential order-of-magnitude enhancement of wind farm power density via counter-rotating vertical-axis wind turbine arrays. J Renew Sustain Energy 2011;3:043104. https://doi.org/10.1063/1.3608170.

[125] Vergaerde A, De Troyer T, Standaert L, Kluczewska-Bordier J, Pitance D, Immas A, et al. Experimental validation of the power enhancement of a pair of vertical-axis wind turbines. Renew Energy 2020;146:181–7. https://doi.org/10.1016/j.renene.2019.06.115.

[126] Mohamed OS, Melani PF, Soraperra G, Brighenti A, Balduzzi F, Bianchini A. Selection criteria for rotor number and rotational direction in arrays of closely spaced darrieus turbines. J Fluid Eng 2025;147. https://doi.org/10.1115/1.4067007.

[127] Brownstein ID, Wei NJ, Dabiri JO. Aerodynamically interacting vertical-axis wind turbines: performance enhancement and three-dimensional flow. Energies 2019;12:2724. https://doi.org/10.3390/en12142724.

[128] Nitzsche F. Vertical axis wind turbines intelligent farms. IntechOpen; 2025. https://doi.org/10.5772/intechopen.1013118.

[129] Bulder BH, Bot ETG, Bedon G, Nederland EC. Optimal wind farm power density analysis for future offshore wind farms. ECN; 2018.

[130] Porté-Agel F, Bastankhah M, Shamsoddin S. Wind-turbine and wind-farm flows: a review. Bound-Layer Meteorol 2020;174:1–59. https://doi.org/10.1007/s10546-019-00473-0.

[131] Meyers J, Bottasso C, Dykes K, Fleming P, Gebraad P, Giebel G, et al. Wind farm flow control: prospects and challenges. Wind Energy Sci 2022;7:2271–306. https://doi.org/10.5194/wes-7-2271-2022.

[132] Stevens RJAM, Meneveau C. Flow structure and turbulence in wind farms. Annu Rev Fluid Mech 2017;49:311–39. https://doi.org/10.1146/annurev-fluid-010816-060206.

[133] Nash R, Nouri R, Vasel-Be-Hagh A. Wind turbine wake control strategies: a review and concept proposal. Energy Convers Manag 2021;245:114581. https://doi.org/10.1016/j.enconman.2021.114581.

[134] Bastankhah M, Porté-Agel F. Experimental and theoretical study of wind turbine wakes in yawed conditions. J Fluid Mech 2016;806:506–41. https://doi.org/10.1017/jfm.2016.595.

[135] Howland MF, Bossuyt J, Martínez-Tossas LA, Meyers J, Meneveau C. Wake structure in actuator disk models of wind turbines in yaw under uniform inflow conditions. J Renew Sustain Energy 2016;8:043301. https://doi.org/10.1063/1.4955091.

[136] Fleming P, King J, Dykes K, Simley E, Roadman J, Scholbrock A, et al. Initial results from a field campaign of wake steering applied at a commercial wind farm

– part 1. Wind Energy Sci 2019;4:273–85. https://doi.org/10.5194/wes-4-273-2019.

[137] Nanos EM, Bottasso CL, Tamaro S, Manolas DI, Riziotis VA. Vertical wake deflection for floating wind turbines by differential ballast control. Wind Energy Sci 2022;7:1641–60. https://doi.org/10.5194/wes-7-1641-2022.

[138] Fleming PA, Gebraad PMO, Lee S, Van Wingerden J-W, Johnson K, Churchfield M, et al. Evaluating techniques for redirecting turbine wakes using SOWFA. Renew Energy 2014;70:211–8. https://doi.org/10.1016/j.renene.2014.02.015.

[139] Exploring wake losses in offshore wind - empire engineering n.d. https://www.empireengineering.co.uk/exploring-wake-losses-in-offshore-wind/. [Accessed 15 April 2025].

[140] Pryor SC, Barthelmie RJ. Wind shadows impact planning of large offshore wind farms. Appl Energy 2024;359:122755. https://doi.org/10.1016/j.apenergy.2024.122755.

[141] Barthelmie RJ, Pryor SC, Frandsen ST, Hansen K, Schepers JG, Rados K, et al. Quantifying the impact of wind turbine wakes on power output at offshore wind farms. J Atmos Ocean Technol 2010;27:1302–17. https://doi.org/10.1175/2010JTECHA1398.1.

