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Urban Wind Turbines: A Feasibility Study

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Abstract

Current planning guidance in London requires all new and refurbished large buildings to produce 20 % of their electrical needs via renewable means (GLA, 2004). This policy came into effect in 2004. In compliance with the guidance London South Bank University installed a 6 kW wind turbine upon a refurbished office building. This paper summarises an investigation into the relationship between wind, energy, noise and vibration for the urban wind turbine. The eighteen month feasibility study took the form of measurement and predictions of wind, noise, vibration and energy generated. It concluded through optimising the position and height of the urban wind turbine it is possible to better harness the local wind resource such that the price per kWh generated is reduced to £0.15 over a 30 year period. This compares to the price per kWh of the current installation of £0.40. It was also found that the local community would normally not be affected by the noise produced by the turbine.

Keywords Noise, Vibration, Wind Turbines, Wind Energy

1.0 Introduction

In 2004 the Mayor of London outlined an energy strategy to make London ‘more green’ by achieving a 60% reduction in London’s carbon emissions and becoming a low carbon economy (1). The government’s reduction targets were set towards supplying 10% of UK electricity demand via renewable energy sources with the goal of extending this to 25% by 2025 (2).These goals are to be met utilizing, amongst other renewable energy systems, wind power. England is fortunate to be surrounded by coastline and have expansive open rural countryside surrounding our major cities; ideal qualities to capture uninterrupted wind flow and build wind farms. Despite an encouraging amount of proposed and successful installations around the country, there is still a great amount of public opposition, usually because of aesthetics, such as the Public Inquiry in Powys (3), or due to the effect on wildlife (4). As such current policy is to construct wind turbines off shore.

Urban wind turbines are an alternative solution where securing an optimum site location is crucial for an efficient installation able to extract the maximum amount of power from a optimistically undisturbed flow of air. A general rule of thumb states that the lowest point of the wind turbines swept area should ideally be at least 30-50ft above the tallest structure within a 500ft radius (5). This ideal wind flow situation in a city environment would be unusual. The local topography of rooftops, tall structures and long, winding streets would cause unpredictable, irregular flow, high wind shear and a complex turbulent flow as well as acceleration across rooftops and tunnelling venturi effects at ground level. These conditions equate to urban areas being far from ideal but in 2007 London saw Brookfield Multiplex begin construction on the world's first residential skyscraper to include wind turbines in to the fabric of its design. In June 2010 the Strata Tower was complete, a 150m high, 43 storey complex residency to over 1000 people, see Figure 1. Three 5 m blade, 9 m diameter, 19 kW custom turbines were installed at the very top of the structure with an estimated energy production of 50MWh per year, enough to produce 8% of the tower's annual energy consumption (6). Concurrently, a Proven 6 kW 3 blade wind turbine was installed on top of London South Bank University on a 10 storey building on a 9 m mast, see Figure 1. This paper presents the work undertaken to understand the performance (wind, energy, noise and vibration) of the turbine on the campus of London South Bank University. Full information is available in (7).

Figure 1: Strata Tower's 3 Norwin 18 kW turbines, LSBU's Proven 6kW turbine

2.0 Methodology and Instrumentation

Synchronised measurements of noise, vibration, wind and energy generation were recorded over a period of eighteen months, September 2013- February 2015 on the rooftop of a ten storey office building on the campus of London South Bank University. The collected data was analysed and compared to prediction models to assess the suitability and performance of the wind turbine installation. A full method statement was undertaken for the site to minimise the risk necessary to undertake the research on the rooftop. There were technical difficulties on the Strata Tower site, after which the turbines were switched off and hence this paper focuses on the LSBU site.

Below is the complete list of the monitoring on the LSBU site

1. Monitor and log local atmospheric data, 10 m anemometer on the rooftop
2. Monitor and log real-time energy generation.
3. Monitor and log background and operation turbine noise on the rooftop, in the building and other locations, as appropriate.
4. Generate a noise map around LSBU campus for community noise annoyance.
5. Monitor vibration on the rooftop, offices and other locations, as appropriate.
6. Appropriate aerodynamic modelling of wind flow to analyse energy performance for validation purposes.

2.1 Wind Resource Prediction, Measurement and Electrical Generation

It is essential to have site specific wind data before a wind turbine site can be appropriately chosen. If site specific measurements aren't possible there are extensive winds mapping databases available for public use via the Department of Business, Enterprise and Regulatory Reform, such as European Wind Atlas and the CIBSE TRY data. This data can be used to estimate available power in the wind and therefore potential energy yield of a proposed site. However, these sources usually only list annual average wind speeds which necessitates the employment of probability distribution techniques such as the Weibull or Rayleigh distribution methods to gain an estimate of annual wind speed distribution and hence the likely energy resource.

