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Influence of Building Electric Demands on Performance of a Vertical Axis Micro Wind Turbine in Italy: Energy, Environmental and Economic Numerical Assessment

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ABSTRACT

Vertical axis small-scale wind turbines are gaining popularity because of their capacity to generate electricity from a renewable source by using wind from all directions. In this study, the performance of a commercial Savonius vertical axis micro wind turbine with a rated maximum output of 2200 W have been analyzed through the modeling and simulation environment TRNSYS by varying the served building while installed into 5 different Italian cities. In particular, three typical different building typologies (a single-family dwelling, a small district consisting of 5 single-family dwellings, as well as an office) have been considered and the corresponding electric demands have been developed via an innovative stochastic approach. The climatic conditions have been taken into account by means of detailed weather data files. The building-integrated wind turbine's performance has been contrasted with a reference scenario that corresponds to the same building but uses the central electric grid exclusively. The comparison has been carried out from an energy, environmental, and economic perspective. The findings of simulations indicate that using the wind turbine can cut down the amount of electricity purchased from the central electric grid up to 37.51%, the global equivalent carbon dioxide emissions up to 37.74% and the operating costs up to 85.93%, with a minimum simple pay-back period of 1.09 years.

1. INTRODUCTION

The EU's binding renewable energy objective for 2030 has been raised from the previous aim of 32% to a minimum of 42.5% by the European Commission's updated Renewable Energy Directive [1]. This is a component of the EU's ambitions to reduce net greenhouse gas emissions by at least 55% by 2030 and achieve climate neutrality by 2050 [1]. In particular, the building sector accounts for a relevant global energy consumption (as highlighted by the International Energy Agency [2]). One of the most interesting strategies to lower its primary energy use is to encourage the use of renewable energy sources [3, 4]. Many countries have adopted renewable energy-based technologies to address their ever-growing energy needs by producing clean, inexhaustible energy.

One of the most widely used renewable energy sources worldwide is wind energy [5, 6]. Over the last few decades, the scientific community has shown a great deal of interest in the fast-growing practice of using wind turbines to produce electric power from wind energy [7, 8]. Using the rated output power, they can be categorized as follows: small-scale, medium-scale, and large-scale wind turbines [9]. The International Commission of Electrotechnics has specified limits for the electric output of small-scale wind turbines (SWTs), which are classified as those with a power output between 1 and 50 kW [10]. They are widely used in industrial, agricultural, household, and small-scale commercial contexts. They are located in close proximity to the spot where the energy they create will be consumed and used to meet the on-site load, or they are linked directly to the central electric grid to support its functioning.

Compared to medium- and large-sized wind energy systems, SWTs offer a number of advantages, such as reduced maintenance costs, greater dependability, a broader operating range at wind velocities, the capacity to start at lower wind speeds on their own, a reduction in the amount of space needed for installation, a decreased dependency on central electric grid operation and related transmission lines, reduced investments, etc. Because SWTs may be placed at low elevations in a range of places, including roofs and certain urban areas, they offer a more flexible choice for houses without a large amount of land or a roof facing south for solar panels [11]. Therefore, SWTs may be used and incorporated into urban residential settings. Even with these advantages, there are challenges in the planning, construction, and management of building integrated-SWTs. First and foremost, it should be emphasized that performance of wind turbines is affected by a number of factors, such as installation site and wind velocity; as a result, the unpredictability of wind conditions makes it potentially challenging to supply a continuous and stable source of energy in urban zones [12]. Furthermore, wind turbines in the real world are subjected to sudden changes in wind direction and velocity, but power curves derived by manufacturers do not take such conditions into consideration. The possibility of utilizing SWTs is also highly dependent on other variables, such as the levels and fluctuations of power consumption as well as the modes of export/import of electricity [13].

SWTs may be broadly classified into two categories [13, 14]: (i) vertical axis SWTs (VASWTs); (ii) horizontal axis SWTs (HASWTs). HASWTs rely on the direction of the wind to operate, whilst VASWTs can profit from wind blowing in either direction, making them omnidirectional. VASWTs may be categorized according to the kind of rotor they employ: the drag-based Savonius type and the lift-based Darrieus type. In certain versions, a hybrid Savonius-Darrieus design is also proposed. IEC 61400-2 [15] states that, based on the rated power output and the rotor swept area, SWTs are often divided into three classes, which are shown in Table 1: mini wind turbines (MNWTs), micro wind turbines (MCWTs), and pico wind turbines (PWTs).

Table 1. Small-scale wind turbine classification [15, 16]

Category	Rated Power P_{rated} (kW)	Rotor Swept Area A (m^2)
Mini wind turbines (MNWTs)	7 kW ≤ P_{rated} ≤ 50 kW	A ≤ 200 m^2
Micro wind turbines (MCWTs)	1 kW ≤ P_{rated} ≤ 7 kW	A ≤ 40 m^2
Pico wind turbines (PWTs)	P_{rated} ≤ 1 kW	A ≤ 4.9 m^2

In this study, the operation of a commercial 2200 W vertical axis micro wind turbine placed into five Italian cities (Alghero, Milano, Napoli, Palermo, Roma) have been analyzed via the modeling and simulation environment TRNSYS [17] by varying both the typology of served building as well as the climatic conditions. The adopted software is able to consider that loads are driven by occupants as well as the relationship between electric loads and wind turbine output), in addition to the climatic conditions associated to the installation sites. In particular, in this study three typical different building typologies (a single-family dwelling, a small district of 5 single-family dwellings, an office) have been considered and the corresponding yearly electricity demands have been developed via an innovative tool based on a stochastic approach to assess the effects of load profiles on overall system performance. The operation of the wind turbine integrated into the building has been evaluated against a baseline scenario where the building solely relies on electricity from the central electric grid with the aim of quantifying the impacts in terms of electric energy purchased from the central electric grid, global equivalent carbon dioxide emissions and operational costs.

