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Comparison between Lift and Drag-Driven VAWT Concepts on Low-Wind Site AEO

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***Abstract*—This work presents a comparison between the Annual Energy Output (AEO) of two commercial vertical-axis wind turbines (VAWTs) for a low-wind urban site: both a drag-driven and a lift-driven concepts are examined in order to be installed on top of the new Via dei Giustinelli building, Trieste (Italy). The power-curves, taken from the product specification sheets, have been matched to the wind characteristics of the selected installation site. The influence of rotor swept area and rated power on the performance of the two proposed wind turbines have been examined in detail, achieving a correlation between rotor swept area, electrical generator size and wind distribution, to be used as a guideline for the calculation of the AEO.

***Keywords*—Annual Energy Output, micro-generation technology, urban environment, Vertical-Axis Wind Turbine

I. INTRODUCTION AND BACKGROUND

THE urgent need to reduce dependence on fossil fuels is being met, at least in part, by the development of wind turbines: the awareness of the limited resources of fossil fuels and the rising concern for the effects of the increased amount of greenhouse gases in the atmosphere have given the wind turbine industry a push forward. In late 1997, the Commission of the European Union published its White Paper [1] calling for 12% of gross energy demand of the European Union to be contributed from renewables by 2010. As pointed out by Campbell et al. [2], while rapid development of huge on- and off-shore wind farms proceeds at high rate, examples of integration in the urban environment – closer to prime consumers of energy such as buildings, remain scarce. Nevertheless, small scale wind turbines installed within the built environment may soon become a commercial reality in Italy, as a result of both advancements in technology and new financial incentives provided by the government.

Small scale wind energy conversion systems installed within the built environment is classified as micro-generation technology: as observed by Bahaj et al. [3], such turbines have the potential to reduce built environment related CO_2 emissions coupled with reductions in consumers' electricity costs. Moreover, the produced energy can be fed directly into the grid of the building, determining a reduction of its external energy demand. Some of the specific technology and design issues in the use of wind energy in buildings have been described by several authors:

- Mertens [4] focused on the design of buildings that maximize wind harvest and examined a set of turbines that provide power for buildings;
- Stankovic et al. [5] focused on the potential for exploiting wind power in urban areas, identifying three main categories of project, that is small wind and retrofitting, large-scale stand-alone turbines and building-integrated turbines;
- Van Bussel and Mertens [6] provided a literary review of the technical potential of small wind turbines on buildings, considering small VAWT, whose typical dimensions are around 10 to 20% of the characteristic building height, as a good solution. The Savonius rotor was not considered well suited for urban installations, due to a fairly low power coefficient. Also standard Darrieus wind turbine was rejected, due to its too high noise level, while the modification of the Darrieus concept - obtained by reducing the design angular velocity and by applying blade sweep in order to minimize noise production - was considered the best solution for application on existing buildings;
- Heat et al. [7] by considering the urban landscape to be an array of cubes, described a method for calculating the surface roughness length and displacement height of the urban boundary layer wind profile. The wind flow around a simple pitched-roof building was also simulated using Computational Fluid Dynamics (CFD), adopting a semi-logarithmic inflow profile. An array of similar pitched-roof houses was then modeled using CFD, in order to determine the flow characteristics within an urban area. Mean wind speeds at potential turbine mounting points were studied, and optimum mounting points were identified for different prevailing wind directions. A methodology was finally proposed for estimating the energy yield of a building-mounted turbine from simple information, such as wind atlas wind speed and building density;
- Raciti Castelli et al. [8] presented the results of two-dimensional CFD simulations of the flow field around a vertical-axis wind turbine rotor, with emphasis on noise generation and propagation, for application in the built environment. The effect of the central shaft on overall rotor noise emission was analyzed using the Ffowcs-

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Williams and Hawkings acoustic model, in order to gain a first estimation of the influence of the central shaft on VAWTs sound emission;

- Mertens [9] described concentrator effects for wind turbine close to buildings in order to compensate the lower average wind speeds and higher turbulence levels of the built environment.

Although - in a near future - buildings and wind turbines will probably start to be designed as an integrated system, by now, one very real possibility to achieve commercial success is to simply place the wind turbines on the roof of buildings, profiting of the hill effect locally generated. Vertical Axis Wind Turbines (VAWT) seem to be more appropriate than the more commonly used Horizontal Axis Wind Turbines (HAWT), since these kind of machines do not suffer from the frequent wind direction changes and also thanks to structural and esthetical reasons, but especially because VAWT seem to have improved power output in turbulent flows, which are typical of built environments. The work presented in this paper focuses on the Annual Energy Output (AEO) of such installations for the city of Trieste (Italy) and presents a methodology to assess the suitability and the economic viability of micro-wind turbines for domestic dwellings.