One problem with the available wind mapping databases is that they use weather data recorded at airport or in rural areas, which although useful for rural wind farm assessment, may not be reliable or appropriate for urban, built up, areas. Urban environments have a complex topography which leads to lower annual mean wind speeds and increased turbulent flow causing rapid changes in wind direction. This turbulent wind would produce additional stresses on mechanisms and components lowering the life expectancy of a system. However, once an accurate wind resource is known a good estimate of energy yield can be produced to establish the effectiveness of each site, which will contribute towards determining the feasibility of urban turbines. The best estimate of the available wind resource is to use fluid flow modelling.

Fluid flow is a complex discipline, however CFD tools are now available, such as UrbaWind, which can be used to run computational simulations of the topography surrounding each site to assess the available wind resource (8). The UrbaWind simulation used atmospheric data collected from the LSBU rooftop anemometer and the local urban topography to predict the energy generation potential of the site, as suggested by (9). UrbaWind required a 3D model of London SE1 centred on the University built using Google Sketchup, see Figure 2. For computational reasons this was reduced to a 300 m by 300 m grid with a focus on the SW corner due to prevailing wind conditions in London.

Figure 2: A 1 mile radius of London topography centred on the University campus.

The following atmospheric data was collected: wind speed, wind direction, temperature, atmospheric pressure and humidity by the Power Predictor anemometer installed 10 m above the rooftop of the LSBU site (turbine hub height). Logging was undertaken on a 5 minute basis. Analysis of the data allowed predictions of site potential energy yield and was compared with theoretical predictions in an effort to further understand the intricacies of urban wind turbine installation. Electricity generation was simply read off the Windy Boy inverter every day on the LSBU site.

2.2 Noise and Vibration Measurements

For the University rooftop, a 6 channel Svantek SV106 vibration meter was used. This allowed two sets of 1/3rd octave X,Y & Z axis vibration data to be recorded simultaneously, again every 5 minutes, on the turbine and in the building in accordance to BS 6472:2008 (10). The two sets of data allowing the efficiency of the vibration isolation to be assessed. A Norsonic Nor140 Class 1 sound level meter was used to establish the sound power level produced by the turbine under a range of wind conditions in accordance to ISO 61400-11 (11). In addition Class 1 sound level meters were used to measure at four locations, sensitive receptors, the overall dBA values and 1/3rd octave environmental noise levels. The noise, vibration and wind measurements were synchronised and measured every 5 minutes. This data was used to predict and validate the noise levels produced by the CADNA-A noise mapping software package (12). These predictions were then used to assess the impact of the turbine on all local residents in accordance to the World Health Organisation (13).

3. Case Study: LSBU Site

As the Strata Tower site did not provide a complete picture of the wind, electricity, noise and vibration produced by the turbines the focus is on the LSBU Wind turbine installation. For complete data please read (7).

3.1Wind Monitoring and Prediction

To accurately establish the energy resource available on the rooftop of the LSBU building anemometry was undertaken. This report is based on a 6 month sample of the data collected for reasons of brevity; see Figure 3, full data in (7).