The following summarizes the study's primary objectives:

(1) assess the potential advantages from environmental, energy and financial aspects associated to adoption of a commercial VAMCWT with respect to a conventional scenario of electricity generation;

(2) analyze the impact of various building electricity requirements and how they interact with the wind turbine's electric generating profile in Italian settings;

(3) consider the effects of weather conditions on the performance of a commercial VAMCWT;

(4) help in spreading the utilization of wind energy-based via VAMCWTs.

In Section 2, the electricity demands of the building, the chosen wind turbine, and the simulation model used, along with the associated climatic data, are analyzed in detail. Section 3 focuses on presenting the outcomes of the simulations. Section 4 provides a comprehensive discussion comparing the performance of the building integrating the SWT to a reference scenario without SWTs, accounting for variations in the building's electrical consumption and the specific Italian city under consideration.

2. ELECTRICITY DEMANDS, COMMERCIAL WIND TURBINE, NUMERICAL MODEL AND CLIMATIC CONDITIONS

The electric demands of the three building typologies considered in this study (Section 2.1), the features of the selected vertical axis micro wind turbine (Section 2.2), the model used for predicting the wind turbine operation according to the corresponding weather data (Section 2.3) are detailed in this section of the paper.

2.1 Building electricity demands

The possibility of using micro wind turbines is highly dependent on the building's planned usage as well as intensity of its power consumption. These factors make it crucial to research and assess how well micro wind turbines operate under various electric load scenarios. In this study, three typical different building typologies have been considered: (i) an office, (ii) a single-family residential dwelling, and (iii) a small district consisting of five different single-family residential dwellings.

The electricity consumption of residential buildings is influenced by numerous factors. To address these problems, the Loughborough University has developed an innovative tool based on stochastic approach [18] allowing to simulate daily electricity demand profiles corresponding to domestic appliances and lighting systems (excluding cooking devices as well as heating, ventilation and air-conditioning (HVAC) systems), without a detailed description of buildings. This tool considers the maximum number of occupants, the number and types of appliances, the day of the week, and the month. It then randomly determines the number of people and activates the lighting and domestic appliance systems. Finally, it calculates the associated electric consumption. Specifically, this tool has been utilized in this study with the assumption that each single-family home would have a maximum of 4 residents and the following household appliances: one refrigerator, one freezer, one iron, one vacuum, one phone, two TVs, one PC, one printer, one microwave, one washing machine, and one dishwashing machine. Figure 1 underlines the yearly electric load of the selected single-family dwelling (resulting from the combination of 365 daily stochastic profiles with an hourly time step), while Figure 2 indicates the values of the yearly electricity demand profile associated to the 5 different single-family dwellings (resulting from the combination of 365 daily stochastic profiles with an hourly time step for each single-family dwelling and then through the superposition of the corresponding 5 yearly stochastic profiles).

The power demand profile due to equipment (printers, monitors, PCs, etc.) and artificial lighting, excluding HVAC units consumption, associated to the office assumed as reference has been defined according to the values suggested by Roselli et al. [19]. Figure 3 describes the yearly electricity demand of the office building; this plot has been derived by considering the 4 different daily electricity profiles (one per season) for weekdays reported in Figure 4 (while the electric load has been considered constant and equal to 250 W during weekends).

Figure 5 reports the electric load-duration diagrams associated to the single-family dwelling, the small district of 5 single-family dwellings, as well as the office investigated in this paper, with all the corresponding values arranged in decreasing order. According to Figures 1-5, the yearly electricity demands of the single-family dwelling, the 5 single-family dwellings and the office assumed as references are 2048.96 kWh, 25423.35 kWh and 7303.64 kWh, respectively, with maximum power demands of 4383 W, 20128 W and 3600 W, respectively.

