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MARKET POTENTIAL OF UNCONVENTIONAL WIND TURBINES.

A TECHNOLOGY REVIEW

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Abstract: *The paper presents an in-depth analysis regarding the market potential of unconventional wind turbines from a technological perspective. The envisaged solutions were identified in literature and are currently in different development stages. The aim of the analysis is to estimate which types of wind turbines are suitable for further development and have the potential to replace someday the traditional vertical axis wind turbines with three blades that currently represent the best solution for onshore and offshore wind farms. The development of wind power conversion solutions is a current topic due to low carbon energy policies and presents several challenges. Essentially, it needs to be cost competitive compared with fossil fuels technologies and other renewable energy sources, especially photovoltaic (PV) power plants that recently gained ground due to a continuous reduction of manufacturing costs. Both the PV and wind turbines must have a complementary approach for a good energy mix. The technology of the wind turbines of today is continuously improved in order to increase their competitiveness on the market. Further developments are expected both for large capacity wind turbines and for low power concepts while the reliability over time will determine the best solution that will be adopted and maintained for years to come. Not all the solutions can have future development potential, but some results and approaches can be applied in the industry having a positive impact in terms of production cost and energy conversion efficiency.*

Keywords*: Wind power, emerging technology, counter rotating turbines, future development*

1. Introduction

The continuous development of wind power conversion systems has a significant impact on their use on large scale. Due to stringent measures, policies and regulations regarding the use of fossil fuels across the world, clean and renewable energy sources must be better harnessed. The purpose of this paper is to gather, organise and analyse wind turbine solutions currently in use or future emerging technologies in order to point out the advantages and disadvantages of each system and determine the current trend in research of wind power energy conversion. A large number of the solutions identified originate from academic work within universities and research institutes. Some of the technologies identified are being developed by university spinoffs or start-up companies [1]. The wind energy industry has gone through intensive technological advancement in terms of aerodynamic design, mechanical systems, electric generators, power electronic converters, integration to power systems and control theory.

From the electrical engineering perspective, the electric generators and power electronic converters are two major components in the operation of wind energy conversion systems (WECS). Since the beginning of grid-connected operation in 1980s, various combinations of electric generators and power electronic converters have been developed in commercial wind turbines to achieve fixed-speed, semi-variable-speed and full-variable-speed operation [2],[3].

The most common type of wind turbine used worldwide is the three-bladed upwind horizontal-axis wind turbine (HAWT), where the turbine rotor is placed in front of the nacelle, facing the wind upstream of its supporting tower. Another popular technology type is the vertical-axis wind turbine (VAWT), with blades extending upwards in a vertical position, strengthen by a frame consisting of two circular plates. Besides these two established solutions, many wind turbine designs are available in different stages of technological readiness level (TRL). The variety of designs reflects ongoing commercial, technological, and inventive interests in harvesting wind resources more efficiently.

Due to the fact that the Betz law cannot be exceeded, certain designs have been developed to maximize the energy conversion efficiency by raising the power coefficient as much as possible. In this category, we mention the diffuser-augmented wind turbine (DAWT) with a cone-shaped wind diffuser and counter rotating wind turbines, described in a separate chapter of the paper. Some unconventional designs have entered commercial use, while others have only been demonstrated through experimental models or by numerical simulations. Unconventional designs cover a wide range of innovations, including different rotor types, electric generators, blade types, rotational speed and movement principle.

2. Unconventional wind turbines

2.1. Airborne wind energy

Airborne wind energy (AWE) defines all the concepts that convert wind energy into electricity with the common feature of autonomous kites or unmanned aircraft, linked to the ground by one or more cables [4]. AWE systems offer several potential advantages over conventional wind turbines. They require less material than tower based turbines, have the potential to be manufactured at lower cost, can be deployed faster and can harness stronger and steadier winds by flying at higher altitudes. Several concepts presented in Fig.1 are currently being pursued and convergence towards the best architecture has not yet been achieved [1].

