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Experimental measurements of the performance of a micro-wind turbine located in an urban area

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ABSTRACT

Among renewable energy sources, the electrical generation at urban level from micro-wind turbines has not yet disclosed its potential. The increasing spread of micro-wind turbines may promote not only the decentralized generation of energy, but also helps to achieve reductions in the emission of greenhouse gases (GHGs) and to support the transition to transport system electrification. However, one of the barriers for the diffusion of micro-wind turbines in urban settlements is the difficulty to estimate its feasibility based on the local wind resource, which is highly site-specific and less predictable than other renewable sources in an urban framework (i.e. solar, biomass).

The paper deals with extensive monitoring and analysis of a micro-wind turbine performed at the outdoor development center HEnergia of HERA S.p.A. in Forlì (Italy). The micro-wind turbine was remotely monitored and data on environmental conditions and electric energy production were continuously acquired and stored by a PC. Therefore, micro-wind turbine performance was measured on-site and correlated with environment conditions. The real energy production of the micro-wind turbine was measured and a method to estimate the performances based on local wind conditions was presented. Based on the results, a simplified approach to evaluate the economic feasibility of micro-wind turbine in urban areas based on the Levelized Cost Of Energy (LCOE) concept was also presented.

1. Introduction

Cities are fundamental in the world's transition to a low-carbon economy, since cities account for about 65% of global energy use and about 70% of man-made carbon emissions. While many cities have so far focused primarily on energy efficiency, the next step towards an urban sustainable energy system will require a significant increase in the use of renewable energy. Renewables can bring tremendous benefits to cities, including cleaner air, modern services and improved living spaces, and have huge impacts on several sectors, from buildings to transport, from lighting to industry (IRENA, 2016).

Biomass, solar and wind energy are the main renewable sources currently used in cities in both centralized and decentralized generation systems. Solar thermal and solid biomass boilers and space heaters are widely used to cover the demands for space heating and domestic hot water (DHW) production (including also integration in district heating and cooling systems). Photovoltaic (PV) is the most applied for power generation (i.e. lighting, electric transport), and have also potential for space cooling (REN21, 2019). A growing research trend is related to mini (20–200 kW) and micro (under 20 kW) wind turbines in cities (Perea-Moreno et al., 2018). In fact, small-scale wind turbines are characterized by low maintenance cost, high reliability, wider wind operation range than industrial wind turbines, and minimum environmental impact.

Several works in literature deal with the techno-economic performance estimation and the environmental impact assessment of small-scale wind turbine in urban areas. In Wang and Teah (2017) the Life Cycle Assessment (LCA) of a 600 W horizontal axis wind turbine (HAWT) in the city of Tainan (Taiwan) is developed finding that 100 years are necessary to equalize emissions and 160.9 years for the energy spent for the construction. Hourly local wind speed data were used to estimate energy production. In Glassbrook et al. (2014) a comparative LCA is proposed between wind turbines, diesel generator and local grid installed in Thailand. Wind energy production was simulated using the available data about the local wind speed. Sunderland et al. (2016) estimates the energy production and the Levelized Cost of Energy (LCOE) of a 2.4 kW wind turbine for three geographical locations (Sri Lanka, Ireland and UK) with HOMER tool. They found that for urban contest the investment cost is too high to be justified. An economic assessment for the implementation of a small wind turbine in the North of Europe is reported In Bukala et al. (2015), finding that the economic feasibility is more

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influenced by investment rather than aerodynamic efficiency. In Khraiwish Dalabeeh (2017) a model to forecast energy production in Jordan considering typical wind velocity distribution and five different wind turbines is provided. In Abdelhady et al. (2015) a technical and economic feasibility is performed for eight different small wind turbines in 17 locations in Egypt. For the prediction of energy production, available local wind data are used. In Drew et al. (2015) the energy production of 33 wind turbines was estimated at 91 sites in UK. The results show that energy production simulation is greatly influenced by the accuracy of wind velocity measurement. In Ramenah and Tanougast (2016) a 2.6 kW horizontal three axis wind turbine performance is analyzed considering data registered with a frequency of 1 min in an urban landscape location in Metz City (France). In Brano et al. (2016) a test facility with a 1 kW wind turbine is realized in Palermo to characterize the site and turbine performances. In Li et al. (2012) the economic unprofitability of small wind turbine in Ireland for average wind velocities lower than 6 m/s was calculated through HOMER simulation tool. In Peacock et al. (2008) annual energy production by small wind turbines (0.4–2.5 kW) is simulated through the use of wind velocity data of a specific UK location. The paper shows that long payback time are required to return the investment.

To date no simple approach is available in the literature to evaluate the economic feasibility of micro-wind turbines especially in urban areas. To address also this research gap, at the end of September 2013, Hera S.p.A., which is one of the largest Italian multiutility companies, inaugurated the applied research center on renewable energy called "HEnergia" (HE). HE is a test site located in Forlì, Italy (44°13'30.5" N-12.04'21.1" E), designed in collaboration with the Department of Industrial Engineering of the University of Bologna. Different kinds of renewable energy plants were hosted and tested in the research center (Bianchini et al., 2019, 2018, 2017, 2016). Among the technology, also a micro horizontal axis wind turbine with 1 kW was installed to experimentally validate technology's performances and to assess the conditions that ensure the economic feasibility in the regional and urban context.

The paper aims to show a simplified methodology to evaluate the economic feasibility of micro-wind turbine at urban levels. Since the presence of a significant number of weather data recorded by a local station is not always possible, the approach was designed to use also the accessible weather data recorded by the Regional Agency for the Protection of the Environment (ARPAE). For the purpose, the material and the methods used to estimate the real performances and the economic feasibility of the micro-wind turbine based on weather data are introduced in the second section. In the third section of the paper, the performances of the installed micro-wind turbine are analyzed. Based on the results, the proposed methodology for techno-economic feasibility is validated and discussed. Finally, some considerations about the limits of the analysis and the possible improvements are reported in the conclusions.

2. Material and methods

2.1. The micro-wind turbine and the monitoring system

The micro-wind turbine installed in HE is an Airdolphin Mark-Zero/Pro, produced by Zephyr Corporation, an energy solution company with headquarters in Tokyo (Japan). The main characteristics of the micro-wind turbine installed in the HEnergia research center at Forlì are reported in Table 1. In addition, a picture of the Zephyr Air Dolphin micro-wind turbine is shown in Fig. 1: three blades are installed in the micro-wind turbine resulting in a rotor diameter equal to 1.8 m. Regarding production performances, the installed micro-wind turbine has a cut-in wind speed of 2.5 m/s while it is rated at 1 kW at a wind velocity equal to 12.5 m/s. The stall mode operation is maintained for velocity greater than 20 m/s and production is stopped at the cut-off velocity, i.e. 50 m/s, to preserve the micro-wind turbine as shown in the power output characteristic (Fig. 2).

Table 1
Airdolphin Mark-Zero/Pro micro-wind turbine main characteristics.

Module characteristic	Value
Rotor diameter (mm)	1800
Rotor mass (kg)	18
Type	Horizontal axis
Tower diameter (mm)	48.6
Tower weight (kg)	34
Number of blades	3
Blade construction	Carbon fiber laminate over solid foam core
Blade mass	0.38
Generator	Three phase with permanent neodymium iron boron magnet
Yaw control	Free yaw (360°)
Direction control	Original Swing-Rudder
Cut-in wind speed (m/s)	2.5 m/s
Cut-off wind speed (m/s)	50 m/s
DC Output (kW)	1.0 (wind speed: 12.5 m/s); 0.674 (11 m/s)
Maximum rotor speed (rpm)	1000
Rated Output Voltage	DC 25 V

Concerning the control strategy, the swing rudder system is implemented as yaw control mechanism. With respect to the traditional control systems installed in similar applications, the one installed in the Zephyr Air Dolphin allows the rudder to pivot freely through an angle of almost 80° reducing the detrimental consequences due to the possible severe inertia loadings due to sudden changes in wind direction (Rogers and Omer, 2013). In addition, a "*power assist function*" is implemented in the micro-wind turbine. The function allows the micro-wind turbine to use the electrical power previously generated to spin the rotor when the wind velocity is lower than the cut-in velocity. The operation is repeated for 10 s every minute to reduce the time required to reach the cut-in conditions so to minimize start-up time (Zephyr Corpration, 2011). The required power can be supplied by the two 12 V batteries (produced by Magneti Marelli) or by the national grid.

