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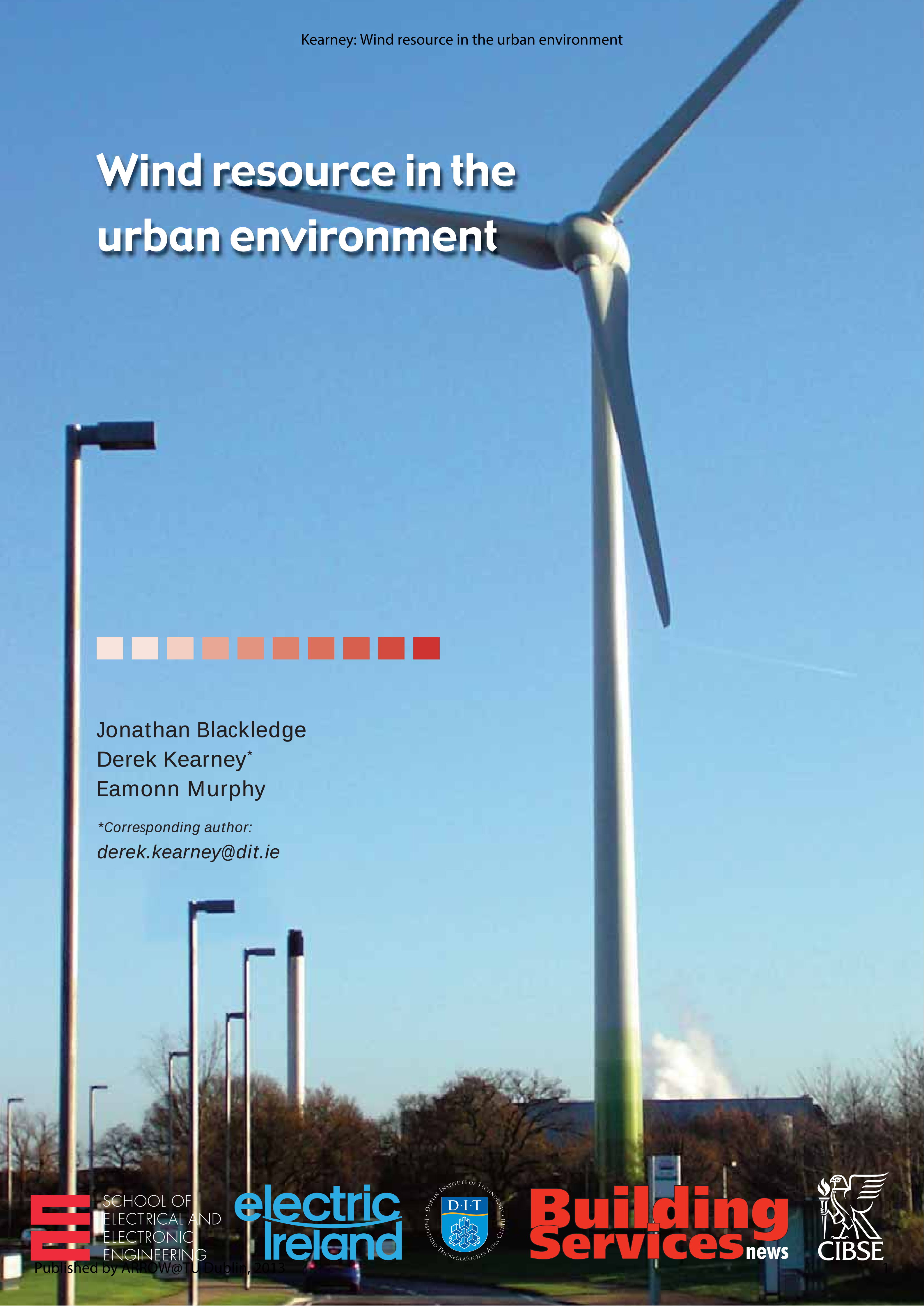
Cover Page Footnote

The authors acknowledge the support of Enterprise Ireland, Science Foundation Ireland, and the Dublin Energy Lab. The authors also wish to acknowledge the assistance of Thomas Shannon and Noel Masterson for their help with the software and hardware associated with the collection of data. Tim Oke of the World Meteorological Organisation, has kindly agreed to allow the use of two of his diagrams in this paper.



Wind resource in the urban environment

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Abstract

Renewable energy technologies, such as wind turbines, have to be considered for new building over 1000m^2 under the Energy Performance of Buildings Directive (2002). Accurate assessment of the wind resource is a key component in the success of a wind installation. Designers, planners and architects also need wind data from urban areas to support low-energy building design, natural ventilation, air quality, pollution control, insurance and wind engineering. Over the last six years instrumentation has been installed at the Dublin Institute of Technology (DIT) in two separate locations to monitor the wind. The data 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. Difficulties were encountered in measuring the wind and turbulence on site. IEC 61400-12-1: 2005 states that "... analytical tools (anemometers presently available) offer little help in identifying the impact of these variables, and experimental methods encounter equally-serious difficulties." The practical experience of measuring wind in the urban environment informed the development of a prototype anemometer that may be capable of digitally mapping accurate real-time three-dimensional data on wind speed, wind direction and, uniquely in the field of wind instrumentation, wind turbulence.