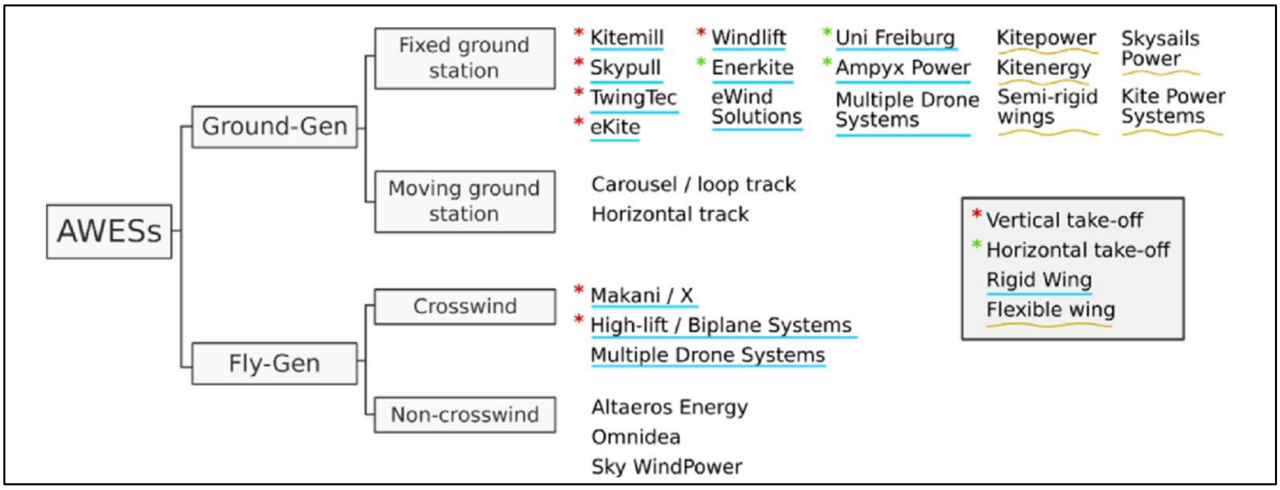

Fig. 1. Classification of AWE systems [1]

According to the above classification, the ground-gen concepts are based on the conversion of mechanical energy into electrical energy at ground level, while fly-gen concepts are based on the conversion in the air, on board the airborne unit. Most ground-gen concepts drive a drum-generator module in pumping cycles, alternating between traction and retraction phases to generate electricity. Fly-gen concepts use on board wind turbines with continuous electrical energy output and a conducting tether to deliver this energy at ground level. Of the fly-gen solutions, crosswind systems can generally produce more power (1-2 orders of magnitude higher) than non-crosswind systems [5]. The main advantages claimed by these concepts are low capital costs, due to the small amount of material used, a relatively simple construction, installation and a higher capacity factor, due to stronger and more consistent high-altitude winds prevalent above 200m altitude.

A potential reduction in weight could reduce the capital expenditure (CAPEX) of platforms and subsea structures; also the reduced size of the devices allows for rapid installation at a lower cost [1]. Important technical challenges of AWE systems are [6]:

- High complexity of the control system since the operation of AWE depends on a fast-feedback control algorithm based on the information gathered by sensors that must ensure precise actions that allows fully autonomous flight, reducing the crash risks.
- Early stage of development. The existing technology demonstrators still rely on supervised operation, especially in the take-off and landing phases. Certain technologies currently developed, can achieve up to 24 h of autonomous flight.

- Limited knowledge. For this type of systems is difficult to predict the economic potential and environmental benefits of AWE based only on the results obtained during supervised flight. For the moment, it is not certain that after full development, the technology will provide the promised energy conversion performance. Therefore, the impact and feasibility of scaling up such systems has not been rigorously assessed so far. The Makani kite system is presented in Fig. 2a. Makani is developing energy kites that use a wing tethered to a ground station to efficiently harness energy from the wind, generating electricity at utility-scale. As the kite flies autonomously in loops, rotors on the wing spin as the wind moves through them, generating electricity that is sent down the tether to the grid. In Fig. 2b, the Kite Power Systems (KPS) technology is presented. While the Makani system is based on an aircraft with rotors for generating electricity, the KPS system uses kites that tension a 100-200m line to be spooled out from a drum on the ground, which is connected to a generator – thus creating electricity. The working principle is based on strong aerodynamic lifting forces which are produced by the wing of the kite, and exerted against its cable.

