

A historical review of vertical axis wind turbines rated 100 kW and above

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ABSTRACT

This paper summarizes and introduces all vertical axis wind turbine (VAWT) projects where 100 kW or larger turbines have been installed. The basis for the review is both existing literature and personal correspondence with people once involved in the different developments. By citing the most relevant work for each project, the paper will also work as an information hub, making information on these projects more accessible.

Since the 1970s, there have been several VAWT projects with installed turbines of significant size, either as attempts to commercialize VAWTs, or as university led research projects, or as a combination of the two. Most have involved Darrieus turbines built in North America during the 1980s. However, H-rotors, which have always been a favored concept in Europe, have seen a revival during the 2010s.

The reason VAWTs have never fully challenged the success of the horizontal axis wind turbine (HAWT) is too broad a question to answer here. However, the reasons some VAWT projects have failed are addressed in this paper. Besides the fact that many of the prototypes had terminal failures, most of the installed medium or large-scale VAWTs have to some extent had problems with metal fatigue and durability. Additionally, a lack of long-term interest from governmental or private funders, as well as the introduction of reliable HAWTs, was a re-occurring theme from those involved in VAWT development, regarding the reason VAWTs so far have failed to succeed.

1. Introduction

European style grain grinding windmills are what usually comes to mind when thinking of early-age wind power. However, even if these types of horizontal axis windmills were introduced in Europe no later than the 12th century, the first recordings of wind turbines are from the 9th century, describing Persian vertical axis windmills [1]. Vertical axis windmills might have been in use in the Afghan highlands as early as the 7th century BC [2]. These early VAWTs were simple devices based on aerodynamic drag rather than on aerodynamic lift. One side of the turbine was covered and the wind simply pushed the blades on the power-generating side of the turbine and thus created torque. Using the aerodynamic lift created by pressure difference due to the shape of the blade is far more efficient than using drag. The first lift-based vertical axis wind turbine was invented by Georges Darrieus in France during the 1920s (French patent in 1925; US patent in 1931). The Darrieus patent [3] covers the “egg beater” shaped turbine with troposkein curved blades, sometimes referred to as a full-Darrieus or Φ -configuration Darrieus turbine but is commonly just called a Darrieus turbine.

The Darrieus patent also covers the straight-bladed H-rotor (or giro-mill). The curved blades of the Darrieus turbine are mounted directly to the vertical torque tube (the rotating shaft, which also serves as the support structure) at the top and bottom. The top of the turbine can be held upright by guy cables or the torque tube can be cantilevered from the base (examples can be seen in Figs. 1 and 3). In contrast, the straight blades of the H-rotor are attached by a crossarm. The H-rotor can drive a generator placed either at the top of the tower or, using a shaft placed inside the tower, at ground level (an example can be seen in Fig. 5).

Starting in the mid-1920s, George Darrieus built several curved- and straight-bladed miniature models [4]. The first power-producing, lift-based VAWTs were constructed by fellow Frenchman Jean-Baptiste Morel who built several straight-bladed Darrieus turbines in southern France in the 1950s [5]. Morel's turbines ranged up to 7 kW, and although straight bladed, they differ from more recent H-rotors, as they had the blade mounted with an angle, making the diameter larger at the base than at the top.

In more recent years, different sub-concepts of both HAWTs and VAWTs have had individual paths of development in both Europe and

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Fig. 1. Upper left: The 34-m 500-kW Sandia research turbine at Bushland, Texas. Photo used with permission from Sandia National Laboratories. Upper right: VAWT-POWER 185 turbines in San Geronio Pass during the 1980s. Lower left: A wind farm with FloWind-19 turbines, in the mid-1980s at Cameron Ridge in the Tehachapi Pass. The 19-m model can be distinguished from the 17-m model by the conventional struts (the FloWind-17 had cable struts). Lower right: The 500-kW ALCOA turbine situated near Newport, Oregon in the 1980s. Photos (except the Sandia turbine) by Paul Gipe. All rights reserved.

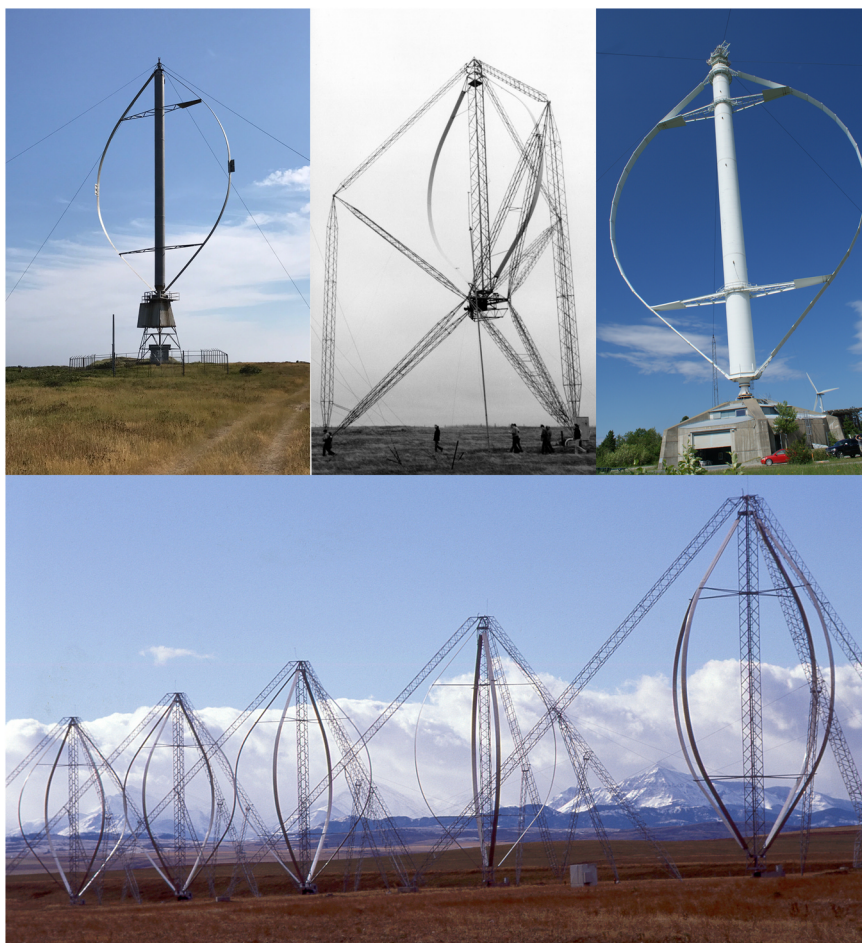


Fig. 2. Upper left: The 230-kW Magdalen Island VAWT manufactured by DAF Indal. Photo by and used with permission from Albert Watts. Upper center: Adecon's 125-kW external lattice framework turbine at the Atlantic wind test site, Prince Edward Island, Canada. Archive photo from the Department of Fluid Dynamics at Eindhoven University. Made available by Jos Beurskens. Upper right: The 3.8-MW ÉOLE turbine in Cap-Chat, Quebec. Photo by Erik Möllerström in 2016. Lower: Adecon AL-38 turbines in Pincher Creek, Alberta in the mid-1990s. Photo by Jos Beurskens. All rights reserved.