Fig. 3 shows a schematic of the experimental plant, including instrumentations. An inverter (SMA inverter, composed by Windy Boy and Wind Boy protection box) is used to convert the electricity from the wind generator into grid conforming alternate current and to feed into the national AC grid. The following data are registered every 4–5 s by HE general acquisition system: AC voltage and current as transformed by the inverter, AC power produced, AC total energy produced. Furthermore, environmental conditions such as solar global radiation (Kipp & Zonen pyranometer CMP11), ambient temperature and humidity (LSI Lastem thermohygrometric sensor DMA675), wind speed and direction (LSI Lastem wind speed and direction sensor DNA721) are measured through a local meteorological station. Each sensor mentioned above produces signals in 4–20 mA. Particularly, the DNA721 combined wind speed and direction sensors produced by LSI Lastem was installed. Concerning wind velocity, the instrument had a wind speed range of 0–60 m/s, a resolution up to 0.06 m/s and an accuracy equal to 0.1 m/s ± 1% of the readout. With respect to wind direction, instead, a range of 0-360°, a resolution

Fig. 1. Picture of the Zephyr Air Dolphin micro-wind turbine.

up to 0.4° and an accuracy equal to 1% of the full range are ensured by the manufacturer.

Signals coming from the micro-wind turbine are sent to the HE datalogger, while signals coming from the local meteorological station are sent to a dedicated datalogger. Data are acquired and stored in a PC from the dataloggers via LAN network. Data are managed through MySQL Workbench on a PC that can be remotely accessed via internet.

2.2. Site description

HE geographical position and the 3D picture taken from Google Earth are shown respectively in Figs. 4 and 5. If the micro-wind turbine position is analyzed, in the North there are trees and buildings at a distance of almost 100 m. To the East and South there are some offices and other industrial buildings at a distance smaller than 50 m. To the West there is an open space up to 300 m after which several residential properties are located.

To reduce the impact of all these obstacles the micro-wind turbine was installed at 6 m above the ground. Furthermore, since the micro-wind turbine could be installed on the rooftop of urban buildings to maximize the exploitation of available spaces, the selected height was considered as representative for this possible installation.

2.3. Wind velocity: the Weibull distribution

Weibull statistical wind distribution is considered as the most appropriate to estimate installation sites potential (Burton et al., 2011). Particularly, Weibull distribution is a two-parameters function commonly used to describe the wind speed frequency distribution (Seguro and Lambert, 2000). The density function f(v) is defined in Eq. (1) as the probability that wind velocity is equal to v [m/s], wherein Weibull distribution shape k and scale λ are introduced:

$$f\left(v\right)=\frac{k}{\lambda^{k}}v^{k-1}\exp\left(-\frac{v}{\lambda}\right)^{k} \tag{1}$$

Even if the method proposed by Stevens and Smulders (1979) to estimate the Weibull distribution shape and scale should be used for accurate evaluations, due to the high computational effort, a graphical method was used. For the purpose the Weibull distribution parameters were calculated aiming to minimize the error with respect to the cumulative probability F(v) reported in Eq. (2):

$$F\left(v\right)=1-\exp\left(-\frac{v}{\lambda}\right)^{k} \tag{2}$$

To simplify the calculation, wind velocity intervals equal to 0.1 m/s were selected. For example, considering the range 0–15 m/s, 150 intervals were considered. Based on the data, the ideal electrical energy potential through a wind turbine [J] is calculated as in Eq. (3):

$$E_{el,ideal}=\sum_{j=1}^{z}p\left(v_j\right)\frac{1}{2}\rho A v_j^3\times N \tag{3}$$

where j is the velocity interval, z is the total number of intervals, $p(v_j)$ is the probability in the *j*th interval, A is the rotor area of the micro-wind turbine [m^2], ρ is the air density [kg/m^3], and N is the total investigated period [s].

2.4. Micro-wind turbine real energy performance assessment

A series of parameters are usually considered to evaluate the technical performances of a micro-wind turbine such as, for example, i) the real mechanical power generated by the air flowrate, ii) the ideal mechanical power and iii) the power coefficient C_p, defined as the ratio between the two so. Since they are evaluated in standardized laboratory conditions, these indexes result very useful as a comparison metric between different wind turbine models.

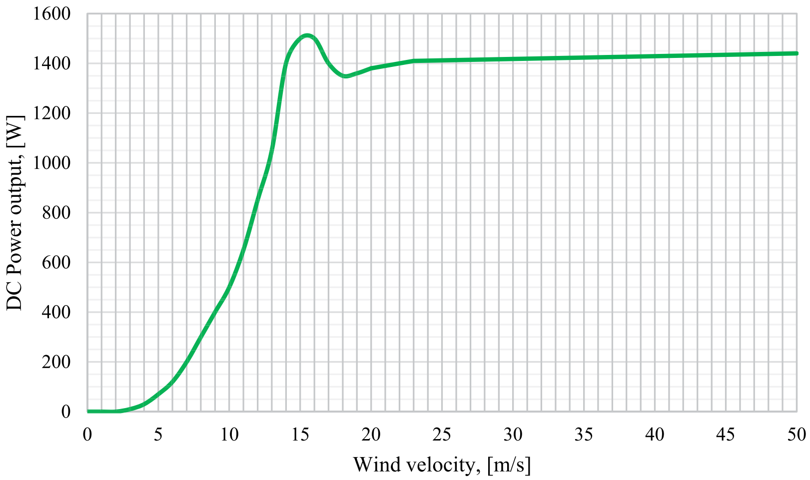

Fig. 2. Zephyr Air Dolphin micro-wind turbine's power output characteristic as reported by Manufacturer (Zephyr Corpration, 2011).

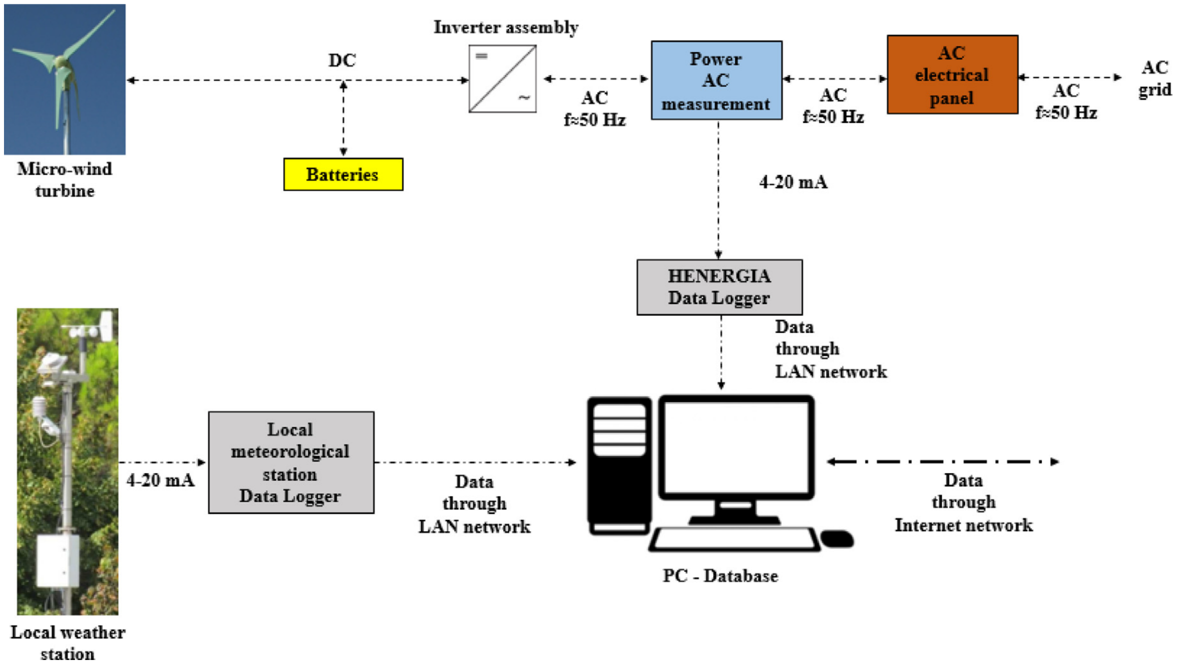

Fig. 3. Layout of the data acquisition system.