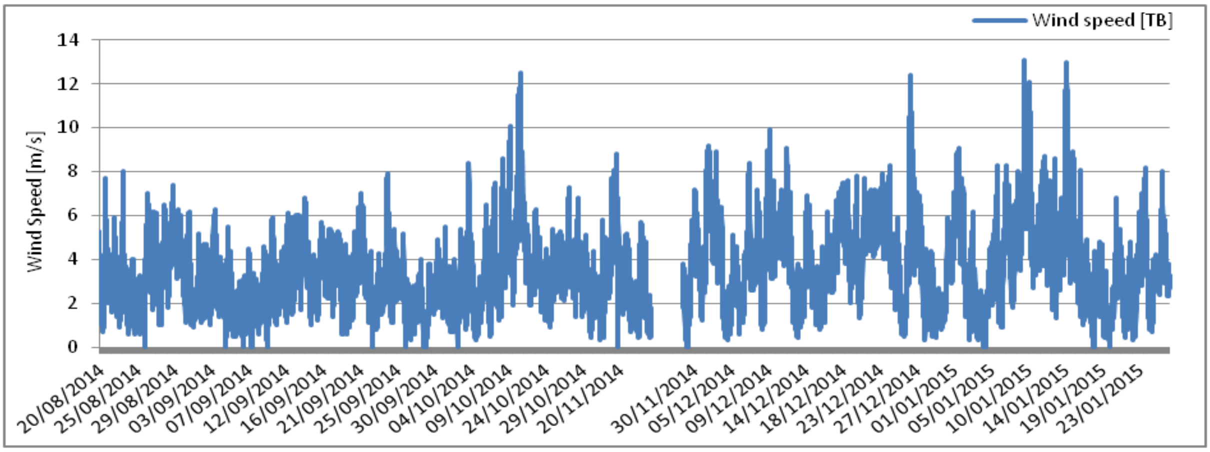

Figure 3: Wind speed on LSBU rooftop August 2014-January 2015

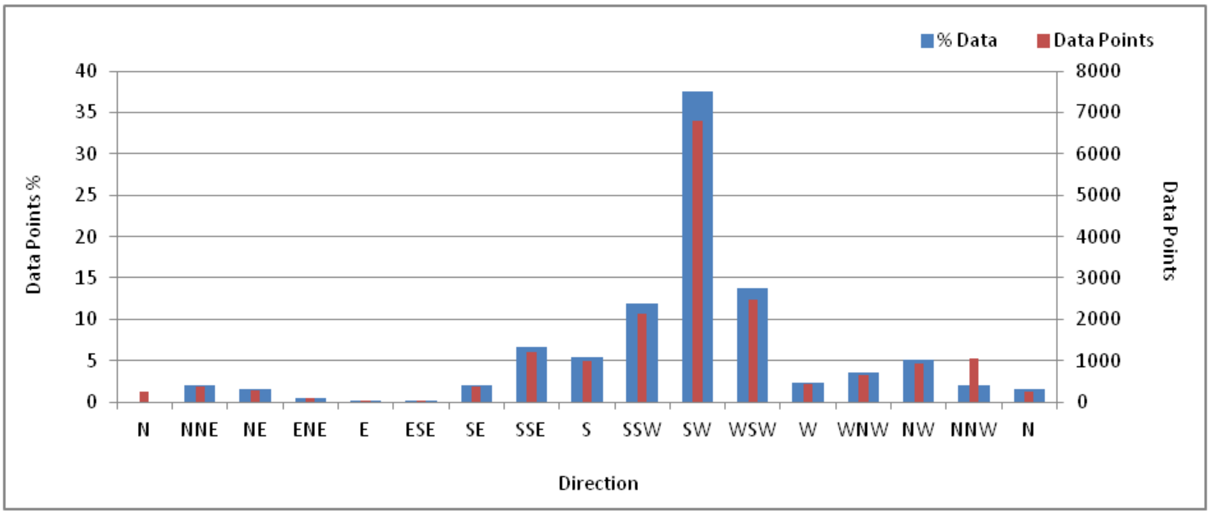

Figure 4: Wind direction distribution data collected at the LSBU rooftop.

LSBU’s rooftop measured data showed a significant difference in wind speeds when compared to the Numerical Objective Analysis Boundary Layer (NOABL) database based on Heathrow data (14).
NOABL predicted a wind speed of 6 m/s at hub height as opposed to the measured average of 3.5 m/s on the LSBU Building see Figure 3. The dominant wind direction gave good agreement with NOABL, see Figure 4. One of the main reasons for this is the uncertainty of the local wind regime and a lack of archived averaged wind speed reference data. Incorrectly estimating the available wind resource would be detrimental to any planning, technological or financial investment, therefore site specific wind data, or an accurate simulation using CFD analysis within the urban environment is intrinsically necessary for an accurate estimate.

Weibull and Rayleigh probability density functions were used as auxiliary prediction tools to assess their applicability in the urban environment. The Weibull with Maximum Likelihood Method (MMLM) was shown to correlate closely with measured data, but still undertake estimated energy yield by 8%, Rayleigh over-estimated by 24% and power curve method by 43% for the 2014 data set. The difference is attributed to the shift in wind speed bin predictions around the criteria cut in speed of 3-4 m/s for the turbine.

The effect of design ideas can be evaluated through the application of CFD analysis. As turbulent airflow is the main reason for the reduction in energy potential increasing the height of the turbine is the simplest solution. For the LSBU rooftop an increase in mast height to 20 m was modelled, see Figure 5. This 10 m increase in height kept the wind flow more laminar giving a 40% increase in wind speed for the primary wind direction. Give that power in the wind is proportional to velocity cubed (V^3), this increase in speed equates to a 2.75 multiple increase in power.

