ROSEO: Novel Savonious-type BIWT Design based on the Concentration of Horizontal and Vertical Circulation of Wind on the Edge of Buildings

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Abstract: In this paper a new Building Integrated Wind Turbine (BIWT) called ROSEO-BIWT is presented. The ROSEO-BIWT is installed on the edge of the buildings and it consists of a Savonius wind turbine and two concentration panels that have the purpose of accelerating the usual horizontal wind together with the vertical upward air stream on the wall of the building, improving the performance of the wind turbine and also getting a good architectural integration. We have studied its hypothetical performance and design configuration in a tall building of Bilbao using wind data from the reanalysis ERA-Interim (European Centre for Medium-Range Weather Forecasts' reanalysis), from an anemometer to calibrate the data, and its real small-scale behavior in a wind tunnel. Promising preliminary results have been obtained, which could suppose an energy production increment of 20%.

1 INTRODUCTION

In general terms,the market of the small wind turbines is currently growing although the sector of small wind turbines to be installed in buildings is increasing at a lower speed. According to the World Wind Energy Association (WWEA) (WWEA, 2016), the installation of small-wind turbines will increase by around 12 % annually in the 2015-2020 period. The good economic profitability of small-wind turbines and the constant technological advances are the determinant factors that justify the rising of the small-wind turbines market. On the other hand, in the last years, more and more research is being focused on the development of different technologies that help minimize the buildings energy consumption. This philosophy is known as nZEB (nearly Zero Energy Building) (Chastas et al., 2017) and it is included in the EU 2010/31/CE directive related to energy efficiency in buildings. After 2018 every public building constructed should consider this regulation and, after 2020, every new building.

The goal is to maximize as much as possible the energy efficiency and reduce the primary energy from fossil resources so that the required energy demand may be covered by renewable sources. In this sense, the mini wind technology, which consist in generating energy with wind turbines of 100 kW or less to cover an area smaller than 200 m^2, can play a very interesting role. For this purpose, some technological challenges are yet to be fully solved such as the vibrations, the generated noise levels and the device's aesthetical and architectonic integration. Many are the advantages of these devices.

Many are the advantages of these devices:

1. They can work as stand-alone devices thus providing energy in isolated locations, not connected to the electric grid;
2. They work in distributed micro-generation mode, thus minimizing energy losses due to transport and distribution. These devices generate energy close to the final user thus dramatically reducing the need of electric infrastructures;
3. Furthermore, it can be combined with photovoltaic energy in hybrid installations allowing an optimal use and management of shared electric accumulators.

1.1 State of the Art

The recent developments on wind energy in urban environments have inspired different types of BIWT projects. For example, in London Strata SE1 is a tall

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building of 43 floors that will include 3 wind turbines with a diameter of 9 meters in the roof of the structure. These wind turbines would cover the lighting demand of the building (Bogle, 2011).

On a smaller scale there are a lot of projects that includes Horizontal Axis Wind Turbines (HAWT) integrated in the building and also Vertical Axis Wind Turbines (VAWT). These projects are focused on integrate wind turbines in existing buildings. So, these buildings are no previously designed to accelerate air streams like the World Trade Center of Baharein (Smith and Killa, 2007) or the mentioned Strata S1 building. According to this post-integration tendency, building integrated wind turbines are being implemented in strategic locations to capture the acceleration of air streams that is produced because of different shapes. In this sense, the most interesting locations are the upper and lateral edges of the building, mainly the first one because it is at reasonable distance from the homes.

Nowadays there are several ongoing projects to develop an optimal system to harness wind energy in urban environments. Most of them conclude that wind turbines that are used in obstacle-free environments are not adequate for urban environments due to the turbulent urban flow. For that reason, HAWT devices, which usually exhibits a good performance with laminar flows, shows a low performance in urban environments and also originate high noises of up to 200 dB within a radius of 500 m (Oerlemans et al., 2007). Conversely, VAWT plays an important role, since its performance is not affected by turbulent flows and tend to be noiseless. Additionally, VAWT has a lower cut-in speed than HAWT and a larger cut-off speed, ensuring longer operating time (Manwell et al., 2010; Dilimulati et al., 2018). Although the power coefficient is lower, the design is simpler and the manufacturing process is easier to carry out.

