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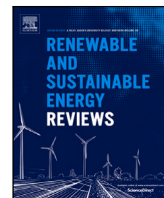
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Review article

Floating Vertical Axis Wind Turbines for offshore applications among potentialities and challenges: A review

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ABSTRACT

Among the primary uses of Vertical Axis Wind Turbines (VAWTs) are small-scale applications, such as electricity generation in urban areas or isolated contexts, which are not grid-connected. However, a promising field of application for VAWTs to be investigated concerns floating offshore applications, where the more consolidated technologies based on HAWTs face significant challenges due to the harsh environment. The purpose of this study is to review the main floating VAWT concepts developed over the last few years and those currently under development, focusing on the projects and analysing the experimental prototypes and small-scale demonstrators. The main advantages of VAWTs compared to HAWTs are elaborated and presented: among the main ones is the more cost-effective maintenance due to the arrangement of the rotor nacelle assembly at the base of the VAWT, the increased static stability, which allows to reduce the mass of the floating foundation or to support a larger turbine, the reduced aerodynamic losses which allow turbines to be installed closer together and require a small installation area. A particular focus is made on the most urgent needs that demand to be addressed for the development of VAWTs, like the lack of experimental data and the installation of a multi-MW demonstrator to corroborate the technology reliability and challenges, such as the power upscale, the fatigue damage and mooring lines loads. Among the possible floating applications investigated is the energy supply for small isolated islands or offshore installations, like oil and gas platforms or fish farms.

1. Introduction

Offshore wind power is becoming one of the best options for renewable energy: far offshore wind turbines are attractive, exploiting high-speed winds and high wind availability while reducing the impact on the human population, limiting land consumption, noise and visual pollution. At an international level, 2021 has witnessed a significant growth in offshore wind capacity, with 21 GW of installed power, three times higher than in 2020 [1]. Out of this new installed capacity, 17 GW of installations concerned China, reaching a cumulative power of almost 28 GW. The second largest market is the European market: 3 GW of offshore power have been installed in 2021, reaching a cumulative capacity of 28 GW [2,3]. However, this potential concerns bottom-fixed installations: in 2021, only 57 MW of floating offshore wind have been installed worldwide, reaching a total cumulative capacity of 121 MW globally [1]. Of this potential, in addition to some floating wind farms already installed, such as HyWind Scotland (30 MW) [4], WindFloat Atlantic (25 MW) [5], and Kincardine (50 MW) [6], a large part appears to be made up of demonstrators with

sizes in the order of a few MW, such as that of BW Ideol (2 MW) [7,8], HyWind Demo (2.3 MW) [9,10], Tetraspar (3.6 MW) [11,12], and SATH (2 MW) [13]. The purpose of these demonstrators has been to validate the FOWT technologies, demonstrating their technical and industrial feasibility, while the choice of a reduced nominal power has been driven by the need to minimize investment costs and risks.

The totality of Floating Offshore Wind Turbines (FOWTs) demonstrator installations is made of Horizontal Axis Wind Turbines (HAWTs). Indeed, HAWT is a more mature and consolidated technology, which, in addition to exploiting decades of experience in onshore wind power, boasts consolidated experience in bottom-fixed offshore wind farms. A few floating Vertical Axis Wind Turbines (VAWTs) have been installed, but only as small prototypes of a few kW of power for research and experimentation needs. However, the high investment, construction and maintenance costs of FOWTs represent a strong limit to the industrialization of floating wind farms. The Levelized Cost Of Energy (LCOE) of floating wind depends on many factors, such as wind availability,

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Nomenclature

BEM	blade element momentum
CFD	computational fluid dynamics
COG	centre of gravity
CTV	crew transfer vessel
DMST	double multiple stream tube
DTU	Danmarks Tekniske Universitet
ECN	École Centrale de Nantes
EDF	Électricité de France
ENSAM	Ecole Nationale Supérieure D'Arts Et Metiers
FAWT	Floating Axis Wind Turbine
FOWT	floating offshore wind turbine
GWIND	Gyro stabilized Vertical Axis Wind Turbine
HAWT	horizontal axis wind turbine
IFREMER	Institut Français de Recherche pour l'Exploitation de la Mer
INFLOW	INDustrialization setup of a FLOating Off-shore Wind turbine
LCOE	levelized cost of energy
LEGI	Laboratoire des Écoulements Géophysiques et Industriels
MODEC	Mitsui Ocean Development Engineering Company
NEDO	New Energy and Industrial Technology Development Organisation
NOVA	NOvel Vertical Axis wind turbine
NTNU	Norwegian University of Science and Technology
O&M	operational & maintenance
OC4	Offshore Code Comparison Collaboration Continuation
PID	proportional integral derivative
RANS	Reynolds-averaged Navier–Stokes
RNA	rotor nacelle assembly
S4VAWT	Semi-Submersible Support Structure for vertical Axis Wind Turbine
SIL	software-in-the-loop
SKWID	Savonius Keel and Wind Turbine Darrieus
SOV	service operational vessel
TLP	tension leg platform
TRL	technology readiness level
VAWT	vertical axis wind turbine
WCM	Wind turbine, Materials and Constructions knowledge centre
X-ROTOR	X-shaped Radical Offshore wind Turbine for Overall cost of energy Reduction

seabed depth and distance from the coast, and currently varies from 95–110 €/MWh in the North Sea to up to 160 €/MWh along the Spanish coast of the Atlantic Ocean [14], undoubtedly higher than other renewables, such as solar and onshore wind. Achieving a significant LCOE reduction of current FOWTs (i.e. floating HAWTs) requires to address various challenges, the most urgent of which are listed below.

Upscaling: the adoption of larger turbine sizes, up to 15 MW, while increasing the static stability of the FOWT system, involves the introduction of significant loads associated with inertial and gravitational forces. Due to extreme tower loads recorded when wave and wind loading is at its highest, a new tower design is required [15,16]. The

aeroelastic blade deformation, the acoustic noise generated, and new control strategies must be investigated through software simulations and wind tunnel tests [17–19].

Standardization of substructures: heavy substructures are indispensable to counteract the wind thrust force and increase the stiffness of the FOWT. Several studies have been concerned with the geometric optimization of the foundations to reduce the cost while respecting the constraints imposed by international standards [20–23]. Another challenge concerns the future industrialization of these structures, given the difficulties in implementing an adequate supply chain [24–26].

Wakes effects: the need for compact wind farms to limit the required maritime space, collides with the problem of wake interference between the turbines, which negatively affects the aerodynamics of the downstream turbines, reducing productivity and aggravating the fatigue loads [27–30].

O&M: different studies report that RNA (Rotor-Nacelle-Assembly) components are the most prone to failure: gearbox, generator and hydraulic system (blade pitch) [31–34]. Moreover, given the size of the turbines, O&M activities involve operating at heights exceeding 100 m and specialized vessels that are rarely available on the market. In addition, accessibility for O&M operations is strongly linked to the metocean conditions [35,36] and involve substantial economic repercussions for machine downtime [37–39].

