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Estimating the Yield of Micro Wind Turbines in an Urban Environment: *A Methodology*

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***Abstract*- Micro wind turbines currently have the majority share of micro (electricity) generation installations in Ireland. These technologies are being installed predominantly in rural environments, and current applications to the *Distribution Services Operator* (DSO) for connection of all types of micro generator stand at less than 500. Poor market dissemination of information and research findings compounded with poor options for spill payment - as well as onerous planning restrictions do not –it appears - create a platform conducive to encouraging development in this market.**

This paper outlines the complexities associated with evaluating the wind resource within an urban environment and investigates the means to 'estimate' wind regimes in an urban environment based on an extrapolation of a reference wind speed from a rural environment into the urban area. Methodologies for estimating the wind speed in such circumstances are considered with modeled wind data – benchmarked against wind data acquired from a site in the city centre - being applied to a set of commercially available wind turbines.

***Index Terms*— microgeneration, canopy layer, capacity factor, displacement height, friction velocity (u_*), surface roughness, (z_0), urban, surface layer**

I. INTRODUCTION

Micro generation integration into the Irish distribution network is at an incipient stage of development. When one looks holistically, however, at Irish policy towards renewable technologies against its European commitments [1], there have been achievements [2]. The target of a 16% share of renewable energy in the final consumption currently stands at 4.7% and in terms of generation, the contribution from renewable sources in 2008 was 14.4% [2] as against the aspirational 15% target as set in [3]. With respect to wind capacity contribution to the delivery of renewable energy, the rural environment offers the preferred installation settings for micro wind technologies, including a more laminar wind profile. But in the context of the urban populous, if sustainability is to be truly embraced, the application of the entire range of generating technologies - including micro wind - is required.

The wind resource, however, is complicated in the urban environment where the resource is proportionate to the surface topography, temperature influences and the dynamic nature of the environment. Such complexity ultimately leads to reduced yields from the micro wind technologies installed in urban settings. With respect to urban wind, modeling, is implemented either empirically, using Boundary Layer theory (based on general information on the urban surface, e.g. roughness) or through detailed computational fluid dynamics (CFD) approaches.

Both require information on wind flow applicable to the area of study. The latter is probably more detailed but also more expensive and unlikely to be of use in the field in assessing the resource range. The former requires us to translate conventional observations into those useful for urban situations. The mean wind speed and surface stress near the surface are the most important considerations - the surface stress, in particular, characterises the turbulence levels and mean wind within the canopy and roughness sub layers [4].

Mertens [5] in his work presents a methodology to extrapolate a rural wind into an urban transition in terms of a *step change* which was further developed by Heath [6] in which a CFD model was used to simulate the wind flow around a simple pitched roof building with regard to the potential energy yield of a micro wind turbines installed at optimal heights within an urban canopy. Watson [7] synopsizes the work by both Mertens and Heath, where based on an initial Wind Atlas mean wind speed and in conjunction with CFD analysis with respect to local building geometries, the temporarily and spatially averaged wind profile was investigated. From this investigation, the Weibull wind speed distribution was used to calculate micro wind turbine yield and capacity factor.

There are studies [8] where technology performance within the urban environment has been analysed, but even if site selection was based purely on wind surveys, the complex flows evident in such situations lead to unreliable information and ultimately inappropriate positioning in many instances. Understanding the wind resource is therefore *key* to successful uptake of micro wind turbines.

II. AIRFLOW IN THE BOUNDARY LAYER

Most conventional wind observations are made at 'rural' sites where the airflow has an uninterrupted flow across a surface of low roughness (usually grass). In these circumstances the vertical profile of wind in the boundary layer (BL), that portion of the atmosphere affected directly by the surface below, is described by,

$$\frac{\partial u}{\partial z} = \frac{u_*}{k(z-d)}.\varphi_m\left(\frac{(z-d)}{z_0}\right) \tag{1}$$

Where u is average windspeed, z is height, u_* is the friction velocity (ms^{-1}) and k is the von Karman constant (0.4). Roughness length (z_o) represents the drag exerted by the underlying surface and d is a displacement height (m). For grass the value is 0.01 (approx), and for urban areas it approximates between 0.8 and 1.5 (medium height and density). The influence of the thermal structure of the atmosphere is captured by a stability parameter (φ_m), which equals one when the atmosphere is neutrally stratified. In other words, the turbulent eddies that transfer surface effects into the overlying atmosphere are a product largely of surface drag. In unstable atmospheres (characterized by strong surface warming), vertical exchanges are enhanced as warmer (and lighter) parcels of air move upwards to be replaced by cooler, descending parcels of air. Stable atmospheres, by comparison inhibit vertical exchanges. Thus, in neutral atmospheres characterized by strong winds and weak surface heating (prevalent the Irish climate), the wind speed at any height in the BL is given by