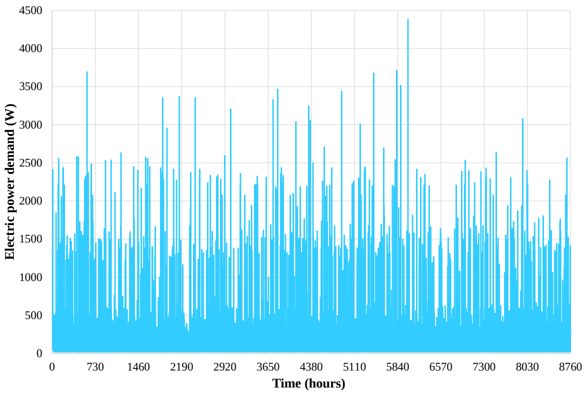

Figure 1. Yearly electricity profile of demand for the single-family dwelling

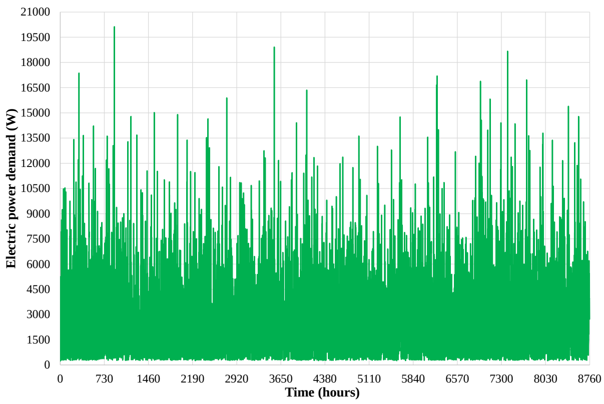

Figure 2. Yearly electricity demand profile of the 5 single-family dwellings

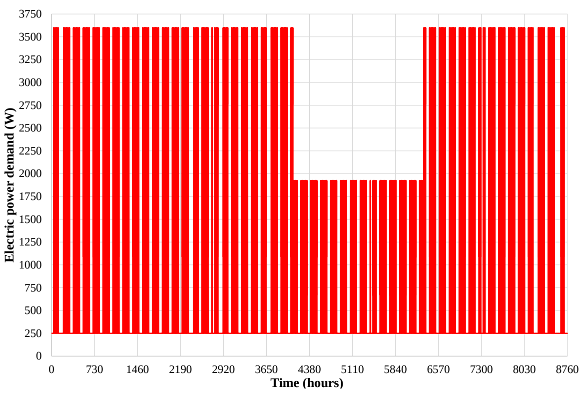

Figure 3. Yearly electricity demand profile of the office

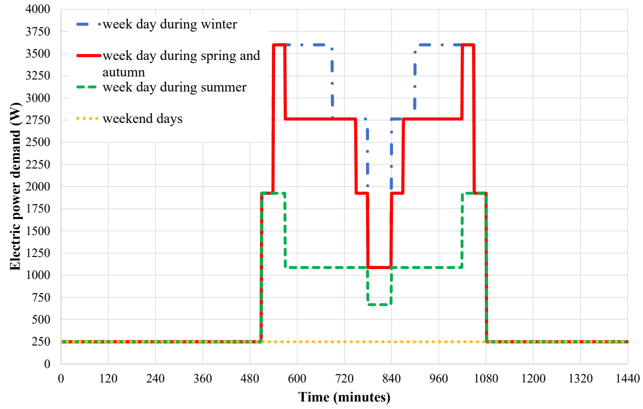

Figure 4. Daily electricity demand profiles of the office [19]

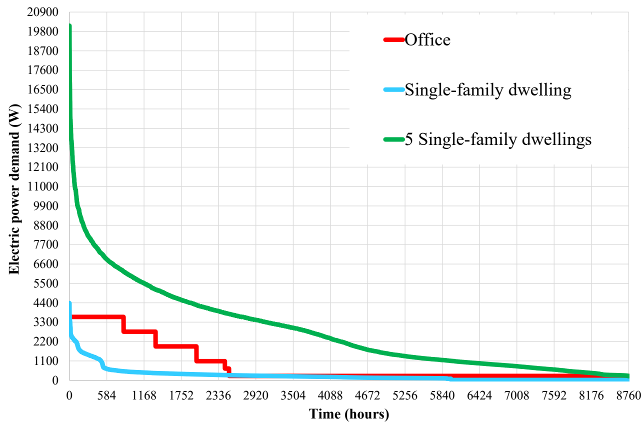

Figure 5. Electric load-duration diagram of the buildings

2.2 Vertical axis micro wind turbine

A commercial Savonius vertical axis micro wind turbine has been considered in the study [20]. Table 2 shows the most important performance parameters of this wind turbine, specifying the blades' number, the rotor diameter, capital cost, tower height, maximum power output, and turbine length. It also displays the start-up wind velocity, which is the lowest speed required to start spinning, even if without electric generation, the cut-in wind velocity, which is the velocity at which electricity production starts, and the cut-off wind velocity, which is the maximum velocity at which the wind turbine can generate useful power.

Table 2. Chosen vertical axis micro wind turbine [20]

Parameter	Value
Number of blades	2
Start-up wind velocity	1.5 m/s
Cut-in wind velocity	2.0 m/s
Cut-off wind velocity	14.0 m/s
Rotor diameter	0.8 m
Capital cost	675.22 €
Tower height	7.0÷12.0 m
Maximum power	2200 W
Turbine length	2.0 m

Figure 6 indicates the performance curve of the selected wind turbine, reporting the generated power according to the wind velocity based on the information provided by the manufacturer [20] in the case of the turbine is installed at a height of 9 m. One single wind turbine has been considered for covering the electric demand of both the single-family dwelling as well as the office, while 5 wind turbines have been used with reference to the case of the 5 single-family dwellings (one turbine per each dwelling). This wind turbine has been selected in order to have a maximum power that can be generated from wind consistent with the yearly electric demands under investigation (i.e., corresponding to about 50%÷60% of the maximum electric load of the selected buildings).

