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COPENHYBRID – DEVELOPMENT OF A CO_2 NEUTRAL HYBRID STREET LIGHTING SYSTEM FOR THE DANISH MUNICIPALITIES' ILLUMINATION CLASSES.

Peter Behrensdorff Poulsen[1], Carsten Dam-Hansen[1], Anders Thorseth[1], Sune Thorsteinsson[1], Johannes Lindén[1], Søren Stentoft Hansen[1], Stine Ellermann[1], Christian Bak[2], Witold Skrzypiński[2], Christina Beller[2], Carsten Weber Kock[2], Fabian Bühler[3], René Kirstein Harboe[3], Per Boesgaard[4], Tim Jensen[5], Ole Søndergaard[6], Christian Andresen[7], Morten Fahlén[8], Thomas Maare[9], Hugo Prestegaard[9], Jan Poulsen[10], Susanne Kremmer[11]
[1]Department of Photonics Engineering, Technical University of Denmark, Building 128, RISØ Campus, Frederiksborgvej 399, 4000 Roskilde, Denmark
Tel. +45 4677 4572, ppou@fotonik.dtu.dk
[2]Department of Wind Energy, Technical University of Denmark, Roskilde, Denmark
[3]Faktor 3, Copenhagen, Denmark
[4]Gate 21, Albertslund, Denmark
[5]Philips Lighting Denmark, Hedehusene, Denmark
[6]Alfred Priess, Vinderup, Denmark
[7]Henning Larsen Architects, Copenhagen, Denmark
[8]DONG Energy, Gentofte, Denmark
[9]Copenhagen Municipality, Outdoor Lighting, Copenhagen, Denmark
[10]Egedal Municipality, Egedal, Denmark
[11]Albertslund Municipality, Albertslund, Denmark

ABSTRACT: A mathematical model has been developed for the energy system of the hybrid street lighting making it possible to simulate a given configuration (solar panel performance data, size and orientation - wind turbine performance data, projected area and height - battery data) over a year in an urban environment of a given configuration based on measured wind/solar/temperature data from nearby meteorological station or other relevant weather data. The simulation can show if it is possible to cover the consumption by the light source over the year. The model can be used to evaluate both commercial hybrid systems and to dimension new systems for use in given environments where the weather data are known. Since weather and day/night length are varying a lot around the world the systems should be dimensioned very differently depending on the place of use. By using the simulation tool it is shown that it is possible to create a hybrid street lighting for an urban environment with a maximum of 2 floor height buildings which governs >70% of the luminaires in Copenhagen (the Capital of Denmark) fulfilling the requirements of 2.5 lux on the street over the year. Furthermore the tool is powerful to evaluate hybrid systems on the market (if all the technical data is known) for use in a given urban placement.
Keywords: solar panel, hybrid luminary, street lamp, CO_2 neutral, small wind turbine, urban wind energy.

1 INTRODUCTION

In the process of converting the societies energy consumption from fossil fuel to renewable energy sources two approaches seems to complementing each other very well. The centralization of power plants based on solar farms, wind farms and other large scale energy harvesting fits quite well into the grid and the supplementing of e.g. solar panels integrated in the buildings close to where the consumption is occurring. In some applications it might be even economical feasible to be self-sufficient off-grid applications even in urban environments since cabling is very costly.

In the present work a group of the leading researchers in Wind Energy, Solar Energy, LED and optics in Denmark have been working together with the relevant industrial technology partners and a wide range of the Danish municipalities with Gate 21 and Copenhagen Municipality in front to investigate the potential for use of hybrid street lighting in the Danish illumination classes in the municipalities and develop a specialized solution based on the specific needs of the municipalities since no perfect match is found on the market at the present time.

The present project focus on luminaires for street lighting and since the light emitting diode (LED) technology are getting more and more energy efficient with record efficiency in lab of close to 250 lm/W for white LEDs and LED systems on the market > 140 lm/W the energy consumption is dramatically declining. Furthermore LEDs are very easy controlled by dimming and intelligent sensor systems are developing making it possible for the lighting to be dimmed to a low level when no people or cars are around and some systems can even separate humans from small animals like cats, birds, etc., so the energy is minimally wasted making light for non-humans. So self-sufficient lighting installations in the urban environments and areas far from grid connection are requiring less and less energy harvesting to meet the lighting requirements. Hybrid street lighting powered by both solar energy and wind energy is very suited for street lighting due to the fact that the pole and luminaire can be considered almost "free" since it should be installed under all circumstances. The added cost for battery, solar cells and wind turbine should as a minimum be paid by the savings on the cables and the energy savings.