Real on-field performances can be very different from those experienced in controlled conditions. For example, plant's efficiency also depends on other devices, such as inverters, batteries, and other ones required to ensure required supply conditions. Therefore, the assessment of micro-wind turbine's field performances is strategic to assess plant's feasibility. Particularly, the daily micro-wind turbine energy production $E_{\text{el,real-day}}$ [J] is calculated as suggested in Eq. (4):

$$\mathrm{E}_{\text{el,real-day}} = \sum \left(\mathrm{P}_{\text{el,real}} \times \Delta \mathrm{t}\right) \tag{4}$$

where $\mathrm{P}_{\text{el,real}}$ is the measured electrical power [W], while Δt is the time interval between two power measurements in the range of 4–5 s.

Furthermore, the equivalent number of daily working hours N_{day} [h] is calculated as shown in Eq. (5):

$$\mathrm{N}_{\text{day}} = \sum \Delta \mathrm{t}_{>0}/3600 \tag{5}$$

where $\Delta \mathrm{t}_{>0}$ are the time intervals in which a net positive power production was measured from the wind turbine.

Based on manufacturer's laboratory data reported in Table 1, a preliminary estimation of the expected micro-wind turbine performances is also possible based on Eqs. (6) and (7):

$$\mathrm{P}_{\text{el,expected}} = \frac{1}{2}\rho \mathrm{A} \mathrm{v}^3 \widetilde{\mathrm{C}}_{\mathrm{p}} \tag{6}$$

$$\mathrm{E}_{\text{el,expected-day}} = \sum \left(\mathrm{P}_{\text{el,expected}} \times \Delta \mathrm{t}\right) \tag{7}$$

where $\widetilde{\mathrm{C}}_{\mathrm{p}}$ is the corrected power coefficient. This coefficient is the product between the power coefficient and the mechanical and the electrical generator efficiencies. By assuming a constant value for the generator efficiencies (i.e. 95%), the power coefficient was calculated as the ratio between the daily real and the ideal power production. However, due to the on-field experimental activities, it is not possible to evaluate the corrected power coefficient for wind velocity greater than 6 m/s. In fact, the corrected power coefficient was calculated on daily basis. Particularly, to evaluate the ideal daily production only wind velocity greater than the cut-in value was considered. Since no day of the analyzed period had an average wind velocity greater than 6 m/s, it was not possible to estimate the corrected power coefficient. Therefore, the corrected power coefficient was iteratively calculated in order to minimize the error between the real (Eq. (4)) and the expected total and daily energy production (Eq. (7)). For the purpose, it was evaluated in the following wind velocity ranges:]2.5;3],]3.;4];]4;5];]5;6]

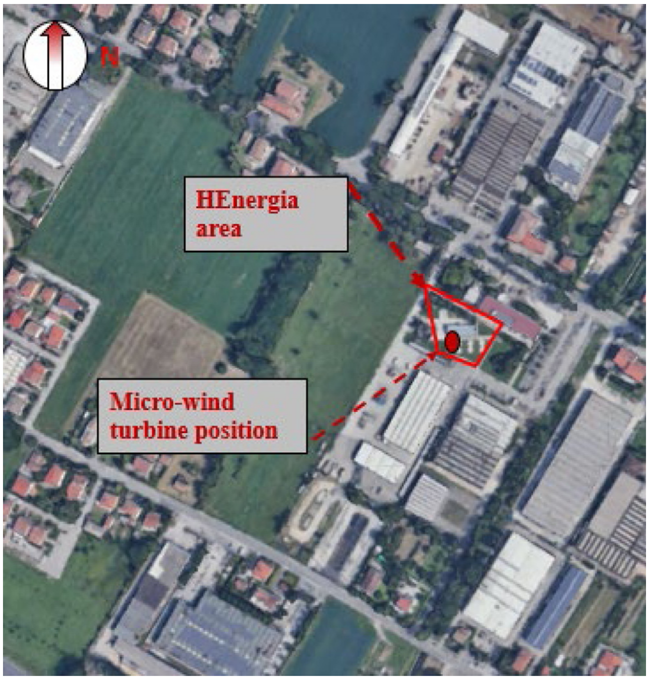

Fig. 4. Geographical position of the micro-wind turbine and surrounding obstacles. The image was taken from Google Earth.

The global micro-wind turbine's efficiency was also calculated as in Eq. (8):

$$\eta_{global} = \sum \mathrm{E}_{\text{el,real-day}}/E_{el,ideal-day} \tag{8}$$

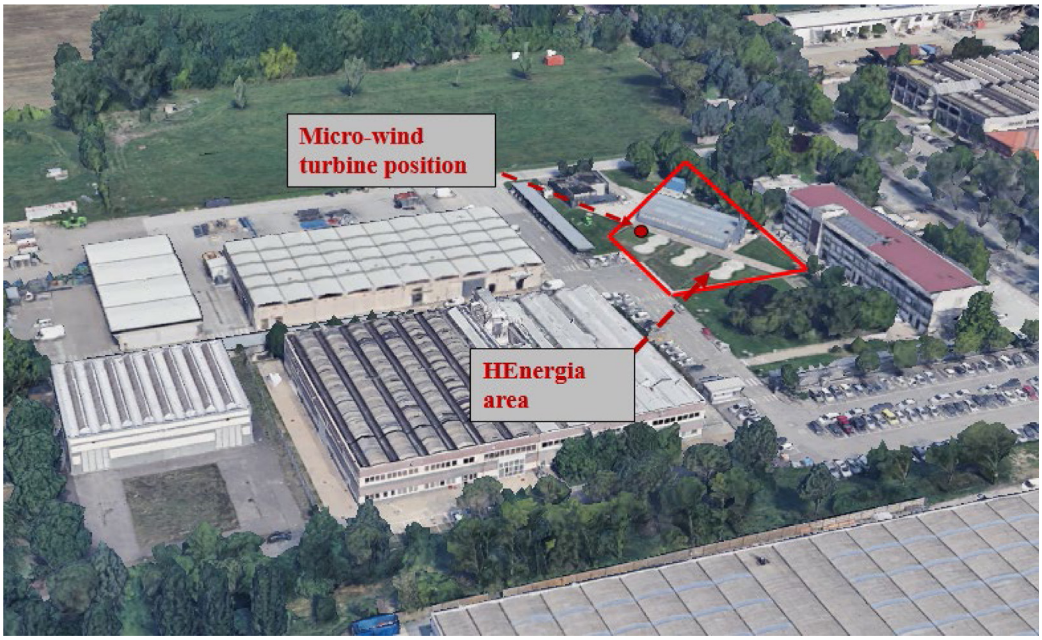

Fig. 5. 3D picture of the location where the micro-wind turbine was installed in the HEnergia Centre. The image was taken from Google Earth.