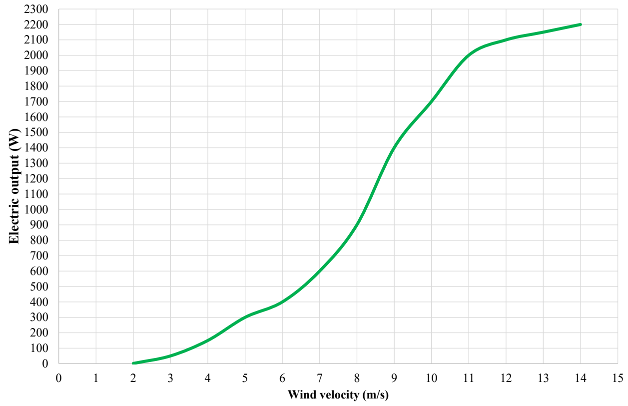

Figure 6. Performance curve of the chosen wind turbine according to manufacturer data

2.3 Simulation model and climatic data

The present study has utilized the version 16 of the TRaNsient SYStems simulation tool (TRNSYS) [17] to model and simulate the performance of the chosen wind turbine under varied building electric demand profiles and environmental data. This software is widely used in the scientific community to model energy systems in detail because it takes into account the transient loads associated to occupants, the part-load characteristics of energy systems, as well as the interactions between thermal/cooling/electric loads of buildings, meteorological data, and outputs of generation systems [21-23]. In TRNSYS, each part of a thermodynamic device is modelled via a component called a "Type" written in FORTRAN code.

In particular, the chosen wind turbine has been modelled in this work by using the TRNSYS Type 90. Six parameters (site elevation, hub height, data collection height, logical unit of the contained power data, number of turbines, and turbine power loss) must be defined for this model. In addition, 6 inputs (control signal, wind velocity, ambient temperature, site shear exponent, barometric pressure and performance curve) to obtain 3 outputs (power output, turbine operating hours and power coefficient).

The turbine power loss and site shear exponent have been considered equal to 0 and 0.26, respectively. The installation height of the turbine has been assumed equal to 9 m above the ground.

The TRNSYS Type 90 requires other specific information, such as outside temperature, wind velocity, atmospheric pressure and site elevation. These parameters are obtained based on the Typical Meteorological Year version 2 weather database (TMY2) [24, 25] by using the Type 15-6 of the TRNSYS platform. This specific "Type" acts as a weather data processor, making it easier to use yearly datasets from an external climate data file. With the use of this "Type", it is possible to include climate parameters specific to different cities, which makes it possible to estimate wind turbine performance accurately. This component reads from a specific EnergyPlus weather data file based on 20-30 years of field measurements [24, 25]. In particular, the following five distinct Italian cities (Alghero, Milan, Naples, Palermo, and Rome) have been considered to account for the diverse climatic conditions prevalent across Italy:

(1) Alghero (longitude: 8° 19' 15.31" E, latitude: 40° 33' 55.48" N);

(2) Milan (longitude: 9° 11' 28.9788" E, latitude: 45° 27' 51.1596" N);

(3) Naples (longitude: 14° 18' 20.0628' E, latitude: 40° 51' 11.8584" N);

(4) Palermo (longitude: 13° 22' 0.0012" E, latitude: 38° 7' 0.0084" N);

(5) Rome (longitude: 12° 29' 46.9176" E, latitude: 41° 54' 10.0152" N).

Figure 7 describes the yearly wind velocity-duration diagrams (with values sorted in descending order) for the selected Italian cities based on the data suggested by the TRNSYS Type 15-6. It is evident that Milan is linked to the lowest yearly mean wind velocity, whilst Palermo is distinguished by the greatest yearly mean wind velocity. The mean yearly wind velocity is 3.19 m/s, 1.10 m/s, 2.48 m/s, 4.24 m/s, 3.19 m/s associated to the cities of Alghero, Milan, Naples, Palermo, Rome, respectively.

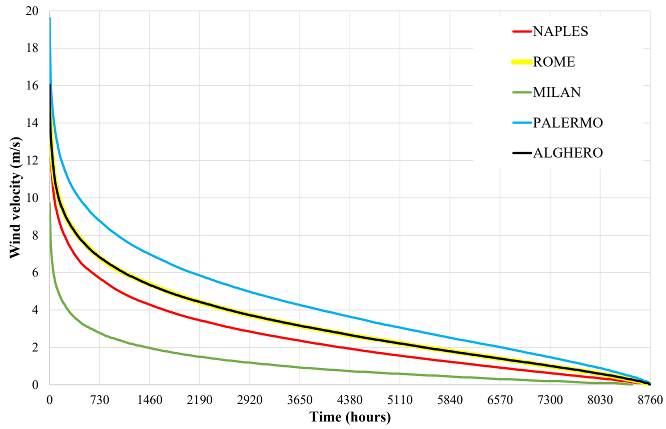

Figure 7. Yearly wind velocity-duration diagrams upon varying Italian cities

3. SIMULATION RESULTS

In this study, the numerical analysis has been carried out over a whole year by adopting a simulation time-step equal to 1 minute. One single wind turbine has been considered for covering the electric demand of both the single-family dwelling as well as the office, while five wind turbines have been used with reference to the case of the five single-family dwellings. This section of the paper describes and discusses the simulation results.