Fig. 2a. Makani energy kite [7]

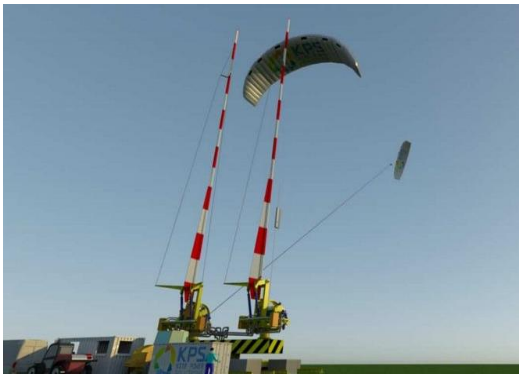

Fig. 2b. Kite Power Systems (KPS)

There is a need for more research on wind potential at high altitudes and how the wind energy can be transformed using on flight sustainable energy systems. The concept is still in its early development stage and there are still several technical problems to address such as: the durability of materials, the complexity of the management system (take off, landing, in flight operation). Another aspect to take into consideration is the space restrictions (a restricted zone is necessary given the altitudes in which these devices would operate), regulation, social acceptance, safety and the risks due to lightning strikes and storms. Broken cables could send the aircraft on a randomly trajectory with the possibility of crashing in inhabited areas. Additional research and improvement is needed to perfect this concept until the commercial version becomes available.

2.2. Multi-rotor wind turbines

Such type of turbines implies the use of more than one rotor in a single and compact assembly. Thus, to improve efficiency and reduce overall loads on a wind turbine, it is possible to replace a large single rotor with a multiple-rotor system (MRS), as shown in Fig. 3. This solution allows a large power system (20MW or more) to be installed on a single pole by using few standardised rotors. Scaling up is seen as a key factor in overall cost reduction for this design. Possible advantage of the MRS is to avoid structural and material problems associated with the scaling up to a large device. In some cases, there is the possibility of yawing without the requirement for a dedicated mechanism. Overall design optimisation is interactive with aerodynamic, electrical, loading considerations and other factors. The main disadvantage for this design is represented by the higher cost because it involves the use of more components. Although the size for each turbine is reduced, the total price could be higher compared to a single turbine. The main advantage of this solution is the fact that there is already a commercial demonstrator of this technology as mentioned below in Fig.3 and there is potential for industrial funding of research to bring this technology to maturity, supported by public funding to tackle some of the more fundamental challenges associated with aero elastic design and control [1].

Fig. 3. Vestas multi-rotor wind turbine

Fig. 4. Turbine with tip rotors [1]

Another interesting approach for multiple rotor turbines is the wind turbine with tip rotors. This conceptual technology consists of wind turbines where the traditional gearbox and generator is substituted by a fast-rotating rotor/generator mounted on the tip of each blade (see Fig. 4). While conventional turbines extract power at a direct wind speed of around 10 m/s by conversion of torque, the tip-rotor converts power at around 70 m/s, being placed at the tip where the tangential speed is higher. The concept can be designed for both two- or three-bladed turbines [8]. The concept is more suitable to very large wind turbines, since larger turbines have fewer challenges related to the centrifugal forces on the rotors. This technology may be more appropriate for the offshore environment, given the additional noise and visual impact compared with conventional single rotor turbines. Regarding the degree of development of this technology, no prototype has yet been constructed or tested. The TRL of such a concept is thus 1–2 with a possible scalability of the same order of magnitude as for a conventional 10 MW offshore turbine. A slow TRL trend is anticipated since investors are reluctant to fund the technology due to its radical and high-risk nature. This form of technology is clearly at a very fundamental level of development with only very basic concepts elaborated. There is the need for detailed concept studies in order to assess the challenges and potential for this system before any industrially-led developments can be expected [1].

The counter rotating turbines are also a dual rotor type of wind turbine. Such systems are most promising, due to sufficient data available regarding their operation, energy conversion efficiency and reliability. This design and the research carried so far, will be detailed in a separate chapter.