Fig. 3. Left: The 94-kW Pioneer I on its floating platform in Amsterdam, the Netherlands. Right: The 160-kW VAWT in Martigny, Switzerland, with a part of its adjacent biogas system seen in the foreground. Photos by Jos Beurskens. All rights reserved.

North America. It was primarily one of these sub-concepts, the upwind three-bladed HAWT, that became established in the Danish market during the 1970s–1980s. Thereafter, this design grew into the large and cost-effective wind turbines of today [6]. Along with the continuing development of HAWTs, there has been several revivals of attempts to commercialize VAWTs. Although the gap between VAWTs and HAWTs is wider than ever, the VAWT concept continues to be explored.

1.1. Aim of paper

The attempts to commercialize VAWTs and information about once-existing, large-scale VAWT turbines are for many cases not well known or easily accessible. Finding and accessing information about the history of these projects, including design, realization and reason for ultimate failure, are essential to avoid old mistakes in future attempts. There are review papers addressing different topics of VAWT. For example, some studies [7,8] focus on different configurations, and others [9] compare VAWTs to HAWTs. There are also review papers and reports focusing on a specific VAWT project [10–12], which all are cited in this paper. Regarding popular science, a well-written and intriguing description of wind energy history (especially for North America) can be found in book format [13]. However, there are no easily accessible paper-format summaries covering all previously existing VAWTs of significant size. This, together with highlighting the most relevant literature for the different projects, is the aim of this paper. The focus will be on VAWTs rated at 100 kW and above.

1.2. Limitations

This paper makes no claim to cover all 100 kW and greater VAWTs ever built. For example, the 17-m, Sandia/DOE design (described in “2.1 Sandia National Laboratories”) may have been applied to minor, free-standing projects in California in the early 1980s other than those found within the work conducted for this review. Turbines with a design fundamentally different from the Darrieus concept (Φ -configuration and H-rotor) are also excluded (for example, the “sails on circular tracks” concept of Transpower, see [14]). The paper makes no claim of answering why the VAWT concept has not been commercially successful, although the reasons for the individual project failures are discussed.

2. Darrieus turbines (Φ -configuration)

In the 1970s, events such as the 1973 Arab oil embargo gave the United States, as well as other western countries an incentive to assess their reliance on foreign energy sources. The Darrieus concept, which was little known outside of France, was reintroduced in the mid-1960s

by Peter South, Raj Rangi and Jack Templin at the National Research Council of Canada (CNRC) [13]. Apparently, they were unaware of Darrieus's 1920s invention until finding it when filing for a patent. A large portion of the Canadian wind turbine development was focused toward VAWTs, and several projects were initiated, lasting until the 1990s.

In the early 1970s, Sandia National Laboratories (Sandia) was assigned by the US Department of Energy (DOE) to investigate alternative energy resources and quickly learned about the Canadian VAWT research. The VAWT concept subsequently became the focus of Sandia's renewable energy research [15]. Sandia developed and tested different configurations and sizes of the Darrieus turbine.

Sections 2.1–2.8 provide descriptions of projects that resulted in Φ -configuration Darrieus turbines rating at 100 kW or above. A summary with technical specifications of the turbines can be found in Table 1.

2.1. Sandia National Laboratories

The US VAWT research was led by Sandia National Laboratories, a multi-program laboratory privately operated through a contractor to the DOE and thereby also the US Government, with its primary facilities in Albuquerque, New Mexico (NM) [16]. Sandia's roots go back to the Manhattan Project. Besides their main mission of developing nuclear weapons, Sandia had conducted research in a variety of other fields, including what was then called “alternative energy sources.” Sandia ran the US' VAWT program from the early 1970s until the 1990s.

The largest Darrieus turbine developed by Sandia (seen in Fig. 1) and the last in the line used a 34-m diameter, two-blade rotor. The rotor's aluminum blades drove a variable-speed, 500-kW synchronous generator via a gearbox [12,15,17]. It was designed so that most parts could be exchanged, thus enabling research on different VAWT components. The strut-free design produced an impressive maximum power coefficient of 0.43, likely the highest C_p measured for a VAWT. The turbine was erected in 1988 and decommissioned in 1998 due to cracks in its foundation.

Although rated at less than 100 kW, Sandia also developed a 17-m diameter, 60-kW, two-bladed Darrieus rotor erected near Albuquerque, NM in 1976 (it became operational by March 1977). For a short period the 17-m turbine was the largest VAWT then in existence [15,18]. For testing purposes, the turbine could switch between a synchronous and induction (asynchronous) generator via a speed-increasing gearbox and reached a power coefficient of 0.38, driving the induction-generator during the extensive field tests [18].

2.2. ALCOA

The Pittsburgh-based Aluminum Company of America (ALCOA)

Table 1
 ϕ -configuration Darrieus turbines ≥ 100 kW [80–87].

Name	Producer / affiliations	No	Location	Year of construction	Dimensions	Rated power	Specific power	Description	Status	Ref
Magdalen Island 230 kW	DAF Indal / CNRC / Hydro Quebec	1	Magdalen Island, QC, Canada	1977	D: 24 m. H_{TOR} : 36.6 m. A: 595 m ² .	224/230 kW	376 W/m ²	Two-bladed. Induction generator. Belt drive. Fixed speed. Air brakes on blades. Alu-blades.	Retired in 1986. Still standing as of 2016.	[13,17,20,29]
Indal 6400-500 kW (CA-turbine a.k.a. AQUILLO)	DAF Indal	2	San Geronio Pass, CA, US The Atlantic wind test site, Prince Edward Island, Canada	1983-84	D: 24 m. H_{TOR} : 41 m. A: 595 m ² .	500 kW (peak 545 kW) @ 22 m/s	840 W/m ²	Two-bladed. Double 261-kW induction generators. Gearbox. Fixed speed. Alu-blades.	US-turbine failed in 1980s. Canadian turbine failed in early 1990s.	[13,17,20,28,30,33,80]
ALVAWT 100 kW ("Low Cost 17-m turbine")	ALCOA / DOE / Sandia	3	Golden, CO, US Bushland, TX, US Martha's Vineyard, MA, US	1980-81	D: 17 m. H: 25 m. H_{TOR} : 28 m. A: 279 m ² .	100 kW @ 14 m/s	358 W/m ²	Two-bladed. Induction generator. Fixed speed. Gearbox. Alu-blades.	San Geronio-turbine failed in 1981.	[5,13,17,19–21,81]
ALVAWT 500 kW	ALCOA	3	Pittsburgh, PA, US Newport, OR, US San Geronio Pass, CA, US	1980-81	D: 25 m. H_{TOR} : 37.5 m. A: 595 m ²	500 kW (PA-turbine 300 kW)	840 W/m ²	Three-bladed. Induction generator. Gearbox. Alu-blades.	The rest scrapped, most of them as early as 1982 after recalled by ALCOA.	[13,17,20,21]
Salinas Valley 150-kW Darrieus	Appropriate Power Inc.	5	Salinas Valley, CA, US	1982	D: 17 m. H: 25 m. H_{TOR} : 28 m. A: 283 m ² (est.).	150 kW	530 W/m ²	Two-bladed. Induction generator. Fixed speed. Gearbox. Alu-blades.	All in-operational by mid-1980s. Prototype dismantled in 1980s, other four in 2000s.	
Pionier I	Polymarin B.V.	1	Amsterdam, Netherlands	1982	D: 15 m. H: 15 m. H_{TOR} : 22 m. A: 150 m ² .	94 kW	623 W/m ²	Two-bladed. Floating platform. Cantilevered. DC-generator. Variable speed. Gearbox. Glass-fiber/polyester blades.	Decommissioned in 1992.	[49–51]
FloWind-17	FloWind corp.	512 + 1	Tehachapi pass, CA, US Altamont pass, CA, US (100-kW prototype: Ellensburg, WA, US)	1983-84 (1982)	D: 17 m. H: 23 m. A: 260 m ² .	170 kW (142 kW) @ 17 m/s	654 W/m ²	Two-bladed. Induction generator. Gearbox. Fixed speed. Cable struts (17-m). Conventional struts (19 & 25-m). Alu-blades.	Dismantled and sold for scrap 1990-2000s.	[13,17,20,27,82]
FloWind-19				1984-86	D: 19 m. H: 25 m. H_{TOR} : 31 m. A: 316 m ² .	300 kW (240 kW) @ 20 m/s	949 W/m ²			
FloWind 25m-prototype		1	Tehachapi pass, CA, US	1986	D: 25 m. H_{TOR} : 28 m. A: 515 m ²	381 kW	740 W/m ²		Dismantled and sold for scrap, late 1980s.	
17-FHD (Adam & Eve)		2	Tehachapi pass, CA, US	1992	D: 17 m. H_{TOR} : 54 m. A: 536 m ² .	300 kW (peak 327 kW) @ 18 m/s	560 W/m ²	Three-bladed. Induction generator. Gearbox. Fixed speed. Fiberglass blades.	One turbine destroyed. Both scrapped 1990s.	
VAWTPOWER 185	VAWTPOWER Inc.	40 + 1	San Geronio Pass, CA, US. (prototype in Albuquerque, NM, US)	1983-84	D: 17 m. H_{TOR} : 25 m. A: 288 m ² .	185 - 200 kW @ 17 m/s	642-694 W/m ²	Two-bladed. Induction generator. Gearbox. Fixed speed. Alu-blades.	Non-operational by 1988 according to CEC. Ultimately scrapped.	[13,17,20,22,83]

