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Evaluation of Wind Potential for the Lagoon of Venice (Italy) and Estimation of the Annual Energy Output for two Candidate Horizontal-Axis Low-Wind Turbines

M. Raciti Castelli, L. M. Moglia and E. Benini

***Abstract* —** This paper presents an evaluation of the wind potential in the area of the Lagoon of Venice (Italy). A full anemometric campaign of 2 year measurements, performed by the "Osservatorio Bioclimatologico dell'Ospedale al Mare di Venezia" has been analyzed to obtain the Weibull wind speed distribution and the main wind directions. The annual energy outputs of two candidate horizontal-axis wind turbines (“Aventa AV-7 LoWind” and “Gaia Wind 133-11kW”) have been estimated on the basis of the computed Weibull wind distribution, registering a better performance of the former turbine, due to a higher ratio between rotor swept area and rated power of the electric generator, determining a lower cut-in wind speed.

***Keywords* —** Wind potential, Annual Energy Output (AEO), Weibull distribution, Horizontal-Axis Wind Turbine (HAWT).

I. INTRODUCTION AND BACKGROUND

THE development of Asian and African economies, the rapid increase of world population, the crescent demand for energy and the quick depleting of fossil fuels have determined the urgent need to develop new technologies in order to reduce the dependency from conventional energy resources. The Italian wind sector has grown significantly over the last years and a further increase is expected over the course of the decade, in order to meet European renewable energy commitments and longer-term energy security. In this scenario, the continuous quest for clean energy is now focusing on the local production of electric power, spread in a wide area, so as to cooperate with the big electric power plants positioned in just few specific strategic locations of the countries. One of the most promising resources is wind power associated with local production of clean electric power inside the built environment, such as industrial and residential areas. As observed by the [1], horizontal-axis wind turbines (HAWTs) remain the most popular installed architecture, even though a renewed interest in the vertical-axis concept is also to be registered [2]. Anyway, horizontal-axis design will continue to maintain a majority share of the domestic installation market.

The production of electric energy by means of small wind systems over a year depends critically on the annual average wind speed and on the Weibull wind distribution at the installation site. To assess these data, on-site wind measurements should be taken over a period of time, prior to installation. Several researchers have focused on the estimation of the wind potential inside urban and residential areas: Lo Brano et al. [3] analyzed the numerical procedures adopted to perform a preliminary statistical analysis of wind speed data inside the urban area of Palermo (Italy), in order to determine the best distribution of the flow velocities that represent the real wind potential. Botta et al. [4] tested the feasibility of wind plants and the viability of commercial medium-sized wind turbines in very harsh conditions on the ridge of Central and Southern Appennines (Italy), focusing on the performances and lifetime of the turbines. Balduzzi et al. [5] examined the feasibility of a Darrieus vertical-axis wind energy conversion system (WECS) in a densely populated area, on top of a building, focusing on both the acoustic emissions and the response of the turbine to a turbulent and skewed incoming flow. A specific numerical model was also developed, in order to correlate the effect of the skewed flow with the aerodynamic performance of the rotor. Ouammi et al. [6] estimated the wind potential of Liguria (Italy), by means of an over 6 year monitoring campaign from 25 stations and comparing the results in order to choose the eligible station for energy production. Baggini et al. [7] described a general picture of wind conditions over the Italian territory to estimate the actually exploitable wind energy potential for electricity generation, predicting a possible future scenario for the wind energy market. Mari et al. [8] evaluated the wind potential of Tuscany (Italy) through the development of an integrated Geographic Information System (GIS) to help operators in the choice of the eligible location for large-scale wind turbine.

The historical city of Venice is one of the most known and famous Italian site worldwide, especially for its unique correlation between land and water. The life of the city depends on the preservation of the delicate equilibrium between the ground level and the sea one [9]. The present study analyzes the data collected by a two-year anemometric campaign performed at the "Osservatorio Bioclimatologico dell'Ospedale al Mare di Venezia" [10]. A quite poor wind potential is recorded, being the average wind speed of 2.2 m/s.

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Nevertheless, the aerodynamic performances of two candidate mini low-wind turbines are evaluated on the basis of the collected wind data, in order to determine the best option for electrical energy production, thus investigating the influence of the ratio between rotor swept area and rated power of the electric generator.

II. WIND DISTRIBUTION

Figs. 1 and 2 show both the position of the Venice Lagoon and that of the anemometric station (45°24'00; 12°24'00), located in the isle of "Lido di Venezia" at a height of about 11 m over the ground. The considered wind data were collected for a 2-year period, from January 2000 to December 2001. Measurements were taken using a SIAP VT_1280 anemometer, shown in Fig. 3: Wind speed data were averaged using a one-hour interval.