Along these lines, the existing wind energy urban potential has encouraged the researchers to develop a propper methodology of wind energy estimation in urban environments (Arteaga-López et al., 2019). The use of anemometers at specific locations can be combined with other advanced computational simulations between buildings and considering the complex urban terrain using CFD (Computational Fluid Dynamics). In this way, the use of reanalysis and meteorological mesoscale models for wind energy potential estimation, which is well-known offshore and onshore an developed also by the author (Ulazia et al., 2017b; Ulazia et al., 2016), can be complemented with different posterior tools.

In this work, we present the design of a Savonious drag driven turbine integrated in buildings called ROSEO-BIWT, which has been especially designed to work in urban environments where the wind is characterized by its turbulence and it is important as well to take advantage of low speed air streams. The germinal project of ROSEO won the first award in the EDP-RENEWABLE UNIVERSITY CHALLENGE 2017 (EDP, 2017), and now the members of the project have created an university start-up called ROSEO. Although it is usually used as an vertical axis turbine, ROSEO-BIWT is formed by a Savonius turbine in a horizontal position and concentration vanes that accelerates the air streams thanks to the Venturi effect (see Section 2.2). These type of vanes are usually called PAGV (Power Augmentation Guiding Vanes) (Chong et al., 2013; Chong et al., 2011; Tong et al., 2010). It has been also designed to be architectonically easily integrated. This is the case of the design proposed by Park et al. (Park et al., 2015), in which several Suetonius turbines are implemented in the facade of the building at different heights to take advance of the vertical currents created by the wind on the walls of the building (Figure 1):

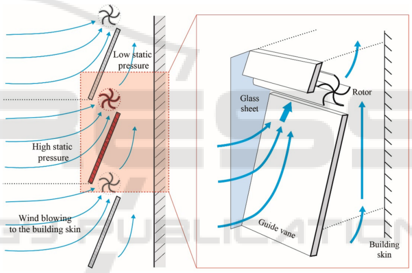

Figure 1: Savonious turbines with PAGVs proposed by Park et al. (Park et al., 2015).

The Savonius wind turbine is a drag-based device, unlike the majority of turbines, that are lift-based. This particular aspect allows producing low noise levels and few vibrations, which is very important in building installations (Zemamou et al., 2017; Kim and Cheong, 2015). The PAGV increases the wind speed as the catching area is bigger, giving as a result a system that is able to start with wind speeds of, about, 1 m/s, which ensures a great number of energy producing hours. Furthermore, energy continues being generated no matter how high the wind speed is.

This paper proceeds as follows: a possible location for the installation has been studied by using ERA-Interim and ERA5 data, a powerful tool for global atmospheric analysis that is updated in real time (see Section on Data and Methodology (Section 2.1). The authors have installed also an anemometer in the roof of their university to calibrate wind data with a period of six months against ERA-Interim or ERA5 (Section 2.1.2). In this way, an empirical method for the estimation of wind energy potential on buildings will be developed, with low computational cost 3.2. Finally, a preliminary small-scale experiment has been developed in a wind tunnel with a small Savonious and different disposition of the PAGV (Section 2.2 and 2.3). The authors finish this work with some relevant conclusions and the possible research lines within a future outlook. The qualitative methodology used here can be considered within the scope of analogical reasoning and model construction (Ulazia, 2016).

2 DATA AND METHODOLOGY

2.1 Data and Location

2.1.1 ERA-Interim

A tall building in Bilbao has been selected (longitude: 2.946° W ; latitude: 43.258° N) for the representation of the integration of the design and to present a method for the preliminary estimation of the energy production. Figure 2 shows the top view of the building and the space of 12 m in the roof where our prototype can be installed.

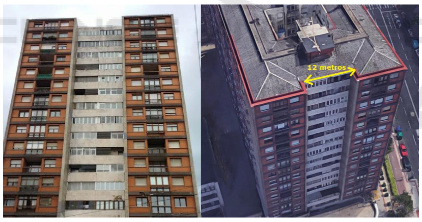

Figure 2: Selected building in Bilbao.