To address some of these issues, new designs with other types of wind turbines, such as with vertical axis, twin-rotor [40] or multi-rotor [41], began to be explored and investigated in the past. As this study focuses particularly on VAWTs, Section 2 presents their main past and current applications.

2. VAWT applications

Among the main applications of VAWTs is the onshore energy production; however, only a few wind farms have been built and put into operation. In 1983–1984, VAWTPOWER Inc. installed 40 turbines in San Gorgonio Pass, USA, each one with a rated capacity of 185 kW, while ten turbines of 150 kW were installed in 1990 by Adecon near Pincher Creek, in Canada [42]. Apart from these and a few other examples, most installations concerned the small scale, from a few kW up to a few tens of kW.

Among the main sectors involved, there are **isolated contexts**, inhabited or not, not connected to the electricity grid: in addition to electricity generation, VAWTs are used for the supply of utilities such as water pumping and desalination [43,44]. Furthermore, coupling with other renewable sources, such as solar photovoltaics, guarantees stable energy production [45–47].

Moreover, another sector concerns the **urban contexts**, in particular, for the installation of turbines on the roofs of residential buildings [48,49].

New fields of application concern remote electrification in developing countries, such as remote areas in Africa or the Far East [50,51], but also niche applications, such as the production of electricity through wakes generated by vehicles along highways [52].

A promising area for VAWTs development is offshore wind electricity generation. Despite the potential, few research works are currently available in the literature: among these, only a few have classified the available technologies on their strengths, advantages and disadvantages. Among the most recent studies are [53,54]. These works focus on VAWTs for onshore applications, with detailed descriptions of the largest turbines built and related projects: floating offshore VAWTs are introduced, reporting some projects or demonstrators, but as a possible future development for the relaunch of VAWTs.

A multi-criteria approach is used to analyse the advantages and disadvantages of floating VAWTs in [55]. However, the analysis of floating VAWTs technologies is missing: only some of the developed concepts are reported, without describing the projects, the demonstrators and possible applications of floating VAWTs.

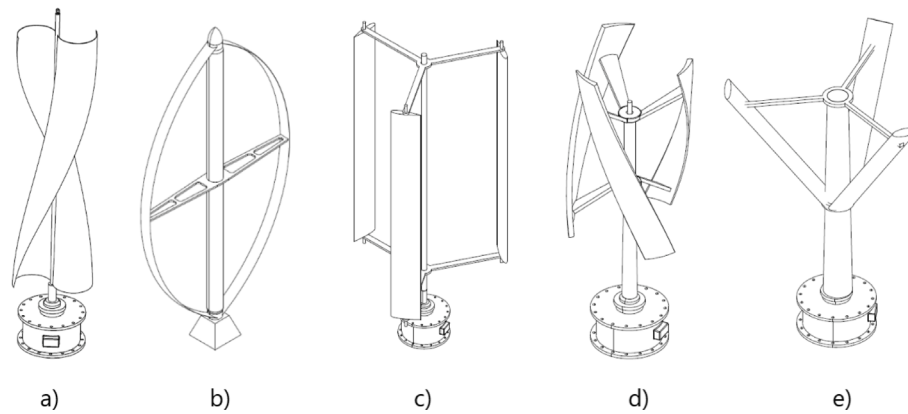


Fig. 1. Graphical representation of Vertical Axis Wind Turbine (VAWT) types: (a) Savonius, (b) ϕ -Darrieus, (c) Darrieus H-rotor, (d) Helical bladed, (e) V-shaped.

Consequently, in order to evaluate the potential of floating VAWTs, it is essential to critically classify all the main past projects which have been developed from 2009 until today, with an alternation of moments of deep-rooted research interest and others of decline and disinterest, also considering those that failed for technical or economic reasons. Furthermore, many of these studies do not consider the possible scope of application of floating VAWTs: considering that the floating offshore wind scenario is firmly oriented on HAWT technologies, the most probable applications remain to be investigated. In addition, comparing the advantages and disadvantages of VAWTs and HAWTs is important to address the possible common challenges of both technologies.

The novelty of this article is to fill a clear gap in the literature, focusing on the applications of floating VAWTs and discussing their role in the offshore scenario. The methodology concerns an exhaustive classification of many floating VAWT concepts and leading academic and industrial projects. To support the potential of floating VAWTs, their main advantages are described and critically analysed, as well as the challenges to overcome. Finally, some possible applications are analysed and justified.

The review is organized as follows: in Section 3, a classification of the main types of vertical-axis wind turbines and floating foundations are reported. Section 4 shows the leading floating VAWT technologies developed, with a brief description of the main characteristics, while in Section 5, the ongoing projects are reported. Section 6 describes the main advantages of VAWTs, compared to HAWTs, and the challenges. Section 7 reports the discussion, while the conclusions are contained in Section 8.

3. State of the art

Vertical axis wind turbine

Several onshore vertical axis turbines have been developed, each with a different operating principle, aiming at small-scale electricity production for rural or urban contexts. Fig. 1 presents a graphical representation of the main VAWTs working principles, which are:

- Savonius wind turbine;
- Darrieus wind turbine (ϕ configuration);
- Darrieus H-rotor;
- Helical bladed wind turbine;
- V-shaped wind turbine.

Savonius wind turbine usually consists of two half cylinders facing opposite directions to form an S-shape in the cross-section. The advantage of having a low cut-in wind speed is contrasted by low aerodynamic performances, compared to lift force designs. This design is particularly suitable for applications where reliability and low cost are more prevalent than efficiency. Consequently, the size of such

turbines is typically limited to a few kW, preferring other designs for larger sizes [56–59].

Darrieus wind turbine (ϕ configuration) [60,61] consists of two or more curved aerofoil blades mounted on a rotating shaft or framework. The working principle is based on the lift force: the relative motion between the blade airfoil and the direction of wind flow creates a force in the forward direction that creates a positive torque to the rotor [48]. Among the main drawback is the required external source to start spinning due to a low starting torque: various solutions have been proposed to overcome this constraint, such as integration with a Savonius turbine integral with the axis of rotation to facilitate the start-up of the complete system.

Unlike ϕ -Darrieus, which results in higher manufacturing costs than curved blade profiles, the **Darrieus** with straight blade design, also known as **H-rotor**, brings good reliability, aerodynamic performance, more straightforward construction and lower costs [62–64]. Designs range from 2 to 5 blades, with the most popular configurations being 2- or 3-bladed. The blades can have fixed or variable pitch [65]: variable pitch blades have the potential to overcome the starting torque issues.

