



## Vertical vs. Horizontal Axis Small-Scale Wind Turbines Serving a Typical House in Italy and Norway: Numerical Energy, Environmental and Economic Assessments

Antonio Rosato<sup>1</sup> , Achille Perrotta<sup>1\*</sup> , Tania Bracchi<sup>2</sup> , Luigi Maffei<sup>1</sup> 

<sup>1</sup> Built Environment Control Laboratory RIAS, Department of Architecture and Industrial Design, University of Campania Luigi Vanvitelli, Aversa 81031, Italy

<sup>2</sup> Faculty of Engineering, Department of Energy and Process Engineering, Norwegian University of Science and Technology, Trondheim 7004, Norway

Corresponding Author Email: [achille.perrotta@unicampania.it](mailto:achille.perrotta@unicampania.it)

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### ABSTRACT

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*small-scale vertical wind turbines, small-scale horizontal wind turbines, TRNSYS, renewable energy sources, energy efficiency in buildings*

The performance of three commercial small-scale wind turbines (SWTs) serving a typical house have been analyzed via the software TRNSYS upon varying the climatic conditions of 5 Italian and 3 Norwegian cities. A Savonius vertical axis SWT (power output of 2100 W at 12 m/s and rotor swept area equal to 1.60 m<sup>2</sup>) has been compared with two horizontal axis SWTs, the first one characterized by the same power output at 12 m/s (but 3.8 times larger rotor swept area) and the second one with almost equal rotor swept area (but 6.8 times lower power output at 12 m/s). The selected SWTs have been compared with a baseline scenario where the same building is served by the central electric grid only from energy, environmental and economic points of view. The simulations highlighted that the vertical axis SWT produces 1.05÷11.54 times larger annual electric energy than the horizontal axis SWTs. The data also underlined that, with respect to the baseline scenario, the selected SWTs reduce annual electric energy imported from grid (up to 37.5%), the equivalent global CO<sub>2</sub> emissions (up to 37.8%) and the operating costs (up to 112%), with a minimum simple payback period of 2.8 years.

## 1. INTRODUCTION

Fossil fuel usage and greenhouse gas emissions are increasing, and the International Energy Agency has highlighted that residential applications account for the bulk of global energy consumption [1]. EU members must guarantee that average energy demand of residential sector decreases by at least 16% by 2030 (based on the new Energy Performance of Buildings Directive). With reference to this perspective, it is well known that promoting the utilization of renewable sources is one of the most promising approaches to reduce primary energy demand and mitigate climate change [1, 2]. Many nations enhanced the adoption of technologies based on renewable sources in order to produce clean energy to meet their increasing demands. Wind energy is among the most widely used renewable sources [2]. One of the renewable energy source-based solutions that is rapidly gaining a lot of attention from the scientific community in recent decades is the use of wind turbines (WTs) to convert wind energy into power [2-4]. Rated power output of WTs is generally used for their categorization as follows [5]: (i) small-scale WTs, (ii) medium-scale, (iii) large-scale WTs. Small-scale wind turbines (SWTs) are those having an electric output up to 50 kW together with a rotor swept area (i.e., the area within which a wind turbine's blades rotate) lower than 200 m<sup>2</sup>, according to the study [6]. SWTs are situated near or on the "customer" side of the area where the power they generate is utilized. SWTs

are often used in small-scale commercial, industrial, and agricultural contexts; however, because they can be installed even in certain urban areas, they are also a good choice for homeowners [3, 5]. They can be utilized to meet the on-site load or directly connected to the central grid. Additionally, they may be used in hybrid energy systems that integrate other technologies (like different energy conversion units, batteries, etc.). Compared to large- and medium-scale WTs, SWTs can offer a number of potential advantages, such as reduced maintenance costs, improved reliability, a greater range of wind speeds at which they can operate, a smaller installation space requirement, less dependence on grid-connected power and long transmission lines, lower capital costs, etc; SWTs might therefore be used and incorporated into urban residential settings. Even with these possible advantages, building-integrated SWTs can be difficult to design and efficiently run. First and foremost, it should be considered that the potential of SWTs is dependent on various factors, such as wind speed and installation site. From this perspective, the presence of various physical obstacles, such as buildings and trees, can make it challenging to create a consistent energy source in urban settings [3, 5, 7]. Additionally, a real SWT is exposed to wind that abruptly changes speed and/or direction; manufacturers' power curves typically do not take into account such transient operation and related efficiency losses. The performance of SWT may be significantly impacted by these factors [3, 5, 7, 8]. SWTs may be broadly categorized into two main categories

[9]: (i) vertical axis small-scale wind turbines (VASWTs); and (ii) horizontal axis small-scale turbines (HASWTs). VASWTs are distinguished by an axis of rotation that is perpendicular to the wind flow, whereas HASWTs have an axis of rotation that is parallel to the wind flow. HASWTs rely on the direction of the wind to function, but VASWTs are omnidirectional in their operation taking into account that they can use wind from any direction [9, 10]. Based on the rotor type, VASWTs may be categorized into two sub-categories [11]: the drag-based Savonius models and the lift-based Darrieus models. A hybrid Savonius-Darrieus design can be also recognized. It can be highlighted that there are very few scientific studies in the literature that have compared vertical and horizontal SWTs with the same rotor swept area or rated electrical power. For example, Fadil and Ashari [12] compared a VASWT with a HASWT (not commercial models) characterized by the same rotor swept area ( $3.14 \text{ m}^2$ ) and blades (3); they found a maximum power output of 1363.6 W and 505.69 W, respectively, for the HASWT and the VASWT.