(continued on next page)

Table 1 (continued)

Name	Producer / affiliations	No	Location	Year of construction	Dimensions	Rated power	Specific power	Description	Status	Ref
ÉOLE	CNRC / Hydro-Quebec / Lavalin Inc. / Shawinigan Inc.	1	Cap-Chat, QC, Canada	1987	H_{Rotor} : 96 m. H_{Rotor} : 110 m. A: 4000 m ² . D: 64 m.	3.8 MW @ 22 m/s	950 W/m ²	Two-bladed. Synchronous generator (electromagnet). Variable speed. Direct-drive. Steel-core blades.	Intact but non-operational since 1993.	[17,26,44,45]
Alpha Real 160-kW VAWT	CREM / Alpha Real AG	1	Martigny, Switzerland	1987	H_{Rotor} : 28.4 m. D: 19.2 m. A: 320 m ² .	160 kW	500 W/m ²	Two-bladed. Induction generator. Gearbox. Two-speed. Coupled to a 131-kW motor.	Still standing (2017) but non-operational since mid-1990s.	[47,48]
Sandia 34-m 'test bed'	Sandia / DOE	1	Bushland, TX, US	1988	D: 34 m. H_{Rotor} : 50 m. A: 955 m ² .	500 kW (peak 625 kW) @ 12.5 m/s	524 W/m ²	Two-bladed. Synchronous generator. Variable speed. Gearbox. Alu-blades.	Decommissioned in 1998.	[12,13,17,84]
AES 125	Adecon / Aeolus	1	The Atlantic wind test site, Prince Edward Island, Canada	1984	D: 17 m. H_{Rotor} : 43 m. H_{Rotor} : 26 m. A: 283 m ² .	125 kW	442 W/m ²	Two-bladed. Induction generator. Gearbox. External lattice framework. Alu-blades.	Operation halted after accident 1985.	[31,33]
Adecon – 150 kW (a.k.a. SL-38)	CWT Power Inc.	11	Pincher Creek, AB, Canada (10) Near Toronto, ON, Canada (1)	1991 (1) 1995 (10)	D: 19.22 m. H_{Rotor} : 30.5 m. A: 316 m ² .	150 kW (a few de-rated to 100 kW)	475 W/m ²	Four-bladed. Belt drive. Fixed speed. Lattice shaft and lattice mast instead of guy cables. Alu-blades.	Last turbine dismantled in 2006.	[13,17,41]
WindStor 100 kW (a.k.a. DWT 100 kW)	WindStor Power Co. / Dermond Inc. / McKenzie Bay	1	Rouyn-Noranda, Quebec, Canada	2004	D: 17 m. H_{Rotor} : 12 m. A: 150 m ² (est).	100 kW	667 W/m ²	Three-bladed. Cantilevered. Induction generator. Gearbox. Coupled to batteries and diesel generator.	Still standing (2017).	[52,53,85]
WindStor 200 kW		1	Ishpeming, MI, US	2010	H_{Rotor} : 49 m. D: 24 m. A: 378 m ² .	200 kW	529 W/m ²	Three-bladed. Cantilevered. Induction generator.	Still standing (2017). Non-operational since 2010.	[54,55]

started its wind energy program by fabricating wind turbine blades in 1975. In 1977, the range of products was broadened with a VAWT development program [19,20]. Benefiting from a technology transfer agreement with Sandia, ALCOA developed a line of VAWTs under the trade name ALVAWT. In addition, ALCOA won a contract to construct four 100-kW, 17-m turbines, of which ultimately three were built in 1980–1981, partly based on the Sandia 17-m turbine [15,19]. It is worth mentioning that one of ALCOA's 100-kW turbines had over 10,000 h of operation and sustained storms exceeding 54 m/s [17]. Besides the three 100-kW turbines, another three, three-bladed, 25-m turbines (one seen in Fig. 1) that rated either 300 or 500 kW were built in 1980–1981 [21]. The 500-kW version provided ALCOA with the new world record for VAWT size, a record matched by DAF Indal's 6400 model in 1983 and ultimately broken by ÉOLE in 1987.

One of the 500-kW turbines, located in the San Geronio Pass, California (CA), collapsed just before the 1981 California Energy Commission (CEC) Conference in adjacent Palm Springs. A late control system response during a brief power outage resulted in the rotor over-speeding, destroying the disc brakes when finally activated, and having the blades break loose from the lower attachment to the torque tube. During one revolution, the blades then cut the guy cables before flying off about 300 m, and the turbine fell to the ground.² Naturally, the planned demonstration had to be cancelled, but, boldly, a video of the incident was instead shown during the conference with a standing ovation from the audience.² This turbine failure, together with an earlier collapse of a smaller turbine in Pittsburgh were strong contributors to ALCOA's cancellation of its VAWT program and recall of its installed prototypes (although some turbine owners decided to keep theirs).