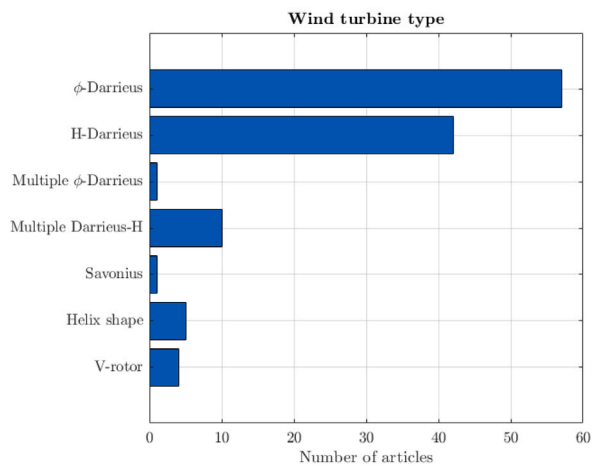
Less widespread than the previous ones, especially for urban applications, **helical**-bladed turbine allows advantages such as low noise, increased blade life due to low vibrations and self-starting capability [61,66]. On a negative note, the helical blade manufacturing cost is higher than straight blades because the helical blade can only be manufactured through a mould, unlike the straight blades, which can be manufactured by aluminium extrusion.

The **V-rotor** design, proposed by Olle Ljungstrom in 1973, aimed to mimic the lower half of ϕ -rotor [67]. Among the advantages are a shorter tower than ϕ or H-rotor and a lack of struts and supporting arms [68]. The first prototype, a 5 kW two-bladed V-rotor device, was designed and tested in 1987 [69].

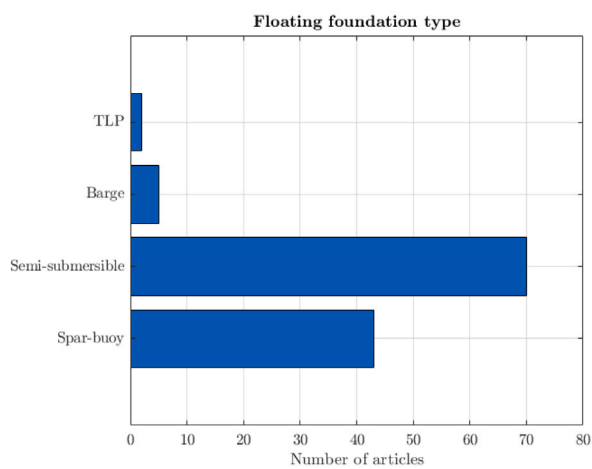
Currently, the most used VAWTs used for offshore applications are the ϕ -type Darrieus and Darrieus H-rotor: in Fig. 2(a), the results from the Scopus database, by searching the keywords “floating” and “vertical axis wind turbine” from 2009 to March 2023, are reported. It is evident that ϕ - and H-Darrieus wind turbines types are considerably more studied for floating VAWTs; moreover, the whole body of literature accounts to less than 150 articles in 15 years, highlighting the low scientific maturity of this application area, as well as the need for the rigorous review effort presented in this study.

Floating foundations

Floating foundations, designed and implemented to support HAWTs, are classified according to the principle leveraged to guarantee stability [20,70–72]. The **spar-buoy** foundations, made up of long cylinders weighted below, guarantee stability thanks to the deep draft. Spar-buoys are easily adapted according to the wind turbine size but require large quantities of ballast material, thus increasing manufacturing costs. Furthermore, the installation of the turbine cannot be done in



(a) Wind turbine types



(b) Floating foundations types

Fig. 2. Wind turbines and floating foundations types for floating VAWTs (data obtained from Scopus, from 2009 to March 2023, keywords: vertical axis wind turbine, floating).

port due to the deep draft: consequently, the use of crane ships is essential for the installation, which must take place in the absence of adverse meteocean conditions. **Semi-submersibles** and **barges** achieve stability by using a high waterplane area at the level of the free surface of the water. Even the semi-subs can be adapted according to the turbine size and have the advantage of having a draft suitable for construction in dry docks, to allow the installation of the turbine directly in port. The barges differ from the semi-sub for the greater surface extension at the level of the waterplane: consequently, they are not suitable for contexts characterized by high waves. Finally, the **Tension Leg Platforms (TLP)** are rigidly fixed to the seabed using taut moorings, usually made with rope or metal cables. The process of installing TLPs is complex and requires the use of special laying vessels.

New technologies have been developed alongside these more consolidated concepts, featuring more complex designs, such as Tetraspar [11,12], developed by Stiesdal, or Hexafloat [21,22], a pendulum floater developed by Saipem. In both concepts, the advantages of the semi-sub have been integrated with the use of a submerged counterweight, made of inert material which, by replicating the operating principle of a spar-buoy, contributes to the stability of the FOWT system. According to Fig. 2(b), the most used types of foundations for VAWTs are the semi-sub and the spar-buoy. In Table 1, a summary of the main characteristics of floating foundations is reported.

Table 1
Summary of floating foundations characteristics.

Type	Stability	Mass	Mooring complexity	Installation complexity	Cost
Spar	+++	+++	++	++	+++
Semi-sub	+++	++	+	+	++
Barge	++	+++	+	++	+++
TLP	++	+	+++	+++	++

4. Floating VAWT technologies

Many floating VAWT technologies have been developed in projects such as NOVA [73], DeepWind [74] and S4VAWT [75], which involved universities, research centres and industrial partners. Given the interdisciplinarity of the partners, it was possible to cover all the main areas of the entire life cycle of a VAWT, dealing with numerical modelling, foundation and turbine design, material stress and fatigue analysis, rotor performances and upscale to multi-MW capacity, experimental tests in wave tanks, wind tunnel and marine operational environment. On the other hand, technologies such as Vertiwind and Skwid-MODEC resulted from industrial research applied to VAWTs, by companies such as Nenuphar or Moddec. In Fig. 3, floating VAWT technologies have been classified on the base of floating foundations while in Table 2, a summary of the main floating VAWTs is reported.

One of the first concepts of floating VAWT dates back to the NOVA (NOvel Vertical Axis wind turbine) project in 2009: the rotor concept, proposed by David Sharp and developed by Wind Power Ltd, combined a V-rotor made of several blades located along the span, angled to minimize the aerodynamic over-turning moments [68]. To evaluate the aerodynamic performance of VAWTs, a numerical model based on Paraschivoiu's Double Multiple Stream Tube (DMST) was developed [82], which evaluates momentum losses for several vertical and lateral streamtubes passing through the rotor [83]. The initially proposed design was optimized to balance aerodynamic performances, such as maximizing torque, reducing mechanical and structural constraints, and minimizing the internal rotor volume to reduce manufacturing costs and Levelized Cost Of Energy (LCOE). As a result, a 'sycamore'-shaped rotor was obtained [68]. Different configurations of floating foundations were analysed and optimized, including the barge and the semi-sub, trying to combine platform stability in terms of good wave response dynamics and low amount of material to reduce costs [84–86].