In this work, the performance of the following 3 commercial SWTs have been analyzed:

- a Savonius VASWT with a rated output of 2100 W (at 12 m/s) and swept area equal to  $1.60 \text{ m}^2$  [13];
- a HASWT with a rated output of 2100 W (at 12 m/s) and swept area equal to  $6.15 \text{ m}^2$  [14];
- a HASWT with a rated output of 307 W (at 12 m/s) and swept area equal to  $1.43 \text{ m}^2$  [15].

The above-mentioned VASWT has been selected taking into account that its performance has been already analyzed by the authors in previously published scientific papers [16-18], where its energy, environmental and economic suitability have been demonstrated. The other two SWTs have been considered in this study with the aim of compare the performance of the selected VASWT with a HASWT characterized by the same power output at 12 m/s (but 3.8 times larger rotor swept area) as well as with a HASWT characterized by a very similar (differing by about 10%) rotor swept area (but 6.8 times lower power output at 12 m/s). The performance of the above-mentioned SWTs have been assessed via the dynamic TRAnsient SYStems simulation tool (TRNSYS) [19] (version 18) while serving the same typical single-family house (assumed as reference) upon varying the locations; in particular, 5 different cities in Italy (Alghero, Milan, Naples, Palermo, Rome) and 3 Norwegian cities (Bergen, Karasjok, Tromsø) have been considered. The annual power demand profile associated to the operation of lighting systems and domestic appliances of the house has been defined via a stochastic tool [20]; in addition, wind velocity profiles corresponding to urban settings have been considered by means of a specific TRNSYS mathematical model. The energy, environmental and economic performance of the building-integrated SWTs have been contrasted with that of one of a baseline scenario (where the electric demand of the same house is totally covered by the central grid only) with the aim of assessing the potential benefits in terms of imported electric energy, equivalent global  $\text{CO}_2$  emissions as well as operating costs. The simple payback period has been also evaluated. The main goals of the paper can be summarized as reported below:

- compare the performance of a commercial VASWT with those associated to commercial HASWTs characterized by the same power output at 12 m/s or similar rotor swept area upon varying the boundary conditions in order to assess suitability of the vertical axis SWTs with respect to horizontal axis SWTs;

- evaluate the potential energy, economic, and environmental benefits of using horizontal and vertical axis SWTs in comparison to a traditional scenario (without the use of SWTs);
- assess the impact of climatic conditions on the operation of building-integrated horizontal and vertical axis SWTs;
- encourage the adoption and diffusion of energy systems based on the use of horizontal and vertical axis SWTs to harness renewable wind energy.

Section 2 details the electric load profile of the building, the selected SWTs' models, as well as the simulation model and the corresponding climatic data used for running the simulations; Section 3 reports the simulations results, while Section 4 compares the energy, environmental and economic performance of the selected SWTs with respect to a baseline scenario without SWTs.

## 2. ELECTRIC LOAD PROFILE, SMALL-SCALE WIND TURBINES, SIMULATION MODEL AND CLIMATIC CONDITIONS

This section of the paper describes the electric demand of the residential building assumed as reference (Section 2.1), the characteristics of the selected horizontal and vertical SWTs (Section 2.2), as well as the mathematical models adopted for simulating the SWTs as well as the climatic conditions (Section 2.3).

### 2.1 Building electric demand

It is commonly recognized that a wide range of factors influence how much electricity homeowners use. In order to predict the corresponding daily electric energy demand profiles linked to the operation of lighting systems and household appliances, an original tool created by Loughborough University based on a stochastic method [20] has been applied in this work. The maximum number of occupants, the day of the week or weekend, the month of the year, and the quantity and kind of household appliances can all be used to generate these daily profiles. The electric demand for cooking appliances, water heating, and air conditioning systems is not taken into consideration by this tool. The associated daily electric profile is then computed based on the actual number of people and the random activations of the lighting and household appliances. Profiles that may be regarded as representative of common homes can be obtained using this method [21]. In this study, in particular, a maximum of 4 people is assumed and the most commonly used domestic appliances have been considered. The annual electric demand of the house considered assumed as reference in this study has been defined by combining 365 different daily electric demand profiles obtained via the above-mentioned tool [20] with a time-step equal to 1 minute. Figure 1 reports both the annual electric demand profile as a function of the time (black curve) as well as the corresponding electric load-duration diagram with the values sorted in descending order (red curve). The annual electric energy required by the building assumed as reference is 2408.96 kWh.