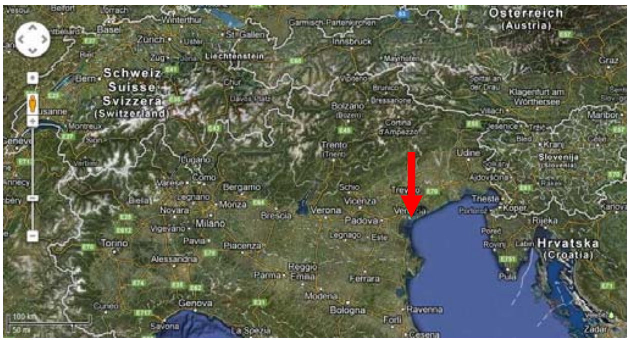

Fig. 1 Location of Venice (evidenced by the red arrow) in the Italian territory

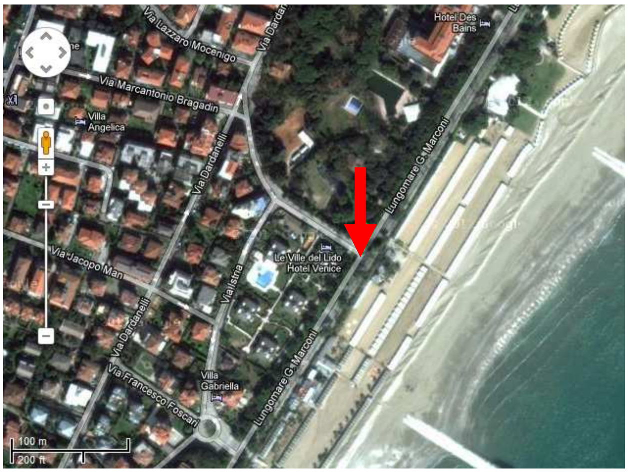

Fig. 2 Aerial view of the position of the measurement station (evidenced by the red arrow) in the isle of "Lido di Venezia"

Being the hub height of the two candidate WECS of 18 m/s, measured data were extrapolated using the power law:

$$v_{18} = v_{11}(z_{18}/z_{11})^{\alpha} \quad (1)$$

A roughness coefficient $\alpha = 0.12$ was considered, due to both the proximity of the measurement site to the sea and the presence of vegetation and isolated constructions.

Fig. 3 View of the anemometric station on top of the "Osservatorio Bioclimatologico dell'Ospedale al Mare di Venezia"

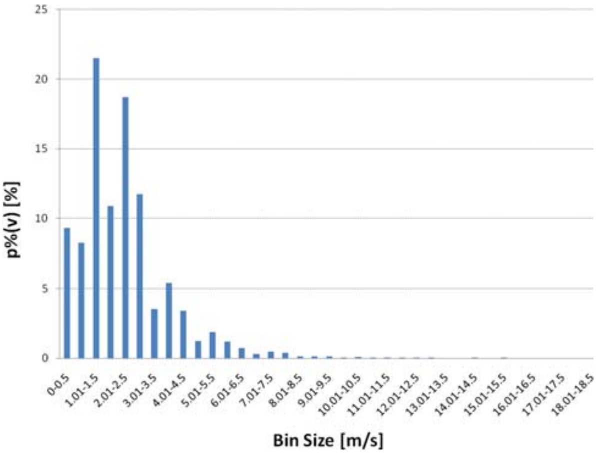

Fig. 4 Weibull wind distribution at 18 m above the ground, from 2-year (2000/2001) anemometric campaign

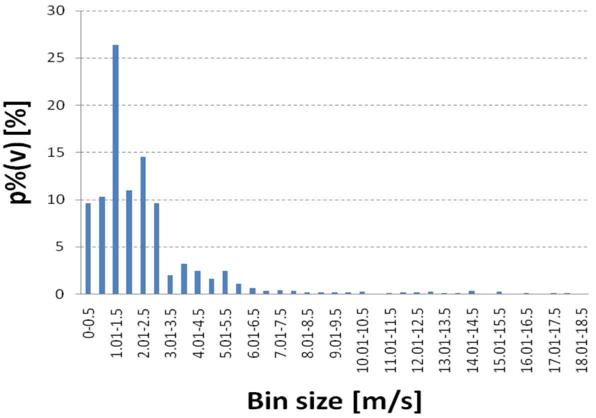

Fig. 5 Weibull wind distribution at 18 m above the ground for the month of January