2.3. Diffuser augmented wind turbines

A diffuser-augmented wind turbine (DAWT) is a wind turbine with an added cone-shaped wind diffuser used to increase the efficiency of converting wind power to electrical power.

The increased efficiency is possible due to the increased wind speeds that the diffuser can provide. In traditional bare turbines, the rotor blades are vertically mounted at the top of a support tower or shaft. In a DAWT, the rotor blades are mounted within the diffuser, which is then placed on the top of the support tower. Additional modifications can be made to the diffuser in order to further increase efficiency though the structure of the diffusers remains a challenge.

DAWT devices are at a semi-commercial level of development in Japan, with power ratings of the order of tens of kW. The most advanced projects have been developed by Kyushu University, who have studied several configurations, from single DAWT to multi rotor systems [9]. In addition, tests on floating platforms were performed in Hakata bay.

Multi-rotor DAWTs appear to display convincing performance with the typical challenges of MRS, enhanced by complex interactions with the diffusers.

Fig. 5. Different types of DAWT wind turbines

Another interesting solution is the INVELOX technology. The turbine works like a wind injection system. A large intake captures wind and funnels it to a concentrator that ends in a Venturi section and finally wind exits from a diffuser. The turbine is placed inside the Venturi section of the INVELOX. Inside the Venturi the dynamic pressure is high while the static pressure is low. The Turbine converts dynamic pressure or kinetic energy to mechanical rotation and thereby to electrical power using a generator [10]. Although this technology is not likely to be significantly cheaper than the non-ducted technology, it could be suitable for a niche-market. The TRL is around 5–6, with a scaling up target of 1 MW. The TRL evolution is expected to be average [1]. This type of technology will be more suitable for smaller scale applications and it is not expected that there will be major industrial investment in associated research in the near future.

2.4. Magnus effect turbine

One type of wind turbines that can harvest wind energy at lower wind speed is the horizontal-axis Magnus Wind turbines (MWT) [11]. The main difference is the replacement of airfoil-shaped blades with rotating cylinder blades, thus harvesting wind energy at low wind speed condition. Additionally, the performance of MWT can be increased by enhancing the surface of the rotating cylinder blades. There are several innovations for increasing the performance of MWT rotating cylinder blades such as using different shapes for dimple and fins to ensure the rotation. Figure 6 shows the MWT with spiral fins coiled around the rotating cylinder blades that has been developed in Japan.

Fig. 6. Magnus wind turbine with fin-like on rotating cylinder blades [11]

2.5. Vertical axis wind turbines

Darrieus's patent from 1927 covers practically any possible arrangement using vertical airfoils. One of the more common types is the H-rotor (fig. 7), also called the Giromill or H-bar design, in which the long curved blades of the common Darrieus design are replaced with straight vertical or twisted blade sections attached to the central tower with horizontal supports.

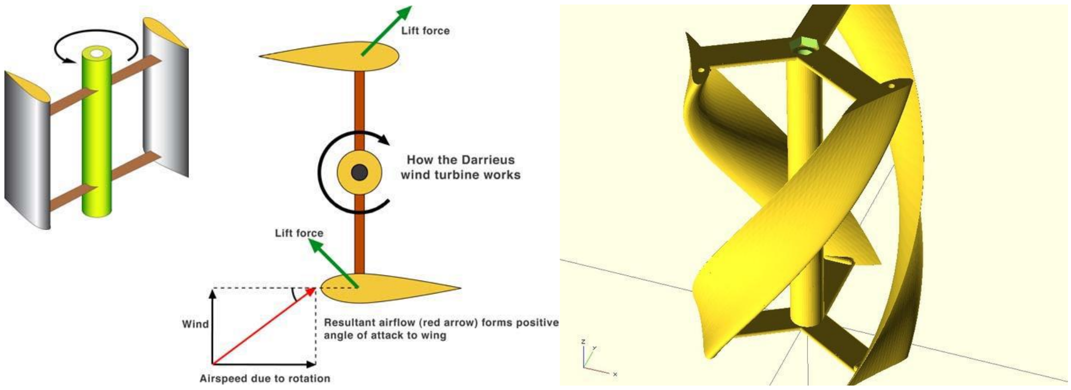

Fig.7. Darrieus vertical axis turbines variations [12]