### 2.2 Wind turbines

Three commercial SWTs (a Savonius SWT with vertical axis [13], and two SWTs with horizontal axis [14, 15]) have

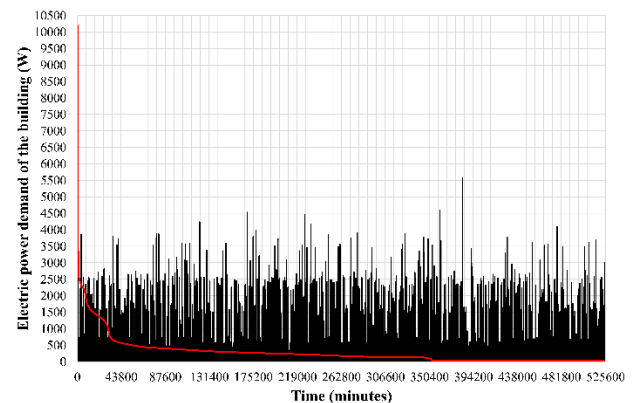
been investigated in this work. Table 1 reports the axis type (horizontal or vertical), manufacturer, model, power output at 12 m/s, rotor swept area, rotor diameter, blades height (for the VASWT only), number of blades, cut-in wind speed (i.e., the minimum wind speed at which the SWTs begin providing an usable electric power), cut-out wind speed (i.e., the highest wind speed at which the SWTs are intended to produce useable electric energy), and capital cost of the selected SWTs. The rotor swept area of the HASWTs is given as  $\pi R^2$  (where R is the rotor radius), while for the Savonius VASWT it is calculated as  $DH$  (where D is the rotor diameter (equal to 0.80 m) and H is the blades height (equal to 2.0 m)) [12]. This table indicates that the rotor swept area of the HASWT FK-2000 is 3.8 and 4.3 times larger than that one of the VASWT FS-2000 and the HASWT ATO-WT-NE-300S5, respectively. Figure 2 reports the power curves of the selected SWTs according to the data provided by the manufacturers; these curves show the operating ranges of both wind speed (from the cut-in up to the cut-out) and power output of the SWTs. This figure shows that:

- for a given wind speed, the HASWT ATO-WT-NE-300S5 generates much less power than the other two SWTs;
- the HASWT FK-2000 produces more electric output than the VASWT FS-2000 in the wind speed range between about 6.5 and 11 m/s.

### 2.3 Simulation model and climatic data

The TRaNsient SYStems simulation tool (TRNSYS) [19] (version 18) has been adopted in this paper in order to model and simulate the SWTs performance and related climatic

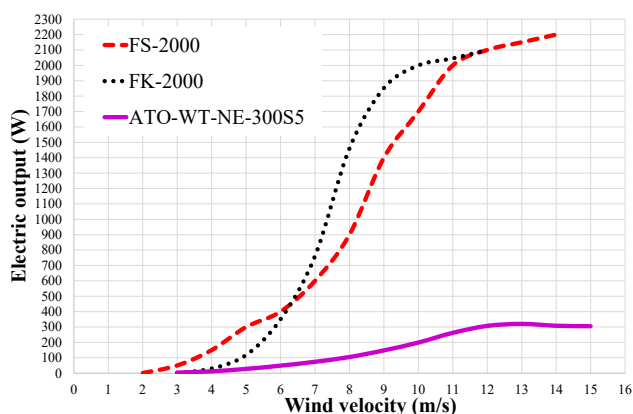
conditions. Taking into account that it considers the part-load operation of the energy conversion systems as well as the interactions between electric demand and generation, the platform TRNSYS is usually utilized by the scientific community [22-24]. The TRNSYS library includes a number of mathematical models (called “Types”). In this work, the TRNSYS Type 90 has been considered to model and simulate the performance of the SWTs. This model needs the definition of some parameters (site elevation, data collection height, hub height, turbine power loss) and inputs (wind velocity, ambient temperature, site shear exponent, barometric pressure, control mode, rotor height, rotor diameter, sensor height, turbulence intensity, air density, power rated, speed rated, power curve).



**Figure 1.** Annual electric demand profile and load-duration profile of the residential building

**Table 1.** Selected SWTs

|                                    | VASWT [13] | HASWT [14] | HASWT [15]      |
|------------------------------------|------------|------------|-----------------|
| Axis type                          | Vertical   | Horizontal | Horizontal      |
| Manufacturer                       | FLTXNY     | FLTXNY     | ATO             |
| Model                              | FS-2000    | FK-2000    | ATO-WT-NE-300S5 |
| Power output at 12 m/s (kW)        | 2.100      | 2.100      | 0.307           |
| Rotor swept area (m <sup>2</sup> ) | 1.60       | 6.15       | 1.43            |
| Rotor diameter (m)                 | 0.80       | 2.80       | 1.35            |
| Blades height (m)                  | 2.0        | -          | -               |
| Blades number                      | 2          | 3          | 3               |
| Cut-in wind speed (m/s)            | 2          | 3          | 3               |
| Cut-out wind speed (m/s)           | 14         | 12         | 15              |
| Capital cost (€)                   | 684.39     | 535.72     | 334.52          |



**Figure 2.** Power curves of the selected SWTs [13-15]

According to the above-mentioned parameters/inputs, the model allows to calculate 3 outputs (power output, power coefficient and time of continuous wind turbine operation).