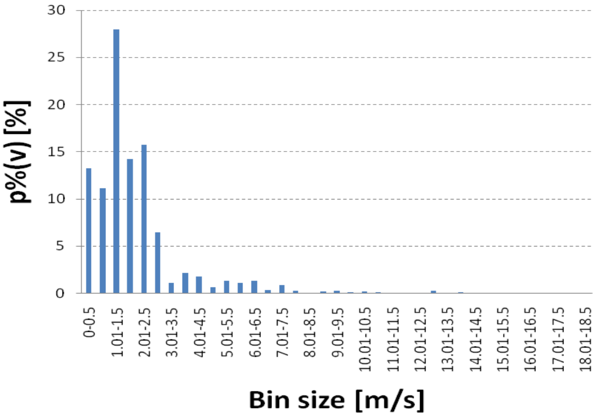

Fig. 6 Weibull wind distribution at 18 m above the ground for the month of February

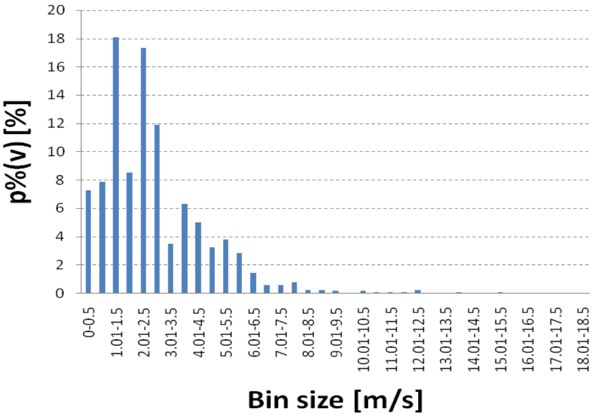

Fig. 7 Weibull wind distribution at 18 m above the ground for the month of March

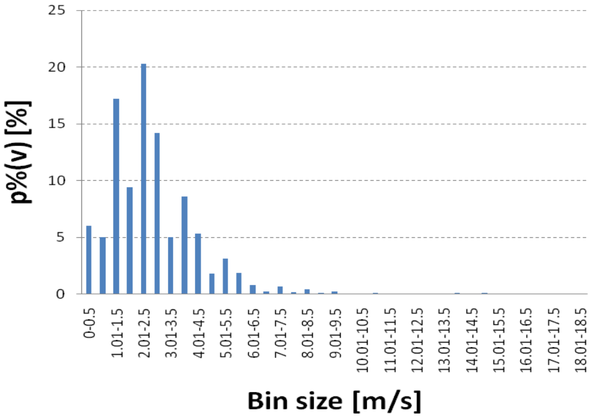

Fig. 8 Weibull wind distribution at 18 m above the ground for the month of April

The Weibull shape is widely adopted to describe wind speed distributions: also in the present work, the great amount of wind data was processed in order to compute the Weibull distribution of the wind velocities during the considered 2 years of measurement campaign. Fig. 4 shows the Weibull distribution of the 1 hour averaged wind speed using bins of 0.5 m size ranging from 0 m/s to 18.5 m/s (maximum wind velocity measured during the whole campaign).