For the approximate estimation of the wind statistics data from ERA-Interim have been used. ERA-Interim is a reanalysis from the global atmospheric data sets provided by the European Center for Medium-Range Weather Forecasts (ECMWF) (Berrisford et al., 2009). It is continuously updated once per month, and contains data from 1979. The spatial resolution is approximately 75 km and time output is achieved every 6 hours. Zonal and meridional components of the wind (U and V) can be downloaded at 10 m height.

2.1.2 Anemometer and Calibration

A cup anemometer has been installed in one of the buildings of the University of Basque Country in Eibar (see Figure 3) to develop a preliminary calibration methodology based on quantile-matching techniques used previously by the authors in wind energy and wave energy(Ulazia et al., 2017a; Penalba et al., 2018; Ulazia et al., 2018). For this paper the authors will obtain 8 months of 10-minute data series, which should be filtered every 6 hourly to match the ERA-Interim data series or the new ERA5 reanalysis (1-hourly time resolution in this case) (Olauson, 2018). Having the average wind speed $\overline{U}$ after calibration on the corresponding facade and considering the typical form parameter in the Rayleigh distribution (k=2), the corresponding scale parameter can be obtained:

$$c = \overline{U}/\Gamma(1+1/k). \qquad (1)$$

In this way, the cumulative distribution function and the fraction of time between two wind speeds is determined:

$$F(U) = 1 - exp(-(U/c)^k) \qquad (2)$$

and the augment factor of the PAVG can be implemented in the c parameter (Manwell et al., 2010).

Figure 3: Anemometer on the roof of the building.

2.2 ROSEO-BIWT Design

2.2.1 The Location on the Upper Edge of the Building

The effect of the wind against buildings have been largely studied by the sector of architecture with the purpose of study the dynamic loads generated by air streams. Because of that, there is a large knowledge about the behavior of wind in urban environments. Through scale experiments and also CFD simulations, similar to the Figure 4 generated using CFD by (Mertens, 2006).

Most of the studies that have analyzed the behavior of the air streams around the buildings agree in the great potential of the upper edge of the windward face of the building. It happens because the wind have to surround an object. The effect is even more intense when the building is taller and also when the

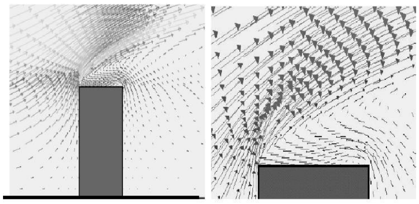

Figure 4: CFD image where the acceleration in the windward upper edge can be appreciated (Mertens, 2006).

wind direction is perpendicular to the building facade. For example, in a 5-stor building the wind velocity increases 1.2 times in the windward edge (Mertens, 2006).

2.2.2 Savonious Turbine

That is why our ROSEO-BIWT's Savonious axis is positioned horizontally along the superior edge on the building. There are several recent studies about the performance of the Savonius turbine. Mohamed et al. (Mohamed et al., 2010) have improved the performance using plates to eliminate the negative torque in the returning blade. They have carried out tests for a two bladed and for a three bladed wind turbine and in both cases they have improved the C_p of the wind turbine until a 27 %, being the 15% the typical value.

Apart from these intrinsic improvements, some engineers have developed the mentioned PAGV systems to accelerate the air streams. Shikha et al. (Bhatti et al., 2003) increased 3.7 times the wind speed in a experimental way using a specific well-studied nozzle. Additionally, Altan et al. (Altan and Atılgan, 2012) have studied the influence of the inclination angle of the plates and its length. In these experiments they found out that when the longitude of the PAGV increases the power also increases. So the important consideration here is the relationship between the diameter of the rotor and the length of the PAGV. They even obtained a C_p of 38.5 %. Other types of PAGVs called omni-directional reached a C_p of 48%, implying an increase of 240% in relation to a Savonius rotor without a PAGV system.

In terms of longitude and diameter, (Roy and Saha, 2013) shows that the best performance of a Savonius rotor is reached with a Length/Diameter ratio of 6:1. In the same way, Park et al. (Park et al., 2015) tested different kind of Savonius rotors and they discovered that the best design was a 6 bladed rotor. Therefore, for our purpose, a similar rotor with these proportions is chosen.