Table 2 summarizes the values assumed in this study for the parameters and inputs of the TRNSYS Type 90 for the SWTs. The SWTs power loss has been considered equal to 0, while a site shear exponent of 0.26 has been adopted with the aim of modelling the scenario corresponding to obstructed airflows (according to the study [25]). The option “P” (i.e., pitched-control) has been selected as control mode for both the HASWTs FK-2000 and ATO-WT-NE-300S5 taking into account that the initial outward pitching manoeuvre serves to reduce the blade’s effective angle of attack, delay the moment when the critical static stall angle is exceeded, and reduce the maximum effective angle of attack [26]. The turbulence intensity is a dimensionless number defined as the standard deviation of wind speeds within a simulation time step divided by the average wind speed over that simulation time step; in this study a value of 10% [27] has been assumed as turbulence intensity, whatever the SWT model is. The weather conditions (site elevation, wind velocity, ambient temperature as well as barometric pressure) required by the TRNSYS Type 90 have

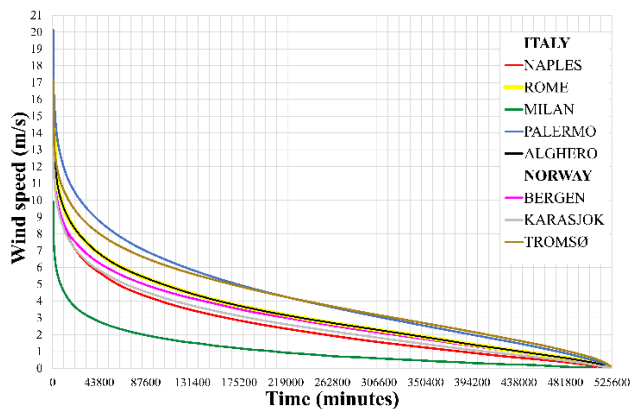
been set based on the Typical Meteorological Year version 2 weather database (TMY2) [28] via the TRNSYS Type 15-6. This Type is a weather data processor reading an external weather data file and providing climate conditions representative of the selected cities. In this paper, 5 cities in Italy (Alghero, Milan, Naples, Palermo, Rome) and 3 cities in Norway (Bergen, Karasjok, Tromsø) have been considered as installation sites for the SWTs to take into account the influence of different climatic scenarios on SWTs performance. These cities are characterized by the following

coordinates: Alghero (latitude 40° 33' 55.48" North, longitude 8° 19' 15.31" East); Milan (latitude 45° 27' 51.1596" North, longitude 9° 11' 28.9788" East); Naples (latitude 40° 51' 11.8584" North, longitude 14° 18' 20.0628" East); Palermo (latitude 38° 7' 0.0084" North, longitude 13° 22' 0.0012" East); Rome (latitude 41° 54' 10.0152" North, longitude 12° 29' 46.9176" East); Bergen (latitude 60° 23' 34.4736" North, longitude 5° 19' 27.7788" East); Karasjok (latitude 69°28' 18" North, longitude 25° 30' 40" East); Tromsø (latitude 69° 39' 0.9108" North, longitude 18° 59' 42.4140" East).

**Table 2.** Parameters and inputs of the TRNSYS type 90

|                                         | FS-2000                                                                                                   | FK-2000 | ATO-WT-NE-300S5 |
|-----------------------------------------|-----------------------------------------------------------------------------------------------------------|---------|-----------------|
| Site elevation (m)                      | 72 (Naples), 3 (Rome), 211 (Milan), 34 (Palermo), 40 (Alghero), 12 (Bergen), 129 (Karasjok), 102 (Tromsø) |         |                 |
| Data collection height above ground (m) | 10                                                                                                        | 9       | 9               |
| Hub height above ground (m)             | 9                                                                                                         | 9       | 9               |
| Turbine power loss (%)                  | 0                                                                                                         | 0       | 0               |
| Site shear exponent                     | 0.26                                                                                                      | 0.26    | 0.26            |
| Rotor height above ground (m)           | 9                                                                                                         | 9       | 9               |
| Rotor diameter (m)                      | 0.80                                                                                                      | 2.80    | 1.35            |
| Sensor height (m)                       | 10                                                                                                        | 9       | 9               |
| Turbulence intensity (%)                |                                                                                                           |         | 10              |
| Air density (kg/m <sup>3</sup> )        |                                                                                                           |         | 1.225           |
| Power rated (W)                         | 2100                                                                                                      | 2100    | 307             |
| Speed rated (m/s)                       | 12                                                                                                        | 12      | 12              |

Figure 3 reports the annual wind velocity-duration diagrams upon varying the city (according to study [28]), with the data in descending order. This plot indicates that Palermo is characterized by the largest average annual wind speed (4.24 m/s), while the minimum average annual wind velocity (1.14 m/s) corresponds to the city of Milan.