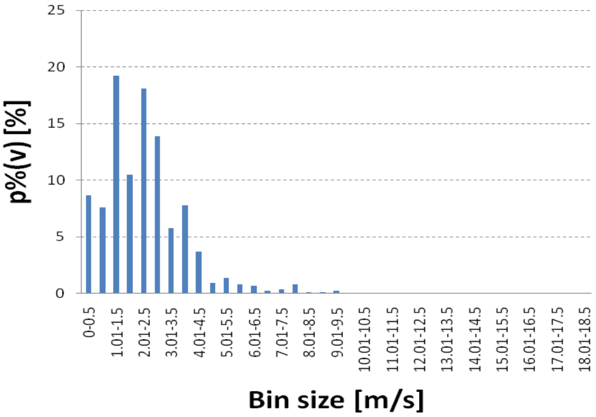

Fig. 9 Weibull wind distribution at 18 m above the ground for the month of May

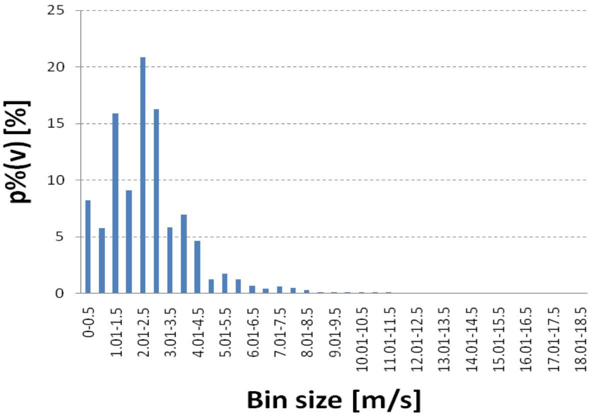

Fig. 10 Weibull wind distribution at 18 m above the ground for the month of June

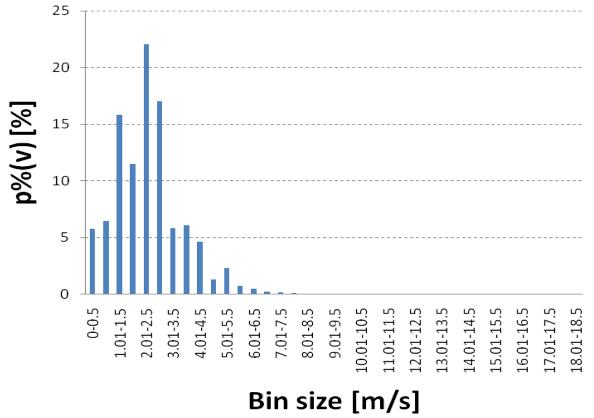

Fig. 11 Weibull wind distribution at 18 m above the ground for the month of July

Figs. from 5 to 16 show the evolution of the Weibull wind distribution as a function of each month of the year, whose average wind speed is shown in Fig. 17: as can be clearly seen, no significant variation is registered during the year time.

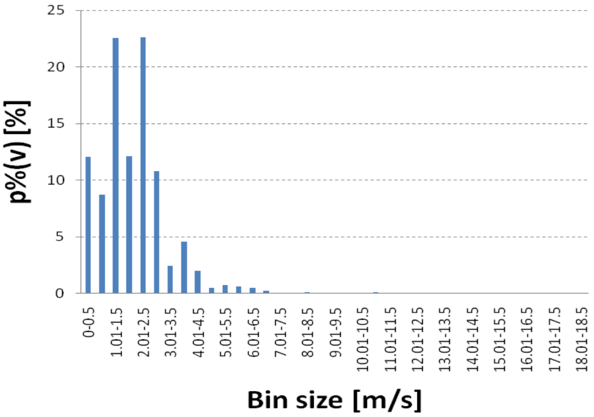

Fig. 12 Weibull wind distribution at 18 m above the ground for the month of August

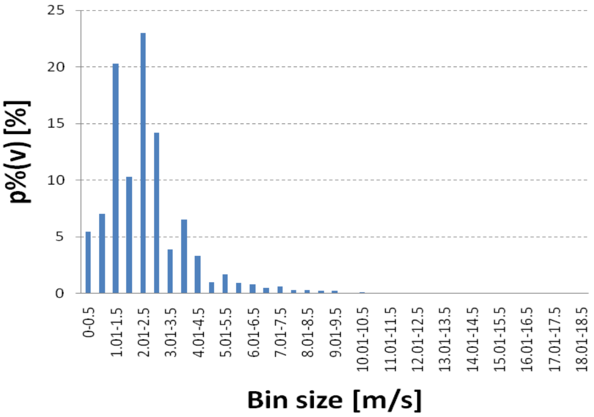

Fig. 13 Weibull wind distribution at 18 m above the ground for the month of September

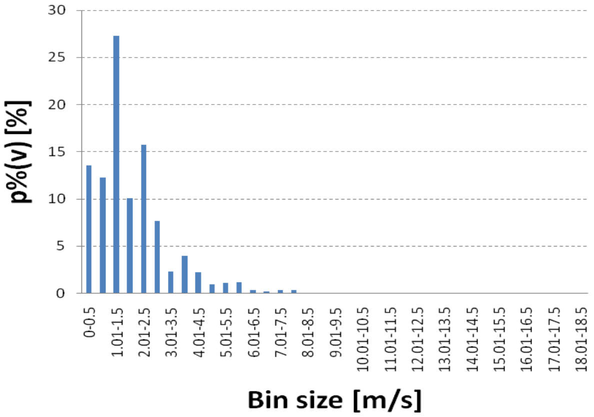

Fig. 14 Weibull wind distribution at 18 m above the ground for the month of October

Fig. 18 shows the wind rose plot for “Lido di Venezia” from the considered 2-year (2000/2001) anemometric campaign, while Figs. from 19 to 30 show its evolution as a function of each month of the year. It can be clearly seen that NE is the prevalent wind direction (as was registered by [11] for the site of Trieste), while the SE direction appears to present some seasonal variations (maximum from March to July).