Figure 8 shows how the selected wind turbine serving the single-family house operates in Naples on 15 April by reporting the profiles associated to the building power demand, the wind velocity, the produced power, the power purchased from the central electric grid, and the power sold to the central electric grid.

Figure 9 indicates the yearly electricity energy produced by the selected wind turbine by varying both the city and the end-user. This graph shows that, for a given city, the generation of electric energy is larger with respect to the five single-family dwellings thanks to the utilization of five wind turbines (instead of just one). In addition, it can be noticed that, for a given end-user typology, the electricity production is largest in Palermo (corresponding to the largest yearly mean wind velocity), whilst it assumes the lowest value in Milan (corresponding to the smallest yearly mean wind velocity). In greater detail, the values range from 138.50 kWh to 13698.52 kWh.

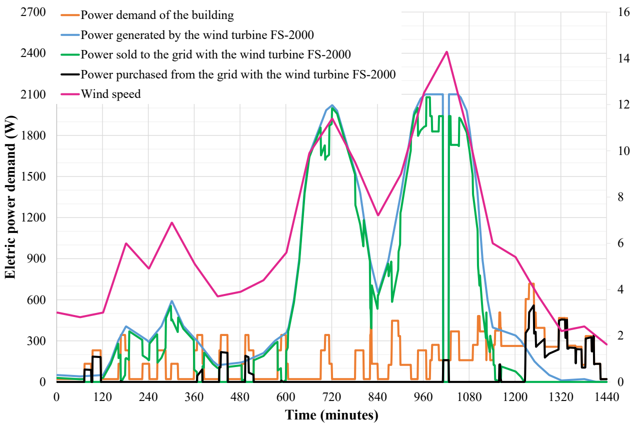

Figure 8. Example of typical daily performance of the wind turbine on 15 April in Naples for the single-family dwelling

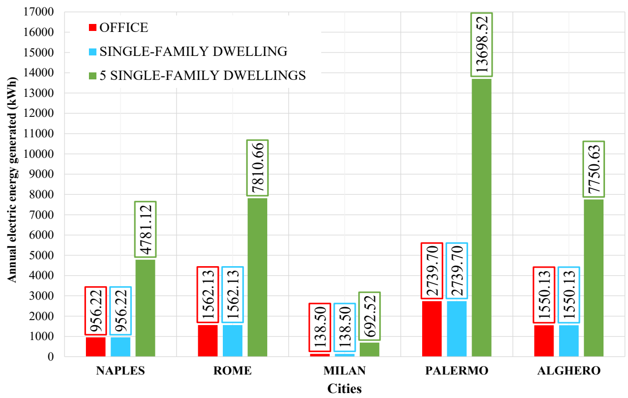

Figure 9. Yearly electric energy produced upon varying both the end-user and the city

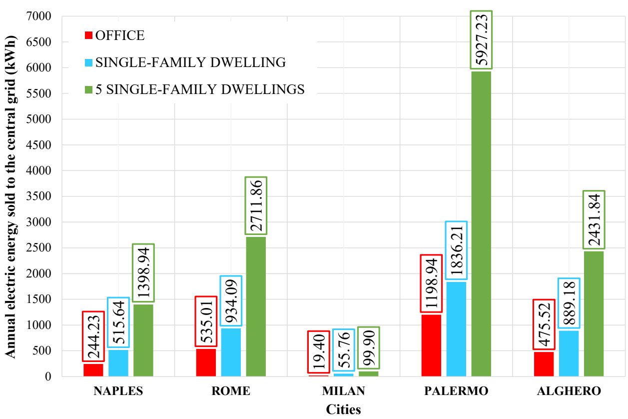

Figure 10. Yearly electricity energy sold to the central electric grid upon varying both the end-user and the city

If the amount of electricity generated exceeds the amount required by the building, the excess is sold to the central power grid as displayed in Figure 10. This figure underlines that, for a given city, the electric energy purchased by the central electric grid is larger for the five single-family dwellings thanks to the utilization of five wind turbines (instead of just one). This figure also underlines the effects of the electric demand profile; in particular, whatever the city is, the amount of electric energy purchased by the central electric grid is maximum in the case of the five single-family dwellings. For a given end-user typology, the electric energy transferred to the central electric grid is maximum in Palermo (corresponding to the largest yearly mean wind velocity), whilst it is lowest in Milan (corresponding to the smallest yearly mean wind velocity). In greater detail, the values in the plot vary from 19.40 kWh to 5927.23 kWh.

It is necessary to buy electricity from the central electric grid to make up the difference between the building's electric consumption and the electricity produced by the wind turbine. The yearly electric energy acquired from the central electric grid upon varying both the city and the end-user in Figure 11. This graph shows that, for a given end-user typology, the quantity of electricity purchased from the central electric grid is greatest in the case of Milan (corresponding to the smallest yearly mean wind velocity) and minimum in the case of Palermo (corresponding to the largest yearly mean wind velocity). The quantity of electricity purchased from the central electric grid is maximum in the case of the five single-family dwellings (this pattern holds true regardless of the city). In particular, this figure shows values ranging from 1505.47 kWh up to 25337.91 kWh.