The project has shown it very useful and powerful to have such a simulation tool in the process of developing hybrid street lamps to different global positioning, climates and urban environments (shielding PV and wind turbine in certain direction). A market scan in early 2012 showed a total of 29 manufacturers of hybrid street lighting around the world and an evaluation of the data obtained from the vendors of their products showed very few that could operate in Denmark even in a street class with very low buildings and lux levels of only 2.5 on the street when simulated. 4 commercial hybrid systems was bought, installed and evaluated and was shown to operate poorly due to bad quality components in the energy systems. It was though possible to validate the mathematical model when the electrical characteristic parameters were measured for PV, wind turbine, luminaire, controller box and battery. The systems though need to run for a longer period of time and in different urban environments to fully evaluate the model which is work in progress.

By using the simulation tool it is indicated that it is possible to create a hybrid street lighting for an urban environment with a maximum of 2 floor height buildings which governs >70% of the luminaires in Copenhagen (the Capital of Denmark) fulfilling the requirements of 2.5 lux on the street over the year. Furthermore the tool is powerful to evaluate hybrid systems on the market (if all the technical data is known) for use in a given urban placement.

2 MARKET SCAN

To investigate the solutions already on the market 29 hybrid systems was identified January 2012 from mostly Chinese suppliers and the rest from USA, Canada, Korea and France. Based on the technical data for the systems it was possible to obtain from the manufacturers 4 hybrid systems was selected by the project partners for having the best potential for use under Danish weather conditions and fit to the lighting requirements for street lighting. The 4 systems was purchased to test under characterized conditions on the Technical University of Denmark, RISØ Campus to investigate the energy systems of the hybrid systems in real life test and calculate the potential use of them in different street classes in the Danish Municipalities.

3 MATHEMATICAL MODEL OG THE SYSTEM

To calculate the needed dimensions of the hybrid systems active components (wind turbine, solar panel, battery, LED etc.) a mathematical model was created based on these modules.

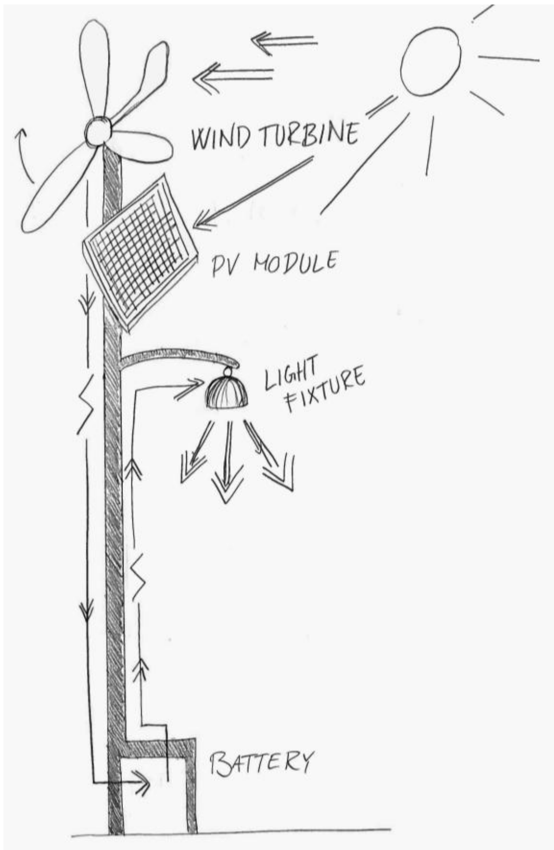

Figure 1: The active components in the hybrid system

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 [1]. Solar Energy was likewise simulated by irradiance data for the same area obtained from SoDa (www.soda-is.com). A modeling tool is developed in MATLAB taking as input the parameters of lighting illumination class, urban landscape, solar panels (size, orientation, etc.), wind turbine (swept area, power curves etc.), battery (capacity, charge/discharge curves etc.), temperature and other relevant factors as shown by the flow diagram in figure 2.

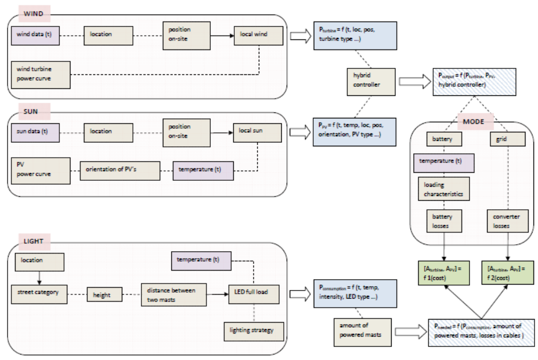

Figure 2: Flow diagram of mathematical modules in the tool to evaluate and dimension hybrid systems.