2.3. VAWTPOWER

Paul Vosburgh, a key person behind ALCOA's VAWT program, moved on to start the Albuquerque-based VAWTPOWER Inc. (originally Forecast Industries Inc.), and from ALCOA and Sandia technology, they developed the 185-kW (later a 200-kW version), two-bladed, VAWTPOWER 185, seen in Fig. 1 [13]. Simultaneously, while testing a prototype in Albuquerque, VAWTPOWER installed a total of 40 turbines in the San Geronio Pass between 1983 and 1984 [22]. Reportedly, the turbines performed well, but after some of the investors backed out, VAWTPOWER filed for bankruptcy in 1985.² According to the CEC reporting system, by 1988, none of the turbines were operational [23,24].

In 1995, the VAWTPOWER brand was resurrected as VAWTPower Management, Inc., with the aim to build multi-MW turbines [22,25]. In 2004, they did build a three-bladed, cantilevered prototype, designed for 100 kW. However, the prototype had to be down rated to 60 kW (and eventually to 20 kW) after a crane incident during installation damaged the blades.² The turbine is still spinning, filling the function of a tourist attraction at its location at Clines Corners, NM.²

With around 8 MW of installed capacity, VAWTPOWER is only beaten by FloWind regarding both installed capacity and number of turbines over 100 kW. Regarding his experience from the ALCOA and VAWTPOWER projects, Paul Vosburgh² stresses the need to keep the design focused and under the control of a single competent leader, rather than a committee, as was the case for many large VAWT projects, and he quotes Henry Ford: "If you have to ask who is in charge, nobody is." In 1983, Vosburgh [20] described the ongoing attempts at the time to commercialize wind power (both HAWTs and VAWTs) in North America.

2.4. FloWind

The FloWind Corp. also utilized Sandia's technology to build a product line of Darrieus turbines which was installed in commercial wind farms in California in the 1980s [12,13,20,26]. FloWind's concept had a two-bladed rotor coupled to a ground-based gearbox feeding an induction generator. After building a prototype in Ellensburg, Washington in 1982, commercial installations in California started in 1983 with FloWind's 17-m model which was followed by the 19-m model in 1984. Both turbines used two aluminum blades (see Fig. 1). The models were rated 170 kW and 300 kW respectively, although they never achieved their rated capacity.³ FloWind attributed this to the lower air density at the 1200-m (4000 ft) site in the Tehachapi Pass, about 100 km north of Los Angeles.³ A solution that was beneficial for the aerodynamic performance of the 17-m model was the use of cable struts to stabilize the rotor at high wind speeds. However, these were abandoned for the subsequent 19-m model, where conventional struts (support arms) were used to restrain the blades under operational conditions. In 1986, a 25-m prototype, based on the 19-m model was erected, although it was soon taken down³ and never put into commercial production [13].

Up to this point, all FloWind turbines used aluminum blades, which were designed to flex. This led to fatigue induced failures due to the aluminum's poor ability to withstand cyclic stress. In 1986, a FloWind-19 had a catastrophic failure that threw a blade into an adjacent measurement trailer, destroying the DOE/Sandia computer inside. After this incident, the 19-m model became difficult to sell.⁴ Additionally, the early FloWind projects suffered from a combination of over estimating the wind resource, inflating the turbine's power curve and underestimating wake losses, which led to the underperformance of the turbines and the corresponding projects. FloWind subsequently lost the confidence of the investment community.⁴ This and several other factors led the company to bankruptcy. In the early 1990s, after reorganization, FloWind introduced a three-bladed model using fiberglass blades instead of aluminum. The company hoped that this rotor could be retrofitted to the drive trains on the 19-m turbines [12]. Three blades were thought to reduce the torque ripple on the drive shaft. This 17-m turbine had a greater height compared to the earlier models and thus it was called the extended height to diameter (EHD) turbine. Two EHD prototypes were installed in the Tehachapi Pass, one of which soon had a catastrophic failure during high winds. Together with an unsuccessful endeavor with a two-bladed downwind HAWT, this led to the sale of FloWind, and its VAWT development ended.³

In addition to the problems with the aluminum blades, FloWind's turbines had other problems, for example with the quality of the gearboxes [27]. Besides the Tehachapi Pass, FloWind turbines were also installed in the Altamont Pass east of the San Francisco Bay. Due to the cool and thus high-density marine air coming in from the ocean, this location features an uncommon negative wind shear that, in theory should be beneficial for the close-to-ground Darrieus turbine. It is however unclear to what extent this actually affected the relatively short FloWind turbines, as the local shear is still positive very close to the ground.⁴ Unprecedented in the history of VAWTs, the > 500 FloWind turbines (> 95 MW) did all together generate close to 1 TWh of electricity during their decade of operation [13]. By 2004, all were out of operation, and the last FloWind turbines were dismantled around 2010 when their Altamont Pass site was repowered with Vestas HAWTs.

³ Ed Taylor, construction manager and later VP of operations at FloWind; personal correspondence: 2017 November 5.

⁴ Tom Hiester, director of business development and responsible for meteorology at FloWind 1981–1985; personal correspondence: 2017 October 31.

² Paul Vosburgh; personal correspondence: 2017 October 31.

2.5. DAF Indal

The Canadian aluminum manufacturer Dominion Aluminum Fabricators (DAF) Indal, later known as Indal Technologies Inc., became CNRC's main collaborator. Starting in the mid-1970s, they developed and manufactured commercial Darrieus turbines [13,20,28]. In collaboration with CNRC and Quebec's provincial electric utility (Hydro-Québec), DAF Indal installed a 230-kW prototype in 1977 on Magdalen Island (*Iles-de-la-Madeleine*) in the Gulf of Saint Lawrence. The turbine was mounted on top of a truss tower and used flaps at the midpoint of each blade as air brakes. (Air brakes were a key feature of DAF Indal turbines. However, they were abandoned on the later 6400 model). The turbine failed in 1978 when technicians left the rotor decoupled from the drivetrain overnight. Despite VAWTs being considered not self-starting, the rotor went into overspeed, reaching 75 rpm (twice the normal rotational speed). Eventually a guy cable failed and the rotor corkscrewed itself to the ground [13,29]. This incident proved that, under certain circumstances, VAWTs can indeed self-start. The turbine was rebuilt and put back in service in 1980 [21]. When built, the 230-kW Magdalen Island turbine was the largest VAWT in the world, taking the record from the 17-m Sandia turbine built the year before and keeping it until the first ALCOA 500-kW turbine was installed in 1980.

Between 1983 and 1984, DAF Indal built two prototypes of the three planned of their 500-kW 6400 model (rotor swept $6400\text{-ft}^2 = 595\text{ m}^2$). The turbine used two 261-kW induction generators coupled to a single-stage transmission [30]. One of the prototypes was installed in California's San Geronio Pass where it collapsed before commencing operation when a forged twin shackle failed during the first guy-tensioning test. This accident took the life of a DAF Indal technician who was on top of the turbine when it fell.⁵ The other prototype was installed at the Atlantic wind test site on Prince Edward Island. The Atlantic wind test site was established by the Institute of Man and Resources and was Canada's main wind energy testing facility. The Prince Edward Island prototype suffered a blade failure in 1985, causing the turbine to fall to the ground. This unit was later repaired and ran for a few more years [13,31]. Finally, DAF Indal halted its VAWT program in 1991.⁵

Additionally, DAF Indal installed several smaller 50-kW turbines at various locations, primarily in North America but also in Australia [28]. Perhaps most impressively, one 50-kW DAF Indal turbine on Vancouver Island had generated 600 MWh by 1997 and had been in service for 35,000 h during 16 years of operation [13].

