Extended summary

Design, testing and simulation of hybrid wind-solar energy systems

Curriculum: energy sciences

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Abstract. The hybrid micro-generation technology aims to bring the energy production closer to the demand, in order to supply electricity to remote loads in particular. Moreover it is suitable to incorporate renewable energy sources, such as wind and solar ones, which allow environmental sustainability. Their discontinuous nature can be partially compensated through wind/solar hybrid energy systems. A promising concept for micro-wind is represented by Savonius vertical axis wind turbines (VAWT). An innovative VAWT hybrid micro-generation unit has been designed to be fully embedded into a dedicated LED street lighting system. On the top of the lamppost a photovoltaic panel is integrated to contribute to power generation and battery charging. A full scale prototype has been installed for testing. Two Savonius rotor types are designed and made of PMMA and fiberglass. The maximum rotation speed and the structure stiffness have been studied with criteria of efficiency and security, according to FEM structural analysis. A dedicated safety equipment has been designed and installed to prevent turbine over-speed by automatic stop in extreme wind condition. Early on-site tests and meteorological data are processed by a dedicated energy simulation model.

Keywords. Micro-generation, Savonius, Street lighting, VAWT, Wind-solar hybrid

1 Introduction

One of the most promising applications related to renewable energy is the hybrid energy technology. It is based on the favourable combination of two or more energy sources within the same system, such as wind and solar ones. The source multiplicity aims at both electrical reliability and greater energy savings. Hybrid systems are usually installed in remote areas, where the grid is not present for cost issue, but they can also work as additional contribution to conventional power generation systems [1]. Moreover they are compatible with the smart grid concept, which involves not hierarchical distributed micro-generation of electricity [2]. In renewable energy micro-generation technology a key issue is the synthesis of efficiency and urban integration. Wind and solar energy are free and clean sources, maybe the most promising alternative of fossil fuels power generation. This idea has been leading the energy market in recent years. However small wind turbines in particular have to face some obstacle related to noise, turbulent winds and visual impact.

Building mounted wind turbines could be a solution [3], [4] to gain elevation over the urban boundary layer, where the available air stream is stronger. Nevertheless power level of this type of installations is seriously limited by the structural resistance of existing buildings and the transmission of vibrations. This is why an embedded wind-solar power solution would be preferable. Among fields ready for a coupling between electrical sources and load there is outdoor lighting. Pole structures carrying on lamps can be suited to allow the installation of renewable energy devices. Such systems, especially powered by PV panels and batteries, are currently sold. Their main application is the lighting in remote areas, as standalone generation units. There are some commercial products provided with both PV and either vertical (VAWT) or horizontal (HAWT) axis wind turbines technology, such as those in [5], [6]. HAWTs generally take advantage of a greater power factor as shown in Figure 1. However in the micro-generation field their aerodynamic efficiency is penalized by the lack of active control, in particular with respect to the yaw error and the start-up operation. Such issues do not involve micro-VAWTs like Savonius type which get competitive, especially in highly variable wind conditions.

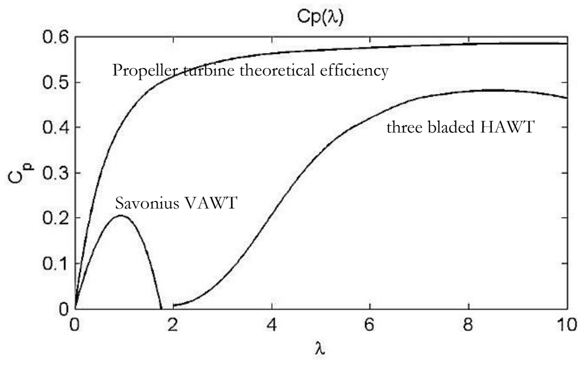


Figure 1 Typical aerodynamic efficiency Cp: comparison between different wind turbine types.