[142] Pryor SC, Barthelmie RJ, Shepherd TJ. Wind power production from very large offshore wind farms. Joule 2021;5:2663–86. https://doi.org/10.1016/j.joule.2021.09.002.

[143] Simão Ferreira C, Larsen GChr, Sørensen JN. A theoretical upper limit for offshore wind energy extraction. Cell Rep Sustain 2026;3:100573. https://doi.org/10.1016/j.crsus.2025.100573.

[144] Ferreira C, Bensason D, Broertjes TJ, Sciacchitano A, Martins FAC, Ajay AG. Enhancing wind farm efficiency through active control of the atmospheric boundary layer's vertical entrainment of momentum. J Phys, Conf Ser 2024;2767:092107. https://doi.org/10.1088/1742-6596/2767/9/092107.

[145] Huang M, Vijaykumar Patil Y, Sciacchitano A, Ferreira C. Experimental study of the wake interaction between two vertical axis wind turbines. Wind Energy 2023;1. https://doi.org/10.1002/we.2863.

[146] Mendoza V, Goude A. Improving farm efficiency of interacting vertical-axis wind turbines through wake deflection using pitched struts. Wind Energy 2019;22:538–46. https://doi.org/10.1002/we.2305.

[147] Li Y, Fijen M, Dsouza B, Yu W, Sciacchitano A, Ferreira C. Experimental study of regenerative wind farms featuring enhanced vertical energy entrainment. Wind Energy Sci Discuss 2025:1–49. https://doi.org/10.5194/wes-2025-156.

[148] Martins FAC, Ferreira CS, Van Zuijlen A. Numerical investigation of atmospheric boundary layer control in wind farms with multirotor systems. J Phys, Conf Ser 2024;2767:072006. https://doi.org/10.1088/1742-6596/2767/7/072006.

[149] Avila Correia Martins F, van Zuijlen A, Simão Ferreira C. Proof of concept for multirotor systems with vortex-generating modes for regenerative wind energy: a study based on numerical simulations and experimental data. Wind Energy Sci 2025;10:41–58. https://doi.org/10.5194/wes-10-41-2025.

[150] Ribeiro AFP, Ferreira CS, Casalino D. Vertical axis wind turbine wake steering by pitched struts and blades. J Phys, Conf Ser 2024;2767:092004. https://doi.org/10.1088/1742-6596/2767/9/092004.

[151] Bensason D, Sciacchitano A, Giri Ajay A, Simao Ferreira C. A study of the near wake deformation of the X-Rotor vertical-axis wind turbine with pitched blades. Wind Energy 2024;27:1388–411. https://doi.org/10.1002/we.2944.

[152] Giri Ajay A, Simao Ferreira C. A numerical investigation of wake recovery for an H- and X-shaped vertical-axis wind turbine with wake control strategies. Phys Fluids 2024;36:127161. https://doi.org/10.1063/5.0244810.

[153] Bensason D, Sciacchitano A, Ferreira C. On the wake re-energization of the X-Rotor vertical-axis wind turbine via the vortex-generator strategy. Wind Energy Sci 2025;10:2137–59. https://doi.org/10.5194/wes-10-2137-2025.

[154] Broertjes TJ, Bensason D, Sciacchitano A, Ferreira C. Lift-induced wake Re-Energization for a VAWT-based multi-rotor system. J Phys, Conf Ser 2024;2767:072012. https://doi.org/10.1088/1742-6596/2767/7/072012.

[155] Martins FAC, Ferreira CS, Van Zuijlen A. Numerical investigation of atmospheric boundary layer control in wind farms with multirotor systems. J Phys, Conf Ser 2024;2767:072006. https://doi.org/10.1088/1742-6596/2767/7/072006.

[156] Avila Correia Martins F, van Zuijlen A, Simão Ferreira C. Proof of concept for multirotor systems with vortex-generating modes for regenerative wind energy: a study based on numerical simulations and experimental data. Wind Energy Sci 2025;10:41–58. https://doi.org/10.5194/wes-10-41-2025.

[157] Vita L, Paulsen US, Madsen HA, Nielsen PH, Berthelsen PA, Carstensen S. Design and aero-elastic simulation of a 5MW floating vertical axis wind turbine. Vol. 7 ocean space util. In: Ocean renew. Energy. Rio de Janeiro, Brazil: American Society of Mechanical Engineers; 2012. p. 383–92. https://doi.org/10.1115/OMAE2012-83470.