**Figure 3.** Annual wind velocity-duration diagrams

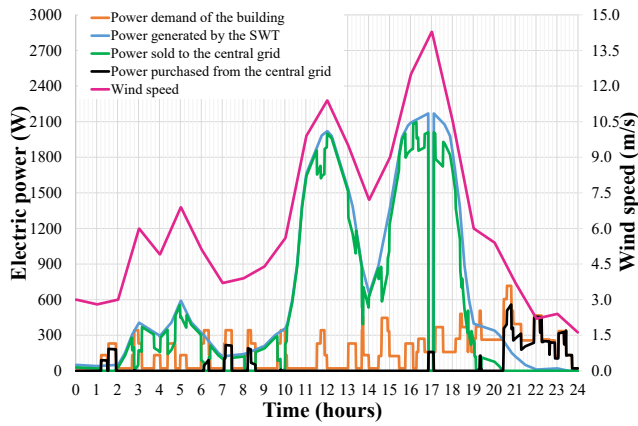
### 3. SIMULATION RESULTS

The simulations have been carried out with a simulation time-step of 1 minute over an entire year. The outputs are described in this section. Figure 4 shows an example of daily operation of one of the selected SWTs (VASWT FS-2000) operating in one of the selected cities (Naples) during a specific day (April 15<sup>th</sup>); in particular, it reports the values of wind speed, power produced by the SWT, building power demand, power produced by the SWT and sold to the grid (in excess with respect to the power demand), power imported from the grid to cover the electric load not covered by the SWT production as a function of the time. Figure 5 indicates the

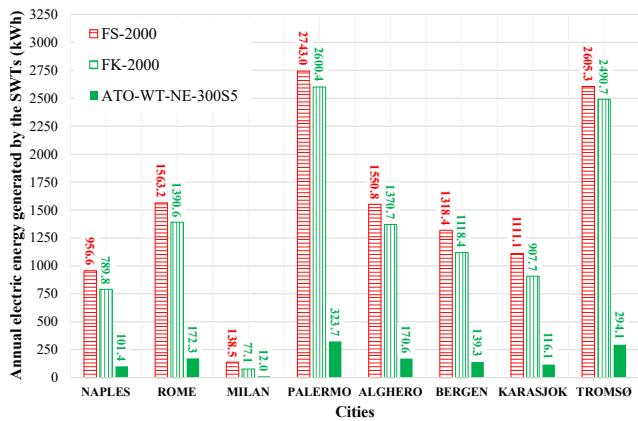
annual electric energy produced by the selected SWTs upon varying both the SWT model and the city. This figure shows that the annual electric generation varies between a minimum of 12.0 kWh (corresponding to the HASWT ATO-WT-NE-300S5 installed in Milan) up to a maximum of 2743.0 kWh (corresponding to the VASWT FS-2000 installed in Palermo). Moreover, it can be underlined that, for a given SWT model, the annual generated electric energy is maximum in the case of the city of Palermo (city characterized by the largest average wind speeds), while it is minimum for the city of Milan (corresponding to the lowest average wind speeds), with values in Palermo between 19.8 and 33.7 times larger than those associated to Milan. The comparison between the VASWT FS-2000 and the HASWT FK-2000 (characterised by the same power output at 12 m/s) shows that, whatever the city is, the VASWT FS-2000 produces larger annual electricity than the HASWT FK-2000 (thanks to the fact that, as indicated in Figure 2, the SWT FS-2000 is characterized by larger power outputs for wind velocities up to 6.5 m/s) by a minimum of 1.05 times (in the case of Tromsø) up to a maximum of 1.80 times (in the case of Milan). In addition, the comparison between the VASWT FS-2000 and the HASWT ATO-WT-NE-300S5 (characterised by almost the same rotor swept area) shows that the VASWT FS-2000 generates greater electric output with respect to the HASWT ATO-WT-NE-300S5 (thanks to the fact that, as reported in Figure 2, the SWT FS-2000 is characterized by a much larger power output, whatever the wind velocity is) by a minimum of 8.47 times (in the case of Palermo) up to a maximum of 11.54 times (in the case of Milan). Finally, it should be underlined that the VASWT FS-2000 is also characterized by a reduced size in comparison to the selected HASWT FK-2000.

Depending on the simultaneity and levels of electricity production and demand, the output of SWTs could exceed the power demand with the eventual surplus sold to the grid. Figure 6 indicates the annual electric energy sold to the grid upon varying both the SWT model and the city.