2.2.3 The Final Design

Park et al. (Park et al., 2015) developed the idea of using a bigger surface of the facade to generate energy installing a lot of Savonius rotors at different heights, and also using PAGV to improve the performance of the wind turbines. The system that they propose is similar to a ventilated facade and it is important to emphasize that they want to capture the vertical air streams that are generated on the windward side of the building, as in our case. However, they use parallel vanes in the facade, with a small concentration angle, and our case the upper edge is used augmenting the concentration angle and capturing also the horizontal component of the wind, and not only the vertical stream on the facade. Furthermore, the background of the Savonious rotor is free in the edge of the building, an important aspect that is not met by turbines installed in the facade. Although the influence of this aspect is out of the scope of this study, it is an obvious aerodynamic advantage.

Another innovation that we include is that it can be installed in existing buildings: it is not a design only for new buildings. To sum up, ROSEO-BIWT shows a good architectural integration in existing buildings, with high economical viability due to the simplicity of the design.

Figure 5 shows this design of the ROSEO-BIWT viewed from above and from below. This is a schematic perspective which does not take into account the influence of the angle between the two PAGVs.

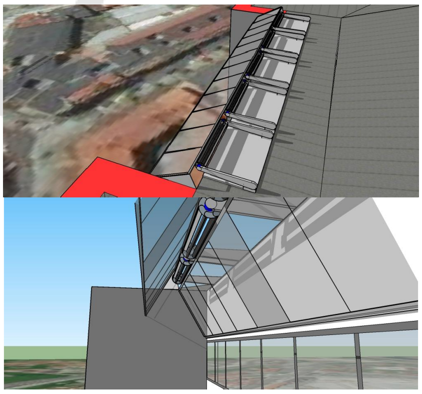

Figure 5: ROSEO-BIWT design.

Figure 6 shows the schematic profile of the installation with the appropriate measures for the building of Bilbao. The areal ratio of the PAGV between the entrance and the exit of the air is 4:1, expecting an analog augment of wind speed due to the Venturi effect. In any case, the upper vane is adjustable, and its angle can be changed up to a horizontal position, to capture the free wind speed.

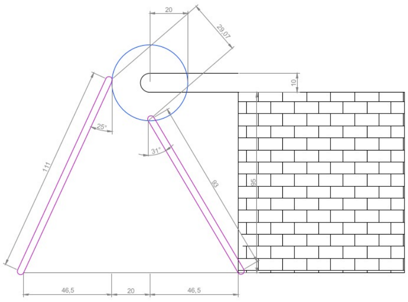

Figure 6: Schematic profile of the design.

2.3 Experiments in the Wind Tunnel

Although there are results provided by previous studies, in the following sections the authors describe the general experimental methodology that will be developed in the future. The model construction is proposed in analogy to previous findings and design procedures (Ulazia, 2016). These are the main steps:

1. First, the augment factor of the wind speed on the edge of the building should be empirically studied: this occurs due to the union of the horizontal usual component and the vertical component.
2. Then, the previous augment factor should be multiplied by the new augment factor provided by the PAGVs. These factors will be measured for different wind speeds in the wind tunnel of the university using a scale model of a building.
3. The power curve of a longitudinal section of the Savonious prototype will be also measured in the tunnel.
4. Finally, the Weibull distribution at the location obtained by the previously described calibration methodology will be implemented on the measured power curve considering also the augment factors.

Figure 7 shows the wind tunnel and the installation of PAVGs and a Savonious rotor. The measurement of the wind speed at specific points via a Pitot tube shows an augment between 3-4 in the convergence center of the structure, corroborating the augment factors obtained in previous studies (Wong et al., 2017), or even more due to the corner effect of our design. However, until now, these preliminary measurements have been only performed with few values of steady wind speed without considering important effects such as the blockage ratio of the tunnel.

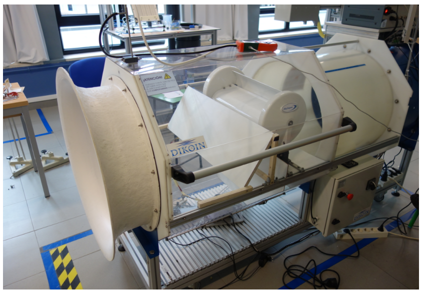

Figure 7: The Savonious turbine inside the wind tunnel with the PAVGs around.

