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Wind Resource in the Urban Environment

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ABSTRACT

The World Meteorological Organization (WMO) Commission for Instruments and Methods of Observation recognized the need to include in the 1996 WMO Guide to Instruments and Methods of Observation, WMO-No. 8 a new chapter on Urban Observations (Oke 2006). There is an increasing demand for meteorological data to support building and urban design, energy conservation, micro-wind turbine installation, air quality, pollution control, insurance, wind engineering, etc. Over the last six years instrumentation has been installed at the Dublin Institute of Technology (DIT) in two separate locations to monitor the wind. Research has shown that the wind resource will vary quite considerably on a given site and this is due to local variations in topography, and other factors associated with wind and turbulence in the built environment.

Key Words: wind, turbulence, natural ventilation, small wind turbines

1. INTRODUCTION

The European Communities Energy Performance of Buildings Directive SI 666 (2006) came into force on January 1st 2007. Part 2 states that: "A person who commissions the construction of a large new building shall ensure, before work commences on its construction, that due consideration has been given to the technical, environmental and economic feasibility of installing alternative energy systems in the proposed large building, and that the use of such systems has been taken into account, as far as practicable, in the design of that building." The alternative energy system is further defined as a "…decentralised energy supply systems based on renewable energy…". So it is reasonable to assume that micro-wind turbines should be part of the design considerations in any future buildings. Also natural ventilation systems can help to reduce the energy rating of buildings.

The objective of this research is to assess the variation in wind resource across two locations on one site in an urban location. Cup anemometers have been installed on the site to monitor the wind. It is intended to use this data to provide an example of wind resource in the urban environment and to indicate the inherent difficulties and pitfalls associated with engineers and designers trying to assess the wind resource in the urban environment.

2. LITERATURE REVIEW

In the Initial Guidance to Obtain Representative Meteorological Observations at Urban Sites, Oke (2006) recognises the need to quantify urban wind climates at the micro-, local- and meso-scale. Of particular interest to the

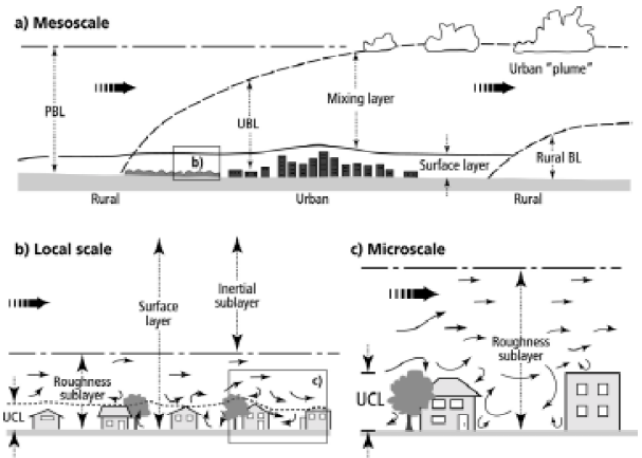

Fig. 1. Schematic of climatic scales and vertical layers found in urban areas. PBL – planetary boundary layer, UBL – urban boundary layer, UCL – urban canopy layer (Oke 2006).

World Meteorological Organization (WMO) is the Urban Canopy Layer (UCL) which is beneath roof level and directly above it.

The difficulty identified by the WMO is that most developed sites make it impossible for a weather station installed in an urban environment to conform to the standard installation and site location guidelines in the Guide to Meteorological Instruments and Methods of Observation (WMO 2008). Fig. 1 give an indication of the complex nature of wind flow around buildings and this is further complicated by proximity to other buildings.

The turbulence encountered in the urban environment adversely affects the performance of wind turbines in the urban environment. The existing cup anemometer with a wind direction indicator does not accurately convey the level of turbulence present on a site (Hölling, Schulte et al. 2007). Experience from the micro-wind turbine installed in the Dublin Institute of Technology (DIT), Church Lane, Kevin Street has shown that the cup anemometer will spin quickly when the turbine is not moving and also there are occasions when the turbine will rotate even when the cup anemometer is not moving.