According to Malcolm Lodge,⁵ the Institute of Man and Resources wind program manager from 1981 to 1990, the Indal technology was simple and showed promise during the introduction of the 500-kW-scale model. However, the turbines had some technical issues; for example, they experienced blade fatigue at either the strut or root connection, which was typical for Darrieus-turbines of the period. Additionally, torque ripple resulted in power quality issues. The voltage ripple during operation of the Indal-6400 at the Atlantic wind test site was 10%. It was concluded that, because of the rotor torque response to system impedance, such problems would not be dampened within a multi-machine wind farm and thus were difficult to solve with the power electronics used at the time. Further, the need for the relatively flat land required for guy cables was an obvious disadvantage of the Darrieus concept.

2.6. Adecon

Adecon, another Canadian effort, involved Peter South, one of the re-inventors of the Darrieus concept at CNRC. In the early 1980s, Adecon started developing an external lattice framework to replace the

guy cables on a Darrieus rotor. The lattice framework could enable positioning the rotor higher above ground level than earlier designs. Adecon tested a two-bladed, 125-kW turbine with the rotor base raised 17 m as early as 1984. This turbine can be seen in Fig. 2. It only operated for a few hours before going into overspeed and destroying itself.⁵ In theory, the concept of the lattice framework had other advantages over conventional designs than the high rotor position. It was lightweight and required less land than Darrieus turbines using guy cables. However, development was halted after the company abandoned multi-turbine projects in both California and Greece [31–33].

In the late 1980s, CWT Power Inc. took control and changed the design's direction. They developed a rotor with more of an ellipse than in the previous version, stood the rotor on the ground, and used four aluminum blades rather than two [13,17,34]. They abandoned the lattice framework but did use a lattice tower instead of a conventional torque tube and used lattice masts instead of guy cables. After a prototype built in 1991, they installed ten 150-kW turbines (seen in Fig. 2) that went operational in 1995, at a test site near Pincher Creek, Alberta, Canada [34–36]. Although in some respects clever, the lattice 'tripod' induced resonances, which were the primary cause of component failure. It also significantly increased the turbine's visual impact. The lattice work could also be expected to cause additional incoming turbulence [37,38]. Two out of the ten turbines toppled due to metallurgical failures [39] with some of the other turbines operating up to 1998. The last test was made in 2002 and the last turbines were dismantled in 2006 [40,41].

The Adecon project was sold several times. One of the owners, Sustainable Energy Technologies Ltd, tried without success to utilize the then still-standing Pincher Creek turbines to market a 250-kW version (known as the Chinook 2000 or 250) in India and China as late as the mid-2000s [42,43].

2.7. ÉOLE

All discussions on North American VAWT history eventually culminate at the record-breaking Darrieus turbine ÉOLE (French for Aeolus, the ruler of wind in Greek mythology) that can be seen in Fig. 2 [17,26,44,45]. ÉOLE was inaugurated in 1987 in Cap-Chat, situated on the south shore of the Saint Lawrence river in Quebec. With a total height of 110 m, rotating mass of 880 metric tons and a rated power of 3.8 MW, ÉOLE was by far the largest VAWT ever constructed. It was initiated by CNRC and Hydro-Québec with the Montreal-based engineering firm Lavalin Inc. responsible for the technical design. In addition, the total cost of 37.5 million C\$⁶ was an enormous investment at the time in new wind power technology.

Unlike the gearbox-equipped Sandia and FloWind turbines, ÉOLE had a directly driven synchronous generator based at ground level. Furthermore, it was coupled with a DC to AC inverter, enabling variable-speed operation of the two-bladed rotor [17]. Unlike the blades on other Darrieus designs at the time, ÉOLE blades used a steel core. During the initial start-up and commissioning stage, a management decision was taken to operate the unit at constant speed (12 rpm instead of the designed upper limit of 14.25 rpm). This reduced the rated electrical power output to about 2.5 MW [44]. However, the turbine did achieve 3.4 MW in 1988 [17,46]. After 18,550 h of operation and around 12 GWh of electricity generation, ÉOLE was shut down in 1993 due to failure of the bottom bearing which, although possible, was deemed uneconomical to repair [44]. Nevertheless, the turbine has not been dismantled and continues to serve as a popular tourist attraction with guided tours during the summer.

The director at Lavalin Inc., Saeed Quraeshi,⁶ was responsible of the technical design for ÉOLE, and states that ÉOLE, which operated for nearly five year in continuous service, was one of the world's largest,

⁵ Malcolm Lodge; personal correspondence: 2017 October 14.

⁶ Saeed Quraeshi; personal correspondence: 2018 January 30.

longest running, most reliable MW-scale wind turbines at the time, considering both VAWTs and HAWTs. According to Quraeshi, who still favors VAWTs over HAWTs, the design limitations of wind turbines became obvious when installed in large numbers during the 1980s. Limitations such as safety in operation, lightning strikes, noise and killed birds/bats spawned the “NIMBY” (Not in My Back Yard) syndrome. He suggests that the future of the wind turbine industry depends on how it adapts to innovations in the designs of wind turbines that specifically address these criteria for public concerns with respect to acceptability, reliability, and affordability. Quraeshi promotes a shrouded version of the H-rotor that is described in his book [44], which also includes a good description of the ÉOLE project.

According to Albert Watts,⁷ the Research Institute of Hydro Quebec research program leader and the main individual responsible for the ÉOLE project and the Magdalen Islands VAWT, the main lessons from ÉOLE are the difficulties of designing large Darrieus turbines without encountering vibration and fatigue problems of the rotor and guy cables due to cyclic aerodynamic forces. In addition, composite materials are a better choice than steel for such large blades due to both mass and damping issues. Watts argues that the abundance of cheap oil and hydroelectricity in Canada, in particular the dominance of hydropower in Quebec, was the principal reason that Canadian VAWT efforts, including ÉOLE, were halted.

2.8. Other Darrieus turbines

Using the DOE plans (see “2.1 Sandia National Laboratories”) as the design base, the California-based company Appropriate Power Inc. installed a wind farm of four 150-kW Darrieus turbines (preceded by one non-functioning prototype) in 1982, near Soledad in the Salinas Valley, CA. As a commercial attempt to generate electricity, the project was not a success, although it probably filled a function as a tax shelter. Failing gearboxes resulted in only one of the turbines operating for a year or two before the entire farm was non-operational.⁸

The vast majority of all large Darrieus turbines have been erected on North American soil. One exception is a 160-kW turbine that was erected in 1987 in Martigny, Switzerland, which was initiated by *Centre de Recherches Énergétiques et Municipales* (CREM) and designed by Alpha Real AG [47,48]. This dual-speed turbine was coupled to a biogas motor to test off-grid application and was functional for several years until the mid-1990s. At its best, the turbine reached about half of its projected annual electricity generation. The lower-than-expected generation was primarily due to multiple failures with struts and the disc brake [47].

