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Skrzypinski, Witold Robert; Bak, Christian; Beller, Christina; Thorseth, Anders; Bühler, Fabian; Poulsen, Peter Behrensdorff; Andresen, Christian

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Wind Turbines on CO2 Neutral Luminaries in Urban Areas

Witold Skrzypiński
DTU Wind Energy
wisk@dtu.dk

Christian Bak
DTU Wind Energy
chba@dtu.dk

Christina Beller
Formerly DTU Wind Energy

Anders Thorseth
DTU Photonics Engineering
andt@fotonik.dtu.dk

Fabian Bühler
Faktor-3
fabian@faktor-3.dk

Peter Behrensdorff Poulsen
DTU Photonics Engineering
ppou@fotonik.dtu.dk

Christian Andresen
Henning Larsen Architects
ca@henninglarsen.com

Abstract

In the present work, an overview of three different wind turbines used in hybrid luminaries is presented. The turbines are: vertical-axis twisted Savonius, three-blade horizontal-axis, and vertical-axis three-blade helical H-rotor. The considered luminaries are also equipped with photovoltaic panels and batteries, detailed investigation of which is outside the scope of the present manuscript. Analysis of the turbines' performance based on producer-supplied power curves is presented together with an estimation of the wind climate in Copenhagen district comprising 1-2 story single family buildings. A new vertical-axis twisted Savonius rotor is proposed for a luminary being designed for such a district within the "Development of CO2 neutral urban luminary" project.

Keywords:

hybrid luminary, street lamp, CO2 neutral, small wind turbine, Savonius, urban wind energy

1 Introduction

Wind turbines in urban areas are very different from modern megawatt wind turbines, e.g. in offshore farms. They are challenged by two issues. First, the wind energy is much lower in urban environment than in environments typical for megawatt wind turbines. Second, the power efficiency of small rotors is much lower due to Reynolds number effects. These differences in size and resource lead to the cost functions used for the large onshore and offshore turbines being very different from those used for small urban turbines.

On the other hand, one of the advantages of the urban turbines is that they are close to the power consumption which decreases the cost of energy transport. Further, small turbines could be used in places where the energy grid is either underdeveloped or non-existent, or the investment in grids can be simply avoided.

What requires attention is the fact that urban turbines are currently erected despite the uncertainties in power and cost efficiencies.

This paper describes the work carried out in the project "Development of CO2 neutral urban luminary", where the design goal is an autonomous luminary comprising a small wind turbine and photovoltaic panels, supported by a battery, powering the luminary throughout the year without being connected to the grid.

The idea of combining a wind turbine and photovoltaic panels is old, but the dimensioning of the system in relation to energy production and power consumption has been uncertain. These uncertainties exist despite the fact that many products with this concept are currently manufactured. The objectives of the project are to investigate the potential of combining wind energy and solar energy to power a luminary and to design and construct a prototype. In the present manuscript, especially the wind energy part of the concept is in focus. The basis of the design of the wind turbine is made by Mertens [1] and Beller [2].

An exemplary hybrid luminary equipped with a horizontal axis wind turbine and a photovoltaic panel is presented in Figure 1.

Figure 1: Exemplary hybrid luminary equipped with a horizontal axis wind turbine and a photovoltaic panel; *United Electricity*

2 Tools and Methods

2.1 Assessment of wind climate

The wind climate in urban areas depends on several parameters. One very important parameter is the location of a city. The energy potential of a city can be approximated e.g. by using The European Wind Atlas [3] which describes the wind climate in Europe, based on several wind measurements and topologic descriptions.

If the landscape was regular and smooth with no changes in roughness the wind energy could be estimated with rather good accuracy by using models as those described by Troen and Petersen [3].

The situation is unfortunately much more complex in the case of a city where the displacement height is so big due to obstacles like buildings that the wind turbine will operate below the boundary layer in which the wind speed could be approximated in a relatively easy manner and in a way that has been validated throughout many years.

Also, the typically irregular pattern of houses in a city makes the prediction of the wind energy challenging. This challenge is e.g. described by Beller [2], Dadde and Plate [4], and Wieringa, et al. [5]. In Copenhagen, as the city of choice, measurements on a few sites have been carried out and three of them were analysed to gain an overview of the wind characteristics in the city.

In the present work, three luminaries equipped with different types of rotors were simulated in wind climate representative to one of the new districts in Copenhagen, comprising 1-2 story single family buildings with gable roofs.