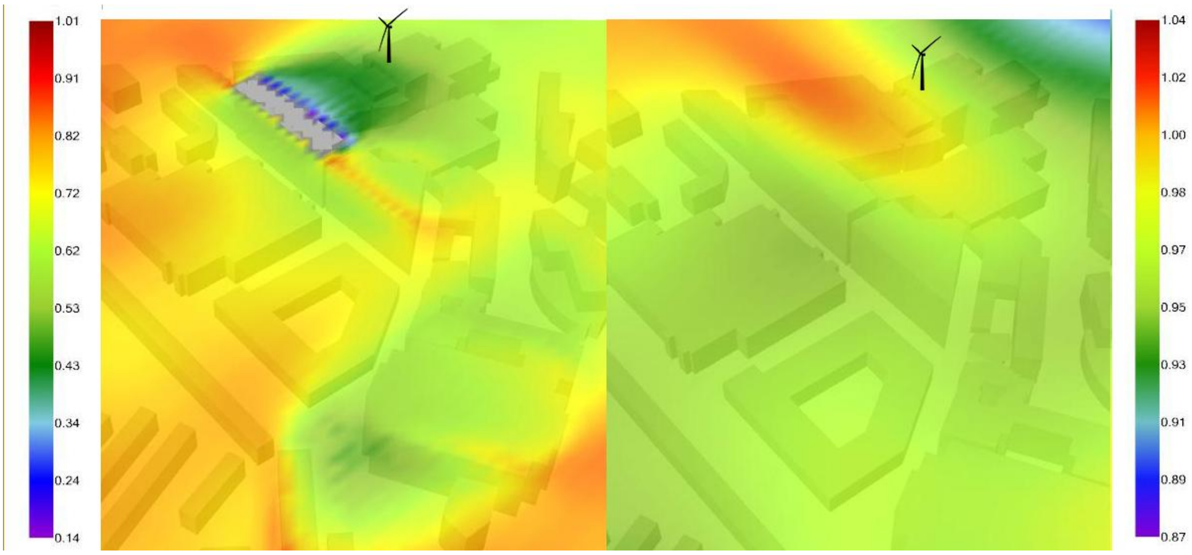

Figure 5: LSBU Rooftop turbine site. Left side shows CFD mean wind speed analysis at installed hub height. Right side: the effect of an extra 10 m in height (200m by 200m)

3.2 Noise Monitoring and Prediction

The noise monitoring consisted of two parts: firstly on the rooftop to assess the relation between noise and wind both with and without the turbine operating and secondly, to determine the environment noise condition in the area, in particular at the nearest sensitive residences.

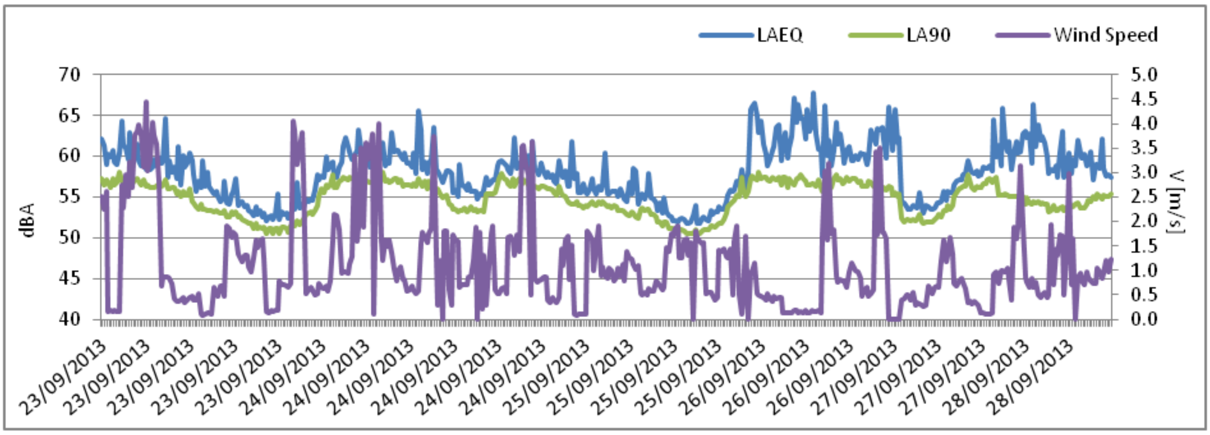

Figure 6: Background noise and wind speed levels at the LSBU rooftop (Dec 2013).

Figure 6 demonstrates no strong correlation between overall noise level, $L_{Aeq,}$ and wind speed on the rooftop without the turbine. The consistent, repetitive fluctuation of noise levels suggests the background noise within the area was predominantly dictated by other factors such as traffic, HVAC etc.