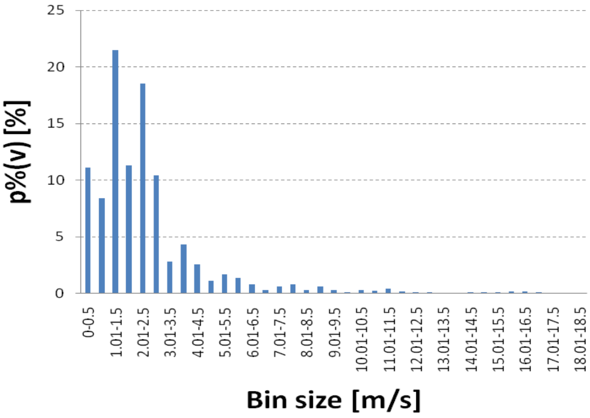

Fig. 15 Weibull wind distribution at 18 m above the ground for the month of November

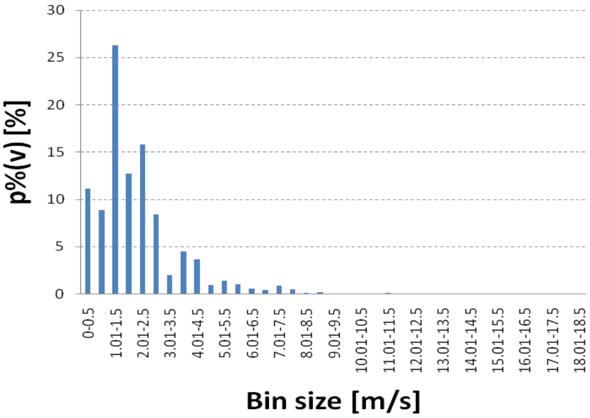

Fig. 16 Weibull wind distribution at 18 m above the ground for the month of December

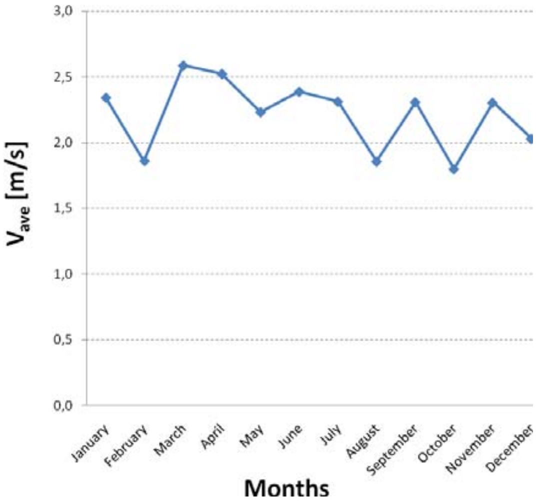

Fig. 17 Yearly evolution of the average wind speed at 18 m above the ground

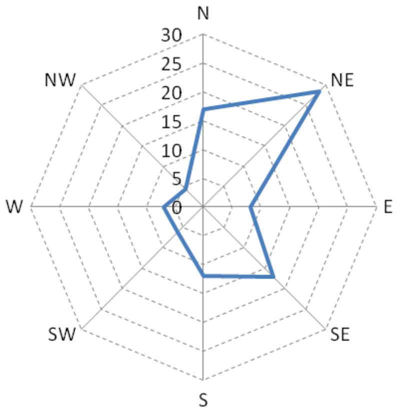

Fig. 18 Wind rose at 18 m above the ground, from 2-year (2000/2001) anemometric campaign