In a series of articles for Renewable Energy Focus Holdsworth (2009a; 2009b) identifies a number of key areas where further research into micro-wind technologies is required. Working as a consultant in this area he identified a number of major impediments to the development of the urban wind industry. Holdsworth draws the distinction between wind at a height of 100 metres and wind closer to the ground in the urban environment. At a height of 100 metres wind speed and direction will be the same over a large area

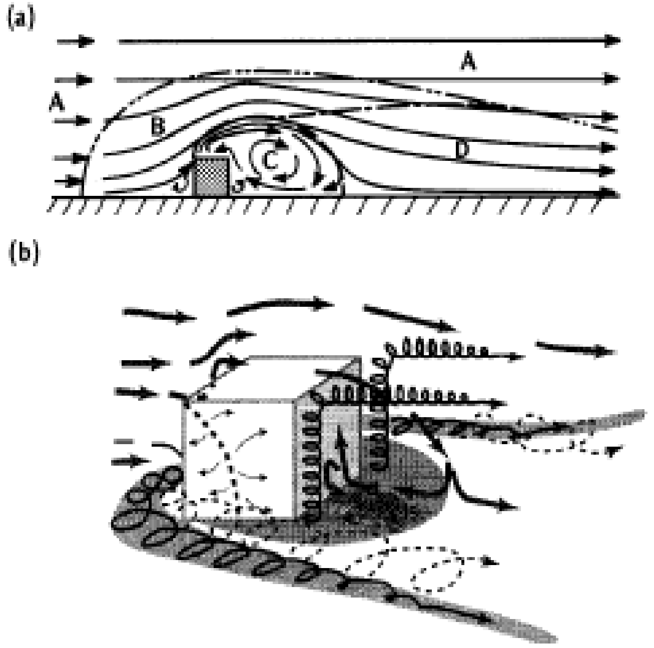

Fig. 2. Two dimensional flow around a building with flow normal to the upwind face (a) stream lines and flow zones; A -undisturbed, B - displacement, C - cavity, D – wake, and (b) flow, and vortex structures (Oke 2006).

whereas closer to the ground the pattern changes due to resistance the wind meets from terrain roughness. Wind is also affected by the shape, height and relationships that buildings have with each other; the impediments of parks and streets; and the creation of dead-zones that alter according to higher-level wind flows. According to Holdsworth what the urban wind industry needs at this point is a much more thorough understanding of the physics of wind.

The reason why Holdsworth (2009a; 2009b) has identified this as such a problem is that a relatively small difference in average wind speed results in a big difference in the energy output of a turbine. Also the wind turbine has to have the capability to adapt to the wind regime that occurs within the micro or meso climatic context of the building or group of buildings where it is installed – if it is to be effective. This industry is only in the early stages of development and there has been what Holdsworth describes as a 'rush to please' in the urban wind industry, resulting in failures to achieve the capacity promised – due to ignorance of the way wind energy behaves in an urban landscape. This has been reflected in the very poor results of recent trials in the United Kingdom (UK) (Encraft, 2009).

3. WIND RESOURCE IN THE BUILT ENVIRONMENT

The European wind energy resource map indicates that Ireland and Scotland enjoy the highest wind resource in Europe (Gardner, Garrad et al. 2009). The European map indicates a uniform wind speed at ground level inland. In reality though there are a number of different factors that can effect wind at a particular location such as obstruction by buildings or trees, the nature of the terrain and deflection by nearby mountains or hills (ME 2010). An example of this is the rather low frequency of southerly winds at Dublin Airport and this is due to the sheltering effect of the mountains to the south. Another example of local topography causing variations in the wind speed is Leinster where average annual wind speeds range from 3 m/s in parts of south Leinster to over 8 m/s in the extreme north.

On average there are less than 2 days with gales with wind speeds above 17 m/s each year at some inland places like Kilkenny but more than 50 days a year at northern coastal locations such as Malin Head. The uninterrupted wind flow from the Atlantic makes the north and west coasts of Ireland two of the windiest areas in Europe and they have considerable potential for the generation of wind energy.

The local variations in wind have two principle causes; friction with the earth's surface, which can be extend as far as flow disturbances caused by topographical features such as hills and mountains; and secondly thermal effects, which can cause air masses to move vertically as a result of variations in temperature (Burton et al., 2001). As the height above the ground increases the effect of earth's surfaces weakens, and above a certain height the wind can be generally free from surface influences. Here the wind can be considered to be driven by large-scale pressure differences and the rotation of the earth, and this air flow is known as the geostrophic wind. Below this level where the effects of the earth's surface can be felt is known as the boundary layer.

3.1 Boundary Layer

The ground surface has the effect of reducing the speed of the wind and this is because of the drag. The level of drag will vary depending on the surface roughens and there are many charts of the roughness factor associated with various terrain. The drag caused by the roughness is transmitted to the wind at higher levels by the action of turbulent stresses (Best, Brown et al. 2008).