The existing solutions typically use vertical axis turbines, mainly Darrieus type, arranged on the top of traditional poles. Power generation units therefore appear geometrically disjointed from the whole streetlight. Berdanier et al. have presented in [7] the incorporation of a Savonius type wind turbine, along with a tilted PV panel, into the light housing of a light

post prototype. This option too is characterized by only one wind rotor on the top of the pole.
The main object of this study is a new prototype of wind-solar hybrid street lighting system, named *Generator*. A Savonius type rotor has been studied through wind tunnel tests [8], [9] and designed for the purpose. This type of wind turbine exhibits several advantages with respect to this application, mainly due to its low speed of rotation and its "vertical" geometry, well incorporated in a slender object such as a street light.
A special attention has been paid in the project both to the safety systems of wind rotors and to the supervision system with an Information and Communications Technology (ICT) interface, which is capable of broadcasting to a server all real time state variable of the machine. The main objective of this work was to design the necessary components in order to permit a safe installation of a working prototype along with an early experimental and a numerical study to evaluate the potential and focalize the improvement areas of the system.

2 A novel hybrid wind-solar streetlight

This novel hybrid streetlight (Fig. 2) is constituted of 3 main substructures:

- the 4-pile supporting structure provided with the drive train and hardware vanes;
- the multi-pile wind turbines structure, which houses the 3 Savonius rotors through 2 bearings each. For the sake of security they stay well above the pedestrian height i.e. more than 3 m above the ground;
- the top lighting and photovoltaic body

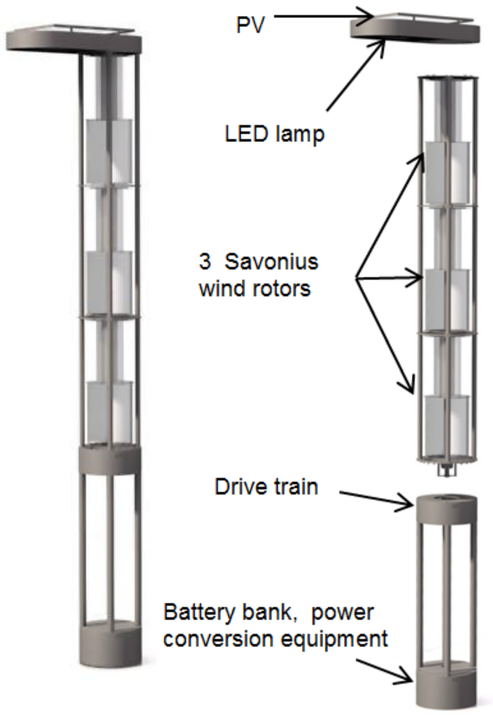


Figure 2 "Generator" wind-solar lamppost prototype.

The *Generator* prototype has been installed at Polytechnic University of Marche where it has been giving field experimental data in association to a dedicated 10 m meteorological tower which allows a full energy characterization of the hybrid micro-generation system.
The project was aimed to find a feasible compromise between proportionate architecture, energy efficiency and structural effectiveness. It has been developed through a close collaboration between University and industrial partners within a project sponsored by the Italian Ministry of Economic Development. Each partner has contributed to the development in his field of competences:

- Wind turbines;
- Drive train;
- PV panel;

- LED lamp;
- Structure design;
- Electronic devices and battery

2.1 Design aspects

2.1.1 The wind turbines

Wind turbines selected for this renewable energy system are Savonius rotors. They consist of vertical axis wind turbines based predominantly on the action of drag aerodynamic force over two buckets with an "S-shaped" cross section. Indeed this rotor is a low lift to drag ratio machine [10].

Various rotor configurations have been defined for this project. A straight rotor with two stages (90 degrees staggered each other) has been installed in order to smooth aerodynamic static moment and to confer structural stability to the rotor through an intermediate plate. Moreover a helical Savonius was constructed, with a 105° maximum section rotation.