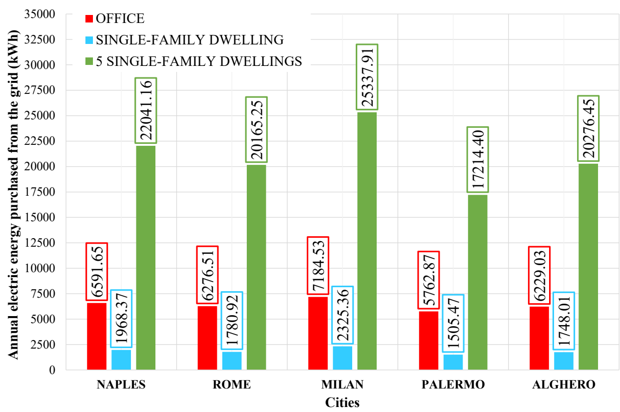

Figure 11. Yearly electricity energy purchased from the central electric grid upon varying both the end-user and the city

4. PROPOSED SYSTEMS VS. REFERENCE SCENARIO

The performance of the reference scenario, which corresponds to the case where the end-user is using only the central electric grid (excluding electricity generated from the wind turbine), has been compared with that of the scenario proposed in this study (where the end-user is served by both the wind turbine and the central electric grid). Energy, environmental, and economic analyses have been conducted with the aim of determining potential effects on primary energy demand, equivalent global carbon dioxide emissions, and operational costs. Therefore, the feasibility of the suggested system in comparison to the conventional scenario has also been evaluated.

4.1 Energy analysis

The following formula has been used to determine the percentage difference ΔE_{el} between the yearly electric energy $E_{el,imp}^{PS}$ purchased from the central electric grid in the suggested scenario (integrating the wind turbine) and the yearly electric energy $E_{el,imp}^{RS}$ purchased from the central electric grid in the case of the reference scenario (without electricity produced by the wind turbine):

$$\Delta E_{el} = \frac{E_{el,imp}^{PS} - E_{el,imp}^{RS}}{E_{el,imp}^{RS}} \quad (1)$$

The values of ΔE_{el} are shown in Figure 12 by varying both the city and the end-user. All of the values shown in this plot are negative, indicating that, regardless of the end-user type or city, the suggested scenario (integrating the wind turbine) permits a reduction in the amount of electricity purchased from the central electric grid in comparison to the baseline scenario (without the utilization of the wind turbine). In particular, this graph underlines that, for a given Italian city, the worst values of ΔE_{el} are obtained in the case of the office, while the best values of ΔE_{el} correspond to the single-family dwelling. In addition, it can be noticed that, for a given end-user typology, the best results are achieved in the case of the wind turbine operates in Palermo (corresponding to the largest yearly mean wind velocity), whilst the worst data correspond to Milan (corresponding to the smallest yearly mean wind velocity). In greater detail, the use of the wind turbine reduces the electric energy purchased from the central electric grid between a minimum of -1.63% (for the office located in Milan) and a maximum of -37.51% (for the single-family dwelling in Palermo).

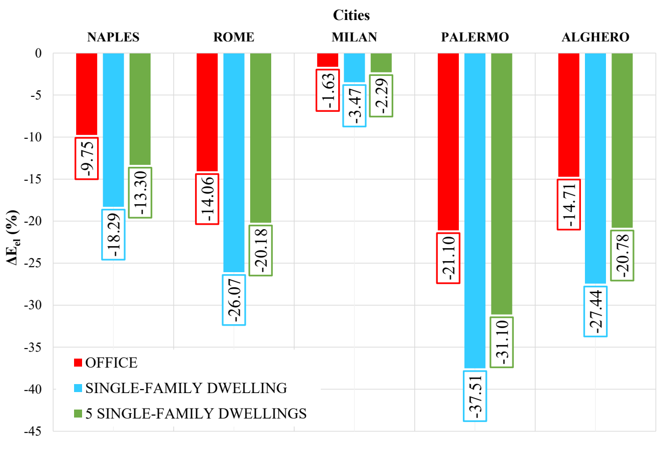

Figure 12. ΔE_{el} by varying both the end-user and the city

4.2 Environmental analysis

The energy output-based emission factor technique proposed by Chicco and Mancarella [26] has been used in this study to evaluate the environmental impact. This method allows one to compute the global equivalent mass m_x of a specific pollutant x released during the production of the energy output E as follows:

$$m_x = u_x^E \cdot E \quad (2)$$

where, u_x^E is the specific emission of x per unit of E (known as energy output-based emission factor). The carbon dioxide emission factor corresponding to the production of electricity in Italy $u_{co_2}^{Eel}$ depends on the day, the time of the day, as well as the location. Figure 13 describes the values of this factor suggested in the study [27] with reference to the Italian cities considered in this research.