In order to simulate the luminaries as working in these districts, time series of wind speed measured at a location 20 km north of Copenhagen (Sjaelsmark) was delivered by the Danish Meteorological Institute (www.dmi.dk). This was the closest available location from which a complete year-long time series was available. Then, this data was corrected to account for the specific urban landscape – building height and density – using the roughness step method described by Beller [2].

2.2 Computational model of the luminary

Prediction of the power output from the wind turbine requires the knowledge of the power efficiency of the rotor. The power efficiency is very dependent on the rotor concept and the size of the rotor. Traditional large rotors are so called horizontal axis wind turbines with three blades. They are lift driven which means the blades are sucked through the air because of the suction pressure close to the leading edge of the blades. This mechanism is also used for some vertical axis wind turbines as e.g. the Darrieus type or H-type. For the lift driven concepts, the lift-to-drag ratio is crucial for the overall rotor performance.

However, in contrast to the large modern rotors, as e.g. the 5 MW sweeping through 12000m2 of air or more, the size of the urban turbine is very small. They might only sweep through 2 m^2 of air as in the case for the present simulated rotors. This difference in size is also reflected in the chord lengths of the blades and thereby on the Reynolds number. With the much lower Reynolds number, the lift-to-drag ratio becomes much lower and therefore the power efficiency decreases significantly, as described by Bak [6]. For this reason and for the reason of safety and aesthetics it is of interest to explore other possible concepts.

The investigated turbines were: vertical-axis twisted Savonius (*Green power* – see Figure 2), three-blade horizontal-axis (*United Electricity* – see Figure 3), and vertical-axis three-blade helical H-rotor (*Sanya* – see Figure 4).

Figure 2: Vertical-axis twisted Savonius rotor; *Green Power*

Figure 3: Horizontal-axis three-blade rotor; *United Electricity*

These turbines are actual components in luminaries manufactured by the corresponding producers. Each of these turbines is of different size. However, in the present work, each swept area was scaled in the analysis to be of 2 m^2 for a better comparison.

Also the remaining parameters of the simulated luminaries were assumed to be identical. These are listed in Table 1. These parameters were not meant to represent any specific luminary, but were meant to fall in the regime representative to most of the devices available on the market.

Figure 4: Vertical-axis three-blade helical rotor; *Sanya*

Table 1: Parameters used in the simulations of the considered luminaries

Rotor hub height	8 m
Photovoltaic cell efficiency	20 %
Photovoltaic area	1.5 m^2
Photovoltaic height	6 m
Photovoltaic tilt	45 deg
Photovoltaic azimuth	0 deg
Battery capacity	8 kWh

In order to simulate the photovoltaic panel, illumination values representative to the considered district were supplied by *Soda-Is*. Simulation of the turbines was a simple table lookup based on the producer-supplied power curves presented in Figure 5. Note that according to Mertens [7] producer-supplied power curves concerning small turbines are often poor indication of the actual performance of the turbines. Therefore, in order to perform more accurate simulations, power curves should be verified experimentally by a third party. Especially the power curve of the horizontal axis turbine, which despite the turbine's small size and therefore low lift-to-drag ratio operates relatively close to the Betz limit just above the cut-in wind speed, craves for verification.

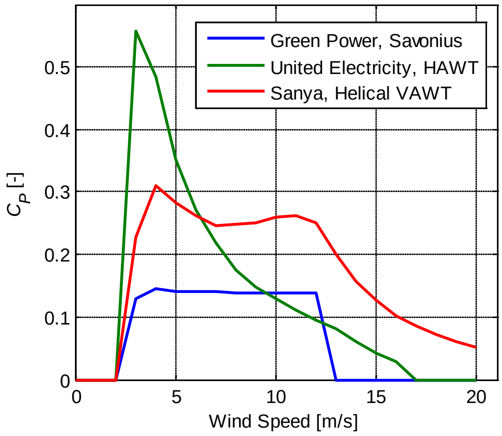

Figure 5: Producer-supplied power curves concerning the three simulated rotors

3 Results

3.1 The wind climate in Copenhagen

The analysis of the wind climate described in the preceding section showed that the wind energy in the considered urban environment was rather low relative to sites in the free field. The time series of the wind speed used in the simulations is presented in Figure 6 together with the 30-day-window running mean.