Each geometrical parameter has an important effect on VAWT power performances [11] and has been evaluated and verified through wind tunnel tests with the experimental procedure explained in [9], [8]. The measured quantities (power *P* and torque *M*) were combined in order to obtain the performance parameters commonly used in the aerodynamics of wind turbines i.e. the moment coefficient and the power coefficient. Both were evaluated as function of the dimensionless parameter Tip-Speed-Ratio λ.

$$C_m = \frac{M}{\frac{1}{2}\rho u_\infty^2 RA}$$
$$C_p = \frac{P}{\frac{1}{2}\rho u_\infty^3 A} \qquad (1)$$
$$\lambda = \frac{\omega R}{u_\infty}$$

Where *A=2RH* is the frontal area of a rotor, u_∞ is the incoming wind speed.
In Figure 3 it is shown the experimental power factor C_p of a straight and a helical Savonius model, including the penalizing effect of the surrounding multi-pole structure.

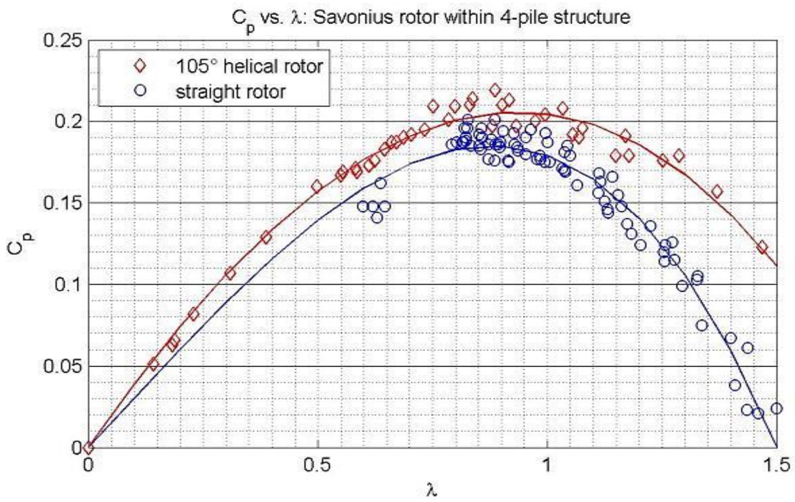


Figure 3 : Experimental power factor of straight and helical Savonius rotors from wind tunnel tests.

It is evident the better performance of helical rotor with the presence of pillars. C_p values reach the maximum of 0.21 and moreover they keep at a higher level also at greater Tip-Speed-Ratios. This turns to be the most desirable configuration for *Generator* and is one of the reasons that suggested the option of two-stage straight rotors, what represents a discretized-like helical feature.
The variable speed operation of wind turbines consists of tracking (MPPT) the optimal tip speed ratio ($\lambda_{opt} = 0.94$ for the case) through the generator torque controller. This makes the turbine deliver the maximum power at every wind speed.

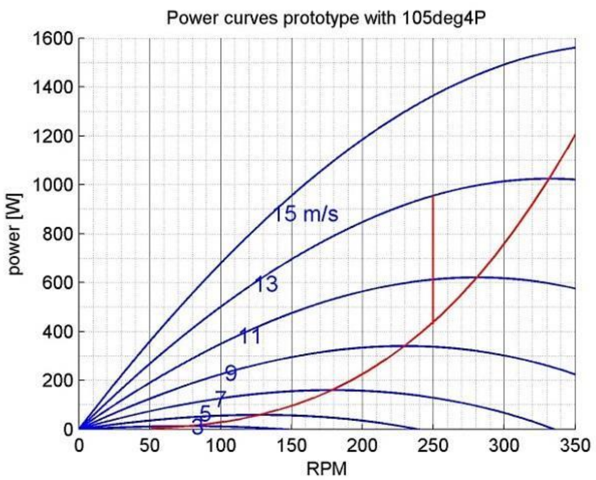


Figure 4:Aerodynamic power curves of 105deg4P. Red lines represent maximum power with or without the RPM limit.

However a maximum RPM condition imposes a deviation from optimal curve. In order to harness wind energy at higher speed it would be advantageous to track mechanical power equilibrium along the vertical segment (Figure 4).