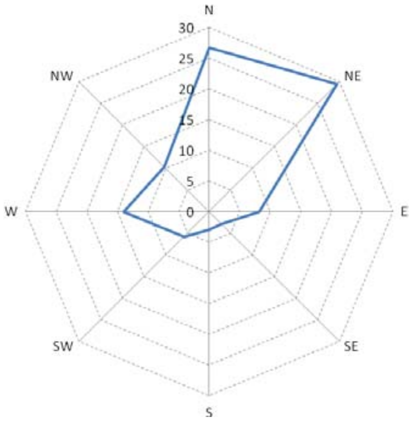

Fig. 19 Wind rose at 18 m above the ground for the month of January

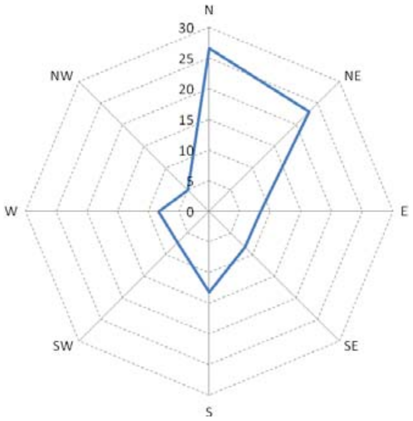

Fig. 20 Wind rose at 18 m above the ground for the month of February

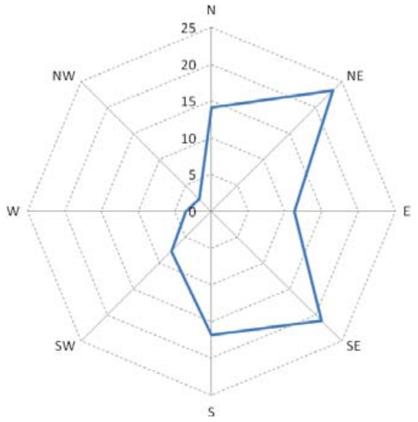

Fig. 21 Wind rose at 18 m above the ground for the month of March

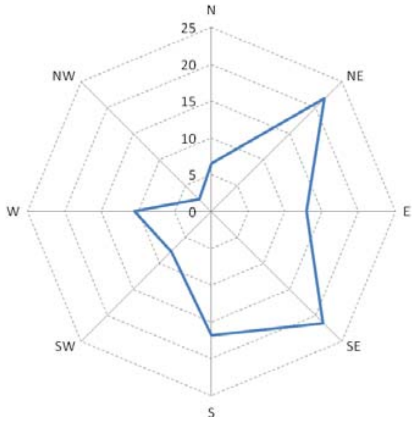

Fig. 22 Wind rose at 18 m above the ground for the month of April

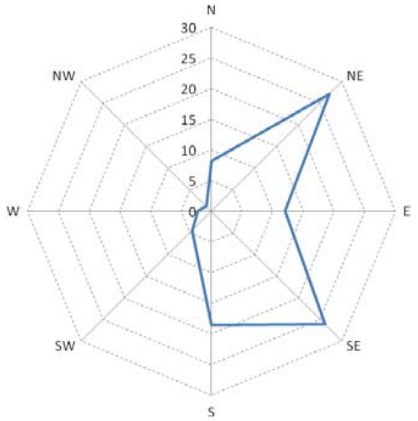

Fig. 23 Wind rose at 18 m above the ground for the month of May

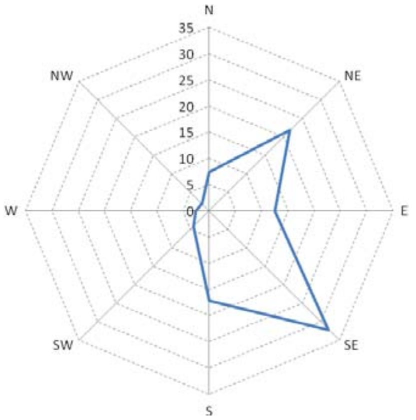

Fig. 24 Wind rose at 18 m above the ground for the month of June

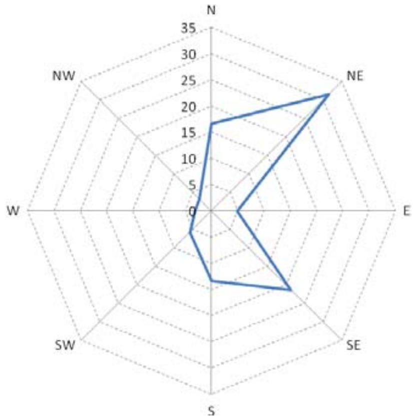

Fig. 27 Wind rose at 18 m above the ground for the month of September

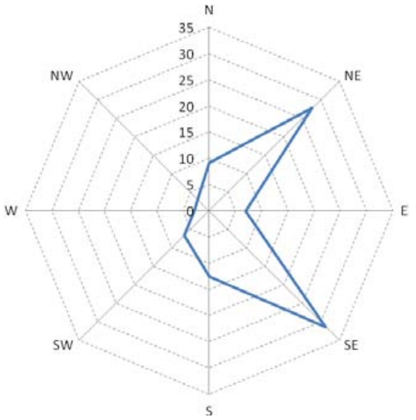

Fig. 25 Wind rose at 18 m above the ground for the month of July

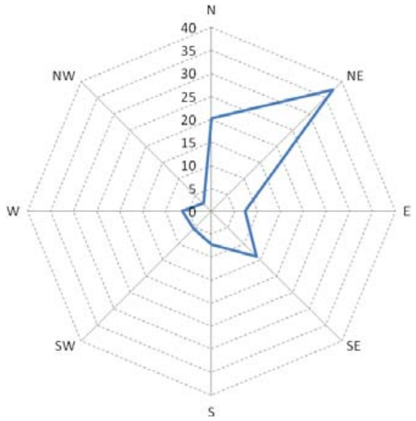

Fig. 28 Wind rose at 18 m above the ground for the month of October

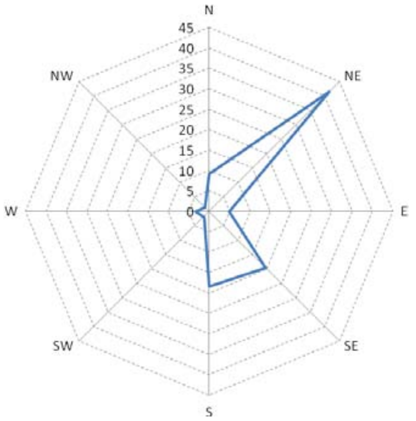

Fig. 26 Wind rose at 18 m above the ground for the month of August

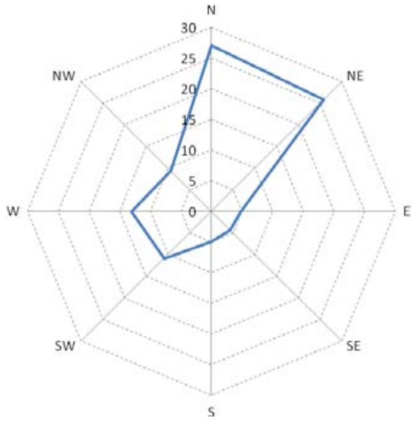

Fig. 29 Wind rose at 18 m above the ground for the month of November

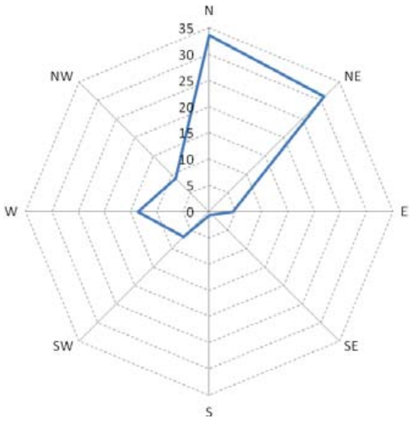

Fig. 30 Wind rose at 18 m above the ground for the month of December

III. CANDIDATE MINI-WECS SPECIFICATIONS AND ESTIMATION OF THE ANNUAL ENERGY OUTPUT

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