Another variation of the Giromill is the Cycloturbine, in which each blade is mounted so that it can rotate around its own vertical axis. This allows the blades to be "pitched" so that they always have some angle of attack relative to the wind. The main advantage of this design is that the generated torque remains almost constant over a wide angle, so a Cycloturbine with three or four blades has a fairly constant torque. Over this range of angles, the torque itself is near the maximum possible, meaning that the system also generates more power. The Cycloturbine also has the advantage of being able to self-start, by pitching the "downwind moving" blade flat to the wind to generate drag and start the turbine spinning at a low speed. On the downside, the blade pitching mechanism is complex and generally heavy and some sort of wind-direction sensor needs to be added in order to pitch the blades according to the wind direction.

These types of wind-turbines are suitable for building roofs. Examples include Marthalen Landi-Silo in Switzerland, Council House 2 in Melbourne, Australia. Ridgeblade in the UK is a vertical wind turbine on its side mounted on the apex of a pitched roof. Another example installed in France is the Aeolta AeroCube. Discovery Tower is an office building in Houston, Texas, that incorporates 10 wind turbines. Rooftop wind turbines may suffer from turbulence, especially in cities, which reduces power output and accelerates turbine wear. Due to structural limitations of buildings, limited space in urban areas, and safety considerations, building turbines are usually small (with capacities in the low kilowatts). This technology can be used as an alternative for low power energy system and has many challenges when scaling up for large wind farms. The main disadvantage is the low starting torque. This can be improved using J-shaped straight-blades or incorporate a Savonius rotor to provide a quick start even at low wind speeds.

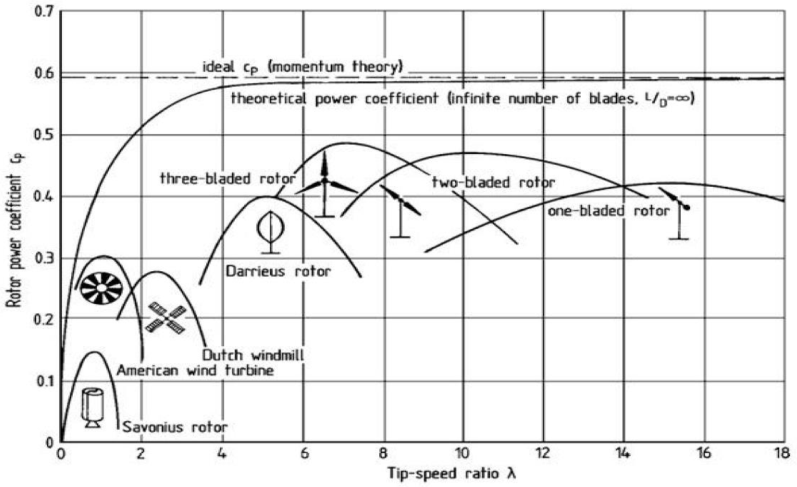

Fig. 8. Power coefficient for a wide range of wind turbines

Although over the years some improvements were made to increase the efficiency of vertical wind turbines, their power coefficient is still reduced compared to classical 3 blade horizontal axis, as shown in figure 8.

2.6. Bladeless wind turbines

Air flow-induced vibrations of mechanical systems can be exploited to extract energy, when specifically designed to experience large-amplitude oscillations. The mechanical system has to be combined to work with suitable energy-conversion apparatus, such as electromagnetic or piezoelectric transducers. This type of technology will not be used for large-scale generation, but for applications where a small amount of autonomous power is required, e.g. wireless sensors or structural health monitoring. These energy harvesting devices have possible applications in urban settings and for energy harvesting at small and micro-scales [1]. Flutter-based devices involve a rigid, streamlined model (a simple flat plate or aerofoil) of finite length, which is elastically suspended to oscillate along two degrees of freedom: heaving (cross-flow translation) and pitching (rotation). The energy extraction is activated in the heaving motion component, being less sensitive to a damping increment. Linear generators, typically solenoids, are used (see Fig. 9). Depending on the application, different governing parameters can be selected. The design configuration can be adapted to specific operating ranges of flow speed. [13], [14].