The **DeepWind** Project concerned the design, verification and experimental validation of a floating Darrieus turbine. The proposed concept involved a 5 MW ϕ -Darrieus turbine supported by a floating spar-buoy foundation: differently from floating HAWTs, the entire structure is rotating, and the power is produced by a generator located at the bottom of the structure [87]. The concept optimization turned out into an asymmetric Troposkien shape by evaluating the influence of the number of blades and different airfoils to maximize the power production and minimize the blade stress, and a tubular steel structure as a foundation, with adequate roll and pitch stiffness, to avoid excessive tilting of turbine and to prevent accelerations that could damage the machinery components [88]. The mooring lines for the DeepWind concept were optimized to withstand the significant yaw moment from the rotating turbine [89].

An experimental campaign conducted in the wind tunnel at Politecnico di Milano with a 1 kW rotor prototype investigated the effect of tower tilting on rotor aerodynamics to reproduce the operation in the skewed flow of a floating VAWT at its maximum allowable pitch angle [90,91]. The lift and in-line forces, the friction torque acting on the spar buoy due to waves, and currents loading were instead evaluated in a current flume [92]. A complete 1 kW demonstrator was manufactured: with a 2 m \times 2 m rotor diameter and a cylinder length of 5 m, the proof-of-concept was installed in the test site in Roskilde fjord, near Risøcampus (Denmark) during October–November 2012 [93].

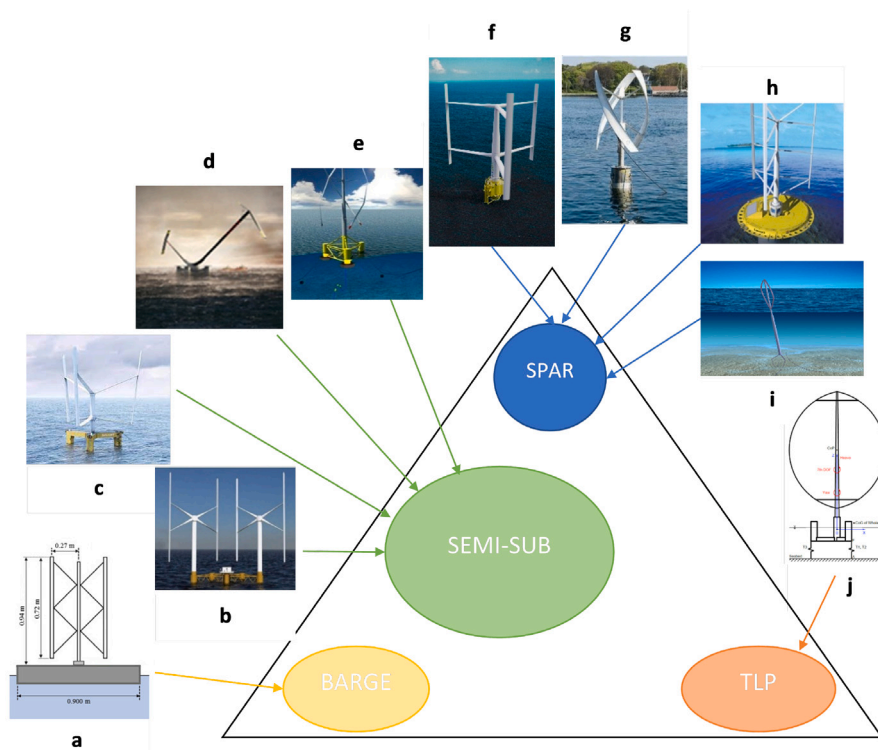


Fig. 3. Floating VAWT foundations classification: (a) barge [76], (b) Twin-VAWT [48], (c) Semi-Submersible Support Structure for Vertical Axis Wind Turbines (S4VAWT) [75], (d) NOVEL Vertical Axis wind turbine (NOVA) [68], (e) Vertiwind [77], (f) SeaTwirl [78], (g) Gwind [79], (h) Skwid-MODEC [80], (i) DeepWind [74], (j) Tension Leg Platform (TLP) [81].

In the following projects, interest was focused on other VAWTs dealing with aerodynamic performances. For example, **Vertiwind** project aimed to develop a floating multi-MW VAWT with helical blades. Starting from the VAWT design developed by Nenuphar Company, consisting of a three-bladed H-rotor connected with struts to the support arms, without a yaw and pitch system and no gearbox [61], tested in 2010 with a 35 kW onshore demonstrator, the blade fatigue behaviour, due to not evenly distributed load and cyclic torque, resulted in a new design of Vertiwind. Adopting quasi-helicoidal blades with straight segments reduced the dynamic stall and a more uniform torque [94].

From Vertiwind results, the Inflow (INDustrialization setup of a FLOating Offshore Wind turbine) project proposed the **twin-VAWT**: made of two 2.5 MW turbines placed on the same semi-sub floater for a nominal power of 5 MW [27,109], the power performances were increased due to the proximity of the two rotors, that generates a contraction of the streamtubes, thus increasing the airflow rate going through both the rotors' swept areas [108]. This project paved the way for studying wake dynamics in VAWT wind farms, highlighting some substantial advantages over HAWTs.

Many projects focused on foundations that minimize the required mass to reduce investment costs without affecting dynamic stability. In **S4VAWT** (Semi-Submersible Support Structure for Vertical Axis Wind Turbines), a GustoMSC Tri-Floater [114], designed to support a 6 MW VAWT, was used. In contrast with previous concepts with a fixed pitch angle, blade pitch control was introduced in S4VAWT: unlike those with a fixed angle, subject to high loads in extreme wind conditions, which therefore required an oversizing of the concept, this issue was solved, allowing a saving of material and, therefore, of costs [98].

The Floating Axis Wind Turbine (**FAWT**), proposed by Akimono [115], consists of a vertical axis wind turbine with a variable inclination angle [118]. The floater could rotate with the turbine to guarantee stability and buoyancy, and the turbine axis tilts to balance the thrust force. The tilt angle is settled at 30° at nominal power. Unlike traditional VAWTs turbines, the power is produced from the

torque generated by rollers in contact with the cylindrical surface of the float. Each roller unit has an electric generator, allowing various configurations and designs [115,125]. A variable tilt angle aimed to reduce the support structure and floater mass: further analysis supports the economic competitiveness compared to traditional HAWTs. Funded by New Energy and Industrial Technology Development Organization (NEDO), an experimental campaign of a 1/100 scaled prototype of a 5 MW wind turbine was made in the wave tank of Osaka University in 2017 [117].

The **WindQuest** concept, also called OWLWIND, consists of two vertical axis turbines in a counter-rotating twin-rotor configuration installed on a semi-sub foundation [120]. Each rotor has a rectangular shape of two blades connected with horizontal arms to a central tower. Due to the proximity between the two counter-rotating rotors, the system benefits from the aerodynamic interferences increasing the power output. The WindQuest aerodynamics was tested in the wind tunnel of ISAE-ENSMA in Poitiers, where it was shown that the wake recovery was even zero up to 5.5 diameters downstream [122]. In 2019, the WindQuest was tested at a 1:42 scale in the Wave&Wind tank of IFREMER with a hybrid Software-in-the-loop (SIL) methodology, simulating the thrust of the turbine by a fan [121]. A 10 kW onshore prototype (11 m height with two 4 m height blades) was installed in 2021 near Brest, France [123].