The characteristics of the wind flow in the urban canopy layer are markedly different to the roughness layer (Ricciardelli and Polimeno 2006). In the urban canopy layer the flow is influenced more by local geometry than by energy transfer between the different layers.

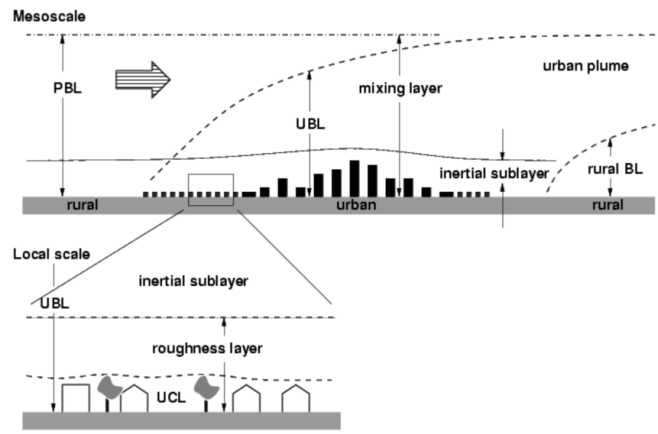

Fig. 3 The layers of the atmosphere: PBL = planetary boundary layer; UBL = urban boundary layer; UCL = urban canopy layer (Best, Brown et al. 2008)

3.2 Wind Resource Measured at the DIT

Wind data was taken from anemometers installed at the DIT over a number of years. The sample period for this paper is January to June 2009 and the sites chosen were the car park in Church Lane and the roof of the Focas building. The car park is totally enclosed by buildings and trees with the slightly more open view to the east; the anemometer was mounted on a pole approximately 6 metres above ground. The rationale behind choosing the Church Lane car park was that it was that the site roughly matched the location where small wind turbines had been installed on houses etc. in the UK and Ireland. The Focas building is a four storey building that is open to the wind from all directions except the north-east. Data from these two buildings were compared with an average of Met Éireann data from Malin Head, Johnstown Castle, Valentia and Kilkenny Weather stations.

Over the six months there was a marked difference between the sites that was consistent.

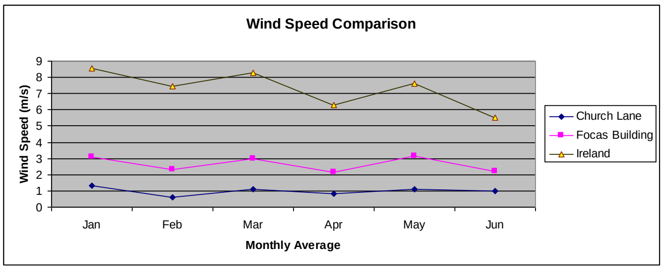

Fig. 4 Monthly average of wind speed data from Church Lane, Focas Institute and Met Éireann weather stations

The more exposed Met Éireann weather stations recorded a higher value of wind when compared with the Focas building and the Church Lane car park. As the mounting height and exposure of the cup anemometers decreased there was a corresponding decrease in the wind speed measured. This pattern is repeated in the daily and hourly averages of the data.

A more in-depth analysis of the data measured at the DIT using the Levy Index was published in Wind turbine Power Quality Estimation Using a Lévy Model for Wind Velocity Data (Blackledge, Coyle et al. 2011).

The disappointingly low wind resource recorded is not the only consideration when evaluating the wind speed; turbulence also needs to be taken into consideration.

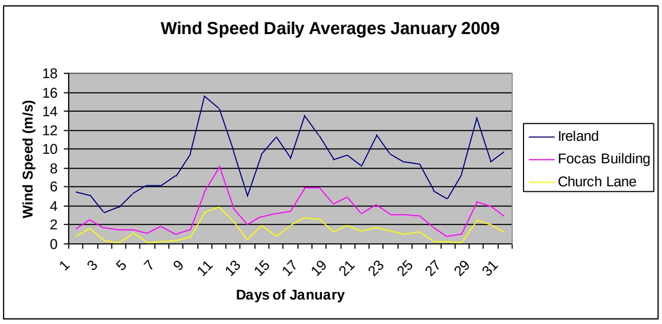

Fig. 5 Daily average of wind speed data from Church Lane, Focas Institute and Met Éireann weather stations