$$E_k^{'} = \frac{1}{2} m^{'} v^2 \qquad (2)$$

Fig. 31 Aventa AV-7 LoWind turbine

As reported by Stankovic et al. [12], for convenience the wind turbine power equation is expressed in terms of swept area. Therefore, the mass flow rate is replaced with the term:

$$m^{'} = \rho A v \qquad (3)$$

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

$$P = C_p \frac{1}{2} \rho A v^3 \qquad (4)$$

Figs. 31 and 32 show the two candidate wind turbines, while their main technical specifications and power curves are summarized in Table I and Fig. 33. The Aventa AV-7 LoWind turbine is a classical three-bladed and pitch-controlled HAWT, designed for quite low wind regimes (6 m/s design wind speed), while the Gaia Wind 133-11 kW turbine is a two-bladed, stall-regulated turbine characterized by the uncommon adoption of a downwind rotor.

Fig. 32 Gaia Wind 133-11kW turbine

TABLE I
MAIN TECHNICAL SPECIFICATIONS OF THE TWO CANDIDATE HAWTS (FROM: [13], [14])

	Aventa AV-7 LoWind	Gaia-Wind 133-11kW
D_{rotor} [m]	12.9	13
Blade number [-]	3	2
Rotor swept area, A [m^2]	129	133
Rated power, P_r [kW]	6.5	11
Design wind speed [m/s]	6	about 11
Cut-in wind speed [m/s]	about 2	3.5
Cut-off wind speed [m/s]	14	25
Angular speed [rpm]	20-66	56
Tower height [m]	18	18

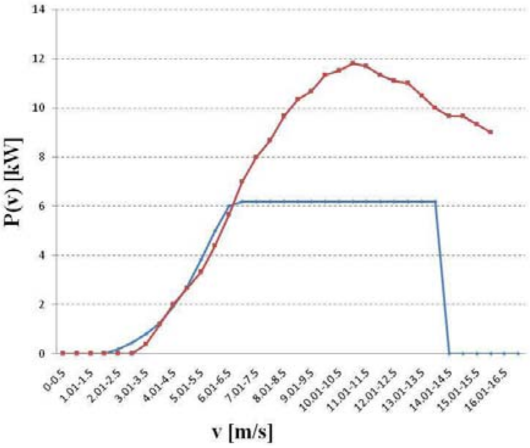

Fig. 33 Comparison between the power curves of the two candidate wind turbines (blue line: Aventa AV-7 LoWind; red line: Gaia Wind 133-11kW)