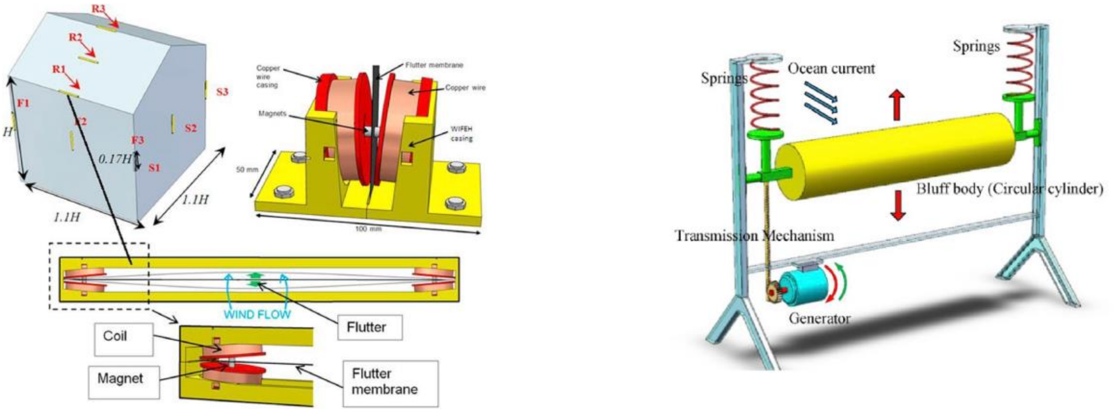

Fig. 9. Devices exploiting the induced vibration [13], [14]

Another new concept is the Saphonian turbine which implements a patented system called “Zero-Blade Technology” in order to harness the wind’s energy. This is said to involve channelling the wind then produce hydraulic pressure, which can be instantly converted to electricity via a hydraulic motor and a generator, or stored in a hydraulic accumulator (fig.10).

Fig. 10. Saphonian turbine

The Saphonian, invented by Anis Aouini, promises to offer an efficient, reliable and eco-friendly way to harness wind and generate Green Energy. The creators stated that Saphon Energy is in process of building its 1st industrial design Saphonian machine in partnership with Microsoft Corporation.

3. Analysis of the performance and development stage of counter rotating turbines

Counter-rotating wind turbines (CRWT) represent a system of two rotors which rotate in opposite directions. For horizontal axis wind turbines, the rotors are placed at a certain distance, either both in the front of the generator, or one in front and one in the rear of the generator. The performances of the counter-rotating wind turbines have been intensively approached recently. Some research is focused on numerical investigations of counter-rotating wind turbines, while others approach the study of CRWT both numerically and experimentally [15]. The investigated systems enclose different generators' concepts: one generator for each wind rotor [16], one electric generator coupled to the rotors using a differential planetary system [17] or a single permanent magnets generator, with mechanical coupling of the wind rotors [18]. Beside the other two solutions, the last one presents some advantages such as: decreasing the overall size of the electric generator, increasing the rotational speed, eliminating the mechanical power losses induced by the use of a gearbox.

Promising results were obtained by the research team of ICPE-CA [15] when testing a CRWT experimental model in a wind tunnel. The experimental model of 1 kW rated power shown in fig. 11 consists of:

- Up-wind rotor (Diameter D = 2.66 [m]): chord at the hub level cr0 = 0.1 [m]; chord at the blade's tip level cR = 0.1 [m]; the blade's torsion angle 0 [°] (the blade has no torsion);NACA 6409.
- Down-wind rotor, (Diameter D = 2.46 [m]): chord at the hub level cr0 = 0.15 [m]; chord at the blade's tip level cR = 0.044 [m]; the blade's torsion angle Δβ = 15 [°];EPPLER 664
- Electric generator with counter rotating armatures.