The different street illumination classes can be build up based on general characteristics for the streets (building heights, road widths etc.) and some rough standard scenarios can be made for each illumination class to evaluate the wind potential for the street class. The simulation can then run with the given parameters of the turbine of the hybrid system.

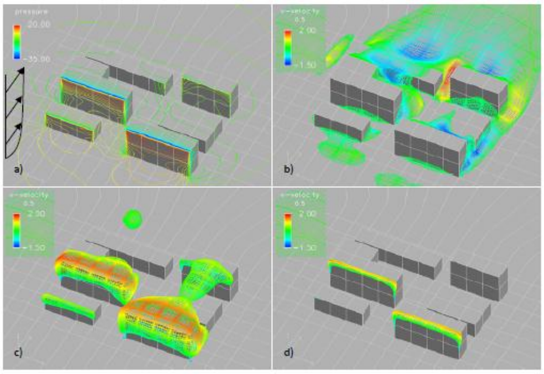

Figure 3: a) Static pressure distribution; b)-d) tke iso-surfaces (tke = 0.5; 3; 6 m^2s^2) with velocity component v distribution.

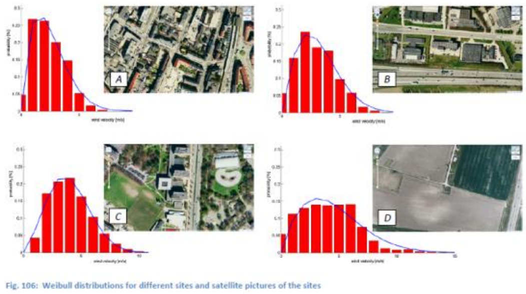

Figure 4: Weibull distributions for different sites and satellite pictures of the sites. The denser the urban environments are the wind turbines have to harvest energy at lower wind speed more optimally.

The sun path and the shading from buildings and the weather parameters can be modeled by the same urban environments shading model as for the wind in figure 3 evaluating the potential for solar energy harvesting by a given solar panel in a given position if the electrical parameters for the panel is known (figure 5).

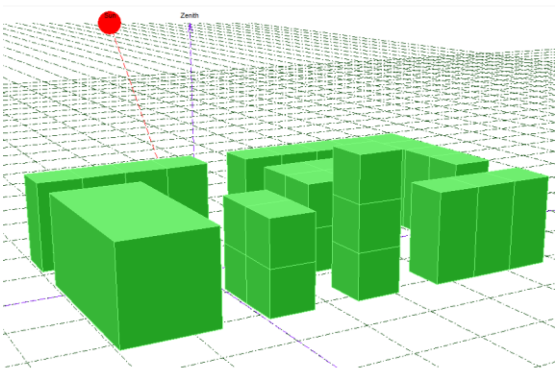

Figure 5: The solar energy harvesting potential can be calculated by modeling the sun path over the year shaded by buildings and the weather etc.

The tool can be used to evaluate hybrid systems on the market (if all the technical data is known) for use in a given urban placement. In figure 6 an example of a commercial system is evaluated.

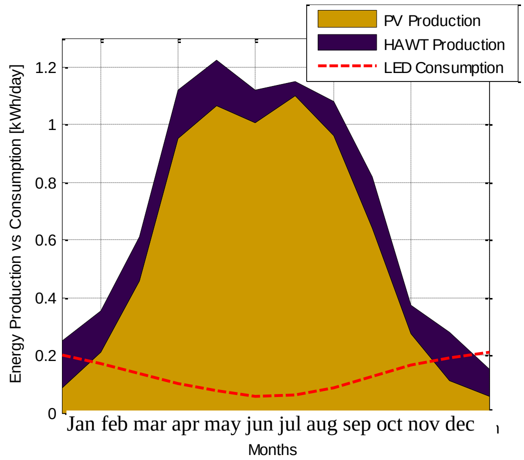

Figure 6: Balance between energy production by the turbine and the photovoltaic panel, and the consumption by the LED for a given hybrid system. The wind turbine production is added on top of the PV production.

The tool can furthermore be used to develop new and better hybrid systems, since the individual technical parameters and its effect on the system performance can be evaluated so the relevant parameters can be optimized.