As can be clearly seen, the Gaia turbine is characterized by a rated power that is twice the one of the Aventa, which presents a lower cut-in wind speed (just 2 m/s). In order to determine the annual energy production as a function of the wind speed, the wind distribution probability for each bin element (from Fig. 4) was first multiplied by the number of hours during a year-time (8760) and successively by the corresponding wind turbine power outputs (from Fig. 33), in formula:

$$E(v) = \sum_{bin} p\%(v) \cdot 8760 \cdot P(v)/100 \qquad (5)$$

Fig. 34 represents the annual energy production as a function of the wind speed for the two candidate wind turbines. The areas underlined by the two curves represent the global Annual Energy Output (AEO) of the two turbines during a year-time.

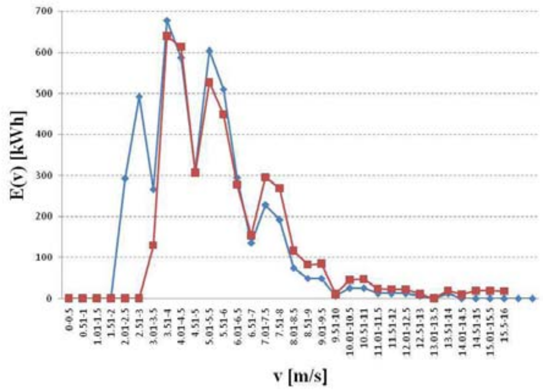

Fig. 34 Annual energy production for the two candidate HAWTs as a function of the wind speed (blue line: Aventa AV-7 LoWind; red line: Gaia Wind 133-11kW)

TABLE II
COMPARISON BETWEEN THE ANNUAL ENERGY PRODUCTIONS OF THE TWO CANDIDATE WIND TURBINES

	Aventa AV-7 LoWind	Gaia-Wind 133-11kW
AEO [kWh]	4877	4216

TABLE III
RATIOS BETWEEN ROTOR SWEPT AREA AND RATED POWER OF THE ELECTRIC GENERATOR FOR THE TWO CANDIDATE WIND TURBINES

	Aventa AV-7 LoWind	Gaia-Wind 133-11kW
k [m^2/kW]	19.8	12.1

As expected, the Aventa AV-7 turbine is capable of generating a great amount of electrical power also for very low wind speeds, determining a higher global production with respect to the Gaia Wind turbine, as can be drawn from Table II. As evidenced from Table III, the higher energy performance of the Aventa turbine is due to the higher ratio between rotor swept area and rated power of the electric generator, in formula:

$$k = A/P_r \qquad (6)$$

This, combined with a higher electrical efficiency (due to the operation of the generator at a power level closer to the nominal one), determines a much higher machine efficiency for low wind sites, as the Lagoon of Venice.

IV. CONCLUSION

The wind potential of the Lagoon of Venice (Italy) has been investigated through the analysis of measured wind data from the "Osservatorio Bioclimatologico dell'Ospedale al Mare di Venezia" for a continuative period of about 2 years. A preliminary evaluation of the monthly-averaged wind speeds has been performed, registering a very low wind potential. The predominant wind directions have also been investigated, registering values similar to those obtained for the city of Trieste (Italy).

A comparison between the Annual Energy Outputs of two horizontal-axis wind turbines (“Aventa AV-7 LoWind” and “Gaia Wind 133-11kW”), designed for low wind speeds, has also been presented, registering a better performance of the former due to the higher ratio between rotor swept area and rated power of the electric generator.

NOMENCLATURE

A [m^2]	rotor swept area
AEO [kWh]	global annual energy output
C_p [-]	wind turbine power coefficient
D_{rotor} [m]	rotor diameter
$E_k^{'}$ [kWh]	kinetic energy
E(v) [kWh]	annual energy production as a function of the wind speed
k [-]	ratio between rotor swept area and rated power of the electric generator
$m^{'}$ [kg/s]	mass flow rate
p%(v) [%]	wind velocity probability
P(v) [W]	wind turbine power output as a function of wind speed
P_r [kW]	wind turbine rated power
v [m/s]	wind speed
v_{ave} [m/s]	average wind speed
v_{11} [m/s]	measured wind speed at 11 m over the ground
v_{18} [m/s]	extrapolated wind speed at 18 m over the ground
α [-]	roughness coefficient (assumed 0.12)
ρ [kg/m^3]	air density

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