The two-stage straight Savonius rotor has been made of transparent PMMA, which gains an esthetical value besides an acceptable strength. The helical version has been realized in fiber-glass reinforced polyester (Figure 6).. The more complex geometry required the construction of dedicated molds. This composite material guarantees a bigger strength with respect to both static and dynamical loads. One key design parameter of the wind generator is the maximum rotation speed allowed by materials. PMMA rotor provided with 6 mm thick buckets has shown in FEM analysis a critical centrifugal stress state at about 290 rpm. In order to stay well apart from this state, the current maximum rotational speed is set to 250 rpm. The controller should activate the brake to avoid overspeed. Such a limit influences the efficiency at high wind speed.

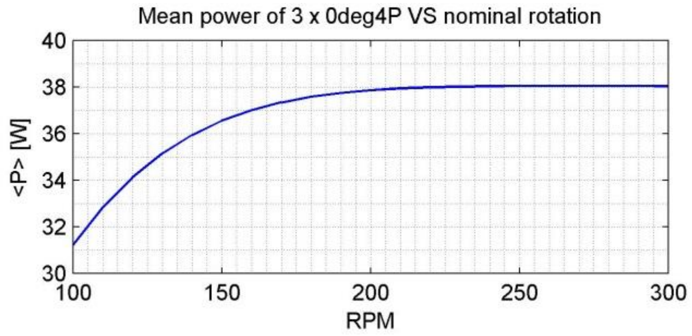


Figure 5:Weibull method expected mean power from 3 straight Savonius as a function of their maximum RPM. (Weibull parameters: k=1.98; c=4.18)

Its effect can be evaluated through a simple estimate applying Weibull wind statistics. The wind turbine mean power versus the system maximum RPM is shown in Figure 5. Due to infrequence of high wind speeds it makes no sense to overcome 200÷250 RPM.
The whole Savonius train is directly coupled through a joint to a three-phase Permanent Magnet Synchronous Generator (PMSG). Its main characteristics are:

- rated speed: 350 rpm;
- rated power: 1444 W;
- voltage at rated power: 232 V;
- polar pairs: 12;
- efficiency at rated power: 75 %

The system is equipped with both a mechanical brake and an electromagnetic brake, using dump loads connected to alternator electrical output.

(a) (b)

Figure 6: Constructed prototypes of Savonius rotors: (a) two-stage straight and (b) helical configurations.

As wind speed and RPM rise over the cut-out limits, which for instance are currently fixed at 250 rpm and 14 m/s, the controller automatically switches the DC load from the battery to the dump load, making the alternator a viscous-like brake. This operation is used to slow the rotors. Then a disc brake is operated in order to bring turbines to rest. A Savonius VAWT is indeed a more insecure machine than classical horizontal wind turbines at extreme wind conditions, because of the absence of stall phenomena. The mechanical brake system has been designed to keep rotors at rest also without actuator powering. This is made possible by an irreversible mechanism that pushes brake pads against the brake disc.

2.1.2 Resonance analysis

A modal analysis of the prototype has been performed by FEM Ansys software in order to understand and solve a potentially dangerous oscillation issue. It is observed that an eventual overspeed of the turbines over 375-400 RPM makes the pole oscillate, in particular at the drive train height, with such a force that brings the Savonius rotors to impacts and failure. This is due to the excessive deformation produced by the second bending eigenmode which is excited by centrifugal loads related to PMMA rotors. Both manufacture-based and dynamical mass imbalance of turbines contribute to create inertial loads that grow with RPMs. The FEM analysis is applied to a simplified CAD model of the lamppost.

Table 1. Effect of lattice structure on resonance (FEM analysis).