Fig. 11. Experimental model of the counter rotating wind turbine [15]

Fig.12. Prototype of the CRWT

The obtained results were centralized in table 1, as a comparative power output of the counter-rotating wind turbine vs. single rotor wind turbine. It can be seen that the contribution of the second rotor is significant compared to a single rotor turbine.

Table 1: Comparative power output of the counter-rotating wind turbine vs. single rotor wind turbine

Wind velocity [m/s]	*5,5*	*6,3*	*6,88*	*7,74*	*8,7*	*10*
P_{max} - Single rotor (up-wind rotor) [W]	98,12	148	192	275	388,84	591,13
P_{max} - Counter rotating turbine [W]	179,1	245	305	461,8	614,9	939,3

Detailed studies on the model revealed that the low power coefficient (Cp) of the first rotor (around 0,2) allows a better output for the second rotor. The experimental model was also tested in situ [19] in order to validate de experimental data. The results are presented in Fig.13.

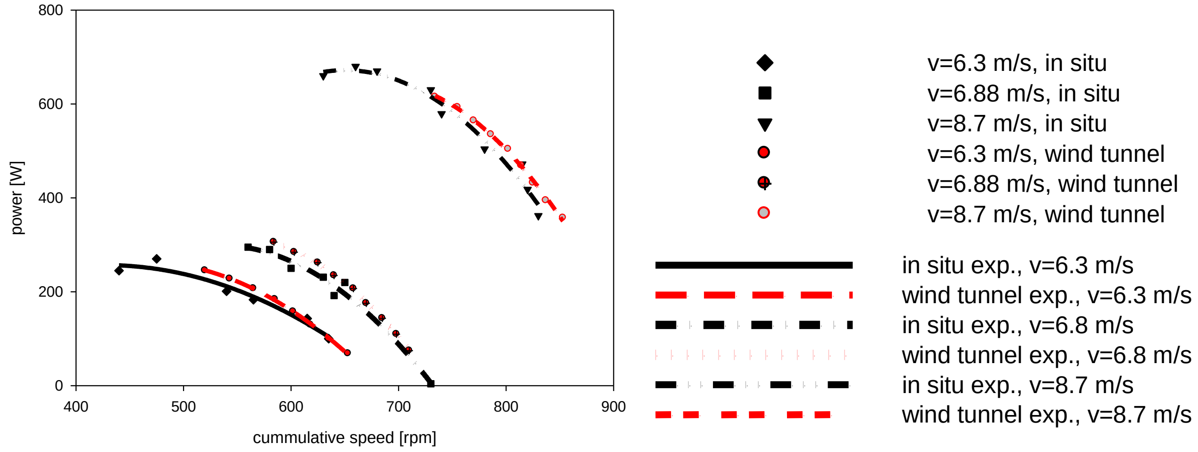

Fig. 13. Power curves at constant wind velocity – comparison between wind tunnel and in situ [19]

Analyzing the plots shown in Fig.13, it can be noticed that there is a good consistency between the two series of curves. Generally, the power characteristic obtained as a result of in situ testing is slightly lower than the one obtained in the wind tunnel. This might be explained by the numerous sudden changes in winds' velocity and direction. Encouraged by the results obtained on the experimental model, the research team from ICPE-CA developed a 10 KW prototype of the counter rotating wind turbine presented in fig.12. Currently, functional tests are being performed and specific parameters are registered for a good characterization of the wind turbine and for further analysis.

4. Conclusions

The wind turbines of today have constant developments in technology in order to increase their competitiveness on the market. Further developments are expected both for large capacity wind turbines and for low power concepts and the reliability over time will determine the best solution to be adopted and maintained for years to come.

From the multitude of the solution analysed in this paper, the counter rotating turbine is within reach and has the potential for developing to large scale installations since it can use the technology already validated in the case of classical three-bladed horizontal axis turbines. However, additional studies and testing are required to establish the technical reliability and also a cost/efficiency analysis is needed to attract investments for this type of wind turbines. Beside the presented solutions, many other wind energy conversion devices can be found in different development stages (simulation, experimental models, patents). Not all the solutions can have future development potential but some results and approaches can be applied in the industry having a positive impact in terms of production cost and energy conversion efficiency.

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