Key Words:
Wind, turbulence, natural ventilation, micro-wind turbines, three-dimensional anemometer.

1. Introduction

The World Meteorological Organisation (WMO) Commission for Instruments and Methods of Observation recognised 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). The foreword to the Report states that "...the realities for those faced with the establishment of a meteorological station at an urban site where application of standard siting is often either impossible or nonsensical." (Oke, 2006). The driver for developing the guide is the ever-increasing demand for wind data from urban sites. An example of this is the European Communities Energy Performance of Buildings Directive SI 666 (2006), which came into force on 1st January 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 "... 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.

Figure 1: Renewable energy plant installed on DIT Kevin St Campus roof as part of Dublin Energy Lab (DEL) experimentation

The objective of this research is to assess the variation in wind resource across two locations on the Dublin Institute of Technology (DIT) campus, and compare it with data taken from the National Meteorological Service in Ireland (Met Éireann). Cup anemometers have been installed on the two sites to monitor the wind. This data was used 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. See Figure 1 for an example of the research being carried out by members of the Dublin Energy Lab. (DEL).

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Lessons learned from this assessment have informed the design of a new three-dimensional wind measurement instrument called a Metometer. The initial outcomes from a year of field trials on the three-dimensional anemometer have yielded some very promising results. The progress of initial developments is explained and industrial partners are being sought for the project.

2. Methodology

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 (Met-Éireann, 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, which is approximately 100 km away.

On average there are less than two 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.

The local variations in wind have two principal causes. One is friction with the earth's surface, which can be extended as far as flow disturbances caused by topographical features such as hills and mountains. The second is "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 weaken, so that by 600m above the highest local obstruction the wind is 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.

2.1 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 roughness 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.

The WMO, in its report on the *Initial Guidance to Obtain Representative Meteorological Observations at Urban Sites (Oke, 2006)*, turned its attention to the measurement of the wind resource within the boundary layer. Of particular interest to the 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)*. Figure 2 gives an indication of the complex nature of wind flow around buildings and this is further complicated by proximity to other buildings.

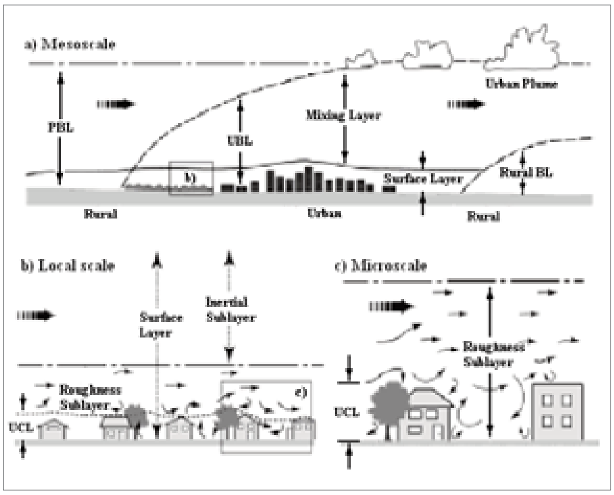

Figure 2: Schematic of climatic scales and vertical layers found in urban areas. PBL – planetary boundary layer, UBL – urban boundary layer, UCL – urban canopy layer (Oke, 2006)

The turbulence encountered in the urban environment adversely affects the performance of wind turbines in the urban environment. The existing cup anemometer, and wind vane 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 (2009) identified 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, whereas closer to the ground, as shown in Figure 2, 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.

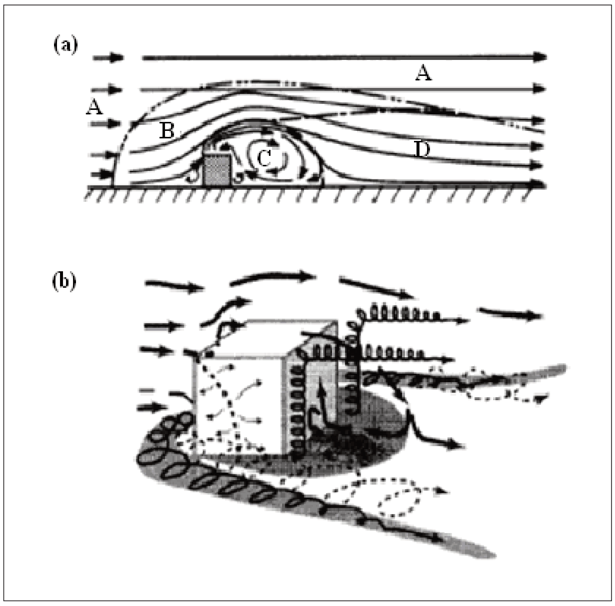

Figure 3: Two-dimensional flow around a building with flow normal to the upwind face (a) stream lines and flow zones; A – undisturbed; B – displacement; C – cavity; D – wake; and (b) flow, and vortex structures (Figure 3 courtesy Oke, 2006)