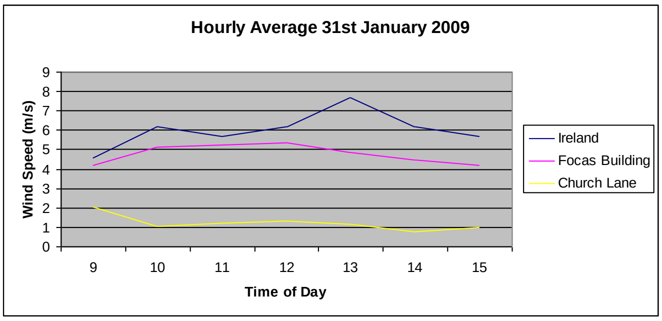

Fig. 6 Hourly averages of wind speed data from Church Lane, Focas Institute and Met Éireann weather stations

3.3 Turbulence

Turbulence refers to fluctuations in wind speed in a time scale of less than 10 minutes, with generally lower timescales for the urban environment. Burton et al., (2001) state that it is useful to consider wind as having seasonal and daily variations with turbulent fluctuations superimposed. Turbulence is generated mainly from two causes; firstly friction with the earth's surface, which is flow disturbances caused by the topographical features and secondly thermal effects, which can cause air masses to move vertically as a result of variations in temperature. Turbulent flow is by its very nature chaotic; the flow velocity is very sensitive to perturbations and fluctuates wildly in time and in space. Turbulent flow contains swirling flow structures (eddies) with characteristic length, velocity, and time scales which are spread over very wide ranges (Burden 2008).

Turbulence in the wind is caused by dissipation of the wind's kinetic energy into thermal energy and this occurs through the creation of progressively smaller eddies (Manwell, MCGowan et al. 2009). Turbulent wind generally has a very variable pattern over a short time frame but it has a relatively constant average over longer time periods and this is why the statistical properties of turbulence are a common means of evaluating the effect of turbulence.

There has been many definitions of turbulence but there is currently no universally accepted definition. In 1937 Taylor and Von Karman gave the following definition: "Turbulence is an irregular motion which in general makes its appearance in fluids, gaseous or liquid, when they flow past solid surfaces or even when neighbouring streams of the same fluid flow past one another." (cited in Hinze 1976). So from this definition a flow has to be irregular to be considered as turbulent.

The National Renewable Energy Laboratory in America (Bailey and McDonald 1997) state that "Wind turbulence is the rapid disturbances or irregularities in the wind speed, direction, and vertical component." The most common indicator of turbulence is the standard deviation (σ) of wind speed. When σ is normalized with the average wind speed it gives the Turbulence Intensity (TI), which gives an indication of a site's turbulence. On this scale low levels are indicated by values less than or equal to 0.10, moderate levels to 0.25, and high levels greater than 0.25. TI is defined as:

$$TI = \frac{\sigma}{V} \quad (1)$$

Where:
σ = the standard deviation of wind speed; and
V = the mean wind speed.
(Bailey and McDonald 1997)

In the standard BS EN 61400-12-1:2006 Wind turbines. Power Performance Measurements of Electricity Producing Wind Turbines (BS 2006) the only reference to measuring turbulence is that an evaluation of a site for a wind farm should include a scatter plot of the turbulence intensity as a function of wind direction. No guidance or standards are included which either state an acceptable range for the approach turbulence or provide any indication of any corrections that may need to be applied to account for the local turbulence (Cochran 2002). In the built environment turbulence will play a significant role as any equipment installed will be below the urban canopy layer.

3.4 Turbulence Intensity

An anemometer has been installed on the Focas building in the DIT for the last number of years. It is installed below the roof level and subject to many obstacles as shown in Fig. 7.

The weather station on the Focas Building, DIT logs a number of parameters and a sample of the data is shown in Table 1. The average for each minute is shown here.

Fig. 7 Anemometer mounted on Focas building, DIT, Kevin St.

TABLE 1
Data from the Focas building DIT for a 10 minute period on the 31st of January 2009

Time	Wind Direction	Wind Speed	Humidity	Temp	Bar.
---	°	mps	%	°C	mm
23:40	74	1.2	56	7	756.8
23:41	173	1.6	57	6.8	756.8
23:42	73	3.9	57	6.9	756.8
23:43	149	2.4	56	6.9	756.8
23:44	87	2.8	56	7	756.8
23:45	23	1.4	56	6.9	756.8
23:46	118	1.6	57	6.8	756.8
23:47	118	1.6	57	6.8	756.8
23:48	29	2.6	57	6.8	756.8
23:49	263	1.6	57	6.8	756.8

The standard deviation of the wind speed from the average can be calculated (2).