Mode	**Resonance RPM**	**Res. RPM with lattice reinforcement**
Cross bending 1	135,096	143,6592
Longitudinal bending 1	138,522	148,218
Torsion	241,692	250,4808
long. bend. 2	454,14	**678,588**
Cross bend. 2	461,424	**694,428**

Results show that the resonance frequency associated with the second eigenmode is about 7.6 Hz, which corresponds to 454 RPM. This is consistent with the observed speed of rotation and so confirms the relation between oscillation and inertial loads.

To avoid the described phenomenon and then limit the danger in case of overspeed it was made a modification to the base frame of *Generator*. It was reinforced and stiffened through a lattice structure that succeeds to reduce the dynamical deformations (see the modal shape modification in Figure 7). Modal calculus results in a much higher frequency of 2nd mode, next to 700 RPM (Tab. 1) which is unlikely to be reached by the current rotors.

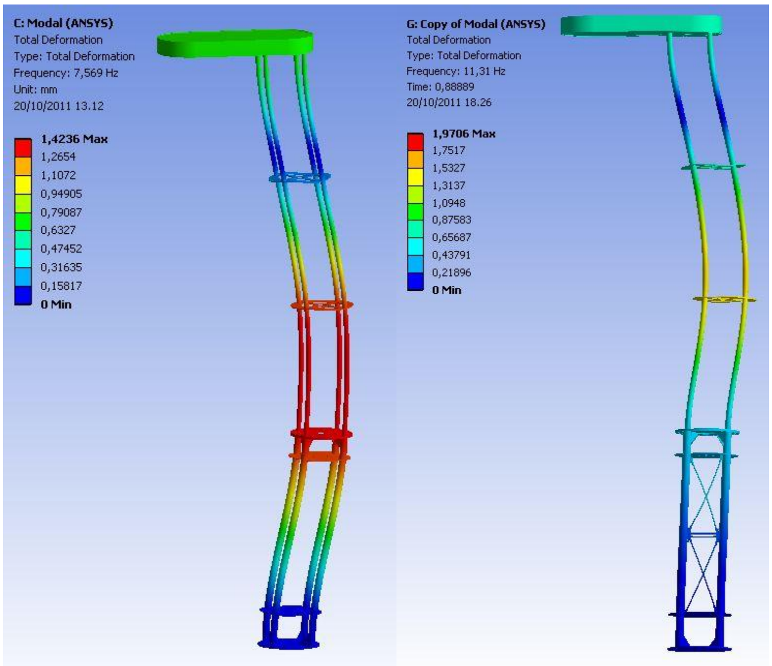


Figure 7 Mode shapes of the 2nd longitudinal bending: the lattice effect changes the mode frequency from 7.6 Hz to 11.3 Hz.

2.2 Testing and simulation

2.2.1 Early testing

The installation site has been characterized, from a wind energy point of view, by a 1 year (from 2011/10/5 to 2012/10/5) weather data collection with the met tower anemometer. The best fit Weibull distribution resulting parameter values are k=1.98 and c=4.18. The mean wind speed over the year is 3.7 m/s. This value is not actually appropriate for a traditional wind farm, so it is important to choose a micro wind technology efficient at low wind speed, as in typical urban areas.

In order to conveniently correlate the met tower wind measurements with the wind energy production at the *Generator* site it has been calculated the wind speed-up factors between the 2 sites. The wind speed data from lamppost is measured by an on-board cup anemometer. They were averaged at the same sample time of tower data. In relation to the direction of air stream at the tower, the ratio u_{Gen}/u_{tower} produces the polar scatter plot in Figure 8. It is applied to speed-up points a harmonic regression with up to 5 frequencies:

$$\nu(\theta) = c + \sum_{j=1}^{5} a_k \sin\left(\frac{2\pi j\theta}{360}\right) + b_j \cos\left(\frac{2\pi j\theta}{360}\right) \tag{2}$$

The resulting polar curve highlights a remarkable wind speed reduction on the streetlight system with wind velocities coming from west and south, correspondent to a hill and a forest.