$$u(z^*) = \frac{u_*(z^*)}{k} \ln\left(\frac{z-d}{z_0}\right) \qquad (2)$$

In this formulation u_* is treated as a constant in the BL and the equation is valid for the region extending from (d+zo) to Z_{BL}, the height of the BL. This equation predicts that the effective momentum sink for the boundary layer is located at a distance (d+zo) from the underlying surface. The displacement height is equal to about 2/3 the average height of the surface elements (whether blades of grass or buildings). The properties of airflow in the layer between the ground and (d+zo) are considered to be chaotic such that the airflow along a given pathway at (d+zo) is zero.

III. AIRFLOW IN THE URBAN BOUNDARY LAYER

Airflow over urban areas is different from that over surrounding rural areas due to its unique surface properties. These properties include a complex surface geometry and the use of manufactured materials that alters the surface energy budget. These properties affect the surface ‘roughness’ and temperature, both of which affect the overlying airflow. Ideally, we could take observations made at a nearby conventional site and transfer these to an urban site using (2). In these circumstances the steps would be:

1. Apply (2) to observations at a rural site to estimate airflow at a reference height (U_{ref}) that is unlikely to be affected by underlying surface roughness.
2. Substitute values for d and z_o suitable for an urban environment
3. Apply (2) to obtain windspeed at a desired height above (d+zo).

This approach is illustrated graphically in Fig. 1 however it is unlikely to capture the urban effect on wind close to the heights of buildings for a number of reasons. Among these is the heterogeneity of the urban surface that means overlying airflow is constantly adjusting to the changing surface roughness and the difficulty of measuring roughness itself in an urban environment. The net result is the formation of a distinct urban boundary layer (UBL) with sub-layers that have implications for evaluating the urban wind resource.

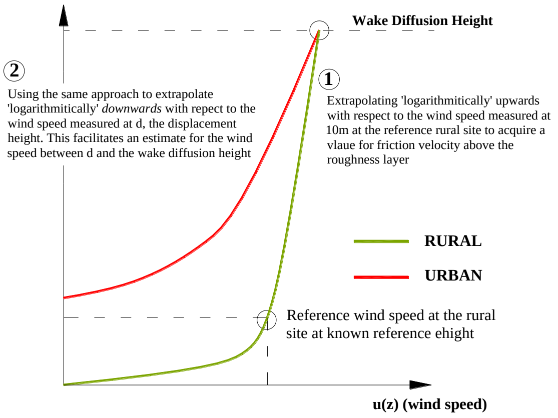


Fig. 1: Simplistic Wind Mapping

UBL Structure

The UBL is formed as air crosses from the urban edge and grows in depth with distance from this edge (at a rate of about 1:200). Within this layer the effects of the surface below are readily detectable in a series of sub-layers (Fig. 2). The lowest of these is the urban canopy layer (UCL), which consists of the layer below the average height (H) of urban roughness elements, that is, the buildings. Within this layer the climate is regulated by micro-scale interactions between individual elements and their surfaces. Aerodynamically, the UCL lies within the roughness sub-layer (RSL), which observations indicate extends to >2H. Observations within this layer display turbulent activity whose properties change rapidly as airflow interacts with the individual buildings it encounters along its pathway. Above this layer lies the inertial sub-layer (ISL), where fluxes of heat, mass and momentum are nearly constant with height. Observations within this zone reflect the average properties of the underlying urban surface and are comparable to conventional observations made at rural sites.

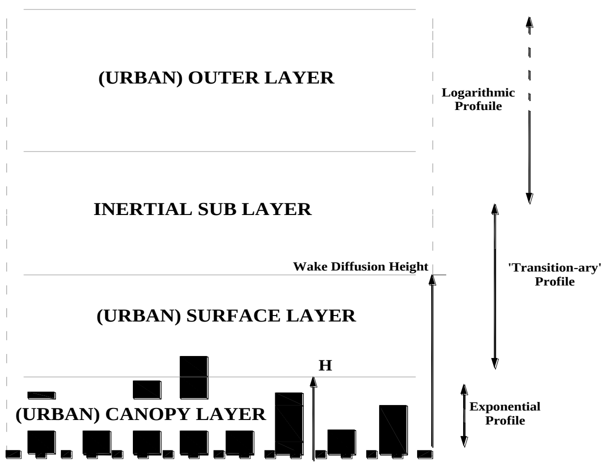


Fig 2.: Wind Speed in the urban context with respect to the boundary layer transitions

MacDonald [9], has suggested that it is fundamentally wrong to extrapolate the logarithmic profile (2) into the urban roughness sub-layer, which is below approx. 2H. Consequently, the simple method for estimating average windspeed at an urban site (Fig. 1) is flawed and another approach is needed. .Here two approaches are outlined and tested with data from two sites in Dublin *Focus* Building (Dublin Institute of Technology and Dublin Airport.