The reason why Holdsworth (2009) 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), where capacity factors as low as 1.5% have been recorded (Encraft, 2009). The poor power output of turbines has put the spotlight on the measurement of the power input … wind.

3. Wind resource measured at the Dublin Institute of Technology

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 six metres above ground. The rationale behind choosing the Church Lane car park was that the site roughly matched the location where small wind turbines had been installed on houses, shops, businesses, 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.

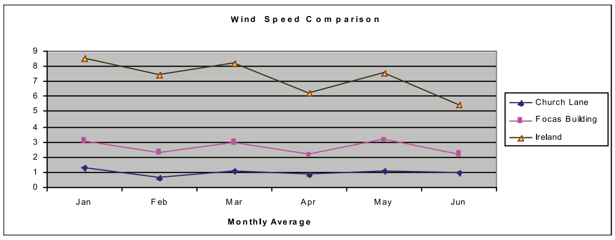

Figure 4: Monthly average of wind speed data from Church Lane, Focas Institute and Met Éireann weather stations

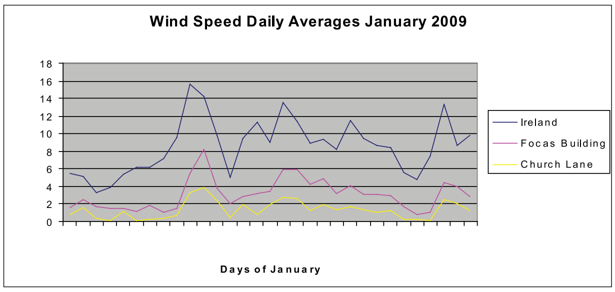

Figure 5: Daily average of wind speed data from Church Lane, Focas Institute and Met Éireann weather stations

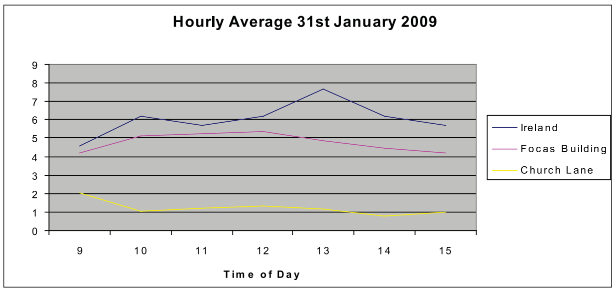

Figure 6: Hourly averages of wind speed data from Church Lane, Focas Institute and Met Éireann weather stations

Figure 4 shows that over the six months there was a consistent marked difference between the sites. 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 as shown in Figure 5 and Figure 6. A more in-depth analysis of the data measured at the DIT, using the Levy Index, is contained 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 as turbulence also needs to be taken into consideration.

3.1 Turbulence

Turbulence refers to fluctuations in wind speed in a time scale of less than ten minutes, with generally lower timescales for the urban environment. Burton et al., (2001) states that it is useful to consider wind as having seasonal and daily variations with turbulent fluctuations superimposed. Turbulence is generated mainly from

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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 timeframe but it has a relatively constant average over longer time periods. This is why the statistical properties of turbulence are a common means of evaluating the effect of turbulence.

There have 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 normalised 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: $TI = \frac{\sigma}{V}$ where:

σ = the standard deviation of wind speed; and

V = the mean wind speed.

(Bailey and McDonald, 1997)

IEC 61400-12-1: 2005 is the only standard that considers the power performance of wind turbines. This standard requires a calculation of turbulence intensity. In an urban environment the turbulence intensity will be higher due to the local obstructions.

3.2 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 Figure 7.

The weather station on the Focas Building, DIT logs a number of parameters and a sample of one-minute averaged data is shown in Table 1.

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

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

Figure 7: Anemometer mounted on bracket over PV array on roof of DIT Kevin St Campus renewable research facility

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

Time	Wind Direction	Wind Speed	Humidity	Temp	Bar.
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 turbulence intensity for the site can be calculated.

$$TI = \frac{\sigma}{V}$$

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

Average = 2.07 m/s

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

σ¬ = 0.79

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 indicates 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 Warwick Wind Trials 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).