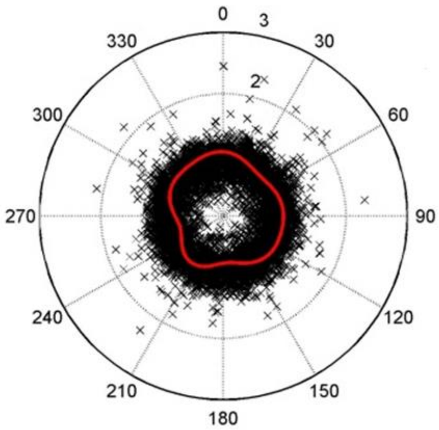


Figure 8: Polar scatter plot of speed-up factor over wind direction and harmonic regression.

Making use of the available global radiation R_{glob} measure over horizontal surface A_{PV} it is immediate to calculate the available solar energy incident and then the operating electrical efficiency of PV panel on the top of light post. The power delivered by PV and the available power are here obtained:

$$\begin{aligned} P_{PV} &= V_{batt} I_{PV-dc} \\ P_{available} &= R_{glob} \cdot A_{PV} \end{aligned} \tag{3}$$

Where A_{PV} = 1.2 m^2 is the panel surface.

The PV does not generate power when radiation R_{glob} is below 200 W/m^2. The resulting scatter plot along with a parabolic regression of PV efficiency is present in Figure 9.

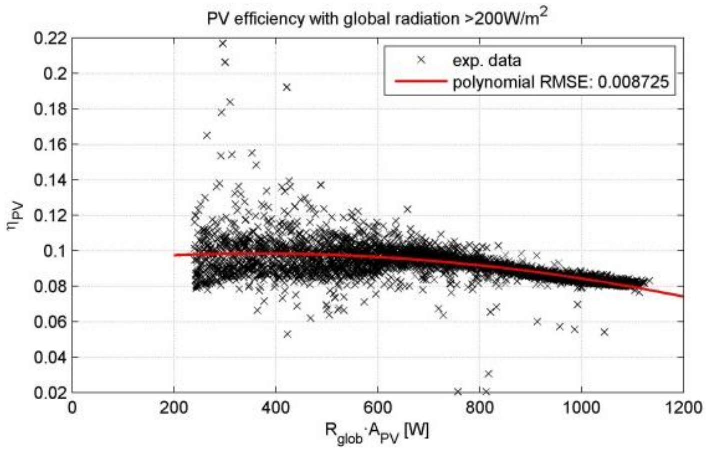


Figure 9: PV panel efficiency.

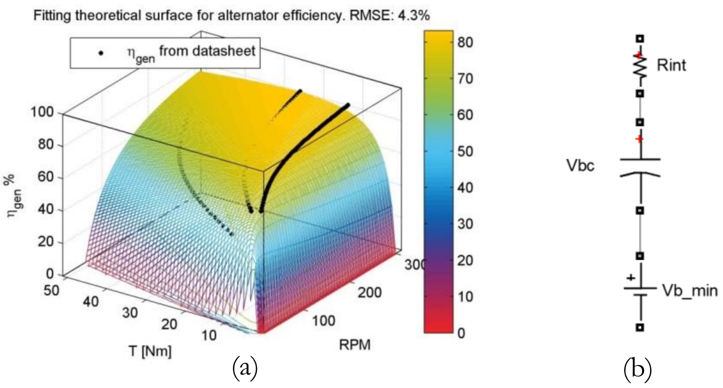
The mean experimental efficiency is 10.7%, calculated as energy generated over interval T divided by incident radiation.

$$\eta_{PV,tot} = \frac{\int_T P_{PV} dt}{\int_T R_{glob} \cdot A_{PV} dt} \tag{4}$$

2.2.2 *Energy model*

The purpose of this simple energy model is to accurately predict the energy performance of the hybrid prototype, in particular its capability to meet the load power requirements. The implemented model calculates the evolution of the physical state of the machine according to the available meteorological conditions. The main parameters that describe the effectiveness of the system are the autonomy, in terms of the energy saving from conventional power generation and the lighting reliability.