[158] Berthelsen PA, Fylling I, Vita L, Paulsen US. Conceptual design of a floating support structure and mooring system for a vertical axis wind turbine. Vol. 7 ocean space util. In: Ocean renew. Energy. Rio de Janeiro, Brazil: American Society of Mechanical Engineers; 2012. p. 259–68. https://doi.org/10.1115/OMAE2012-83335.

[159] Shen X, Zhu X, Du Z. Wind turbine aerodynamics and loads control in wind shear flow. Energy 2011;36:1424–34. https://doi.org/10.1016/j.energy.2011.01.028.

[160] Leithead WE, Amiri AMK, Camciuc A, Morgan L, Carroll J, Feuchtwang J. X-Rotor, an innovative offshore wind turbine to reduce cost of energy. Energies 2025;18:2549. https://doi.org/10.3390/en18102549.

[161] Svendsen HG, Merz KO. Control system for Start-up and shut-down of a floating vertical axis wind turbine. Energy Proc 2013;35:33–42. https://doi.org/10.1016/j.egypro.2013.07.156.

[162] Svendsen H, Merz K, Endegnanew A. Control of floating vertical axis wind turbine, vol. 2; 2012.

[163] Long-term global response analysis of a vertical axis wind turbine supported on a semi-submersible floating platform: Comparison between operating and non-operating wind turbine load cases -DTU Findit n.d. https://findit.dtu.dk/en/catalog/5640d124551c79c54f000034 (accessed March 6, 2026).

[164] Arredondo-Galeana A, Brennan F. Floating offshore vertical axis wind turbines: opportunities, challenges and way forward. Energies 2021;14. https://doi.org/10.3390/en14238000.

[165] Rinaldi G, Thies PR, Johanning L. Current status and future trends in the operation and maintenance of offshore wind turbines: a review. Energies 2021;14. https://doi.org/10.3390/en14092484.

[166] Veers P, Bottasso CL, Manuel L, Naughton J, Pao L, Paquette J, et al. Grand challenges in the design, manufacture, and operation of future wind turbine systems. Wind Energy Sci 2023;8:1071–131. https://doi.org/10.5194/wes-8-1071-2023.

[167] Galinos C, Larsen TJ, Madsen HA, Paulsen US. Vertical axis wind turbine design load cases investigation and comparison with horizontal axis wind turbine. In: 13th Deep Sea Offshore Wind RD Conf EERA Deep, vol 94; 2016. p. 319–28. https://doi.org/10.1016/j.egypro.2016.09.190.

[168] Ouro P, Runge S, Luo Q, Stoesser T. Three-dimensionality of the wake recovery behind a vertical axis turbine. Renew Energy 2019;133:1066–77. https://doi.org/10.1016/j.renene.2018.10.111.

[169] Cazzaro D, Bedon G, Pisinger D. Vertical axis wind turbine layout optimization. Energies 2023;16. https://doi.org/10.3390/en16062697.

[170] Zhu X, Xiao S, Narasimhan G, Martinez-Tossas LA, Schnaubelt M, Lemson G, et al. JHTDB-wind: a web-accessible large-eddy simulation database of a wind farm with virtual sensor querying. Wind Energy Sci 2025;10:2821–40. https://doi.org/10.5194/wes-10-2821-2025.

[171] Barthelmie RJ, Hansen K, Frandsen ST, Rathmann O, Schepers JG, Schlez W, et al. Modelling and measuring flow and wind turbine wakes in large wind farms offshore. Wind Energy 2009;12:431–44. https://doi.org/10.1002/we.348.

[172] Sutherland HJ, Berg DE, Ashwill TD. A retrospective of VAWT technology. Albuquerque, NM, United States: Sandia National Laboratories; 2012. https://doi.org/10.2172/1035336.

[173] Pérez-Rúa J-A, Cutululis NA. Electrical cable optimization in offshore wind farms—A review. IEEE Access 2019;7:85796–811. https://doi.org/10.1109/ACCESS.2019.2925873.

[174] Lozon E, Lekkala MR, Sirkis L, Hall M. Reference mooring and dynamic cable designs for representative U.S. floating wind farms. Ocean Eng 2025;322:120473. https://doi.org/10.1016/j.oceaneng.2025.120473.

[175] Borg M, Collu M. A comparison between the dynamics of horizontal and vertical axis offshore floating wind turbines. Philos Trans R Soc Math Phys Eng Sci 2015;373:20140076. https://doi.org/10.1098/rsta.2014.0076.