Correlations able to estimate daily ideal and real energy production was investigated to simplify the following analysis. Since power is the amount of energy transferred or converted per unit time, the cubic of the daily average wind velocity, $\bar{v}$, and the number of operating hours, h, were included in the analysis. However, only wind velocity greater than 2.5 m/s, i.e. the cut-in velocity of the micro-wind turbine, were considered in the calculation of the average daily wind velocity. The assumed correlations are reported in Eqs. (9) and (10):

$$\mathrm{E}_{\mathrm{el,real-day}} = a \times \overline{v}^3 \times \mathrm{h}^{\mathrm{c}} \tag{9}$$

$$\mathrm{E}_{\mathrm{el,ideal-day}} = b \times \overline{v}^3 \times \mathrm{h}^{\mathrm{c}} \tag{10}$$

where a, b, c are the correlation coefficients. An iterative procedure was implemented to assess these coefficients as shown in Fig. 6. The first step was the assumption of the coefficient c that was assumed equal to 0.1. As second input, the coefficients a and b were firstly assumed equal to 0.0001. In the second step the ideal and the real energy productions were calculated in accordance to Eq. (9) and Eq (10). If the coefficient of determination R^2 resulted greater than 0.9 the set of values, i.e. (a ; c) and (b ; c) were recorded. The iterative procedure was repeated until the coefficient of determination remains greater than 0.9. In the third step, the coefficient c was changed and the iterative procedure repeated up to the threshold, assumed equal to 1. In fact, values greater than 1 were excluded since it would have signified to assume a number of operating hours greater than observed. In the last step, the set of values were compared and the best set of values in terms of coefficient of determination were selected.

2.5. Economic considerations

An economic analysis of the micro-wind turbine plant was carried out through the application of the LCOE method (Short et al., 1995). The analysis is carried out to assess the minimum average wind velocity above which micro-wind turbine installation can be justified. The LCOE methodology is an abstraction from reality and it is used as a benchmarking to assess the cost-effectiveness of different energy generation technologies that ensure the same electrical production in the investigation period. For the purpose, a period of 20 years is assumed in accordance to technology lifetime generally assumed as a basis for dimensioning (DNV GL, 2016).

Table 2
Assumptions about economic assessment for LCOE calculation.

Item	Symbol	Value
Micro-wind turbine cost (including civil works)	F_0	15,000 €
Evaluation period	n	20 years
Discount rate	i	4.0%
Wind turbine maintenance yearly cost	$C_0^{O\&M}$	1.5% of F_0
Yearly inflation rate	e	1.0%
Yearly O&M costs escalation rate	$r_{O\&M}$	1.5%

The method considers the lifetime generated energy and costs to estimate a price per unit energy generated. LCOE can be expressed as in Eq. (11), where t [years] is time, n [number of years] is the time period considered for the investment evaluation (which will be assumed equal to both depreciation and technical life time of the plant for treatment simplicity purpose), i [%] is the discount rate, e is yearly inflation rate (%), $E_{\mathrm{el,y}}$ [kWh/year] is the yearly electric energy production. I_0 corresponds to the starting investment: the simplifying hypotheses of full investment payment and plant operation start in the same year (t=0) are also assumed.

$$\mathrm{LCOE} = \frac{\mathrm{I_0} + \sum_{\mathrm{t}=1}^{\mathrm{n}} \mathrm{C_0^{O\&M}} \cdot (1 + \mathrm{e} + \mathrm{r_{O\&M}})^{\mathrm{t}}/(1+\mathrm{i})^{\mathrm{t}}}{\sum_{\mathrm{t}=0}^{\mathrm{n}} \mathrm{E}_{el,y}/(1+\mathrm{i})^{\mathrm{t}}} \tag{11}$$

The cost to be considered in the LCOE analysis is the operating and maintenance (O&M) cost. $C_0^{O\&M}$ [Euro/year] is the O&M cost that has been estimated as the 1.5% of the total cost of the investment. An escalation rate $r_{O\&M}$ is considered to evaluate the increasing costs of O&M due to plant component (i.e. inverter, wiring, bearing, batteries) wear and tear over the years.

Table 2 summarizes the main assumptions about economic assessment.

To evaluate the influence of each parameter reported in Table 2 and used in the LCOE analysis a sensitivity analysis was performed since uncertainty in the selection of the value of the

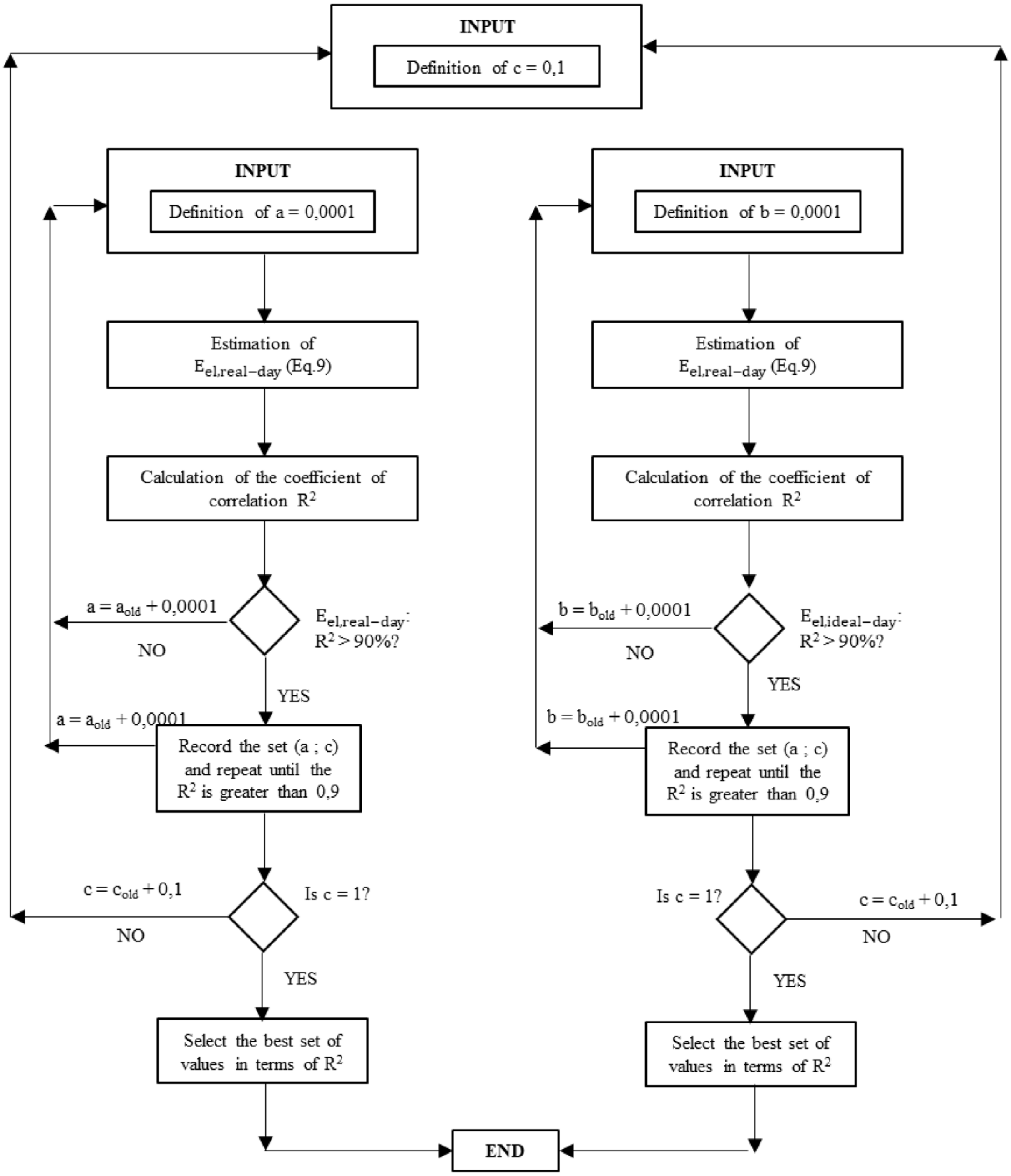

Fig. 6. Schematization of the iterative procedure used for the calculation of the parameters a, b and c.