The method is based upon the met tower data of wind velocity and solar radiation. It makes use of ideal power curve shown in Figure 4 for the wind turbine production and of the efficiency in Figure 9 for the photovoltaic production. The alternator is modeled using an efficiency surface $\eta(RPM, M)$ fitting the manufacturer curves (Fig. 10a).



(a) (b)

Figure 10: (a) Alternator efficiency surface. (b) Electrical model of battery.

The lead acid deep cycle battery installed in the hybrid device is modeled through a capacitor, a voltage source and an internal resistance (Fig. 10b), besides the coulombic efficiency applied to capacitor [12]. Then the electrical loads are taken into account: the LED lamp and the electronic devices consumption. The hybrid controller is implemented as a set of logical conditions mostly related to:

- High wind condition causing the machine cut-out.
- Low wind condition: below cut-in speed.
- Low battery condition: all load are disconnected.
- Full charge condition: renewable energy sources are switched off.

The one year simulations point out that the current prototype in stand-alone configuration, as modeled here, would meet 61 % of hours with lighting need. The low battery state would limit the working time. Below it is represented the contributions of wind and solar to the lighting task of the hybrid system. Wind generator turns to be fundamental in winter as expected, when the solar energy on the horizontal panel falls drastically. Moreover the estimated traditional energy saving is nearly 40 %. The model indicates also the sensitivity of the energy saving with respect to the possible system improvements. With a PV generator global efficiency up to 15 % the energy saving would be nearly 60%.

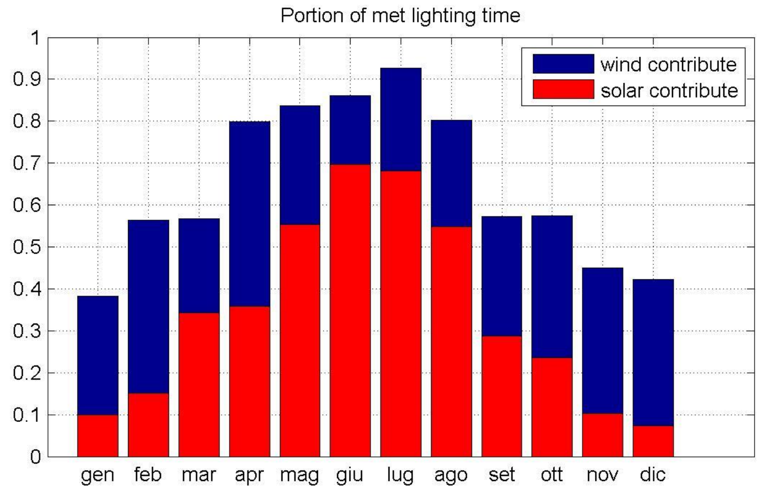


Figure 11: Lighting quality over the year simulated. Comparison between energy sources contributions.

3 Conclusions

The prototype resulting from this project consists of one of the very first hybrid wind-solar street lighting systems. The main innovative feature is the full integration of VAWT Savonius rotor along the structure of the lamppost. Two Savonius rotor options have been designed and realized according to wind tunnel tests geometrical optimization and to the most appropriate nominal speed of rotation for security and efficiency. The designed brake system and the lattice modification of the pole structure have conferred the required safety to the prototype.
It has been set up a field test for wind and solar energy micro-generation unit, based on a meteorological tower and a dedicated algorithm for the correlation of wind speed meas-

urements. Such a detailed experimental apparatus is devoted to give the tools for a comprehensive study of the renewable energy system. Early tests have given data for a detailed energy simulation of the hybrid lamppost. The wind power turns to be an important compensation of solar power for the purpose of smoothing the available power variability. This study has underlined that the standalone configuration would need an upgrade, e.g. of the PV, to be totally self-sustaining in such poorly windy sites. Further work is in progress about the dedicated power conversion control of turbine and PV, in order to track the maximum power points and to carry an efficiency optimization. Also an economical optimization is being done for oncoming industrialization.

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