Another European exception is the Dutch Darrieus prototype *Pionier I*. Although rated slightly below 100 kW, this turbine is also deserving of inclusion, not the least because it was probably the first floating-platform wind turbine ever built [49–51]. This two-bladed, cantilevered, variable-speed Darrieus turbine was installed by Polymarin B.V. in a lake in Amsterdam in 1982. The 15-m diameter rotor drove a 94-kW, DC-generator coupled to a two-stage gearbox and a DC to AC converter. In addition, different from most others 1980s-Darrieus turbines, it used fiberglass-reinforced plastic blades. The turbine operated continuously for nine years with occasional interruptions for maintenance and repairs before being decommissioned in 1992.

The Michigan-based, McKenzie Bay subsidiary, WindStor Power Co. attempted to commercialize a cantilevered, three-bladed rotor. They installed a 100-kW turbine at *Université du Québec en Abitibi-Témiscamingue* (UQAT) in 2004. This unit was sold at an auction a few years later due to unpaid debts from its installation [52,53]. In 2010, a 200-kW turbine was installed close to a housing estate in Ishpeming, Michigan. As of 2014, the Ishpeming turbine had not been in operation

since its initial tests after installation [54,55].

3. H-rotors

Partially overlapping with the North American Darrieus development, VAWTs were also investigated in Europe, but most focus was put on the H-rotor concept with a number of erected turbines of significant size. The H-rotor has some advantages compared to the conventional Darrieus turbine. It is usually placed on a higher tower, which gives better energy yield and enables keeping the rotor above the lower surface-layer turbulence, thus avoiding the fatigue load associated with it. Additionally, the straight blades (which give a larger, square-shaped, swept area) are simpler and cheaper to manufacture, and since guy cables are not needed, the land use is smaller. There are of course drawbacks as well; the bending moments on the blades are larger and the necessity of struts makes aerodynamic and noise optimization more complex [12,17]. Moreover, unlike the Φ -configuration Darrieus, the H-rotor has aerodynamic losses (drag) at the blade attachment points and has tip losses at the free ends of the blade which have a negative effect on the power coefficient [12].

In Sections 3.1–3.4, projects that resulted in H-rotors rating 100 kW or above are described. A summary with technical specifications of the turbines can be found in Table 2).

3.1. Vertical axis wind turbines Ltd

Culminating in the 1980s and early 1990s, the H-rotor was investigated in a British effort led by Peter Musgrove at the University of Reading, which resulted in an attempt by the company VAWT Ltd (a daughter company of Sir Robert McAlpine & Sons Ltd and Northern Engineering Industries plc.) to commercialize the H-rotor [11,56,57]. They used a two-blade rotor coupled to a gearbox and induction generator. Their largest prototypes were the 130-kW, variable-geometry, variable-speed turbine called VAWT-450 (erected in 1986), which could fold the blades to regulate power, and the 500-kW, fixed-blade, stall-regulated, dual-speed VAWT-850 (erected in 1990), both located on Carmarthen Bay in Wales (both in Fig. 4). The 130-kW turbine used a ground-mounted drive train (generator and one stage of the gearbox) [58]. Similar to a HAWT, in the subsequent 500-kW turbine, the drive train was placed at the top of the tower. The variable geometry appeared to be unnecessary, as experimental operation with the blades in the vertical, unfolded position showed that the turbine could be stall controlled [57]. The 500-kW turbine had several failures linked to the power transmission and ultimately a devastating failure of one of the fiberglass blades. Both turbines were dismantled in the early 1990s [57].

Moreover, between the VAWT-450 and VAWT-850, a 100-kW H-rotor called the VAWT-260 was installed on the Isles of Scilly (not to be confused with Sicily, Italy), located offshore from Cornwall, UK [12,59,60]. This variable-geometry turbine was installed in 1987. In 1988, it was modified to have a fixed geometry and most of the performance data on the turbine was collected in this configuration. The ground-mounted drive train drove dual generators: 75 kW and 30 kW. The smaller generator was used for start-up and in low winds. In stronger winds, both generators were engaged [60]. In [60], the aerodynamic power coefficient of this turbine is reported as approximately 0.4. The turbine operated until 1992 [61].

According to Peter Musgrove,⁹ the UK DOE ended the program after it had been concluded that the H-rotor would be more expensive than contemporary HAWTs. A potential for making very large VAWTs more cost efficient than HAWTs was acknowledged, but such sizes were only seen as suitable offshore which the UK DOE did not see as being a future trend at the time. Musgrove believes that medium-sized VAWTs have

⁷ Albert Watts; personal correspondence: 2017 October 3.

⁸ Matt Tritt, partner and wind resource specialist at Appropriate Power Inc.; personal correspondence: 2017 October 25.

⁹ Peter Musgrove; personal correspondence: 2017 September 28.

Table 2
Built VAWT H-rotors ≥ 100 kW.

Name	Producer / affiliations	No	Location	Year of construction	Dimensions	Rated power	Specific power	Description	Status	Ref
VAWT-450	VAWT Ltd / University of Reading	1	Carmarthen Bay, Wales, UK	1986	D: 25 m. H_{HUB} : 25 m. I_{BLADE} : 18 m. A: 450 m ² .	130 kW @ 11 m/s	289 W/m ²	Two-bladed. Variable geometry. Double generators (induction & synchronous). Variable speed (with synch. gen.). Gearbox. Concrete tower. Steel blades.	Demolished in the early 1990s.	[11,12,56,57,59–61]
VAWT-260		1	Isles of Scilly, UK	1987–88	D: 19.5 m. H_{HUB} : 19.5 m. I_{BLADE} : 13.3 m. A: 260 m ² .	100 kW (peak 105 kW)	384 W/m ²	Two-bladed. Double induction generators. Gearbox. Fixed speed. Fiberglass blades. Tripod tower.	Operated until 1992.	
VAWT-850		1	Carmarthen Bay, Wales, UK	1990	D: 35 m. H_{HUB} : 30 m. I_{BLADE} : 24.3 m. A: 850 m ² .	500 kW @ 18 m/s	588 W/m ²	Two-bladed. Induction generator. Dual speed. Gearbox. Drivetrain on top. Concrete tower. Fiberglass blades. Steel crossarm.	Operated until 1991. Demolished in the early 1990s.	
HM300	Heidelberg GmbH	1	Kaiser-Wilhelm-Koog, Germany	1991	H_{HUB} : 50 m. D: 32 m. I_{BLADE} : 21 m. A: 672 m ² .	300 kW	446 W/m ²	Two-bladed. Direct-driven PM generator. Drivetrain on ground. Steel tower and struts. Guy cables.	Demounted in 1994 and in 1996 relocated to Münster. For sale (2016).	[6,86]
H-rotor 300		5		1994	H_{HUB} : 50 m. D: 34 m. I_{BLADE} : 23 m. A: 782 m ² .	300 kW	384 W/m ²	Two-bladed. Direct-driven PM generator. Drivetrain on top. Fiberglass blades. Steel tower and struts.	Dismantled in 1997.	[6,62,63]
T1-turbine	Vertical Wind/Uppsala University	1	Falkenberg, Sweden	2010	D: 26 m. H_{HUB} : 40 m. I_{BLADE} : 24 m. A: 624 m ² .	200 kW @ 12 m/s	321 W/m ²	Three-bladed. Direct-driven PM generator. Variable speed. Drivetrain on ground. Fiberglass blades. Tower of laminate wood. Guy cables.	Operational at limited wind speeds (2018).	[10,64,67,68]
Skwid 500-kW prototype	MODEC/ NEDO	1	Saga prefecture, Japan	2013	D: 24 m. H_{TOR} : 63 m (47 m VAWT & 16 m current). A: 850 m ² (est.)	500 kW @ 13 m/s (peak 900 kW)	588 W/m ²	Three-bladed. Synchronous generator. Gearbox. Variable speed. Floating offshore platform. Coupled to a 60-kW Savonius current turbine.	Sunk in 2014. Salvaged in 2015 but project abandoned.	[69,73,87]
NENUPHAR 600-kW onshore prototype	NENUPHAR (VertiWind)	1	Fos-sur-Mer, France	2014	D: 50 m. H_{TOR} : 40 m. I_{BLADE} : 26 m (30 m for the twisted blades). A: 1300 m ² .	600 kW	462 W/m ²	Two or three-bladed. Direct-driven PM generator. Drivetrain on top. Variable speed. Pitch (only two-bladed set-up). Steel tower. Blades and struts of glass- and carbon fiber.	To be dismantled (2018).	[74]
ANew-M1	ANew Institute / Stalprodukt S.A.	1	Near Krakow, Poland	2015	D: 24 m. H_{TOR} : 29.5 m. A: 360 m ² .	200 kW @ 12 m/s	556 W/m ²	Three-bladed. Direct-driven PM generator. Variable speed. Drivetrain at 1/4-hub height. Steel tower. Blades and struts of glass- and carbon fiber.	Operational (2017).	[79]
ANew-B1		1	Near Krakow, Poland	2017	D: 52 m. H_{TOR} : 66 m. A: 1700 m ² .	1.5 MW @ 13 m/s	882 W/m ²	Three-bladed. Direct-driven PM generator. Variable speed. Drivetrain on ground. Fiberglass blades. Steel lattice tower.	Under testing (2018).	[78]