Table 3
Assumptions about economic assessment for sensitivity analysis.

Item	Symbol	Value
Micro-wind turbine cost (including civil works)	F_0	7,500-22.500 €
Wind turbine maintenance yearly cost	$C_o^{O\&M}$	0.75%-2.25 of F_0
Yearly inflation rate	e	0.5%–1.0%
Yearly O&M costs escalation rate	$r_{O\&M}$	0.75%-2.25%

parameters could be present. A range between [−50%, 50%] was assumed for each parameter as reported in Table 3. Therefore, the LCOE was calculated by changing the parameters one by one while keeping the others as assumed in Table 2.

3. Results and discussion

3.1. Wind velocity distribution and ideal performance

Wind velocity and direction at HE site were calculated based on the analysis of the available 320 days of micro-wind turbine

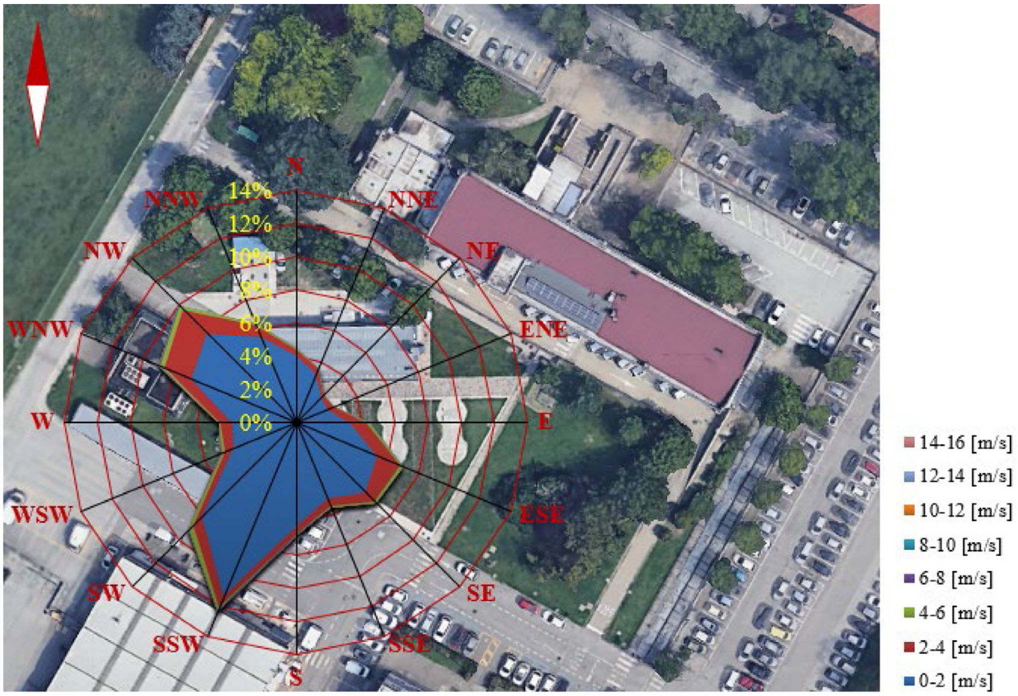

Fig. 7. Measured wind direction for the specific test site in Forlì (44°13’30.5”N -12.04’21.1”E).

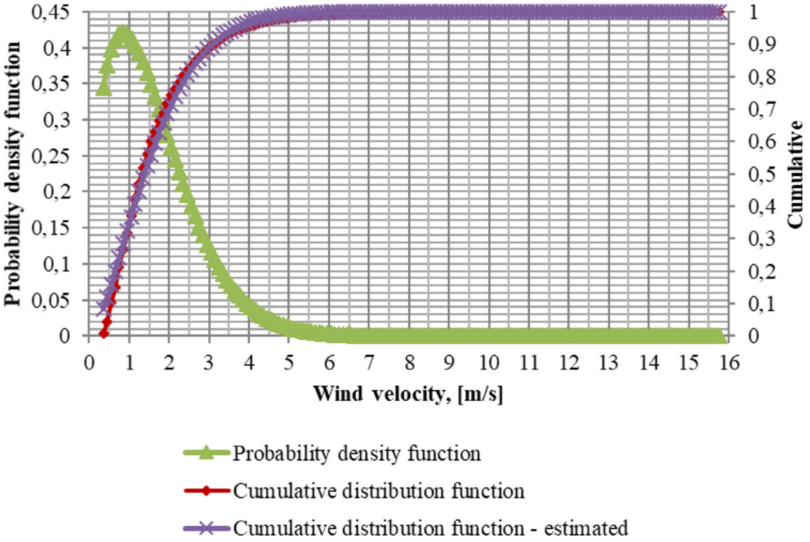

Fig. 8. Measured wind velocity and Weibull distribution interpolation for the specific test site in Forlì (44°13’30.5”N -12.04’21.1”E).

operation. As shown in Fig. 7, wind direction is predominant and with a higher magnitude in the NW as expected by the presence of an open spaces towards the presence of residential buildings. A lower wind velocity was measured in the SSW direction due to the presence of a near building in the NNE direction. As expected, due to the presence of a very high building, wind potential in the direction NE, ENE was negligible.

Concerning the wind velocity, the Weibull distribution is shown in Fig. 8. The Weibull distribution is described by a shape (k) and a scale (λ) factors equal, respectively, to 1.5 and 1.77. Wind velocity results lower than 2.5 m/s, i.e. the cut-in velocity of the micro-wind turbine for more than the 80% of the time, i.e. more than 7000 h per year. These low wind velocities can be partially justified due to the obstacles that are present in the area. An ideal energy production equal to 153.32 kWh was calculated in accordance to Eq. (3). In Fig. 9 the estimated annual energy production for each wind velocity interval is shown.

Since high wind velocities rarely occur during the year, the site energy potential at high values is very limited. Furthermore, more than 35 kWh cannot be exploited by the micro-wind turbine due to a wind velocity lower than turbine’s cut-in one (red columns in Fig. 9).

3.2. Micro-wind turbine real production performance

To evaluate the real micro-wind turbine performances in the site test, daily electrical energy production was calculated and shown in Fig. 10 for the entire period of analysis. Fig. 10 shows that a total energy production equal to 13.68 kWh was measured with a total number of working hours equal to 249 h. The manufacturer declared an energy production of 50 kWh per year

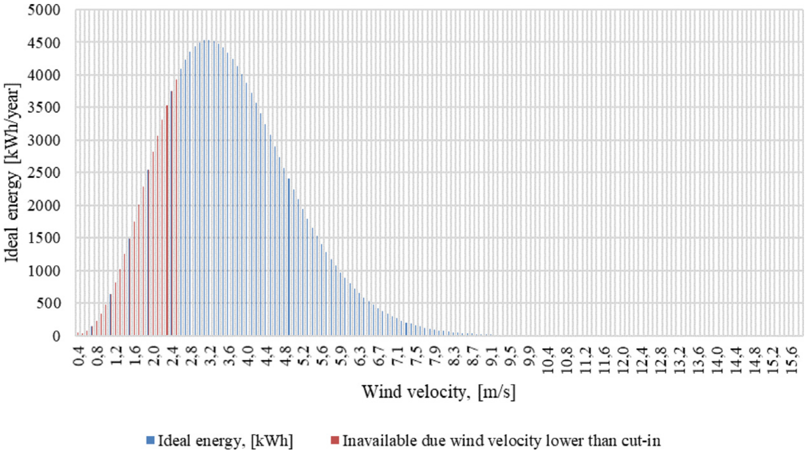

Fig. 9. Estimated annual ideal energy in the specific test site in Forlì (44°13'30.5"N -12.04'21.1"E).. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