3.3 Wind charger

To demonstrate the effect that turbulence can have on the performance of a micro-wind turbine, a domestic 220-watt wind charger was installed in the car park of Church Lane at a height of six metres, as shown in Figure 8.

Figure 8: 220W wind charger installed in Church Lane, DIT Kevin St Campus

The turbulence index according to IEC 61400-12-1: 2005 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 (Encraft, 2009). The turbine installed could be seen constantly "hunting" for the direction of the available wind and therefore producing very little power. The power output for the turbine is shown in Table 2 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 30 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 being 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 (W) (kWhr)	0.33	0.13	0.089	0.127	0.193	0.164	1.033

4. Three-dimensional anemometer – Metometer

The problems identified by observing the instrumentation installed at the DIT was that there were quite clearly swirling winds with very fast fluctuations present on-site that were not represented by the data, or the turbulence model shown in IEC 61400-12-1: 2005. Also, the turbine spent most of the time hunting for the wind direction and as a result produced very little power. IEC 61400-12-1: 2005 states that "...identical wind turbines will yield different power at different sites even if the hub height wind speed and air density are the same. These other variables include turbulence fluctuations of wind speed (in three directions), the inclination of the flow vector relative to horizontal, scale of turbulence and shear of mean wind speed over the rotor. Presently, analytical tools offer little help in identification of the impact of these variables and experimental methods encounter equally-serious difficulties." For the electrical power output side of a wind turbine there are instruments to measure all of the parameters such as current, voltage, harmonics, frequency, etc. present, yet there is no equivalent instrument for the wind industry in an urban or turbulent environment. The need for a new wind measurement instrument capable of measuring three-dimensional variations in the wind and turbulence was identified.

The Metometer uses multiple Pitot tubes incorporated into a spherical design to provide simultaneous real-time data on wind speed, direction and turbulence. The sample and record frequency of the Metometer is up to 1,000Hz, and this is in three-dimensions. The three-dimensional anemometer has a wide range of potential applications that include:

- Enhanced site evaluation, planning, development and monitoring;
- Capability for wind farms and tidal energy farms;
- Superior meteorological data collection and analysis;
- Urban planning applications for civil and mechanical engineers;

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Figure 9: Prototype three-dimensional anemometer, called a Metometer, in author's back yard

- Improved data for decision-making in aviation to enhance efficiency and safety;
- Road safety applications.

The very high sampling rate of the device compares very well with other instruments currently on the market, such as cup anemometers and wind vanes, which have an average sampling rate of just 1 Hz. Sonic anemometers have a sampling rate in the range of 20Hz. The resolution of data provided by the Metometer is only limited by the frequency required by industry, and by the natural fluctuations of wind or fluid to be measured. Wind speeds from 0-250 m/sec can be measured with a certified level of accuracy to less than 0.05% Full Scale Output (FSO). Data from initial trials carried out over 12 months has proven the device to be robust, and it can be built to withstand practically all environments.

The advantages of the Metometer include:

- Improved data accuracy – greater accuracy of wind data, including fluid speed, fluid direction and turbulence;
- 3-D Capability – improved data quality by measuring in three dimensions;
- Sampling frequency – greater number of samples can be taken within a specified timeframe;
- Robust design – device is engineered to be durable, and can be manufactured using a range of materials, including stainless steel;
- Low maintenance – design has no moving parts, therefore maintenance is low, and the effects of rain, frost, snow, dust, or sunshine significantly reduced;
- Wide measurement range – wind speeds from 0-250 m/sec can be measured with a certified level of accuracy to less than 0.05% Full Scale Output (FSO);
- Ease of manufacturing – because the device is based on an innovation in the design concept – has no moving parts and can be built using accessible materials. Aso, it can be easily manufactured at scale.

The stage of development of the Metometer is that a full-scale prototype device has been designed, built and tested. Initial test data has been collected which confirms the high degree of accuracy and frequency of sampling from the device. A patent application was filed in November 2012 by DIT. Currently data logging and interface software is being developed to support the device. DIT is seeking partners and collaborators to licence the technology, or to develop the prototype instrument further into a market-ready product.

5. Conclusion

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.

Even when the lower-than-average wind speeds in the built environment are taken into consideration, there is also the additional factor of turbulence. Current wind instrumentation, according to the WMO, is not up to the job of providing accurate data on the wind resource in the built environment. The Metometer has demonstrated this capability in the prototype device already built. Enterprise Ireland has provided nearly €300,000 in funding to further develop and test the prototype instrument.

Acknowledgements

The authors acknowledge the support of Enterprise Ireland, Science Foundation Ireland, and the Dublin Energy Lab. The authors also wish to acknowledge the assistance of Thomas Shannon and Noel Masterson for their help with the software and hardware associated with the collection of data. Tim Oke of the World Meteorological Organisation, has kindly agreed to allow the use of two of his diagrams in this paper.

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