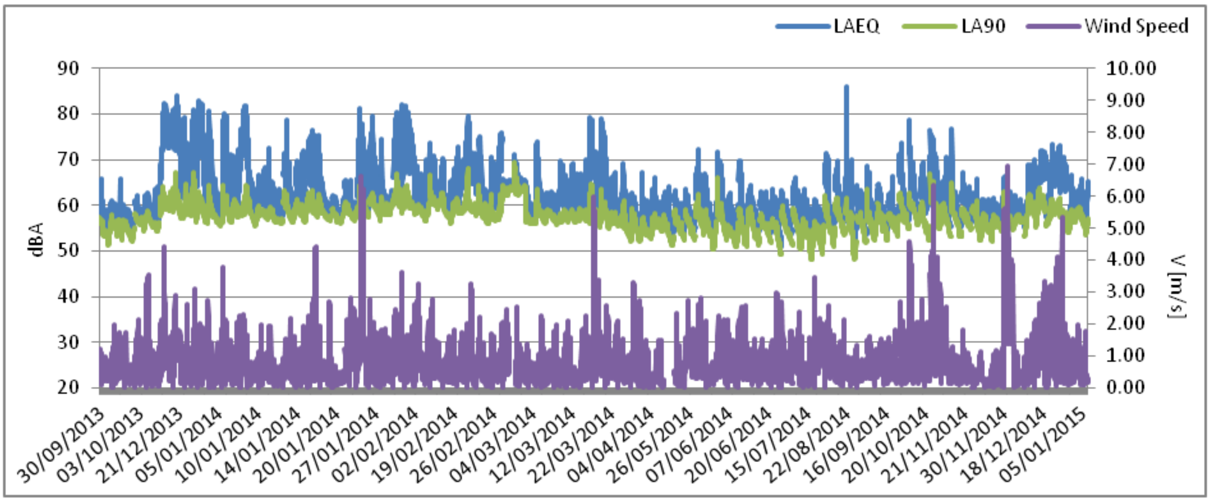

Figure 7: Operational noise levels at the LSBU turbine against wind speed.

Figure 7 shows a relationship between noise levels, L_{Aeq}, and wind speed with a 1 dB increase in noise per wind speed bin above the cut in speed of the turbine, 3 m/s.

An analysis of the noise spectrum was undertaken to determine the frequency content 1//3 octave bands, for below turbine cut in speed, above cut in speed and at high wind speed.

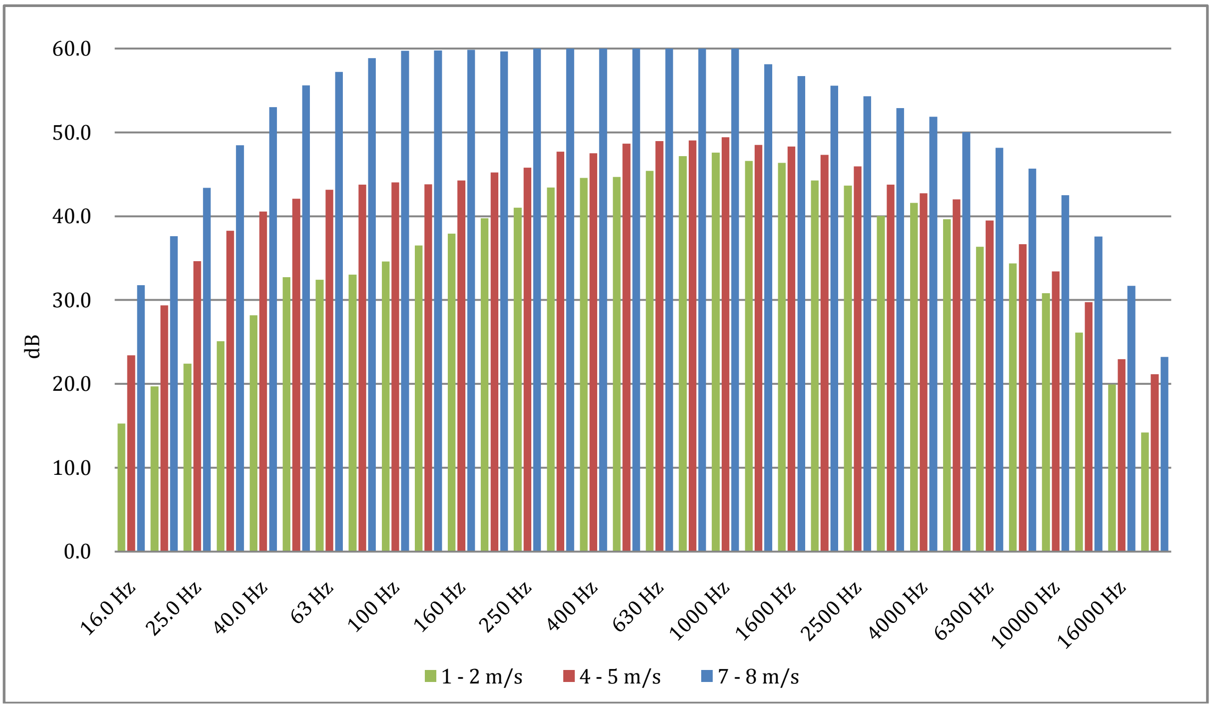

Figure 8 Comparison of operational $^{1}/_{3}$ octave noise level results at low, average and high wind speeds for the operation turbine on the LSBU rooftop.

As can be seen from Figure 8 low frequency noise from the turbine can typically be attributed to changes in wind speed, above the cut-in speed, caused by the blades due to the mast and wind shear. The spectral content of the sound was dominated by the blade passing frequency, 10 Hz, and the harmonics there of. At higher wind speed the spectrum became broadband with a 10 dB increase in noise level across the frequency range. This information was used to determine the maximum, or worst case, sound power level, produced by the turbine.