The reference height at which the wind speed was calculated was 8 m as this was assumed to be the hub height for all the luminaries in the present work. The maximum 10 min average in the time series is above 5 m/s. The mean wind speed is 1.3 m/s. Note that the displacement height in the present case was 4.25 m. On average, it is equal to two thirds of the average obstacle height in the area. The roughness length was 1.3. The sum of these two numbers was 5.55 m which was assumed to be the bottom of the logarithmic wind profile. It was relatively close to the hub height assumed in the simulations which explains why the average wind speed seen in Figure 6 is relatively small. This does not mean that the average wind speed below 5.55 m is zero. However, this wind speed is assumed to be relatively low and difficult to approximate with the available tools. The 30-day-window running mean, in which the month-to-month wind speed variation is visible, shows that July is the month characterized by the lowest average wind speed.

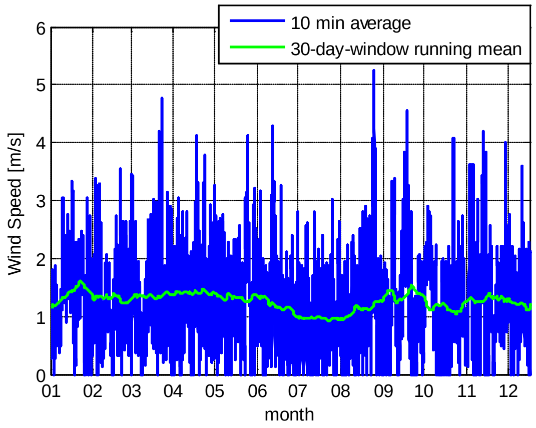

Figure 6: Time series of the 10-min-average wind speed used in the simulations together with the 30-day-window running mean; 8 m reference height

A one-week-long extract from the time series is presented in Figure 7. It shows relatively high variation in the wind speed within a week, i.e. from zero to almost 3.5 m/s which is significant given the range of values visible in the whole year.

Figure 7: One-week extract from the time series of the 10-min-average wind speed used in the simulations; 8 m reference height

3.2 Modelling the luminary

Work of the luminaries of characteristics described in the preceding section throughout one year was simulated. Figure 8 presents time series of the energy level in the batteries. If any of the curves touched the zero level, the simulated luminary would suffer from energy deficit and stopped working. Here, the battery capacity was actually adjusted in order for none of the three curves to touch the zero level.

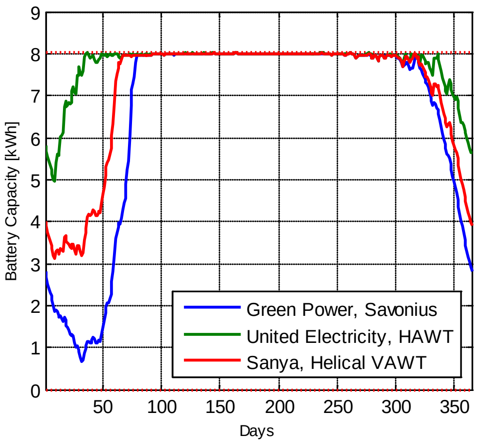

Figure 8: Time series of the energy level in the batteries in the simulated luminaries

Note that the result of the simulation was in good agreement with the presented power curves as the turbine with the most promising power curve (*United Electricity*) maintained the highest battery level throughout the year and vice versa. The simulation was iterated until the start and end energy levels of every luminary were equal. Otherwise, if a simulation started with the full battery and ended with a partly discharged battery, it would not be representative of what would happen in real life, year after year. The simulations also showed that, depending on the efficiency of the photovoltaic panels and the turbine, and the battery capacity, a luminary working in the considered environment could suffer from energy deficit in January, February or December. This is understandable as particularly long nights and short days on one hand increase the energy demand and on the other, decrease the gain.

Figure 9 presents the balance between the energy production by the turbine and the photovoltaic panel of the *United Electricity* turbine, and the consumption by the LED, regardless of the battery capacity. The figure indicates that, in general, energy production by the photovoltaic panel is much larger than by the turbine. In the summer time, the turbine would practically be unnecessary. The situation is different in winter, when the luminary may run into the risk of energy deficit. Then, the turbine and the panel would produce approximately the same amount of energy which indicates that the turbine is actually an important component of the system.

The figure also shows what was indicated by the previous figure, i.e. that the energy demand is higher in winter than summer.