Fig. 4. Left: The 130-kW variable-geometry VAWT-450 with the blades reefed (the blades were straight at maximum power mode). Photo by Jos Beurskens. All rights reserved. Center: The 500-kW VAWT-850 as featured on the front cover of *Modern Power Systems* in the 1990 October issue. Used with permission from Modern Power Systems. Right: The Heidelberg 300-kW H-rotors in Kaiser-Wilhelm-Koog. Photo by, and used with permission from Jörg Bendfeld.

little chance of generating electricity cheaper than HAWTs. However, he postulates that H-rotors can be made larger than HAWTs and be more cost effective in capacities over 20 MW, although the cost of developing such machines makes this unlikely. For multi-MW designs, Musgrove proposes scaling up the two-bladed, VAWT-850 design, but with pitch control for the lower part of each blade to prevent overspeed from destroying the turbine.

An overall review of the Musgrove project can be found in [11], and an in-depth description of the turbines with more of Peter Musgrove's own reflections can be found in [57].

3.2. Heidelberg GmbH

In the 1990s, German inventor and entrepreneur Götz Heidelberg started developing an H-rotor concept at the Munich-based company Heidelberg Motor GmbH. They developed a variable-speed H-rotor with directly driven permanent magnet (PM) generators [6,17,62,63]. Their first large-scale prototype used a ground-mounted, direct-drive generator. In 1991, this two-bladed, 300-kW turbine was erected at Kaiser-Wilhelm-Koog on the German North Sea coast. The turbine was supported by guy cables attached to a bearing, allowing the entire tower to rotate. It operated at the site until 1993 when it was dismantled and moved to a new site near Münster in North Rhine-Westphalia. It operated there for a number of years, according to the company.¹⁰ Heidelberg later abandoned the ground-mounted generator and the rotating tower concept. In 1994, they installed five of the revised two-bladed, 300-kW turbines in Kaiser-Wilhelm-Koog (seen in Fig. 4). This version used a direct-drive PM generator placed on top of a tripod tower. The turbines operated as expected from July 1994 until January 1995 when a problem with the strut-blade welding seam resulted in one turbine destroying itself. In consultation with the manufacturing certification body, the remaining four turbines were taken out of operation and ultimately dismantled in 1997. Until shutdown, the five turbines had operated 2100 h each.¹⁰ The problems with the 300-kW turbine led to the abandonment of an EU-funded development of a 1.2 MW version of the concept.

According to Felix Heidelberg,¹⁰ the tripod-based 300-kW turbine

was very heavy and never reached the efficiency of contemporary HAWTs, partly due to the aerodynamic drag induced by the struts. The tripod tower was also expensive and had structural issues during installation. He still thinks that the two-bladed, direct-drive, tower top-mounted PM generator concept is a good configuration for an H-rotor. However, he acknowledges that finding niche markets is probably necessary for VAWTs to be competitive today.

Heidelberg GmbH also installed several 20-kW three-bladed H-rotors designed for extreme environments. One was installed at Mt. Karisimbi in Rwanda, another at the Mangfall Mountains in the German Alps, and a third at the German Neumayer-Station II research facility in Antarctica. The latter was in operation for more than 15 years before it was decommissioned along with the station in 2008.

3.3. Vertical wind 200-kW prototype

Uppsala University has worked with the H-rotor configuration since the early 2000s [10]. Researchers at the university developed a direct-drive, variable-speed multi-pole synchronous PM generator [10], which they used on a number of small three-blade experimental turbines. The concept was upscaled by Vertical Wind AB, a spinoff from the university's VAWT research, which installed a 200-kW prototype in 2010 that is still operational (see Fig. 5). The turbine is located near Falkenberg on Sweden's west coast. The turbine's blades have a fixed pitch, but the variable speed of operation allows control of the rotor through the stall effect. The aerodynamic power coefficient has been measured to 0.33 [64], and the noise characteristics of the turbine have also been studied [65,66]. As there were problems with the attachment of the wooden tower to the foundation, guy cables were added after two years. These guy cables altered the eigenfrequencies of the rotor and tower, limiting the turbine's operational range. Within this limited range, the turbine operated in automatic mode for nearly a full year from 2011 to 2012. Afterwards, the turbine has been used infrequently for continued experimentation, but as of 2018, it is once again operating in automatic mode at limited wind speeds.

Vertical Wind AB discontinued turbine development when they lost a key investor in 2010 and the 200-kW prototype was soon after sold to Uppsala University. However, Vertical Wind remains active in building generators for other wind turbine manufacturers.

A good review of the 200-kW experimental turbine as well as the university's other work on VAWTs can be found in [10]. Good

¹⁰ Felix Heidelberg, project manager and head of sales at Heidelberg GmbH; personal correspondence: 2017 October 22.



Fig. 5. Left: The 200-kW Vertical Wind H-rotor in Falkenberg. Photo by Erik Möllerström. Center: The 600-kW NENUPHAR onshore prototype. Used with permission from NENUPHAR. Right: The 1.5-MW Anew-B1 turbine during installation in October 2017. Used with permission from the Anew Institute.

descriptions of the 200-kW turbine can also be found in [67,68].