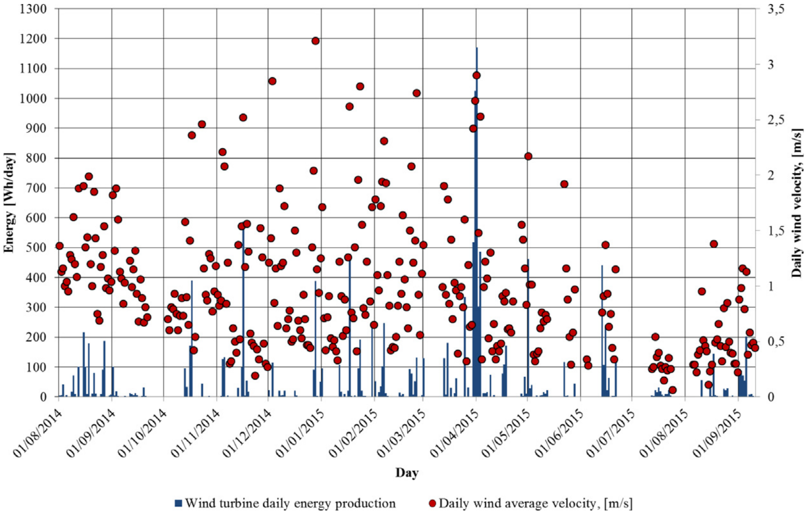

Fig. 10. Micro-wind turbine daily energy production at inverter's terminal.

for an average wind speed of 2 m/s (Zephyr Corpration, 2011). Therefore, an average wind velocity of almost 1.3 m/s should have been present. The calculated data is in accordance with the measured wind velocity data. Therefore, the electrical production is influenced by the low average wind speed during the year in the experimental field. A maximum electrical energy production equal to 1.17 kWh/day (the 8.55% of the total) occurred the 1st of April when a total number of working hours equal to 10.8 h/day occurred with an average wind velocity equal to 2.89 m/s and a maximum up to 15.8 m/s. However, the maximum number of working hours (11.2 h/day) was measured the day before even if a lower production occurs due to a lower average wind velocity equal to 2.67 m/s and a maximum equal to 9.2 m/s. Nevertheless, in some days a positive electrical power production for less than one minute occurred.

In accordance to the ideal energy production, a global energy efficiency equal to 7.3% resulted. Considering only the ideal energy for wind velocity greater than the cut-in one, a global energy efficiency equal to 9.0% was calculated. Concerning aerodynamic performances the corrected power coefficient is shown for wind velocity lower than 6 m/s in Table 4. In fact, by considering only wind velocities greater than the cut-in value, no day with wind velocity greater than 6 m/s occurred in the period. In Fig. 11 the corrected daily average wind velocities calculated discarding all wind velocity lower than the cut-in value are shown.

The good correlation between the total measured and the estimated daily energy production is shown in Fig. 12. In fact, even if some points belonging to the expected values overestimate or underestimate the real measured energy, a good approximation of the real daily energy production is generally present.

As expected, the micro-wind turbine shows its best performances at high wind velocities. Therefore, in addition to the limited energy potential, very low performances were also shown by the micro-wind turbine for the main part of year in the specific site location.

In Fig. 13, real (red dots) and ideal (blue dots) daily electrical energy are compared as a function of the product between the average wind velocity and the number of operating hours. The coefficients a, b and c were calculated in accordance the iterative procedure shown in Fig. 6 resulting equal to 0.9834, 3.179 and 0.8. As shown in the figure, a good estimation both for the real and for the ideal daily energy production was found.

3.3. Economic assessment

Fig. 14 shows the LCOE as a function of different values of the product between the average wind velocity and the number of operating hours. In accordance to Fig. 13, daily energy production was estimated through the interpolating correlation. As expected, high wind velocities and a great number of operating hours are

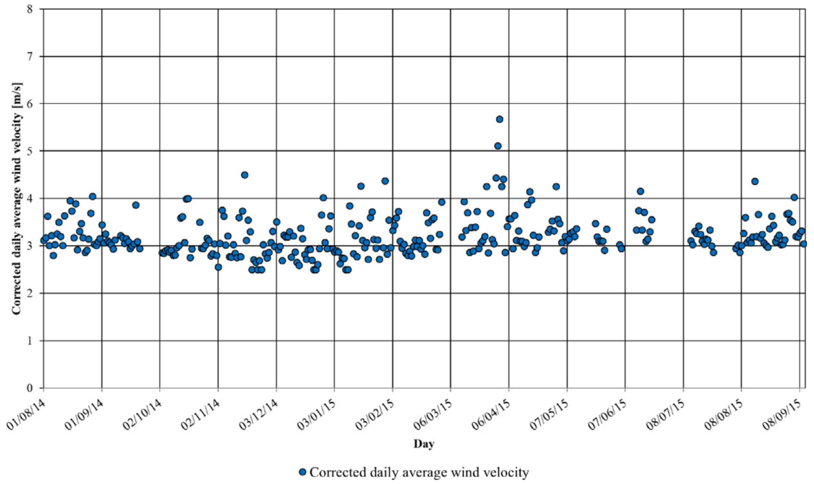

Fig. 11. The corrected average daily wind velocity.

Table 4
Estimated values for $\widetilde{C}_p$.

Wind velocity	Estimated $\widetilde{C}_p$	Total measured energy production, [Wh]	Total estimated energy production, [Wh]
]2.5; 3]	0,02	29,4	29,4
]3; 4]	0,19	6655,0	6655,0
]4; 5]	0,41	4937,7	4937,7
]5; 6]	0,43	2194,8	2194,8

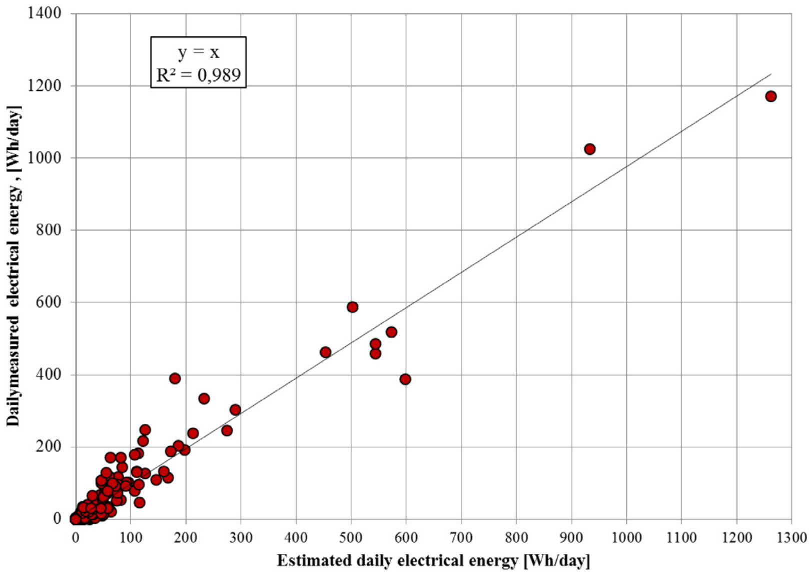

Fig. 12. Comparison between measured and estimated electrical energy.

required to ensure the lowest LCOE as possible. However, due to the hyperbolic trend of the curve, based on the data of Table 2, the LCOE tends to the asymptotic value of 18 c€/kWh while a rapid growth of the LCOE is found at values lower than 2500 $(m/s)^3$ x $h^{0.8}$. Therefore, the micro-wind turbine currently results not convenient with respect to other renewable technologies such as solar photovoltaic.

Since the mean Italian households' electricity purchasing cost is about 0.229 €/kWh, the micro-wind turbine would ensure better economic performances for average daily values greater than 11000 $(m/s)^3$ x $h^{0.8}$. It means, for an average daily wind velocity of 8 m/s, more than 21 h per day.