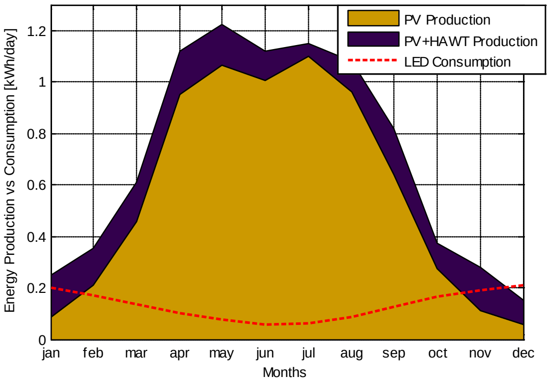

Figure 9: Balance between energy production by the turbine and the photovoltaic panel, and the consumption by the LED; *United Electricity* HAWT

3.3 Choice of the rotor

Although the results shown in the preceding section indicated that a horizontal axis turbine may be the best alternative to use on a hybrid luminary, the actual choice is more complex as more aspects of the design need to be taken into account. The relatively high difference in performance should be verified by doing an experimental study of the actual power curves of the turbines. Also, the low average wind speed at which the turbines would need to operate points either at a two-stage or twisted Savonius turbine which are known for their low starting torque, even though the producer-supplied power curves indicated that all the simulated turbines were characterized by the same cut-in wind speed. The advantage of both twisted and two-stage Savonius turbines over the conventional Savonius design is the lack of negative starting torque which, existing at the conventional Savonius rotors, obstructs their start at certain inflow angles.

Another issue is that the tip speed of lift-driven concepts like the horizontal-axis turbine might run up to approximately15 times the wind speed whereas the optimal tip speed of a Savonius rotor is approximately 0.7 of the wind speed. Thus, concerning safety, Savonius type is more attractive in urban areas. Also, concerning aesthetics, the vertical-axis wind turbines are according to many opinions easier to fit in as a sculptural element of the urban land scape. And finally, the rapidly changing wind direction in urban environment could cause the whole horizontal-axis turbine to flap, decreasing its efficiency due to yaw misalignment.

Taking all these factors into consideration, a decision was made to pursue a 90-degree-twist single-stage Savonius wind turbine with small-size end plates mounted and the top and bottom of the rotor, as presented in Figure 10.

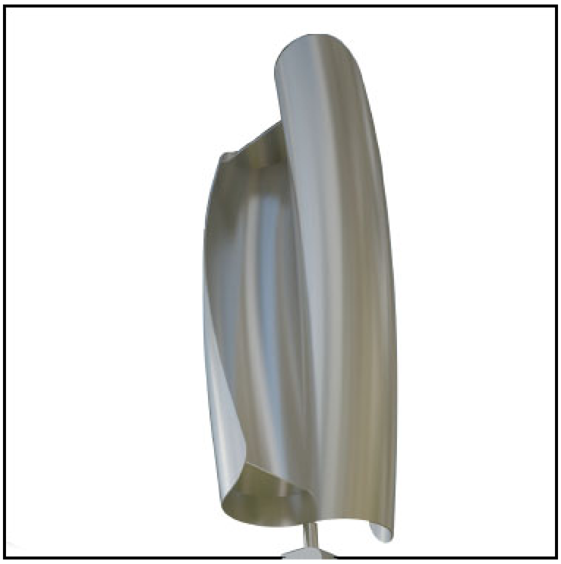

Figure 10: Present design 90-degree-twist single-stage Savonius wind turbine with small-size end plates mounted and the top and bottom of the rotor; source: Henning Larsen Architects A/S

Note that compared to large, modern wind turbines, where the energy production typically can be 1000kWh/m2/year or more it is obvious that focus on cost efficiency is needed even though the cost function for wind turbines in the urban area is very different from wind turbines in other environments. In the case of urban luminaries e.g. the cabling might potentially be avoided, if it is designed as an autonomous system being completely self-sufficient, which can be an important cost saver.

4 Conclusions

In the present work, a simulation of three different wind turbines used in hybrid luminaries was presented. The turbines were: vertical-axis twisted Savonius, three-blade horizontal-axis, and vertical-axis three-blade helical H-rotor.

The considered luminaries were also equipped with photovoltaic panels and batteries, detailed investigation of which was outside the scope of the present work.

Simulation of the luminaries with the turbines based on producer-supplied turbine power curves was presented together with an estimation of the wind climate in Copenhagen district comprising 1-2 story single family buildings. The analysis showed the need for balancing the size of the wind turbine, the photovoltaic panels, luminary and the battery the best way.

A new 90-degree-twist single-stage Savonius wind turbine with small-size end plates mounted and the top and bottom of the rotor was proposed for a luminary being designed for such a district within the “Development of CO2 neutral urban luminary” project.

5 Further work

Based on the current study and literature review the following issues are to be addressed in future work:

- Perform either open field or wind tunnel experiments to estimate the power curve of the designed Savonius rotor.
- If the performance of the designed rotor was lower than expected, introduce changes in the design.

Acknowledgement

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