3.4. Other H-rotors

During the 2010s, MODEC, a Japanese offshore company specializing in floating platforms for the oil and gas industry, developed a floating wind and current hybrid power-generation system called Skwid (for Savonius Keel and Wind Turbine Darrieus). The concept consisted of an H-rotor above the surface and a Savonius turbine harvesting the currents beneath [69]. The Savonius rotor would act as a ballast, making the platform self-righting. Their large 500-kW, 24-m prototype was troubled. First, in October 2013, the Savonius part of the prototype fell off and sank when it was towed to its planned test site off the coast of Kabe Island, Saga prefecture in south Japan [70]. Then, when being re-commissioned in December 2014, the entire platform sank during anchoring [71]. The prototype was salvaged in May 2015 but MODEC has since abandoned the project [72,73].

The French company NENUPHAR made another attempt to commercialize a floating VAWT concept to capitalize on VAWTs low center of gravity to develop a multi-MW, two-turbine floating offshore platform [74]. No large, floating VAWT was ever deployed, but NENUPHAR installed a 600-kW onshore prototype in Fos-sur-Mer on the French Mediterranean coast in 2014 [75,76]. The direct-drive, variable-speed, PM generator was located at hub height for the prototype, although the drivetrain was planned to be placed at deck level for the offshore turbines. The prototype had a 50-m diameter rotor on a rather short tower to test different blade designs. Three different configurations was tested: two fixed-pitch, three-blade versions (one with twisted blades and one with straight blades), and one variable pitch, two-bladed version. After evaluating the test results, the company decided to use three vertically-mounted straight blades with individual pitch control for offshore turbines. The pitchable blades will increase power and reduce loads and can be feathered during storms.¹¹ In 2018, NENUPHAR entered liquidation after abandoned by an industrial partner [77].

Polish steel manufacturer Stalprodukt S.A. has started developing H-rotors under the subsidiary Anew Institute [78,79]. They have built a handful of turbines ranging from 15 kW, most prominently a 200-kW turbine built in 2015, and a 1.5-MW turbine (see Fig. 5) built in 2017 that as of May 2018 is undergoing testing.¹² The 1.5-MW turbine is

second only to ÉOLE (see Section “2.7 ÉOLE”) regarding both power and swept area for a VAWT. For their larger turbines, they have a simple three-bladed concept with a single strut per blade and a steel-lattice tower. The design uses a ground-mounted, direct-drive, PM generator that is manufactured by Vertical Wind AB. They have several pre-orders for the model but are awaiting preliminary results from the first production unit before further commercialization.¹²

4. Discussion and conclusions

As illustrated in Fig. 6, most significant-size VAWT projects took place in North America in the 1980s. However, a renewed interest in the H-rotor concept can be seen in Europe during the 2010s. This is partly due to the interest in offshore floating-platform applications, which combines well with the low center of gravity of the VAWT concept.

It is evident from Tables 1 and 2 that most VAWTs have had high specific power, for some models as high as 1000-W/m² swept rotor area. A modern HAWT typically has a specific power level of between 200 and 500-W/m², depending on the wind regime that the turbine is designed for and the required equivalent annual full load hours. The high specific power for early VAWTs can be explained by the fact that power rather than rotor area was used as a selling point, and since the drivetrain is often ground based, oversizing did not have a large effect on structural aspects. From the point of view of energy output and capacity factor optimization, such a high specific power level does not make sense.

It is clear from the different projects that fatigue issues have been a recurrent problem. This can be understood from the fact that the direction of the aerodynamic forces on the blade, during each revolution constantly change. The material will then experience cyclic stresses with high amplitudes as well as large cycle counts during the lifetime [12]. Additionally, at low tip speed ratio operation (which is normally required at high wind speeds for fixed-pitch VAWTs), dynamic stall will be present, which makes the variation of the aerodynamic forces even more rough. The HAWT design also experiences cyclic stress, but not to the same extent; in steady winds with low turbulence, the aerodynamic force (which is the dominant force) becomes relatively constant. Additionally, at the positions where the bending moments within the blade are large, the cross-section area is also large, which reduces

¹¹ Frederic Silvert, CTO NENUPHAR; personal correspondence: 2017 October 3.

¹² Anew Institute sales office; personal correspondence: 2017 September 30.

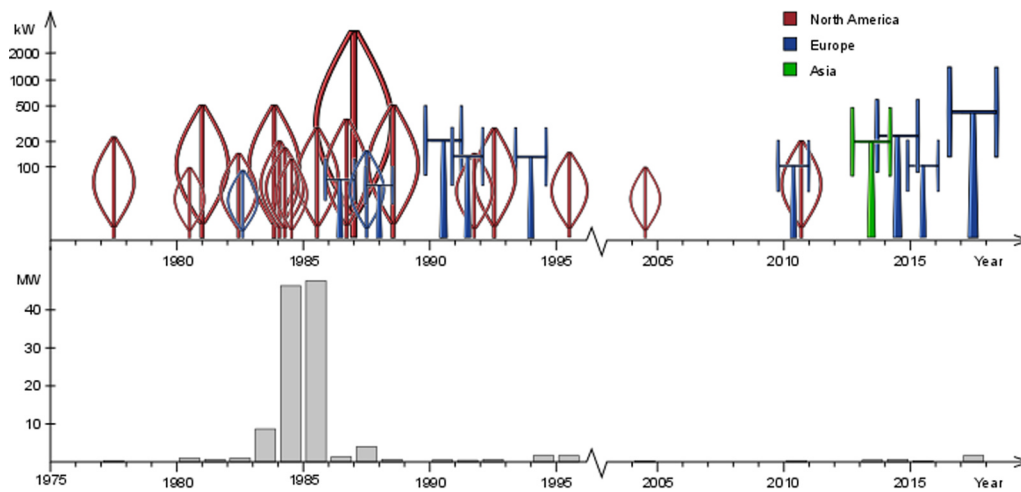


Fig. 6. Timeline of ≥ 100 -kW VAWTs. Upper: VAWT models, including both unique experimental/prototype turbines and models produced in larger numbers. Note the logarithmic kW values on the axis. Lower: Installed capacity including all ≥ 100 -kW VAWTs built in a single year. Most > 100 -kW VAWTs were built during the 1980s. However, during the 2010s, there has been a revival for the H-rotor concept with several large prototypes built. It is also evident that the Φ -configuration Darrieus concept has been the choice of favor in North America while H-rotors have been more common in Europe. For more information about specific turbines, see Tables 1 and 2.

material stress. Modern wind turbines are able to pitch the blades individually to further reduce variable loads from gusts [88]. On the other hand, most of the fatigue issues for VAWTs have been observed for designs with extruded aluminum blades, in which case it is hard to add material close to the critical points where bending moments are high. Sutherland et al. [12] argued that a properly designed fiberglass blade for the Darrieus turbine could be perfectly viable with respect to fatigue.

Although it is difficult to point out the main reasons the VAWT concept has failed to gain commercial success, frequent suggestions are (1) early fatigue and durability problems, (2) a lack of long-term interest from governmental and private funders, and (3) the fact that cost-effective and reliable European manufactured HAWTs were made available on the market. For the Φ -configuration turbines, the typical choice of blade material was aluminum, which features poor fatigue characteristics that poorly cope with dynamic loading. This made fatigue failures common. For both Φ -configuration Darrieus and H-rotors, many turbines were two-bladed which meant it had to cope with cyclic torque, which probably added to increased dynamic structural loading and reduced fatigue lifetime.

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