II. THE CASE STUDY

The presented work is part of a research project finalized to the installation of a wind energy conversion system on top of the new Via dei Giustinelli building, Trieste (Italy). Fig. 1 shows a rendering of the building and the position of the potential turbine mounting point.

Fig. 1 Rendering of the new Via dei Giustinelli building; the red arrow indicates the potential turbine mounting point.

Fig. 2 shows an aerial view of the building site (evidenced by the red arrow), located in the historical center of Trieste, as well as the position of Piazza Hortis anemometric station (evidenced by the yellow arrow), installed in the proximity (nearly 300 m) of the building.

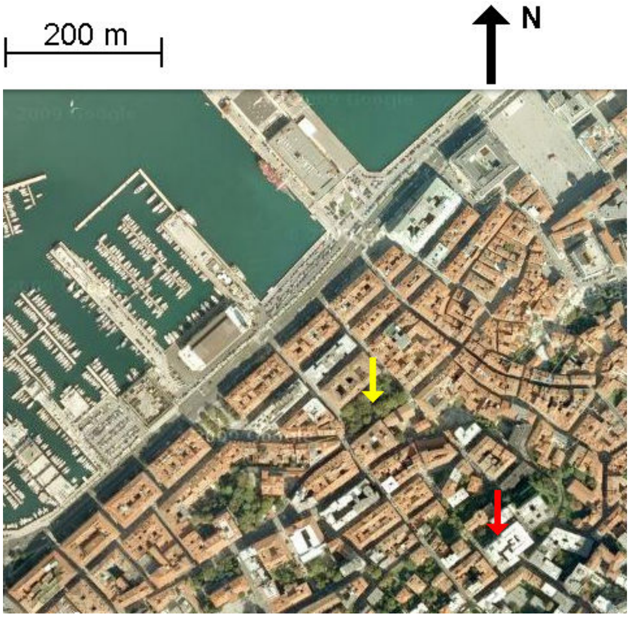

Fig. 2 Aerial view of the building site (evidenced by the red arrow) and of the anemometric station (evidenced by the yellow arrow)

III. WIND DISTRIBUTION

Table I shows the results of a three-year anemometric campaign performed by the Piazza Hortis anemometric station. The average wind velocity and the parameters of the Weibull wind speed distribution are presented.

TABLE I
AVERAGE WIND VELOCITY, SHAPE PARAMETER AND SCALE PARAMETER FOR PIAZZA HORTIS, TRIESTE

Year	v_{ave} [m/s]	k [-]	λ [m/s]
2003	3.2	1.078	3.32
2004	3.2	1.149	3.40
2005	3.2	1.170	3.52

As can be clearly seen, wind potential in the historical center of Trieste is quite poor, being the year-average wind speed of only 3.2 m/s. Fig. 3 shows the wind distribution in Piazza Hortis, obtained from 1 year (2005) anemometric campaign: these data were assumed as representative also for the Via dei Giustinelli site. In order to provide wind potential based on an uniform methodology that will ensure consistency and accuracy, wind data sampling were based on the bin method [10] [11] [12], which is outlined in the IEC 61400-12 standard [13]. In the present case, data were grouped using bins of 1 m/s size.

Partitioning by wind direction was not performed, being the aim of the present research work the simple assessment of wind potential on the building site. Further work should be done in order to consider also the influence of the prevalent wind direction on the flow field around the building.

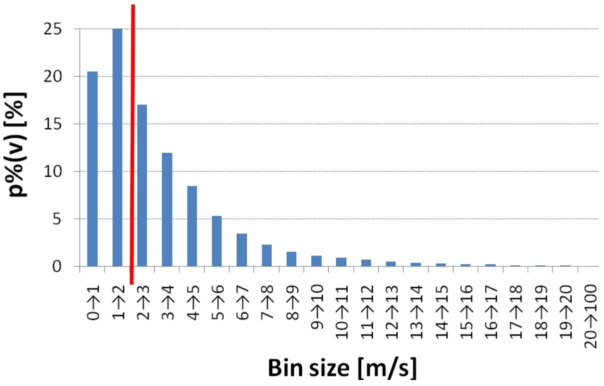

Fig. 3 Wind distribution in Piazza Hortis, obtained from 1 year (2005) anemometric campaign

Fig. 3 offers a visual demonstration of how low and moderate winds are very common inside urban environment, while strong gales are relatively rare. The red line between 2 and 3 meters per second marks the median wind speed: 50% of the time the wind is lower than the median wind speed and 50% of the time it is stronger.