$$\sqrt{\frac{\sum (x-\bar{x})^2}{(n-1)}} \quad (2)$$

The turbulence intensity for the site can be calculated (1).

$$T.I. = \frac{\sigma}{\bar{U}} \quad (1)$$

When considering the data from the Focas building the average value of wind speed for the 10-minute period is calculated.

$$\text{Average } (\bar{U}) = \frac{(1.2+1.6+3.9+2.4+2.8+1.4+1.6+1.6+2.6+1.6)}{10}$$

Average = 2.07 m/s

The standard deviation of the wind speed from the average is:

$$\sigma = \sqrt{\frac{\sum (x-\bar{x})^2}{(n)}}$$

$$\sigma = \sqrt{\frac{(x_1-\bar{x})^2+(x_2-\bar{x})^2+...+(x_n-\bar{x})^2}{n}}$$

$$\sigma = \sqrt{\frac{\begin{array}{l}(1.2-2.07)^2+(1.6-2.07)^2+(3.9-2.07)^2+(2.4-2.07)^2\\ +(2.8-2.07)^2+(1.4-2.07)^2+(1.6-2.07)^2\\ +(1.6-2.07)^2+(2.6-2.07)^2+(1.6-2.07)^2\end{array}}{10}}$$

$$\sigma = 0.79$$

where $|x-\bar{x}|$ is the deviation of the variable x from the mean, and n is the sample size.
The turbulence intensity for the site can then be calculated.

$$T.I. = \frac{\sigma}{\bar{U}} = \frac{0.841}{2.07} = 0.385$$

The turbulence intensity 0.385 measured at the Focas is high as the National Renewable Energy Laboratory (NREL) USA indicate that low levels of turbulence have values less than or equal to 0.10, moderate levels to 0.25, and high levels greater than 0.25 (Bailey and McDonald 1997). The 0.385 measured at the Focas building is in line with the BRE report which shows that the turbulence intensity is greater for the lower mounting positions and that it is increased by the presence of surrounding buildings (Encraft 2009). This is due to the presence of aerodynamic friction and thermal gradients which are responsible for the creation of atmospheric turbulence (Cochran 2002).

3.4 Wind Charger

To demonstrate the effect that turbulence can have on the performance of a small wind turbine a small 220-Watt wind charger was installed in the car park of Church Lane at a height of approximately 6 metres. The turbulence index according to BS EN 61400-12-1:2006 could not be calculated for this site as the data was not available in sufficient resolution. However the turbulence index for this site would be significantly higher than the 0.385 measured on the Focas building nearby, due to the lower mounting height. Notwithstanding the fact that the turbine was installed in the location of high turbulence to match similar installations observed in other locations where the installers had complained of poor results, there was still general surprise at the low performance figures of the turbine. The turbine installed could be seen constantly "hunting" looking for the direction of the available wind and therefore producing very little power. The power output for the turbine is shown in the table below with some correction for gaps in the data measured.

The performance of the micro-wind turbine is comparable with international experience. The Warwick wind trials measured the output of thirty small wind turbines installed in the urban environment in the UK (Encraft 2009). The Average capacity factor for the trial was 1.7%. The Capacity factor is the ratio of the actual energy produced in a given period, to the theoretical maximum possible. A reference wind turbine installed in an open field had a capacity factor of 10.3% and the best turbine in the trial had a capacity factor of 4.4%.

TABLE 2
Performance of Wind Turbine in Church Lane over a six-month period

	Jan	Feb	Mar	Apr	May	Jun	Overall
Average Wind Speed (m/s)	1.3	0.63	1.09	0.84	1.11	0.98	1
Average Power Produced (W)	0.45	0.17	0.12	0.17	0.26	0.22	0.23
Power Produced (kWhr)	0.33	0.13	0.089	0.127	0.193	0.164	1.033

4. CONCLUSION

The main conclusion is that engineers and designers working in the built environment would need to make a very careful assessment of the site before considering any device such as a turbine or natural ventilation system that relies on the natural wind resource to operate. With an average wind speed that can be as low as 0.15 times the national average measured by Met Éireann it can be seen that the built environment has a very significant effect on the wind resource.

Wind chargers have now been installed on the main five-storey building in the DIT with unobstructed view in all direction and no obstacles, and it is planned to commission these shortly and then compare their performance with the Church Lane site. A weather station supplied by Cambridge Instruments has also been installed to monitor the wind speed at the same mounting height as the turbines so the variation in output from the turbines with the change in wind speed can be accurately assessed on the same time base. It is hoped that this data will provide a comparison to the initial findings at the Church Lane site.

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