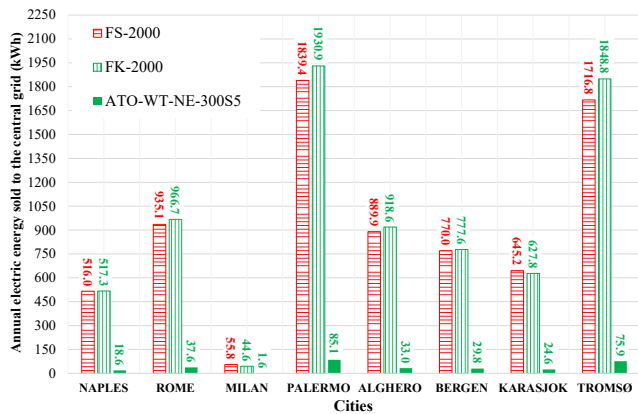




**Figure 4.** Daily operation of the VASWT FS-2000 in Naples on April 15<sup>th</sup>



**Figure 5.** Annual generated electric energy

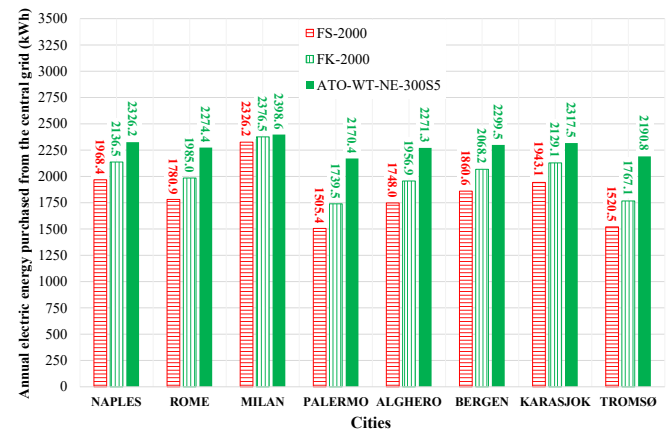


**Figure 6.** Annual electric energy sold to the central grid

This plot indicates that the values range from a minimum of 1.6 kWh in the case of the HASWT ATO-WT-NE-300S5 operating in Milan up to a maximum of 1930.9 kWh in the case of the HASWT FK-2000 installed in Palermo. For a given city and SWT model, the values reported in Figure 6 represent a significant percentage of the corresponding values of generated electricity (reported in Figure 5); this percentage ranges between 40.3% (in Milan) and 67.1% (in Palermo) for the VASWT FS-2000, between 57.8% (in Milan) and 74.3% (in Palermo) for the HASWT FK-2000, and between 13.4% (in Milan) and 26.3% (in both Tromsø and Palermo) for the HASWT ATO-WT-NE-300S5. These values indicate that coupling the selected SWTs with electric batteries could significantly enhance the related performance.

When power generated by the SWTs is lower than the building electric load, the difference has to be imported from the grid. The values of annual electric energy imported from the grid as upon varying both the SWT model and the city are reported in Figure 7.

This graph shows that, for a given SWT model, the annual electric energy imported from the grid assumes the minimum value in the case of Palermo, while the maximum value is achieved for the city of Milan. For a given city, the annual electric energy purchased from the grid is minimum (1505.4 kWh) in the case of the HASWT ATO-WT-NE-300S5. For a given city and SWT model, the values reported in Figure 7 correspond to a relevant percentage of the annual building electricity demand (equal to 2408.96 kWh); this percentage varies between 62.5% (in Palermo) and 96.6% (in Milan) for the VASWT FS-2000, between 72.2% (in Palermo) and 98.7% (in Milan) for the HASWT FK-2000, and between 90.1% (in Palermo) and 99.6% (in Milan) for the HASWT ATO-WT-NE-300S5. These values indicate that the selected SWTs cover only a limited portion of the overall building electric consumption.



**Figure 7.** Annual electric energy purchased from the grid

#### 4. ENERGY, ENVIRONMENTAL AND ECONOMIC COMPARISONS

In this paper the performance of the proposed scenarios where the building is served by both the SWTs and the central grid (as back-up) have been compared with those corresponding to a baseline scenario corresponding to the case where the electric demand of the same building is totally covered by the central grid only (without the SWTs). This comparison has been performed with the aim of determining the potential benefits in terms of electric energy imported from the grid (Section 4.1), equivalent global CO<sub>2</sub> emissions (Section 4.2) and operating costs (Section 4.3); the simple payback period has been also calculated (Section 4.3).

##### 4.1 Energy comparison

The percentage difference  $\Delta E_{el}$  between the values of annual electric energy imported from the grid  $E_{el,imp}^{PS}$  in the cases of the proposed scenarios (including the SWTs) with respect to the case of the reference scenario (without the SWTs)  $E_{el,imp}^{RS}$  has been calculated according to the following formula:

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

Figure 8 reports the values of  $\Delta E_{el}$  as a function of both the wind turbine model and the city. All the values reported in this figure are negative; according to Eq. (1), this means that the proposed scenarios with the SWTs allow to reduce the electricity imported from the grid with respect to the reference scenario, whatever the wind turbine model and the city are. In greater detail, this figure indicates that, for a given city, the adoption of the SWTs allows to reduce the electric energy imported from the grid from a minimum of  $-0.4\%$  in the case of the HASWT ATO-WT-NE-300S5 operating in Milan up to a maximum of  $-37.5\%$  in the case of the VASWT FS-2000 operating in Palermo.

## 4.2 Environmental comparison

This work evaluated the environmental impacts by means of the energy output-based emission factor method proposed by Chicco and Mancarella [29]; it allows to estimate the global equivalent mass  $m_x$  of a given pollutant  $x$  emitted while producing the energy output  $E$  according to the following formula:

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

where,  $u_x^E$  is the energy output-based emission factor of  $x$  per unit of  $E$ .  $CO_2$  emissions generally show to be quantitatively more significant than emissions of other pollutants. The  $CO_2$  emission factor associated to the electricity generation in Italy  $u_{CO_2}^{E_{el}}$  depends on the location, the day of the year as well as the time of the day. According to the values suggested in the studies [30, 31], this factor ranges between  $41.3 \text{ gCO}_2/\text{kWh}_{el}$  and  $827.3 \text{ gCO}_2/\text{kWh}_{el}$  for the Italian cities and between 0 and  $56.1 \text{ gCO}_2/\text{kWh}_{el}$  for the Norwegian cities. The percentage difference  $\Delta CO_2$  between the values of global equivalent  $CO_2$  emissions in the case of the proposed scenarios (including the SWTs) with respect to the values of the reference scenario (without the SWTs) has been derived as follows:

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

where,  $STS$  is the simulation time step (equal to 1 minute), and  $u_{CO_2,i}^{E_{el}}$  is the  $i$ -th  $CO_2$  emission factor associated to the  $i$ -th electric power imported from the grid in the case of the proposed scenario ( $P_{el,imp,i}^{PS}$ ) or in the case of the reference scenario ( $P_{el,imp,i}^{RS}$ ) at the same simulation time. Figure 9 underlines the results in terms of  $\Delta CO_2$  upon varying both the city as well as the SWT model. The data are always negative and, therefore, the proposed scenarios including the SWTs allow to decrease the global equivalent  $CO_2$  emissions with respect to the reference scenario, whatever the city of the SWT model is. In more detail, this figure demonstrates that, for a given city, the utilization of the SWTs reduces the global equivalent  $CO_2$  emissions in comparison to the reference

scenario from a minimum of  $-0.4\%$  in the case of the HASWT ATO-WT-NE-300S5 in Milan up to a maximum of  $-37.8\%$  associated to the VASWT FS-2000 in Palermo.

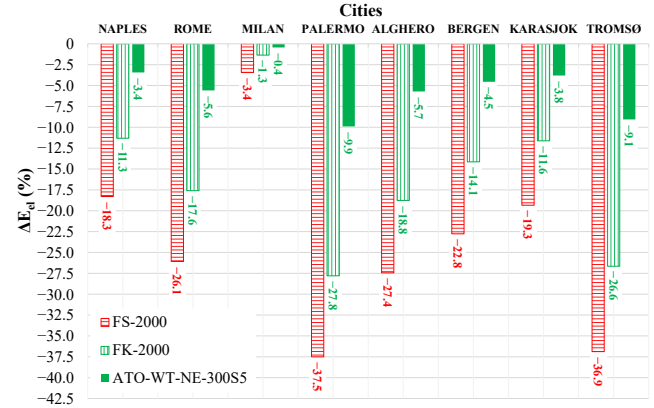


Figure 8.  $\Delta E_{el}$  upon varying the SWT model and city

## 4.3 Economic comparison

The percentage difference  $\Delta OC$  between the values of operating costs (associated to the electricity imported from the grid) in the cases of the proposed scenarios (including the SWTs) with respect to the values of operating costs  $OC^{RS}$  of the reference scenario (without the SWTs) has been calculated via this formula:

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

where,  $REV_{el,sold}$  is the annual revenue obtained thanks to the electric energy sold to the grid,  $UC_{el,sold,i}$  and  $UC_{el,imp,i}$  are, respectively, the unit price of electric energy sold to the grid and the unit cost of electric energy imported from the grid. In the case of the Italian cities, the values of  $UC_{el,imp,i}$  have been obtained according to the values indicated in the study [32] by considering the zone of Italy where the city is located (Central-South, North, Sicily, Sardinia). With reference to Norwegian cities, the values of  $UC_{el,imp,i}$  have been defined according to those suggested by the federation of the European electricity industry based on the zone of Norway (Norway\_4 and Norway\_5) [33] where the considered cities are located. The values of  $UC_{el,sold,i}$  for the selected Italian cities has been adopted according to the study [34]. In the cases of the Norwegian cities, the unit price of electricity sold to the grid  $UC_{el,sold,i}$  has been assumed equivalent to the unit cost of electricity purchased from the grid  $UC_{el,imp,i}$  when the electrical energy production exceeds the demand of the individual residential building [35]. According to studies [32-35], the maximum  $UC_{el,imp,i}$  and  $UC_{el,sold,i}$  for the Italian cities is equal to 400 €/MWh and 170 €/MWh, respectively, while for the Norwegian cities they are both equal to 332 €/MWh. Figure 10 shows the results in terms of  $\Delta OC$  upon varying both the city and the SWT model. This figure reports only negative values (whatever the city or the SWT model is), so the proposed scenarios with the SWTs always allow to decrease

the operating costs in comparison with the reference scenario. In further detail, this plot underlines that, for a given city, the utilization of the SWTs decreases the operating costs in comparison to the reference scenario from a minimum of  $-0.4\%$  in the case of the HASWT ATO-WT-NE-300S5 operating in Milan up to a maximum of  $-112.0\%$  in the case of the VASWT FS-2000 operating in Tromsø.

The utilization of SWTs require a larger investment cost in comparison to the reference scenario. The simple payback period (SPB) represents the period that is needed to recover the extra investment thanks to both the savings in terms of operating costs as well as the revenues corresponding to the electricity sold to the grid; it can be obtained as follows:

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

where,  $WT^{CC}$  is the capital cost of SWTs.