Propagation of induced turbine noise into this area was predicted using CADNA-A based on this worst case condition, 74 dBA at 12.5 m. The CADNA-A model assumed a hub height point source radiating hemi-spherically from the rooftop, giving a Sound Power Level of 106.9 dBZ. Figure 9 presents the noise map of the local area predicting overall noise levels, dBA, at the nearest residential properties in the region of 50-59 dBA. This was just above the measured ambient noise levels, $L_{Aeq,1\ hour}$, 50-55 dBA. Hence, it would be just possible to perceive the turbines in the worst case condition for the nearest residents. It should be noted that for the higher range of wind speeds, over 6 m/s, this occurred for only 13% of the time.

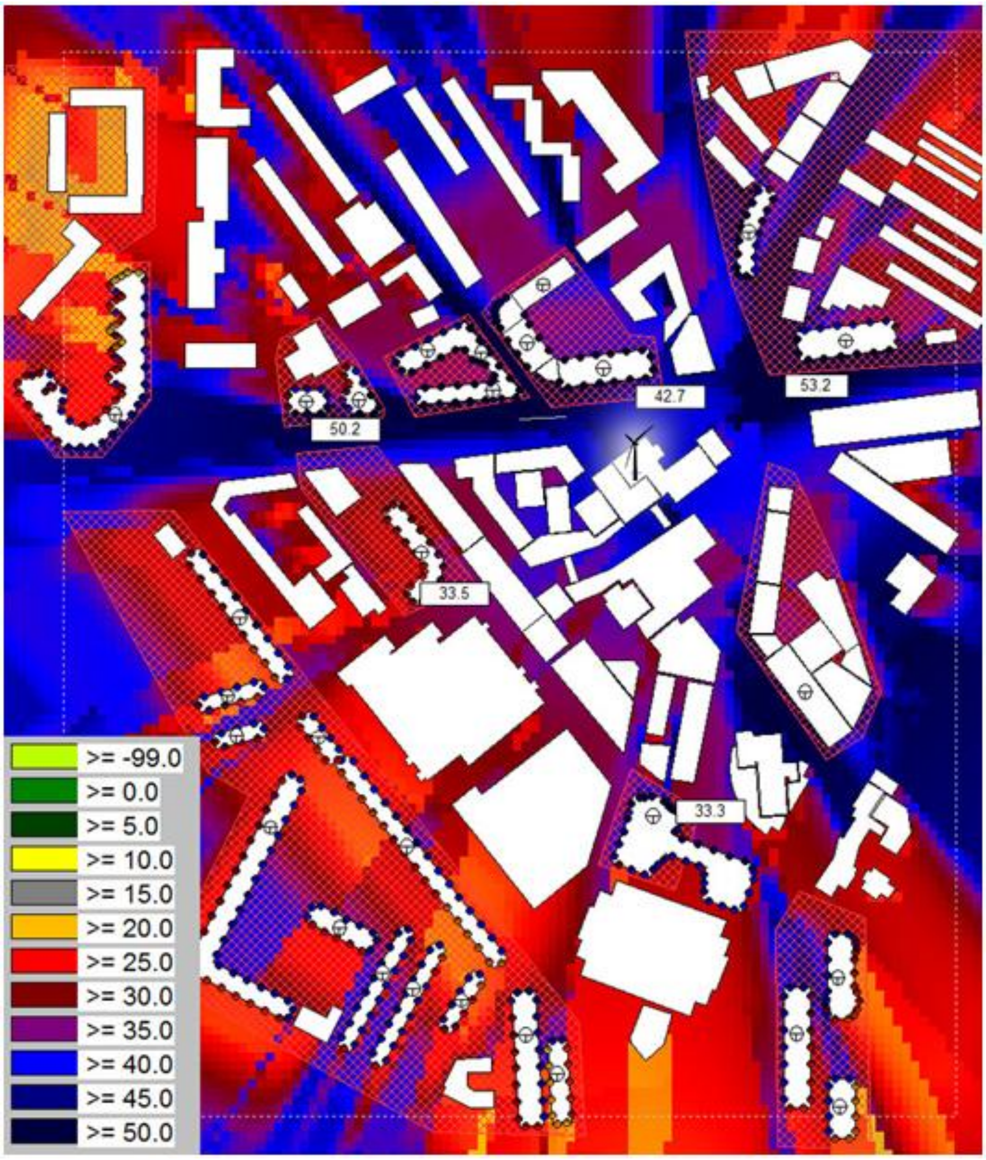

Figure 9: Worst case, operational turbine, scenario L_{Aeq} grid calculations of propagated sound into LSBU residential areas (200m by 300m).

3.3 Vibration Monitoring

Vibration measurements were taken simultaneously on the LSBU turbine mount and the concrete mass beneath the mast. Vibration Dose Values, as well as peak acceleration data was captured and synchronised to the on-site collected atmospheric data, which is shown in Figure 10. X and Y RMS acceleration results have been omitted as no correlation between them and wind speed was observed. However, a correlation of 0.4 was found between wind speed and for the Z axis RMS acceleration.