IV. Description of the Candidate VAWT Concepts

The two selected VAWTs and their technical specifications are described in the present section. Differently from more common horizontal-axis architectures, VAWTs have the main rotor shaft arranged vertically. Key advantages of this arrangement are that the turbine does not need to be pointed into the wind to be effective. This is an advantage on sites where the wind direction is highly variable, for example when integrated into buildings. The key disadvantages include the low rotational speed with the consequential higher torque and hence higher cost of the drive train, the inherently lower power coefficient, the 360 degree rotation of the aerofoil within the wind flow during each cycle and hence the highly dynamic loading on the blade, the pulsating torque generated by some rotor designs on the drive train, and the difficulty of modeling the wind flow accurately and hence the challenges of analyzing and designing the rotor prior to constructing a prototype. One of the key performance differences in wind turbine design is determined by the driving mechanism of the rotor. As focused by Gipe [14], drag devices are quite simple wind machines which use flat or cup-shaped blades to turn a rotor around a vertical axis. In these configurations, the wind merely pushes on the blade, forcing it to move downwind and making the rotor spin about its vertical axis. Though researchers constantly propose innovative solutions in order to use drag to power wind turbines, drag propulsion appears to be affected by intrinsic physical limitations, especially if compared to more efficient lift-driven devices. The differences between the two rotor concepts are in fact quite relevant:

- drag-driven wind turbines typically combine a low aerodynamic efficiency with a high blade surface requirement and, consequently, are usually rather expensive to be manufactured when set against their comparatively limited power output;
- lift-driven wind turbines combine a high aerodynamic efficiency, nearly up to the theoretical Betz limit, with a much more favorable blade surface requirement.

While small scale lift-driven VAWTs have already reached a good level of commercial awareness, drag type devices seem to be limited to prototype stage, mainly used for water pumping or some other direct mechanical applications, being considered not suitable for electricity generation, due to a too low value of the tip speed ratio parameter and, consequently, a comparatively lower power coefficient [15]. Nevertheless, as pointed out by Manwell et al. [16], the main argument in favor of drag-driven machines is the relatively low construction cost, which makes them less expensive than comparable lift-driven devices, thus allowing an initial saving in a micro wind project economics. Another advantage of drag-driven machines is their excellent self-starting capabilities, even for very low wind speeds, in contrast to lift-driven devices, which require external assistance to start, thus loosing much of their aerodynamic advantage, especially in sites characterized by variable winds, as suggested by Dominy et al. [17].

Fig. 4 shows a Qr5 wind turbine, manufactured by Quietrevolution Ltd [18].

Fig. 4 Qr5 VAWT (from: [18])

The Qr5 is a lift-driven Darrieus-type VAWT designed specifically for environments close to people and buildings. In fact:

- it is much more appropriate for winds near and around buildings, which are characterized by gusty wind speeds and constantly shifting wind direction;
- it is significantly quieter because of its limited blade tip speed ratio and thanks to blade sweeping, as observed in [6];

Fig. 5 shows a couple of WS-12 wind turbines, manufactured by Windside Production Ltd [19].

Fig. 5 Couple of WS-12 VAWT at the shopping center "Mylly", Raisio, Finland (from: [19]).

The WS-12 is a custom made unit for specific applications. It is a drag-driven VAWT and can be considered as an evolution of the Savonius-type turbine. Its energy performance is based on the turbines ability to take advantage of low wind speeds. Moreover, the WS-12 doesn't need to be stopped during storms like propeller type turbines.

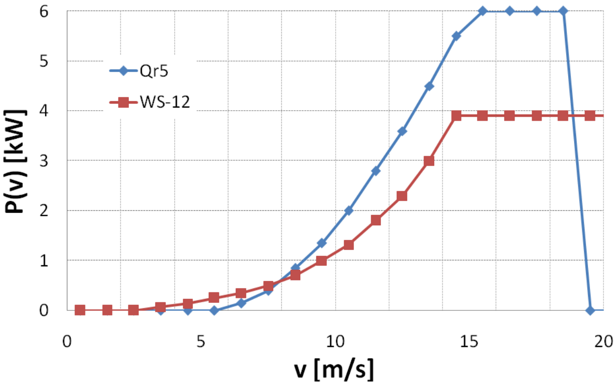

Fig. 6 Comparison between the two selected VAWT power curves (from: [20] and [21]).

V. CANDIDATE VAWT TECHNICAL SPECIFICATIONS AND AEO CALCULATION

The power in "free-flowig" wind (i.e. not locally accelerated) is given by the well-known kinetic power term, in formulas:

$$E_c' = \frac{1}{2} m' v^2 \quad (1)$$

As reported by Stankovic et al. [5], for convenience the wind turbine power equation is expressed in terms of swept area. Therefore, the mass flow rate is replaced with the term:

$$m' = \rho A v \quad (2)$$

and the wind turbine power output as a function of wind velocity (known as power-curve) can thus be written as:

$$P = C_p \, \frac{1}{2} \rho A v^3 \quad (3)$$

Fig. 6 shows a comparison between the two selected VAWT power-curves, while their main technical specifications are summarized in Table 2.