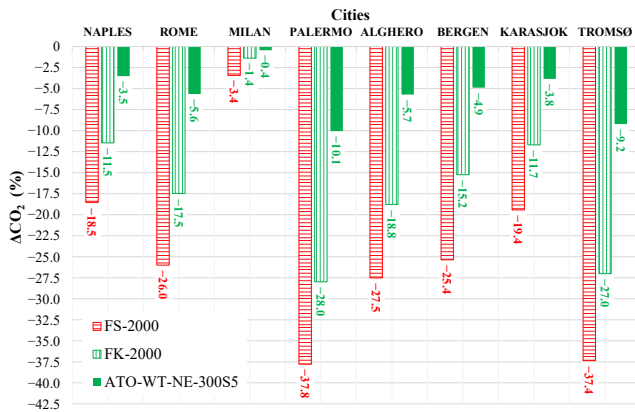


Figure 9.  $\Delta CO_2$  upon varying the SWT model and city

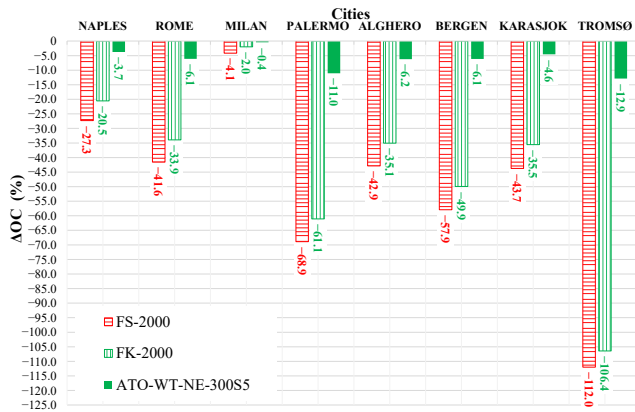


Figure 10.  $\Delta OC$  upon varying the SWT model and city

Figure 11 reports the values of SPB upon varying both the city and the SWT model. This plot highlights that SPB ranges from a minimum of 2.8 years (obtained when the HASWT FK-2000 operates in Palermo) up to a maximum of 241.8 years (that is achieved for the HASWT ATO-WT-NE-300S5 installed in Milan). The HASWT FK-2000 and the VASWT FS-2000 are characterized by similar SPBs, that can be assumed as suitable from an economic point of view (except in the case of Milan) taking into account that the expected SWTs lifetime is about 20÷25 years; the HASWT ATO-WT-NE-300S5 is characterized by much larger SPBs in contrast to the other SWTs, with acceptable values only when it is

installed in Palermo, Rome and Alghero.

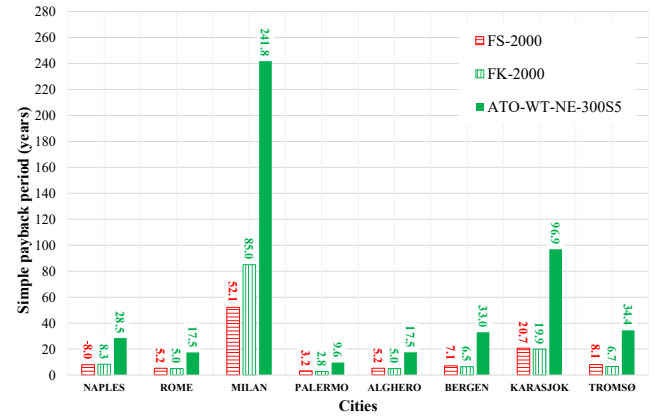


Figure 11. SPB upon varying the SWT model and city

## 5. CONCLUSION

In this study, the performance of a VASWT (model FS-2000 [13] with power output of 2100 W at 12 m/s and rotor swept area equal of 1.60 m<sup>2</sup>) have been assessed and compared with those of both a HASWT (model FK-2000 [14] with power output of 2100 W at 12 m/s and rotor swept area of 6.15 m<sup>2</sup>) and a HASWT (model ATO-WT-NE-300S5 [15] with power output of 307 W at 12 m/s and rotor swept area of 1.43 m<sup>2</sup>) while serving a typical single-family house. The analyses have been performed via the software TRNSYS [19] upon varying the city of installation considering 5 Italian and 3 Norwegian cities. The simulations indicated that, whatever the SWT model and the city are, the SWTs reduce the electric energy imported from the grid, the global equivalent CO<sub>2</sub> emissions and the operating costs up to about  $-37.5\%$ ,  $-37.8\%$  and  $-112.0\%$ , respectively. In particular, the best results have been obtained in the case of the VASWT FS-2000 operating in Palermo, while the worst data have been achieved with reference to the HASWT ATO-WT-NE-300S5 operating in Milan. The results showed that, for a given SWT model, climatic conditions strongly affect the performance, with electricity generation in Palermo between 19.8 and 33.7 times larger than those associated to Milan. In addition, the simulations highlighted that, for a given city, the VASWT FS-2000 can increase the generated electricity by a minimum of 1.05 times (in Tromsø) up to a maximum of 1.80 times (in Milan) in comparison to the HASWT FK-2000, together with a reduced size; with respect to the HASWT ATO-WT-NE-300S5, the VASWT FS-2000 occupies a larger volume, but it can strongly enhance the electricity generation by a minimum of 8.47 times (in Palermo) up to a maximum of 11.54 times (in Milan). The HASWT FK-2000 and the VASWT FS-2000 showed similar simple payback periods, fully suitable from an economic point of view (except in the case of Milan); the shortest SPB (2.8 years) was associated to the HASWT FK-2000 operating in Palermo; the data demonstrated that the HASWT ATO-WT-NE-300S5 is characterized by acceptable SPBs only in the case of Palermo, Rome and Alghero.

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