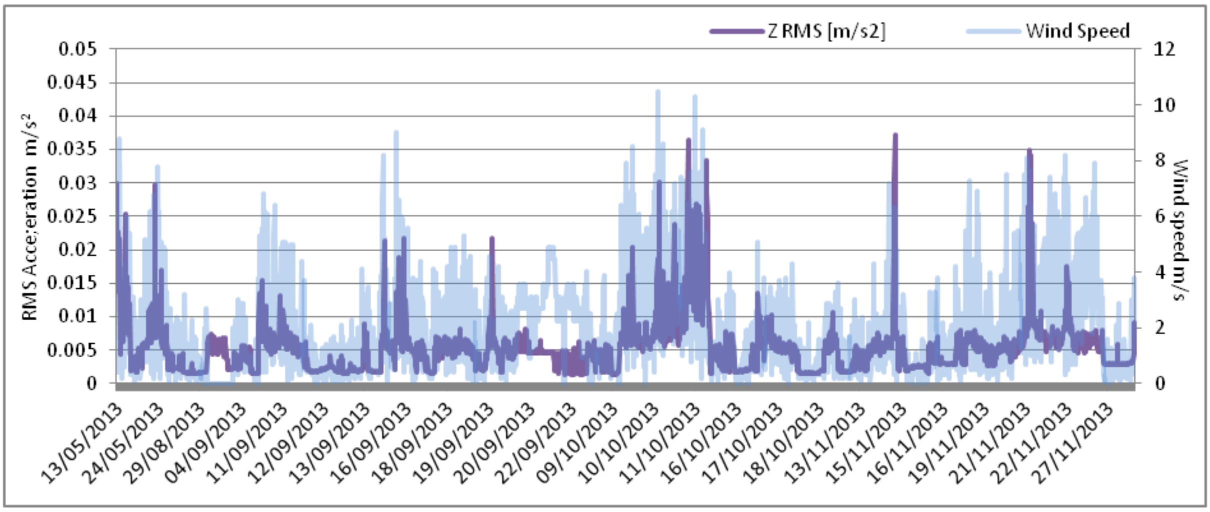

Figure 10: Z-axis RMS acceleration measurements against wind speed on LSBU turbine

The simultaneously measured vibration on the turbine mount and the concrete roof found a general reduction in RMS Z axis acceleration, see Figure 11. However, there was no installed damping or isolation beneath the turbine although it was requested; therefore the reduction is most likely due to the mass of the concrete structure the turbine is mounted on. Appropriate isolation design was offered as mitigation, see (7).

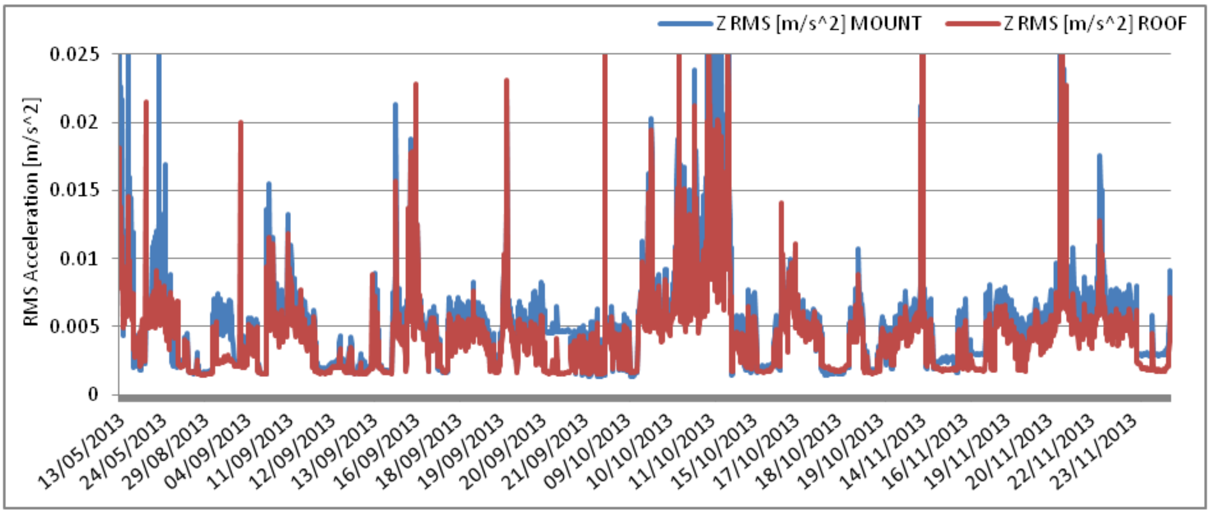

Figure 11: Compares simultaneous Z axis RMS acceleration levels simultaneously measured on the LSBU turbine mount and rooftop

The dynamic wind load on the turbine did cause structural vibration in the mounting system to such as extent that in February 2015, the turbine fell over shearing off its mounting bolts. Unfortunately this irreparably damaged the turbine blades and mounting system and the turbine had to be removed from the rooftop. There was a mitigating factor; the inverter had been switched off which allowed the turbine to run free without the electro-mechanical drag caused by generator. Just before the turbine collapsed there were structural vibrations in the building which caused annoyance in staff offices according to measurement taken to BS 6472:2008, see (7).