3 RESULTS

3.1 Wind Rose Around the Building

The ERA-Interim grid around Bilbao city is shown in the Figure 8 with the points in yellow color. The nearest ones are marked by the numbers in consecutive rows, and the location of the selected building is marked in red color. The nearest gridpoint, number 15 at 6 km distance, has been chosen to download the data (period 2001-2005, that is, 7304 cases 6-hourly).

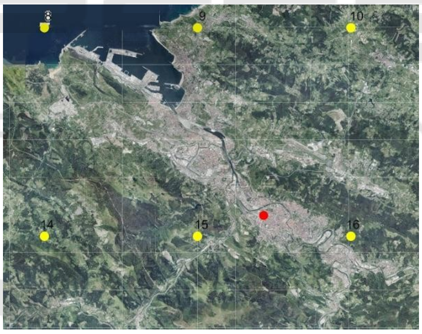

Figure 8: Nearest ERA-Interim gridpoints (yellow) around the study point (red).

These data should be raised to the height of the building (45 m) using the log law and the roughness of urban environments (Manwell et al., 2010). According to usual considerations in wind energy sector, the roughness (z_0) of the urban terrain is around 1 m. Roughness is used to apply the logarithmic law of vertical wind shear,

$$\frac{U(z)}{U(z_r)} = \frac{Ln(z/z_0)}{Ln(z_r/z_0)}, \tag{3}$$

obtaining wind speed at 45 m height, $U(z = 45)$, in terms of the speed of reference $U(z_r = 10)$.

After the application of the log law, a wind rose can be plotted in our location using the time series of U and V. We have represented it around the building in the Figure 9, visualizing the predominant windward facade of the building towards the Northwest as expected according to the climatology of the Gulf of Biscay. This method offers a first estimation of the wind statistics on the edge of the building, because the height of the building guarantees that street-level flows are negligible.

Figure 9: Wind rose according to ERA-Interim around the building.

3.2 Estimation of the Energy Production

We have used previously described concepts and values to estimate the energy production according to these suppositions:

- According to (Mertens, 2006), the wind increments its velocity a 20% at the upper edge of a typical building.
- The simplest PAGVs have increased the wind speed 3.7 times, with corresponding increments in C_p that can reach a value of 0.37 (Wong et al., 2017). Although higher values can be obtained with wider entrances, we will use a low factor of augment of 4 for our estimation, since we have also the 20% due to the other architectonic acceleration in the upper edge.
- Taking into account the wind rose of Figure 9, we have only considered the wind data of ERA-Interim with this direction and also with our turbine in the corresponding facade.

For the estimation of generated power a commercial Savonious model (SeaHawk-PACWIND) is used. Its rated power is of 1.1 kW, the rated wind speed of 17.9 m/s, the cut-in wind speed of 3.1 m/s, the cut-off without a given limit being a drag device, and the swept area is of 0.92 m^2 (SeaHawk, 2017). If the pure ERA-Interim wind speed distribution is considered on the best facade and the average values given by the calibration (around 5-6 m/s), the turbine would be working 1600 hours per year in the interval of rated wind speed: an AEP of around 1700 kWh. However, using a typical Weibull distribution with k=2, an augment factor of 4 via PAGVs would produce an increment of 20% in AEP and working hours (Equations 1 and 2).

4 CONCLUSIONS AND FUTURE OUTLOOK

In the future, the AEP increment of 20% via PAVGs in the edge of the buildings must be shown using a real prototype of ROSEO-BIWT. For that, the building in the city of Eibar will be used within the Bizia Lab project of the University of Basque Country. The anemometer has been installed on the same roof and having the new data provided by ERA5 in the nearest gridpoint, the identification of the best facade and the corresponding wind distribution will be obtained following the methodology described in this paper. These preliminary results and the methodological discussion developed until now encourages us for the future refinement of ROSEO-BIWT.

For that, the novel validation method for anemometers developed by the authors in a recent study for wind farms (Rabanal et al., 2018) will be very beneficial, since it allows to compare and combine the data of more than one anemometer installed on the roof of the building.

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