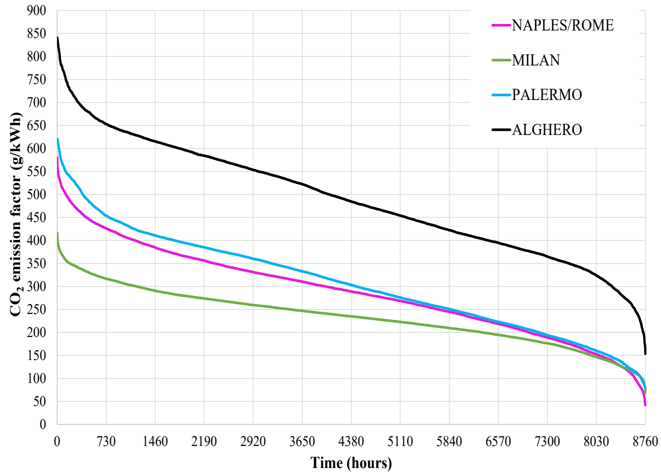

Figure 13. Carbon dioxide emission factor upon varying both city and time

The following formula has been adopted in this study for calculating the percentage difference ΔCO_2 between the global equivalent carbon dioxide emissions CO_2^{PS} corresponding to the proposed scenario (integrating the wind turbine) and the global equivalent carbon dioxide emissions CO_2^{RS} corresponding to the baseline scenario (excluding electricity produced by the wind turbine):

$$\Delta CO_2 = \frac{CO_2^{PS} - CO_2^{RS}}{CO_2^{RS}} = \frac{u_{CO_2}^{Eel} \cdot E_{el,imp}^{PS} - u_{CO_2}^{Eel} \cdot E_{el,imp}^{RS}}{u_{CO_2}^{Eel} \cdot E_{el,imp}^{RS}} \quad (3)$$

where, $u_{CO_2}^{Eel}$ is the carbon dioxide emission factor of the electric energy purchased from the central electric grid when the proposed scenario ($E_{el,imp}^{PS}$) or the reference scenario ($E_{el,imp}^{RS}$) is considered during the simulation time, whit a simulation time step equal to 1 minute. The values of $u_{CO_2}^{Eel}$ by varying both the end-user type and the installation city are shown in Figure 14; since every number in this figure is negative, the suggested scenario reduces global equivalent carbon dioxide emissions with respect to the reference case, regardless of the end-user type or city. Moreover, this plot shows that, for a selected city, the worst values of ΔCO_2 are obtained in the case of the office, while the best values of ΔE_{el} correspond to the single-family dwelling. In addition, it can be noticed that, for a specified end-user typology, the best results are achieved in the case of the wind turbine operates in Palermo (thanks to the highest yearly mean wind velocity), whilst the worst data are related to Milan (due to the lowest yearly mean wind velocity). In greater detail, the adoption of the wind turbine reduces the global equivalent carbon dioxide emissions from a minimum of -1.54% (when the office is located in Milan) up to a maximum of -37.74% (when the single-family dwelling is in Palermo).

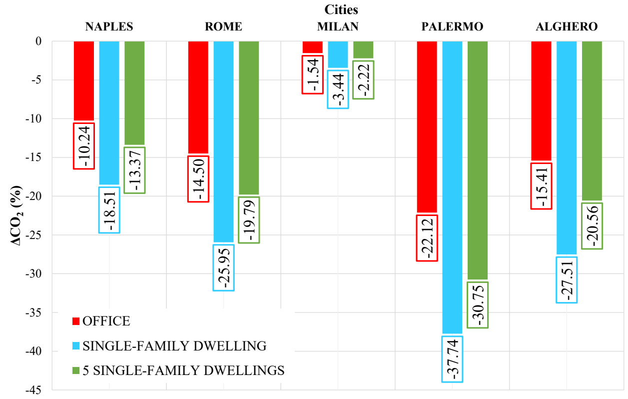

Figure 14. ΔCO_2 upon varying both the end-user and the city

4.3 Economic analysis

In this study the following formula has been considered in order to assess the percentage difference ΔOC between the operational costs OC^{PS} (corresponding to the electricity purchased from the central electric grid) of the suggested scenario (integrating the wind turbine) and the operational costs OC^{RS} (corresponding to the electricity purchased from the central electric grid) of the baseline scenario (excluding electricity produced by the wind turbine):

$$\Delta OC = \frac{(OC^{PS} - REV_{el}) - OC^{RS}}{OC^{RS}} = \frac{(UC_{el,imp} \cdot E_{el,imp}^{PS} - UC_{el,sold} \cdot E_{el,sold}^{PS}) - UC_{el,imp} \cdot E_{el,imp}^{RS}}{UC_{el,imp} \cdot E_{el,imp}^{RS}} \quad (4)$$

where, REV_{el} represents the yearly revenues obtained via the electricity sold to the central electric grid $E_{el,sold}^{PS}$ in the case of the proposed scenario, while $UC_{el,sold}$ and $UC_{el,imp}$ are, respectively, the unit price of electric energy sold to the central electric grid and the unit cost of electricity purchased from the central electric grid; the values of $UC_{el,sold}$ and $UC_{el,imp}$ have been considered equal to 0.19 €/kWh and 0.26 €/kWh, respectively, based on the current situation of the electric market in Italy [28, 29].