Different results could be reached if the economic parameters are changed. Fig. 15 shows the LCOE resulting for different values of the initial investment. Despite the economic improvement in high wind energy potential sites, the installation would still result unfeasible where the wind energy potential is low. In Figs. 16, 17 and 18 the sensitivity analysis for other parameters (i.e. the annual maintenance cost, the yearly inflation rate and the escalation rate) is shown. As reported, only initial investment has a great impact respect to the economic feasibility of the plant, while other parameters can be considered almost negligible.

To evaluate the impact of the economic parameters on plant feasibility, the focus was given to a high potential installation site. In fact, the technology seems to be unfeasible in those areas characterized by a low wind potential. By assuming the value of 11000 $(m/s)^3$ x $h^{0.8}$, which corresponds to a high potential site, the sensitivity analysis in Fig. 19 shows that only the reduction

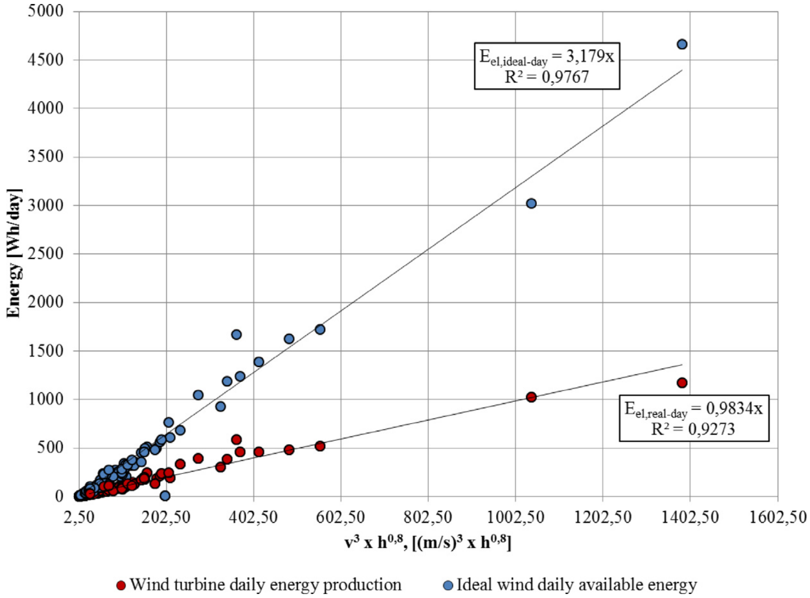

Fig. 13. Micro-wind turbine real and ideal daily energy production as a function of daily wind average velocity and operating hours. Only wind velocity higher than wind turbine's wind velocity (i.e. 2.5 m/s) were considered.. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

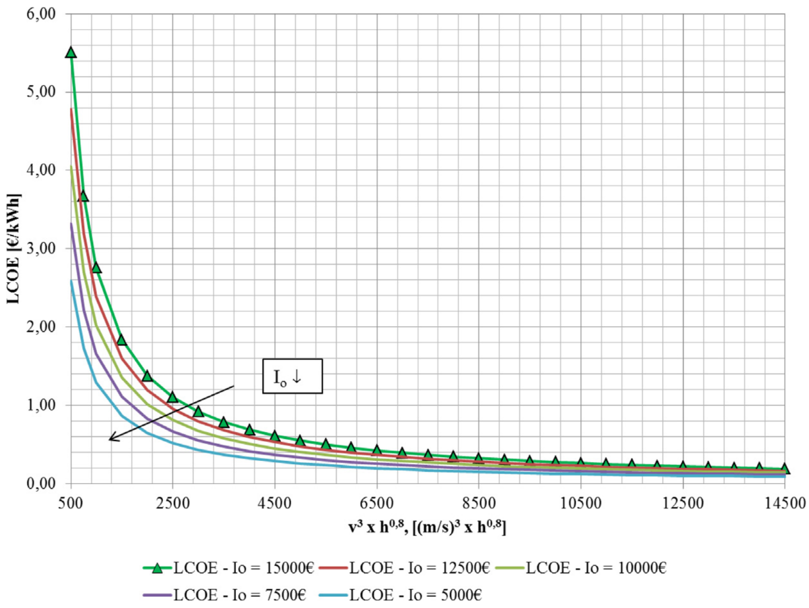

Fig. 14. LCOE of the micro wind technology for different operating conditions. Daily performances of the micro wind turbine were estimated through the interpolating correlation reported in Fig. 13.

of the investment ensures reduction of the final LCOE. The impact of others parameters on LCOE is almost negligible. For example, almost 6 c€/kWh was calculated with a reduction of the initial investment down to 3,750 €, i.e. the 75% of the assumed cost.

Therefore, a robust reduction of the LCOE of the micro-wind turbine can be reached only through a cost reduction. This reduction can be reached through the redesign of the wind system. For example, an easy structure, with no foundation and no heavy pole should be preferred, thus allowing the installation of micro-wind turbine directly on roofs. However, high wind velocities for long periods are an essential condition for the positive feasibility of the installation.

4. Conclusions

The paper deals with more than 12 months of outdoor extensive monitoring activities carried out on a commercial micro-wind turbine at the HEnergia center in Forlì (Italy). The technical performances of the experimental plant have been investigated, and the economic sustainability has been assessed. The results of the experimental campaign show that the investigated technology is not sustainable for an installation site with a very low annual average wind speed such as the one in Forlì, Italy.

However, the measured performances suggest improvements to ensure the economic feasibility also in those context characterized by high wind energy potential. First of all, a crucial aspect to increase the competitiveness of micro-wind turbine lies in the cost reduction as shown by the sensitivity analysis. For example,

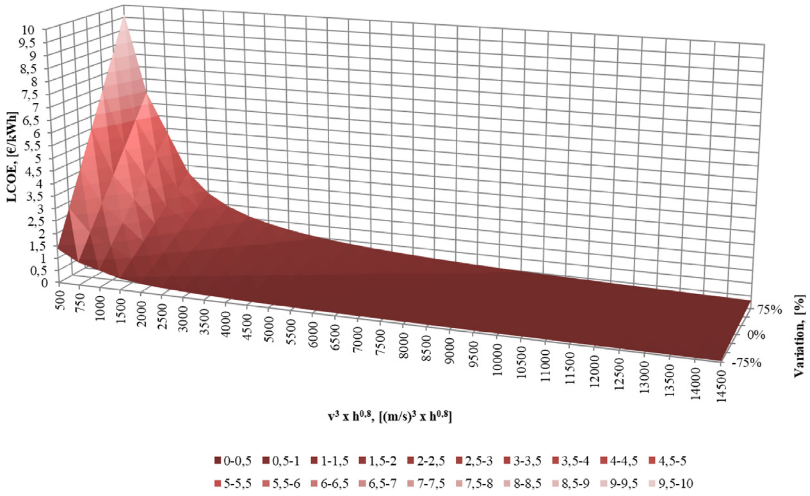

Fig. 15. Sensitivity analysis for different values of the initial investment.

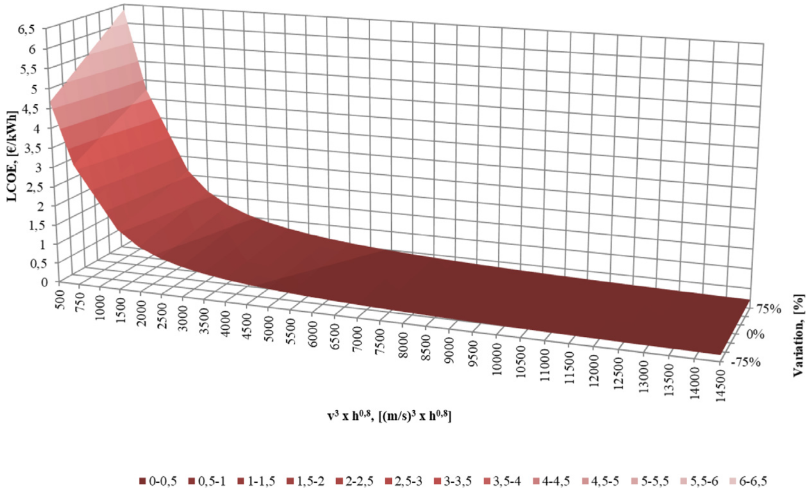

Fig. 16. Sensitivity analysis for different values of the annual maintenance cost.