Another small demonstrator built and installed in a marine environment is the Gyro stabilized Vertical Axis Wind Turbine (**Gwind**). This concept comprises a helical-bladed turbine supported by a gyro-stabilized floating platform developed for nearshore and offshore installations [79]. The spar-buoy foundation contains a gyroscopic element to limit the oscillations of the structure due to the metocean conditions without requiring excessive masses and ballasts [124]. The Norwegian research project, led by the University of Stavanger, ended in 2015 with installing a 1 kW prototype in the port of Stavanger.

Among the largest demonstrators is the Savonius Keel and Wind Turbine Darrieus (**Skwid**) platform, developed by MODEC. It is a

Table 2
Main floating VAWT designs.

Name	Floating foundation	Wind turbine	TRL	Project	Academic partner	Industrial partners	References
Nova V-VAWT	Semi-sub	V-rotor, 10 MW	2–3	NOVA	Cranfield, StrathClyde and Sheffield Universities	Wind Power Ltd, OTM, QinetiQ, James Ingram Associates, CEFAS and DNV-GEC	[61,73,83–86,95]
DeepWind	Spar	Darrieus, 5 MW	6	The DeepWind Project	DTU, Delft University, Aalborg University, NREL, MARIN, SINTEF	Vestas, Statoil	[74,87,89–91,93,94,96–103]
Vertiwind	Semi-sub	Helical, 2 MW	4–5	VERTIWIND: Offshore floating vertical axis wind turbine	TU Delft University	Nenuphar, Technip, ENSAM, EDF Energies nouvelle	[61,77,94,104]
twin-VAWT	Semi-sub	Darrieus H-shape, 2 x 5 MW	1–2	INFLOW	DTU, Fraunhofer Institute	TECHNIP Energies France, DTU, General Electrics Renovables España, Nenuphar, Fraunhofer Institute, EDF, Vicinay Cadenas, Vryhof Anchors, Eiffage Construction Metallique	[27,48,105–109]
Skwid-MODEC	Semi-sub	Darrieus, 500 kW	6	Supported by NEDO	–	MODEC	[61,80,110–113]
S4VAWT	Semi (Gusto MSC)	Darrieus H-rotor, 6 MW	1–2	S4VAWT	ECN, Delft University, MARIN	Gusto MSC, Eolfi, WCM	[75,98,114]
FAWT	Spar	Helical, 5 MW	3	New Energy Venture Business Technology Innovation Program 2015/Model tests of the new floating vertical axis wind turbine, supported by NEDO	Osaka University, Kanazawa Institute of Technology	–	[115–119]
WindQuest (OWLWIND)	Semi-sub	Darrieus H-shape, 10 MW	3–4	OWLWIND	LEGI Grenoble, IFREMER, Poitiers University	Hydroquest	[120–123]
Gwind	Spar	Helical, 5 MW	6	–	University of Stavanger	TTO office Prekubator, CMR Prototech	[79,124]

hybrid wind-currents platform that consists of an H-Darrieus turbine, supported by a floater on which a Savonius turbine is arranged, which in addition to exploiting the currents, also acts as ballast [80,110,111]. The pre-commercial version had a 500 kW wind turbine and a 60 kW Savonius turbine [61,80]. Two unsuccessful attempts were made to install a demonstrator near Kobe Island, Japan, in 2013 and 2014: however, in both times, the device sank during the installation process. The failure of the installation, combined with significant investments spent on the project, led MODEC to abandon the technology.

5. Towards new concepts

The projects described in Section 4 mainly took place mainly between 2009 and 2015. Subsequently, concurrent with the development of floating HAWTs, the number of new projects has drastically decreased. Only with the development of FOWTs, and the analysis of the most impacting problems there has been a rebirth of floating VAWTs, with new concepts and projects. Among the main interests, there has been: (i) the scalability of the size, to reach the order of the MW and compete with the HAWTs, (ii) the improvement of aerodynamic performance, and (iii) the development of control techniques. In Table 3, a summary of new floating VAWT designs is reported.

SeaTwirl is a Swedish company that has developed a Darrieus H-shape turbine supported by a spar-buoy [78,126]. A static and non-rotating generator is enclosed on the substructure, just above sea level, while the system is anchored to the seabed with several catenary moorings. The lack of a yaw system for aligning with the wind or a pitching mechanism requires lower maintenance due to fewer moving parts; moreover, less structural stress affects the bearings since they do not need to carry the weight of the turbine [127]. Adopting Darrieus wind turbines, less sensitive to wake, could reduce the aerodynamic

losses, allowing them to be set up at short distances, curtailing the maritime areas for installation [128]. In [129], the efficiency of two wind farms, one made by the DTU 10 MW, and the other by the upscaled 10 MW SeaTwirl, were compared. Different layouts were considered, each considering 25 turbines, by varying the distances between the turbines in the streamwise and spanwise directions. Due to a lower thrust coefficient and faster wake recovery, VAWTs outperform HAWTs, increasing up to 13% for three layouts [129]. In 2015, a 30 kW prototype, S1, was installed off the coast of Norway, near Lysekil. With a rotor height of 13 m, a turbine diameter of 10 m and a spar depth of 18 m, it withstood Storm Helga, surviving gusts of 35 m/s without sustaining damage. The SeaTwirl concept is scalable for higher powers, up to 1 MW: a device is under construction and will be installed in the Metcentre test area by the end of 2023 [130,131].

Among the most innovative designs, there is the one proposed by the **X-Rotor** Project (X-shaped Radical Offshore wind Turbine concept for Overall cost of energy Reduction) [132,133]. The X-Rotor is a hybrid of vertical and horizontal axis wind turbines, made of two rotors: the primary rotor consists of a double V configuration to maximize the swept area and to minimize the overturning moment [134]. The upper blades' primary function is to contribute significantly to the extraction of mechanical energy from the wind and are allowed to pitch. Two secondary horizontal axis rotors are attached to the ends of the X-rotor's lower half [135,136]. This concept solves one of the traditional problems of VAWTs, namely that of being characterized by power take-off due to low rotational speed and high torque: in this design, the secondary rotors, which size is reduced, provide power take-off by using a conventional generator, without the need for a gearbox or bespoke generators [137]. Primarily designed for installation on fixed structures, such as jackets or monopiles [133], it is characterized by a substantial reduction in turbine costs, up to 32%, compared to

Table 3
New floating VAWT designs.