TABLE II
MAIN TECHNICAL SPECIFICATION OF QR5 AND WS-12 VAWTS (FROM [20], [21], [22] AND [23])

	Qr5	WS-12
H [m]	5	6
D [m]	3.1 (max)	2
A [m^2]	13.6	12
P_{nom} [kW]	6	3.9
P_{nom}/A [kW/m^2]	0.44	0.33
$v_{cut\ off}$ [m/s]	19	none
Blade material	Carbon fiber	Aluminum

As can be clearly seen from Table 2, the ratio P_{nom}/A reflects the higher efficiency of the lift-driven concept with respect to the drag-driven one, being this parameter 33% higher for the Qr5 turbine with respect to WS-12.

In order to determining the annual energy production as a function of the wind speed for the two candidate turbines, the wind distribution probability for each bin element (from Fig. 3) was first multiplied for the number of hours during a year-time (8760) and finally for the corresponding wind turbine power output (from Fig. 6), in formulas:

$$E(v) = p\%(v) \cdot 8760 \cdot P(v) \quad (4)$$

Fig. 7 represents the annual energy production as a function of the wind speed for the two examined VAWTs. The area under the curves represents the global AOP of the turbines during a year-time.

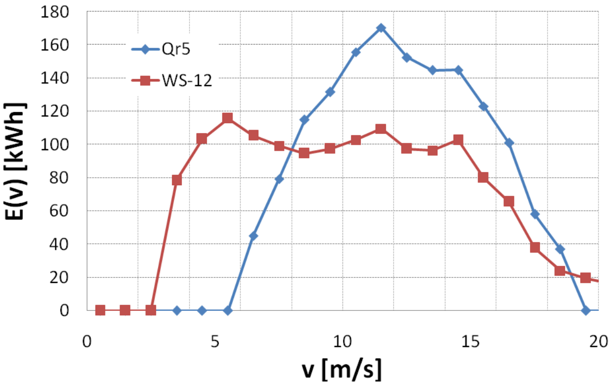

Fig. 7 Annual energy production for the two analyzed wind turbines as a function of the wind speed

It can be clearly seen that, as suggested by Dominy et al. [17], the drag-driven concept performs better for low winds (up to 8 m/s), thanks also to its high self-starting capabilities, while the lift-driven turbine produces most of the annual energy thanks to high winds and its higher rated power. The total amount of energy production is quite similar for both turbines, as can be seen from Table 3.

TABLE III
COMPARISON BETWEEN QR5 AND WS-12 AEO

	Qr5	**WS-12**
AEO [kWh]	1458	1446

VI. CONCLUSIONS AND FUTURE WORK

A comparison between the AEO of two commercial VAWTs - with similar swept area - for a low-wind urban site was presented. The two candidate wind turbines were chosen as representative of both the drag-driven and the lift-driven concepts: the lift-driven turbine was characterized by a higher performance, due to its finest aerodynamics, while the drag-driven machine presented the advantage of self-starting capabilities and higher power output at low-wind speeds.

The total amount of annual energy production resulted quite similar for both turbines, the drag-driven concept performing better for low winds (up to 8 m/s), while the lift-driven turbine produced most of the annual energy thanks to high winds and its higher rated power.

Further work should be done, in order to take into account the following aspects:

- the proposed analysis was based on anemometric measurements made at a different site (even if relatively close). A full anemometric campaign should be performed on the building site, in order to assess local wind potential;
- the proposed analysis was based on measurements made at a lower height (2-3 m) with respect to the top of the building and without considering the interaction of the turbine with the structure and the surrounding environment. A CFD analysis should be performed in order to estimate the wind speed augmentation due to the building. This aspect could alter the conclusions of the present work, favoring the lift-driven turbine AEO, due to the increased wind potential on top of the construction.

NOMENCLATURE

A [m^2]	rotor swept area
AEO [kWh]	global annual energy output of the wind turbine during a year-time
C_p [-]	wind turbine power coefficient
E(v) [kWh]	annual energy production as a function of the wind speed
E_c' [kW]	flux of kinetic energy in a free-flowing wind
k [-]	Weibull distribution's shape parameter
m' [kg/s]	mass flow rate of the air passing through the swept area of the turbine
p%(v) [%]	wind velocity probability during a year-time
P(v) [kW]	wind turbine power output at a given wind velocity
v [m/s]	free wind velocity
v_{ave} [m/s]	average wind velocity
λ [m/s]	Weibull distribution's scale parameter
ρ [kg/m^3]	air density

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