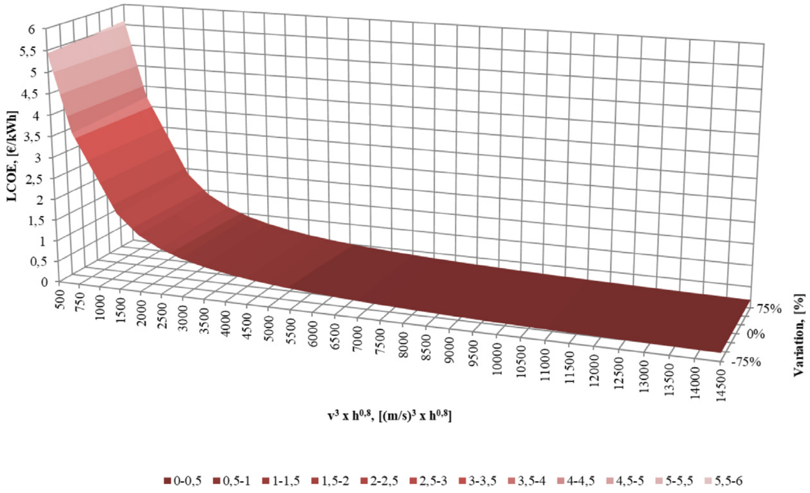

Fig. 17. Sensitivity analysis for different values of the yearly inflation rate.

the LCOE of the micro-wind turbine results equal to about 0.61 €/kWh in the condition of 4500 (m/s)^3 x h$^{0.8}$, corresponding to a velocity of 6 m/s for more than 20 operating hours per day, while a value of 0.15 €/kWh results for a cost reduction up to the 75%. If the first value is quite high if compared with other renewable competing technologies (i.e. PV) or with the purchasing cost of electricity from the grid, the second one can be considered as competitive.

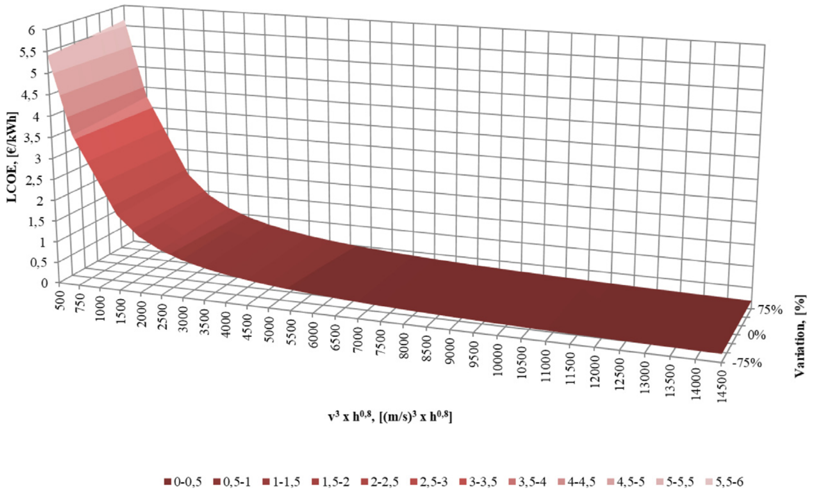

Fig. 18. Sensitivity analysis for different values of the escalation rate.

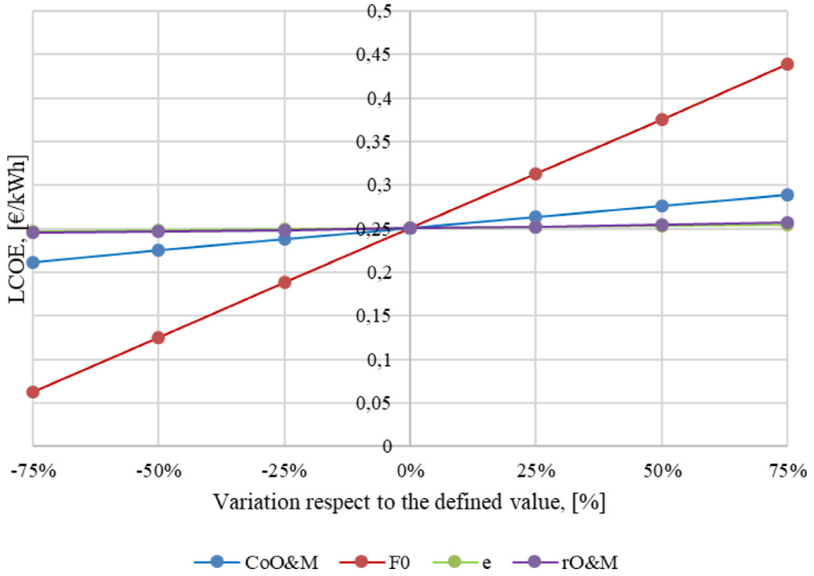

Fig. 19. Sensitivity analysis considering a potential site characterized by 11000 $(\mathrm{m/s})^3$ x $\mathrm{h}^{0.8}$.

Furthermore, it should be noted that the micro-wind turbine currently consume energy every minute for 10 s when wind velocity is lower than the cut-in velocity. However, further experimental work would be required to evaluate the impact on the real performances of this logic. In fact, from the available data of the experimental campaign it is not possible to derive conclusion about how to optimize the control system of the micro-wind turbine since it is not known what will be the efficiency of the plant in case of absence or changes of the installed control system. Even if the energy consumption would be lower, no information is present to define a priori the energy production, so the total efficiency.

Nomenclature

a: Coefficient
A: Wind turbine rotor area [m^2]
b: Coefficient
$C_0^{\mathrm{O\&M}}$: Operation and maintenance costs [€/kWp]
C_p: Power coefficient
$\tilde{C}\mathrm{p}$: Corrected power coefficient
e: Inflation rate [%]
$E_{\mathrm{el,real-day}}$: Real daily electric energy production [J]
$E_{\mathrm{l,expected-day}}$ Estimated daily electric energy production [J]
$E_{\mathrm{el,ideal}}$: Ideal electric energy potential [J]
$E_{\mathrm{el,ideal-day}}$: Ideal daily electric energy potential [J]
$E_{\mathrm{el,y}}$: Annual energy production [kWh/year]
f(v): Density function
F_T: Annual cash flow [Euro]
h: Number of operating hours [h]
HE: HEnergia
i: Discount rate [%]
I_0: Initial investment [€/kWp]
k: Weibull distribution scale factor
LCOE: Levelized Cost Of Energy [€/kWh]
n: Period of investment evaluation [number of years]
N: Number of hours [h]
N_{day} Number of daily producting hours [h]
O&M: Operation and maintenance, [%]
$P_{\mathrm{el,expected}}$: Estimated electrical power downstream the inverter [W]
$P_{\mathrm{el,real}}$: Measured electrical power [W]
p(v): Wind velocity probability, [%]
$r_{\mathrm{O\&M}}$: Operation and maintenance escalation rate [%/year]
t: Time [year]
v: Wind velocity [m/s]

$\bar{v}$: Daily average wind velocity [m/s]
z: Total number of intervals, [#]
λ: Weibull distribution shape factor
ρ: Air density [kg/s]
Δt: Time interval, [s]
η_{global} Global efficiency [%]

CRediT authorship contribution statement

Marco Pellegrini: Conceptualization, Methodology, Writing - review & editing. **Alessandro Guzzini:** Data curation, Visualization, Writing - original draft. **Cesare Saccani:** Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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