For the Danish climate and use in the urban environment here it is clear that the systems on the market can be supplemented by systems designed especially here for. The modeling tool is used as a cornerstone in this design process.

4 EXPERIMENTAL RESULTS

4 commercial systems where selected and bought for testing. The systems were chosen to represent a variety of turbine types and geographical origin. Two of the systems were fairly easy to measure. 1 of the systems were of very poor quality and broke few weeks after installation and the last systems had arrived later and had a power rating that complicated the data logging and is no data from this system is therefore presented in this article. The systems installed are shown below on figure 7.

Figure 7: Picture of 3 hybrid lighting system masts - the two outer masts are equipped with data logging. The masts are numbered 1 to 3 from the right, so the right one is called number 1.

The systems are equipped with data logging systems logging the flow of energy from the active components in the system (Wind turbine, Solar panel, lighting system and battery). The solar irradiation on a planar surface is measured by a pyranometer (Kipp & Zonen SMP3-I) and the wind energy is measured in several height from ground level to 50 meter high as reference close to the hybrid systems. The energy flow from middle November 2012 to the end of January through from the solar panels and electronics into the battery is shown on figure 8 for the 2 outer masts on figure 7.

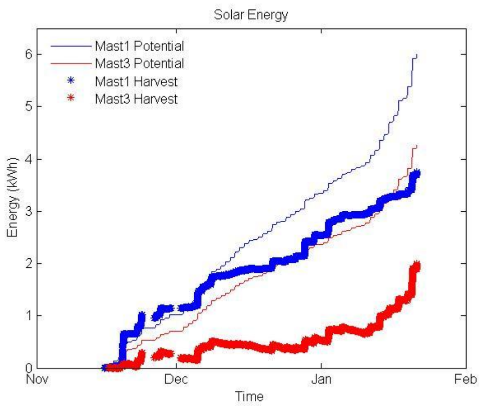

Figure 8: The figure shows accumulated energy harvesting from the solar panels compared to optimal harvesting possible by conventional medium cost small scale PV/battery systems with MPPT. Mast 1 has absence of maximum power point tracking and mast 3 seems to have a poor converter system.

The figure shows that the solar harvesting is far from optimal compared with conventional technology for small PV panels coupled to an electronic converter with maximum power point tracking (MPPT). Mast 3 is especially poor and more than 66% of the energy is lost compared to a conventional medium cost PV/converter/battery system. The total accumulated energy flow in the hybrid systems for mast 1 is shown in figure 9.

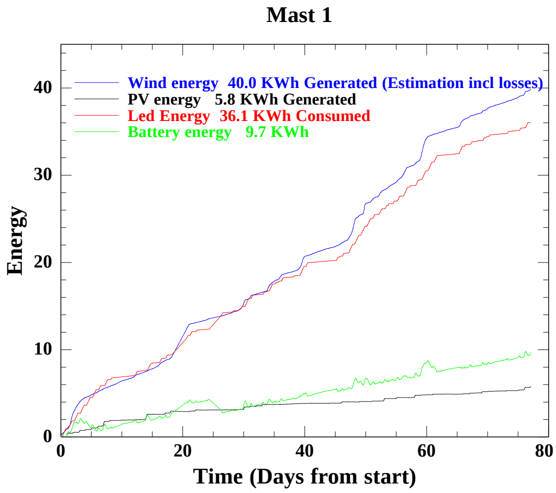

Figure 9: The figure shows accumulated energy harvesting from the wind turbine and solar panel, the accumulated energy consumption from LED (in positive numbers) and the battery balance (which has offset error and should be linear oscillating around the x-axis. The lamp is far from self-sufficient even when placed on an open field.

The figure shows that the lighting system cannot sustain its own energy consumption for a whole night in when the lighting is set to work during all the dark hours during the period. The red curve should have been almost linear. The system is standing on a totally unshaded field which is far from an urban environment situation. It should be noted, that there is an offset error on the green battery curve that should be oscillating around zero. A much better dimensioned hybrid system (mast 3) is shown below in figure 10.