Name	Floating foundation	Wind turbine	TRL	Project	Academic and industrial partners	References
SeaTwirl S1 and S2X	Spar	Darrieus H-rotor, 1 MW	6	The first robust and cost-effective floating vertical axis wind turbine for deep water offshore	SeaTwirl, Chalmers University	[78,126–128,130,131,140–142]
X-rotor	Semi-sub	X-rotor	1	X-ROTOR	StrathClyde and Delft Universities, University College Cork, NTNU, Cener, General Electrics Renovables España	[39,132,133,135–137,143]
WorldWide-Wind	Spar	2 counter-rotating turbines	1–2	–	Uppsala University, Sintef, Hydro	[138,139]

traditional turbines and O&M costs, up to 55% [137]. Additionally, the design allows the ability to upscale in size; among the considered solutions, secondary rotors up to 2.5 MW or three blades arranged at 120° [39]. The project aims to develop the X-rotor concept into a TRL of 3.

WorldWideWind is a Norwegian company that has developed a counter-rotating VAWT [138]. The novel patent-pending technology consists of two coaxial rotors mounted on the same vertical shaft. Each rotor is made of three V-shape blades and is counter-rotating: the upper serves as the rotor in a generator, while the lower stator moves on the opposite side of the rotor, increasing the relative speed of the shafts [139]. The generator, located at the bottom of the substructure, acts as a stabilizer and counterweight.

6. Offshore VAWTS: advantages and challenges

In this section, the main advantages and challenges associated with the VAWT technology used for offshore installations are reported.

The information available in the literature, obtained from a detailed review analysis that considered the main review articles and publications available on the state of the art, is insufficient to carry out a quantitative analysis of the benefits of floating VAWTs and to compare them with HAWTs. However, since this represents a topic of great relevance and one of the gaps that the article wants to cover, the results of this analysis are presented qualitatively.

Advantages

Easier O&M

The maintenance of an offshore wind turbine is a complex operation, especially if carried out at sea and in harsh weather and sea conditions. Among the most stringent operational constraints are the wind speed, which is limited to 12.5 m/s for blade maintenance operations [144], and the wave height, which must not exceed 1.5 m for crew transfer vessels (CTV) and 2.5–4 m for service operations vessels (SOV) [39,145]. These constraints reduce the weather windows suitable for O&M activities. Compared to an onshore turbine, the failure rate of a FOWT is between 26%–28% higher [146,147]. Among the components most susceptible to failures are the mooring system and RNA components, particularly the gearbox, blade pitch and yaw systems [147,148]. In the case of HAWT, this requires the presence of highly specialized operators who can operate at heights exceeding 100 m based on the hub height of the considered turbine. In VAWTs, the arrangement of the RNA at the base of the VAWT, accessible from the floating foundation, allows it to operate at more contained heights, intervening directly from the sea and without necessarily having to resort to helicopters or requesting the transport of the system to the port [149]. Moreover, the ability of VAWTs to exploit the wind regardless of direction avoids complex systems such as that of the yaw and pitch systems for HAWTs, which require numerous moving parts, subject to variable loads and are frequently subject to

damage. According to [147], the hydraulic failures, due to oil leakages and overpressure, contribute to more than 80% of failures of the pitch system.

Static stability & reduced mass

The presence of the RNA near the floating foundation allows a considerable lowering of the centre of gravity, which reduces the topside moment of inertia and increases the system stability. Several studies have tried to compare the stability of HAWT and VAWT with the same turbine power. As for the static stability, in [150] was shown that for a given maximum inclination angle criterion, the potentially lower inclining moment of a VAWT system would result in a lower required minimum stiffness than a HAWT. As a result, a lighter and less expensive foundation is required. In [121], the experimental comparison of the DTU 10 MW (HAWT) and the WindQuest 10 MW (VAWT), mounted on the Nautilus semi-sub platform, was performed. Due to lower centre of gravity and centre of thrust, the WindQuest shows a lower pitching moment leading to a 53% lower torque imposed from the VAWT to the floating foundation than the HAWT. As a result, the floating foundation could accommodate up to a 30% more powerful turbine.

Lower aerodynamics wakes

One of the most significant issues with HAWT offshore wind farm concerns the high surface area required for the installation: this is related to the distance between the turbines to limit aerodynamic losses. As a rule of thumb, it is typically considered a distance of 8–10 diameters in the wind direction and 5–6 in the perpendicular one [149,151]. The area must be banned from navigation and all maritime activities, often leading to opposition from other sea users. In the case of VAWTs, there is a different dynamic of the wake, which is dissipated in a smaller space: several studies have shown that the undisturbed speed is recovered sooner, approximately after 5–6 times the diameter along the wind direction [152,153]. Furthermore, using counter-rotating turbines would increase the wind farm performances, and further reduce the effect of wakes [53,151,154,155]. This would allow for installing turbines closer together, reducing the maritime area, and increasing the wind farm power density [129].

Challenges

Power upscale

The upscaling of VAWTs is one of the most urgent needs to facilitate large-scale industrialization. Although varying according to the type of turbine, the most common sizes are less than a hundred kW, far from the standard of the HAWTs, which far exceed 10 MW. Some upscaling attempts have been made in the past for onshore ϕ -Darrieus turbines [156–158]: in 1983, the Indal 6400 was the first 500 kW vertical axis turbine to be built [159], followed in 1980 by the ALVAWT 500 kW and the Sandia 34-m 'test bed' in 1988 [160]. The largest turbine ever built was made in Canada in 1987 as part of the Éole Project. Characterized by a nominal power of 3.8 MW, it had a rotor height of

96 m, an overall height of 110 m and a diameter of 64 m [157,161–163]; it was in operation until 1993 [164]. VAWTs scaling follows the same scaling laws as HAWTs, but the blades are not affected by gravity similarly. As rotor size increases, the cyclic gravitational loading of HAWT blades creates a more significant fatigue loading on the blades and supporting structure than the cyclic aerodynamic loading of VAWT blades [68]. The upscale of different VAWTs, such as the Darrieus, have been proposed and designed by various researchers and projects for both onshore and offshore applications, demonstrating the technical feasibility and economic competitiveness if developed on an industrial scale.

Fatigue damage

The fatigue behaviour of a VAWT is related to the aerodynamic forces, which differs from that of HAWTs. While the HAWTs have gravitational fatigue issues, VAWTs are subjected to a cyclic torque that can negatively affect transmission and control systems [149]. Generally, VAWT aerodynamic forces are highly oscillatory for identical wind conditions compared to HAWT: in [150], thrust force and rotor inclining moments were reported for a 5 MW HAWT and a 5 MW VAWT. However, considering the average values, the loads associated with the VAWT are much lower than those of a HAWT: in particular, the pitch inclining moment is almost 7 times lower for VAWT [150]. Moreover, by considering multi-megawatt VAWTs, which rotation speed is sensibly lower to small turbines and which rotate few revolutions per minute, this problem is mitigated. As regards the thrust curve, in the case of a turbine with fixed blades, the trend of the thrust force increases as the wind speed increases, involving intense loads for speeds close to the cut-off speed [165]. Adopting an accurate control strategy, like a PID controller and the implementation of a blade pitch controller as done in [166], would allow maximum power and thrust at the rated wind speed, guaranteeing constant values for both variables above the rated one.