The calculated operating costs correspond to the electric energy purchased from the central electric grid to cover the end-user demands (not covered by the wind turbine production). Figure 15 highlights the values of *ΔOC* upon varying both the end-user type and the installation city. Whatever the end-user type and the city are, the proposed scenario always enables lower operating costs than the reference scenario taking into account that every number in this figure is negative. This figure underlines that, for a given city, the worst values of Δ*OC* are obtained in the case of the office, whilst the best values of Δ*OC* correspond to the single-family dwelling. In addition, it can be noticed that, for a given end-user typology, the best results are achieved in the case of the wind turbine operates in Palermo (corresponding to the largest yearly mean wind velocity), whilst the worst data are associated to Milan (corresponding to the smallest yearly mean wind velocity). In greater detail, the installation of the wind turbine decreases the operational costs between -1.82% (when the office is located in Milan) and -85.93% (when the single-family dwelling is in Palermo). Utilizing the wind turbine reduces operational costs in contrast with the reference scenario, but it also necessitates an additional investment cost.

The parameter "simple pay-back period (SPB)" refers to the amount of time that can be used to recoup the additional original expenditure, given a decrease in running expenses and income from selling power to the central electric grid. In this paper, the values of SPB have been obtained by using the following equation:

$$SPB = \frac{WT^{CC}}{(OC^{PS} - OC^{RS}) + REV_{el}} = \frac{WT^{CC}}{(OC^{PS} - OC^{RS}) + E_{el,sold}^{PS} \cdot \mathrm{UC}_{el,sold}} \quad (5)$$

where, WT^{CC} represents the amount of money required to purchase the wind turbine.

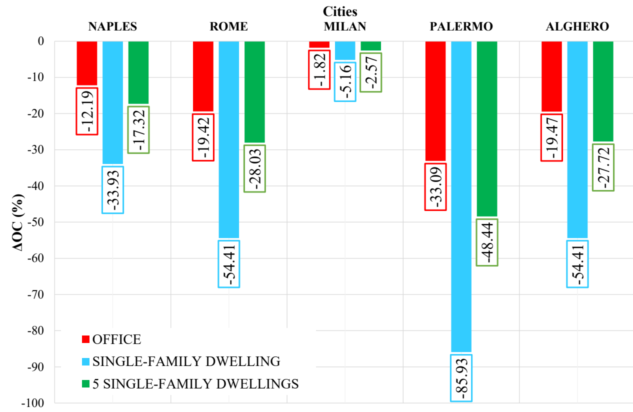

Figure 15. Δ*OC* upon varying both the end-user and the city

Figure 16 describes the values of SPB upon varying both the end-user and the city. This graph underlines that SPB varies from 1.09 years (when the office is located in Palermo) to 21.17 years (when the single-family house is in Milan). It demonstrates that all the proposed scenarios are feasible from a financial perspective, taking into account that SPB is less than the lifetime of the wind turbine (corresponding to roughly twenty to twenty-five years).

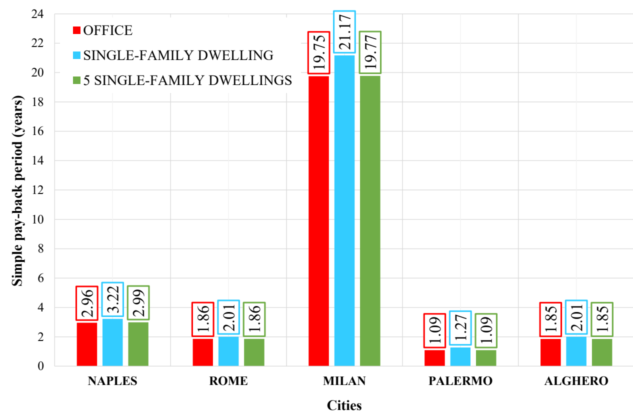

Figure 16. SPB upon varying both the end-user and the city

5. CONCLUSIONS

This study examined the effectiveness of a commercial 2200 W vertical axis micro wind turbine installed in five different Italian cities (Alghero, Milan, Naples, Palermo, Rome) using the TRNSYS simulation platform (version 16).

The analysis considered variations in building types and climate conditions. The study explored three typical building types (single-family homes, small clusters of five single-family homes, and offices). By comparing the turbine-integrated building performance with a scenario where the building solely relies on grid electricity, the study quantified the potential effects in terms of purchased electricity, global equivalent carbon dioxide emissions, and operational costs. This study underlined the need to fully consider the correlation between electric demand and electric generation profile in assessing the performance of SWTs. In particular, the simulation results indicated that, for a given city, the worst results are obtained in the case of the office, while the best performance corresponds to the single-family dwelling. In addition, the study highlighted that, for a given end-user typology, the best results can be achieved when the wind turbine operates in Palermo (Italian city corresponding to the largest yearly mean wind velocity), whilst the worst data are associated to Milan (Italian city corresponding to the smallest yearly mean wind velocity). The potential reductions of electricity purchased from the central electric grid, global equivalent carbon dioxide emissions and operational costs, respectively, are in the ranges 1.63%÷37.51%, 1.54%÷37.74%, and 1.82%÷85.93%. The corresponding simple pay-back period varies between 1.09 and 21.17 years.

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