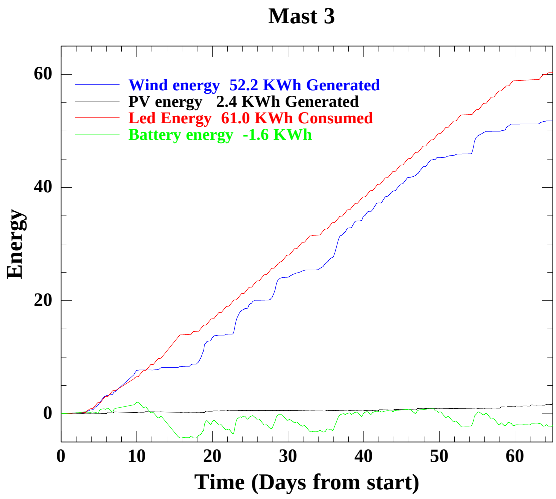

Figure 10: The figure shows that the wind turbine generates almost all energy to the battery and further the

LED consumption is almost a straight line indicating that there is almost enough energy. However the PV part is not regulated properly and is almost not contributing to the energy harvest. This system is performing well almost through the full period. Almost all the energy is coming from wind power since the solar power system is as shown on figure 8 performing poorly. The conclusion is though that the system will not perform very well in a shaded environment like a city street since the system is just able to sustain itself under the ideal conditions on the field leaving no room for loss due to shading of especially the wind turbine.

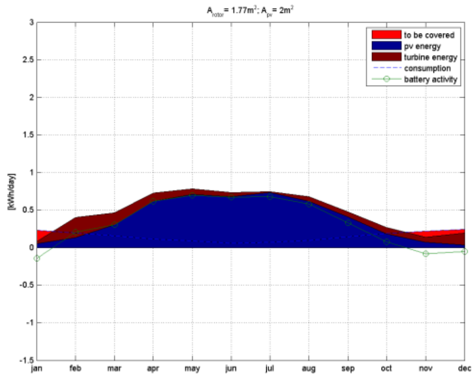

Figure 11: Run of mathematical model for mast 1 placed in an environment like a regular E2 road in Copenhagen using data from the producer for the wind turbine, solar panel, battery and lighting system. The blue area is the energy produced by the solar panel, the brown in energy from the wind turbine and the red is the energy to be covered for the lamp. The system is close to being self-sufficient. When measured in the lab the parameters for the components (wind turbine/PV) are far worse than the ones given by the producer and the system is much further away from being self-sufficient.

As can be seen from the measurements on the real systems the electronic controller box is a very crucial part of such system and therefore efficient MPPT tracking of both the PV and the wind turbine is needed in combination with efficient conversion electronics. Furthermore energy system dimensioning for the given application site is crucial. There is not at one size fits all solution even though the hybrid systems are sold as such.

5 DESIGN PROCES

A design process evaluating a lot of different designs for a specific illuminating class, E2 (which seems to have a good business model behind it and >70% of streets in Copenhagen is this illuminations class) has been realized based on modeling and fitting PV panels and wind turbines to make the systems self-sufficient. The E2 class has quite low lighting requirements (2.5 lux) and can be dimmed between 23:00 and 6:00. The design room are as follows:

- E2: Local roads, suburbs - Minimum illuminance: 2.5 Lux
- Dimming: The lighting requirement is lowered by 50% between 23.00 and 06.00.
- On/off times: The on/off times used here are estimates based on sunrise and sundown. Actual on/off times are forthcoming from Copenhagen Municipality.
- Distance between lighting fixtures: 30 meter
- Road width: 13 meter
- Max 2 floor high buildings

Several mast designs with various technical parameters for the active components in the hybrid system was evaluated to find a valid solution. One of the sketches is shown in Figure 12 which was also made as a mock-up.

Figure 12: Hybrid system with 90-degree-twist single-stage Savonius wind turbine and solar panels integrated in the mast source: Henning Larsen Architects A/S

The modeling shows that the system should be able to be self-sufficient if the assumptions thy are based on are correct. In the next phase of the project a series of real prototypes should be realized and put up in the urban environment to validate the model calculations.

6 CONCLUSIONS

A mathematical model has been developed for the energy system of the hybrid street lighting making it possible to simulate a given configuration (solar panel performance data, size and orientation - wind turbine performance data, projected area and height - battery data) over a year in an urban environment of a given configuration based on measured wind/solar/temperature data from nearby meteorological station. The simulation can show if it is possible to cover the consumption by the light source over the year. The model can be used to evaluate both commercial hybrid systems and to dimension new systems for use in given environments where the weather data is known. Since weather and day/night length are varying a lot around the world the systems should be dimensioned very differently depending on the place of use.

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7 FUTURE WORK

The simulation tool will be evaluated and improved by full year measurements on commercial hybrid street lighting and in a later phase of the project prototypes of the developed hybrid street lighting system will be positioned in different spaces in the Danish municipalities taking part in the project to validate the model as well as the whole system and design.

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9 ACKNOWLEDGMENTS

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