Mooring lines loads

Due to the different nature of the generated torque, the design criteria for the mooring system of a floating HAWT and a floating VAWT are significantly different. While for HAWTs, the generated torque is along the roll axis and is counterbalanced by the platform restoring stability, the oscillatory torque generated by a VAWT acts along the yaw axis, exciting the mooring system [167,168]. The inadequacy of traditional catenary mooring systems used for HAWTs is illustrated in [169], where the dynamic analysis of three platforms, a spar-buoy, a semi-sub and a TLP, supporting a Darrieus 5 MW wind turbine, are simulated. The spar could not sustain the aerodynamic loads in yaw, while the TLP mooring system could not sufficiently restrain the platform in surge and sway. In [166], a comparison between a HAWT, the NREL 5 MW, and 3 configurations of VAWT, a H-rotor Darrieus with two, three and four blades, mounted on the same OC4-DeepCWind semi-sub with three catenary mooring lines, was performed. Results showed that, with the same wind and wave conditions, the maximum mooring tensions for the three and four-blade VAWTs are up to four times higher than that of the HAWT.

LCOE & cost reduction

An essential aspect in the evaluation of floating technology concerns the cost analysis. The offshore environment, characterized by harsh met ocean conditions, involves high investment costs, which require a detailed analysis of the feasibility and sustainability of the projects.

The main Capex cost items of a FOWT project concern the wind turbine, the floating foundation, the mooring and anchoring system, the transmission system, installation and decommissioning: among the most significant are wind turbines and floating foundations [170–172]. The adoption of VAWTs, with a lower COG and lower overturning moments, would allow the use of lighter floating foundations than HAWTs, with a reduction of material, steel and ballast, which leads to a reduction in costs; alternatively, the same foundation can host more or more powerful turbines.

Table 4

Summary of floating VAWTs advantages and challenges.

Topic	Benefit/Criticality
O&M	High benefit
Stability	Benefit
Aerodynamics wakes	High benefit
Power upscale	Benefit
Fatigue damage	High criticality
Mooring loads	High criticality
LCOE reduction	High benefit

As for the wind turbine, few techno-economic analyses of multi-MW VAWTs are available in the literature. In a Sandia Report [173], a cost analysis of a ϕ -Darrieus VAWT rotor includes three major cost components: materials, labour and tooling. While some components like the tower, brackets and supports can be made with conventional processes, the blades, especially curved blades, do not benefit from existing manufacturing processes and should be designed on purpose. As a result, one of the challenges common to floating HAWTs is the definition of an efficient supply chain.

Also, the drivetrain should be explicitly designed: in [173], a new drivetrain with a direct-drive generator, main bearings, low-speed shaft and mechanical brakes was designed for a 6 MW VAWT. The system, equal to 434 tons, was estimated at around 2.97 M\$ (2018).

The absence of the yaw and blade pitch mechanism reduces the drivetrain's mass, cost, and reliability issues. Moreover, since these mechanisms are responsible for frequent failures [55], reliability is improved while turbine downtime is reduced. Furthermore, by considering the more accessible location of the drivetrain that does not require cranes or specific vessels, a decrease in O&M costs is achievable.

Several studies [174,175] have highlighted the possibility of significant reductions in LCOE compared to HAWTs; however, as reported in [173], the LCOE range varies from 274 to 110 \$/MWh, based on the maturity of the technology used. Consequently, the technological development and growth of the TRL are crucial to decrease investment costs.

Table 4 summarizes the main advantages and challenges related to floating VAWTs while in Fig. 4 floating VAWTs are qualitatively compared with floating HAWTs.

Overall, floating VAWTs feature simpler and less expensive maintenance activities, greater stability for the same mass, lower aerodynamic losses, and a larger reduction in cost and LCOE than floating HAWTs. Conversely, the power upscale of floating VAWTs is more complex, the fatigue damage is more difficult to compensate and the loads acting on the moorings are higher than those of floating HAWTs.

7. Discussion and future outlook

VAWT technologies have interesting characteristics for offshore applications, as explained in Section 6. However, one of the most significant obstacles to future development is the **competition with HAWTs**. This more mature and developed technology benefits from years of experience in installing bottom-fixed wind farms. An urgent need is to install a demonstrator of a scale greater than the MW to fill this gap. As shown in Table 5, the most powerful prototype installed is only 30 kW, far from possible industrial development applications. A multi-MW prototype is essential to demonstrate the technology's feasibility and obtain experimental data, indispensable for verifying and optimizing the models and simultaneously with the difficulties associated with the birth of a new supply chain. In this sense, the SeaTwirl demonstrator, installed at the end of 2023–2024, represents a crucial step for testing a VAWT in an open sea environment.

Academia and research

If the broader effort seems linked to the industrialization of VAWTs, many aspects should be deepened at the research level to achieve

Table 5
Pre-commercial floating VAWTs and demonstrators.

Technology	Year	Nominal power	Location	Description	Current status	References
Deepwind	2012	1 kW	Roskilde Fjord (Denmark), Sea depth: 4.5 m, Distance from coast: 50 m	Rotor diameter: 2 m, Rotor height: 2 m, Spar height: 5 m	Prototype decommissioned, Main challenges: blades manufacturing and installation	[93,176]
Skwid - MODEC	2014	500 kW (+ 50 kW tidal)	Kabe Island (Japan), Sea depth: 50 m, Distance from coast: 1.2 km	Rotor diameter: 24 m, Rotor height: 36 m, Savonius tidal turbine diameter: 15 m, Savonius tidal turbine height: 7 m	Installation failed, Project abandoned	[61,80,110, 111,113]
Gwind	2013	1 kW	Stavanger Harbor area (Norway)	–	Project concluded, Prototype decommissioned	[79]
Sea-Twirl S1	2015	30 kW	Lysekil (Sweden), Sea depth: 35 m	Rotor diameter: 10 m, Rotor height: 13 m, Spar length: 18 m	Still operational (2023)	[78]
Sea-Twirl S2x	2023– 2024	1 MW	Metcentre test site (Norway), Sea depth: 200 m, Distance from coast: 10 km	Rotor diameter: 50 m, Rotor height: 40 m, Spar length: 18 m	To be installed	[131]

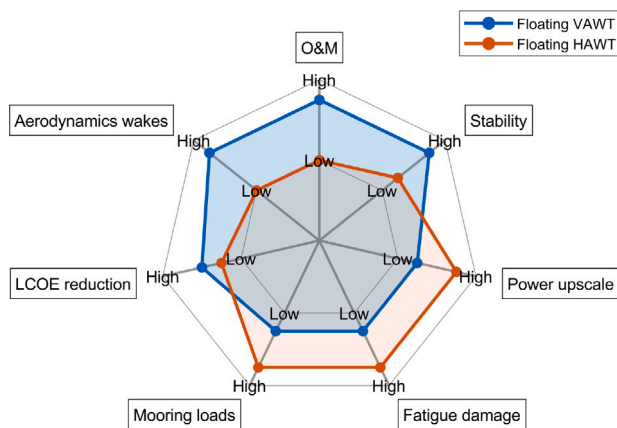


Fig. 4. Comparison between floating VAWTs and floating Horizontal Axis Wind Turbines (HAWTs), where the words “high” and “low” refer to the benefit brought by the specific technology. O&M refers to Operation and Maintenance, while LCOE refers to Levelize Cost Of Energy.