3.4 Electricity Generation and Economics

The turbine cost £25,000 to buy and install on the University rooftop. The electrical power generated was recorded every day, below is the data for 2014.

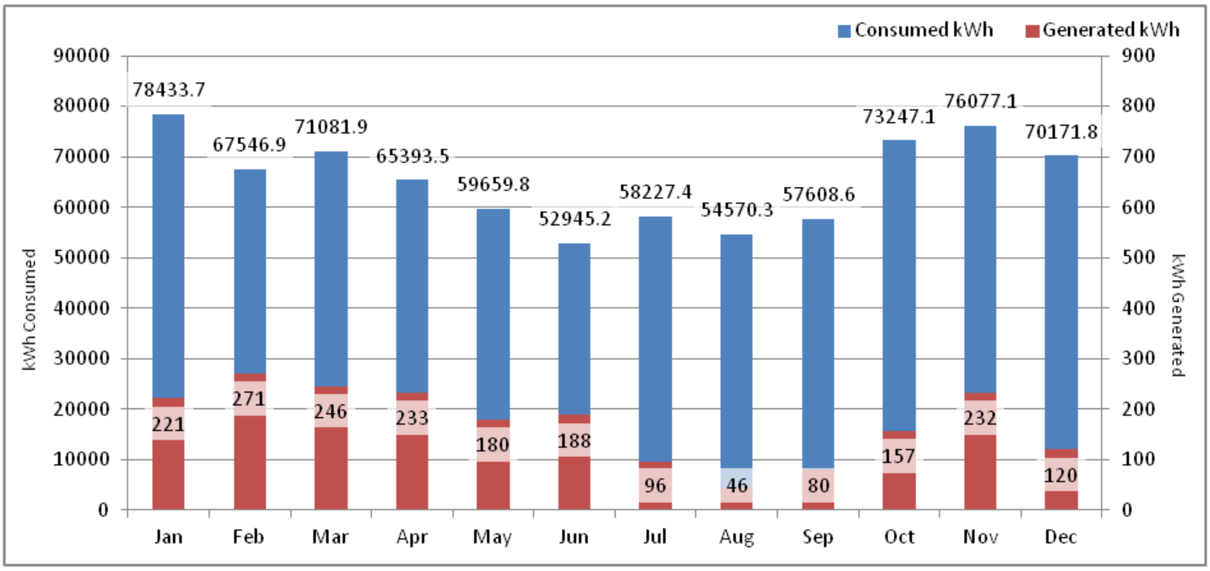

Figure 12: Electrical consumption vs generation for LSBU Building and Rooftop Turbine

As can be seen from Figure 12, the LSBU turbine produced a total of 2070 kWh whilst the building consumed 785 MWh for 2014. This equates to 0.3 % of the building needs, saving the university £550.34 and 1 tonne of $C0_2$ emissions. Comparing the installed against the energy yield over a 30 year period gives an LSBU price per kWh of £0.40 and the systems ROI of 1.16 %. However, if a taller mast was used, as predicted in the CFD model, the price per kWh would be reduced to £0.15, assuming a vibration isolating mounting system was installed.

4.0 Conclusions

This study was instigated from London's need to reduce CO_2 emissions via the employment of renewable energy sources. Central London is densely populated and the topography does not lend itself to traditional turbine placement, hence more bespoke methods are required for successful installation. The wind turbine installed on the newly refurbished building on the LSBU Campus was used as a case study.

The purpose of the investigation was to optimise the design of the installation in order to achieve an efficient installation a multifaceted approach was presented, comprising of:

(i) local noise surveys to inform acceptable turbine operating ranges,

(ii) acoustic modelling of manufacturer provided data and/or acoustic testing of the proposed turbine across all applicable wind speed ranges

(iii) vibration assessment of the turbine system and any lower residential floors

(iv) measurement of site specific wind data to inform architectural design, turbine selection and placement, or

(v) CFD modelling of local topography to gain insight of the wind resource.

The results of this study can be summarised as follows: urban wind turbines, if well located, can generate meaningful amounts of electricity. The installation should account for the wind flow, wind direction and any ability of the turbine to turn to make best use of this energy. For this study it was found that a 275% increase in wind resource was theoretically achievable if the height of the turbine was optimised. The installation should be as high above surrounding property as possible to minimise turbulent airflow. The study also found that any installation should include vibration isolation to prevent annoyance to the users of the property and the safety of the whole system. It was found that the noise levels produced by the urban wind turbine were unlikely to have adverse impact on local residents due to high ambient noise conditions in Central London over almost all wind conditions.

Acknowledgements

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