adequate technological maturity. Due to their complexity, the VAWT dynamics must consider the turbine’s aerodynamics, the floating foundation’s hydrodynamics, the mooring system and the control system. Several review articles have classified the most used techniques: among these in [167] the aerodynamics, in [177] the hydrodynamics and in [168] mooring line and structural dynamics modelling. As for aerodynamics, Blade Element Momentum (BEM) and cascade models provide accurate power predictions with fast computational times [178–183]. Regarding more accurate models, there are vortex and panel models, able to simulate the wake of the VAWT or methods such as Reynolds-averaged Navier–Stokes (RANS) computational fluid dynamics (CFD), used to compare experimental data or for validation [184–186]. Among the coupled software developed, there are FloVAWT [187,188] developed by Cranfield and StrathClyde Universities, and HAWC2 [189], developed by DTU, based on Double Multiple Stream Tube [82] while Qblade [190], developed by TU Berlin, is based on Lifting Line Free Vortex Wake Method.

Implementing suitable control techniques could reduce the turbine blades’ vibration and allow the self-starting at low wind speed. If passive pitch control techniques are developed for small VAWTs [191, 192], to activate self-starting components, variable-pitch control strategies achieve better performances, improving power coefficients and

reducing the starting torque [193]. As regards the latest developments for floating VAWTs, several studies have concerned geometric optimization of the blades and the use of new materials, the analysis of aerodynamic performance in an offshore context [118,169,194,195] and the study of the wake effect [29,196], the dynamic stability of the floating system [197–201] and the size upscaling [202,203]. From the state-of-the-art analysis, the number of published articles is relatively low but growing in recent years (taken from Scopus, from 2009 to March 2023, using the keywords “vertical axis wind turbine” & “floating”): this partly comes from the absence of new research projects. As shown in Table 6, almost all of the projects concerning VAWT were carried out before 2015: among the few European projects in progress is the X-rotor, which proposes an innovative concept with an X-shaped rotor.

Floating VAWTs applications

Possible applications in the short term are also being discussed. If the use of VAWTs for the production of large-scale energy will be possible in a distant future, among the possible areas of application, there is the use for the production of energy on a small scale relative to isolated contexts [206], for example, the small unconnected islands [207]. There are many island in Europe, both in the Mediterranean Sea and in the North Sea, not interconnected with the national electricity grids, whose consumption is too modest for traditional wind turbines.

Other possible fields of application concern the supply of energy for offshore installations: one case would concern aquaculture applications, like fish farms. Despite being located a few hundred meters from the coast, manufacturing an electrical cable duct requires considerable installation and operating costs. Another case could be the installation of VAWTs near ports or sea docks: in this case, the reduced size compared to traditional HAWTs, which involves a smaller occupied area, could allow installation in areas with little landscape interest, such as port quays, docks or dry docks.

8. Conclusions

The purpose of this study is to critically review vertical axis wind turbines used for offshore applications, filling a gap in the literature by focusing on the technologies, the projects and describing both the advantages and challenges for the complete industrialization of VAWTs. The analysis, which has covered journal articles, conference proceedings and books from the Scopus database from 2009 to 2023, has demonstrated an interest in this technology, evident from numerous

Table 6
Main floating VAWT projects.

Name	Duration	Budget	Objectives	Current status	References
NOVA	2009–2010	2.8 M€	<ul style="list-style-type: none"> • Techno-economical feasibility of a novel offshore VAWT • Aerogenerator designs upscale (5–10 MW) 	The rotor concept resumed and improved in the X-Rotor Project	[68,73,83–85]
Deepwind	2010–2014	4.18 M€	Development of: <ul style="list-style-type: none"> • A new floating VAWT design • Numerical tools for the estimation of energy production, dynamics, loads and fatigue • A 1 kW prototype tested under near-to-realistic operating conditions • Upscaling of the 5 MW design up to 20 MW 	Project concluded, Main challenges: blades manufacturing and installation, No further technology improvements expected	[74,97]
INFLOW	2011–2015	21.5 M€	<ul style="list-style-type: none"> • Optimization of the prototype developed • Device industrialization and wind farm layout definition (26 MW) 	Project concluded, No further technology improvements due to the bankruptcy of Nenuphar SA, owner of the technology	[105,106,204]
H2OCEAN	2012–2014	6.5 M€	Development of a multi-use open-sea platform for: <ul style="list-style-type: none"> • Wind and wave power harvesting • Multi-trophic aquaculture farm applications • Hydrogen storage 	Project concluded, No further technology improvements expected	[205]
SeaTwirl	2019–2022	3.5 M€	<ul style="list-style-type: none"> • Verification of the 1 MW S2 design • Demonstration of the competitiveness of S2 in terms of LCOE, Capex and Opex compared to HAWTs 	Project concluded S2 technology under construction	[140]
X-rotor	2021–2023	3.90 M€	<ul style="list-style-type: none"> • Increase of the X-ROTOR concept from TRL 1 to 3 • Design of a power take-off and conversion system • Analysis of the performance of the X-Rotor and estimation of the LCOE reduction 	Project under development	[132,133,143]

past and ongoing projects. The main advantages of floating VAWTs compared to HAWTs have been analysed: among the most promising are the easier O&M, due to Rotor Nacelle Assembly located at the base of the turbine; the lower COG, which reduce the topside moment of inertia and increases the system stability; the wake dynamics, which is dissipated in a smaller distance from the water level, allowing to install turbines closer and to reduce the maritime area. The result of the analysis has been done qualitatively: the absence of specific studies and public data are insufficient to carry out a quantitative analysis of the benefits of floating VAWTs and to compare them with HAWTs.

To reduce the gap with the HAWTs, it is essential to increase their technological maturity: in particular, the installation of a multi-MW prototype would allow the evaluation of the technical feasibility and obtaining experimental data useful for validating the numerical models. Finally, possible short-term installation opportunities that can ramp-up the development of VAWT are highlighted in this study, such as energy production for isolated contexts, like non-interconnected islands, oil and gas platforms or aquaculture.

CRedit authorship contribution statement

Alberto Ghigo: Conceptualization; Data curation; Formal analysis; Methodology; Visualization; Writing – original draft; Writing – review & editing. **Emilio Faraggiana:** Conceptualization; Methodology; Supervision; Writing – review & editing. **Giuseppe Giorgi:** Conceptualization; Methodology; Supervision; Writing – review & editing. **Giuliana Mattiazzo:** Conceptualization; Funding acquisition; Supervision. **Giovanni Bracco:** Conceptualization; Funding acquisition; Supervision.

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.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at <https://doi.org/10.1016/j.rser.2024.114302>.

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