IV. URBAN WIND RESOURCE APPRAISAL

Macdonald [9], cited by Heath and Watson [6, 7], presents a simple model (originally developed for vegetative canopy flows) that recognizes the flow structure described in the above section and applies three profiles:

1. The logarithmic profile is applied to the inertial sublayer, above 2H and up to a height (Z_{ISL}), which is approx. one-fifth of the depth of the UBL.
2. An exponential profile is applied to airflow within the UCL, below the average heights of buildings.
3. A profile that links u_H (i.e., wind speed at building height) with u_{RSL} (i.e. windspeed at the top of the roughness sub-layer).

Two methodologies [9, 10] – summarized in Figure 3 - are employed in a calculator tool developed in EXCEL to estimate the wind resource in an urban environment.

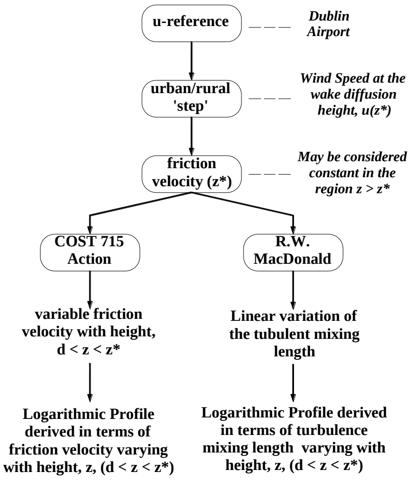


Fig. 3: Summary of the methodologies developed in [9, 10]

In particular, the work in this paper focuses on the COST 715 Action [10] and how estimated urban wind speed varies when compared to a rural reference, whereas the methodologies described by MacDonald [9] is applied to investigate if some cross validation is observed. In [10], a three step process is employed:

1. Roughness Sub Layer height and Zero plane displacement, *d*
   This is a poorly defined parameter. Grimmond and Oke [11] cite a number of references for this parameter in the range of 2.H ≤ z ≤ 5 .H where H is the average building height*
2. Estimating the Friction Velocity
   The basis of this step is that the Reynolds stress varies with height within the roughness sub layer. Above the height of the urban roughness (in this context above z_w), the logarithmic wind speed profile is employed, but below z_w an allowance for variation of friction velocity with height (i.e. within the roughness surface sub layer) based on:

$$\left(\frac{u_*(z)}{u_*(z^*)}\right)^b = \sin\left(\frac{\pi}{2}.Z\right)^a \qquad (3)$$

$$\text{with} \quad a = 1.28, \quad b = 3.0$$

3. Estimating the Wind Speed

$$\frac{\partial u}{\partial z} = \frac{u_{*1}}{\kappa(z-d)}.\phi_m\left(\frac{(z-d)}{L_{1_{(z-d)}}}\right) \qquad (1)$$

The velocity gradient can be parameterized in terms of the local friction velocity with stability effects being represented by using a local Monin-Obukhov length,$L_{1(z-d)}$ defined using the net sensible heat flux from the surface (i.e. a single value independent of height which can be obtained from the energy balance) and the friction velocity [4]. In the context of Neutral atmospheric conditions, ϕ_m can be approximated ≈ 1

The approach in [10] is to evaluate the friction velocity at the height of interest and to treat it as a constant in the integration of (1) when deriving a value for the wind speed. To further this approach therefore, a means to include a height dependent friction velocity (as defined in (3)) - based on a linear approximation - in the integral put forward in this paper is put forward:

$$\frac{\partial u}{\partial z} = \frac{u_*(z)}{\kappa(z-z_d)}.1dz, \Rightarrow \int \frac{\partial u}{\partial z}dz = \int \frac{\boxed{u_*(z)}}{\kappa(z-z_d)}\,dz$$

$$\left[\left(\frac{u_*(z)}{u_*(z^*)}\right)^b = \sin\left(\frac{\pi}{2}.\frac{z-z_d}{z^*-z_d}\right)^a\right]$$

$$u_*(z) = u_*(z^*) \times \sqrt[3]{\sin\left(\frac{\pi}{2}.\frac{z-z_d}{z^*-z_d}\right)^{1.28}}$$

$$\Rightarrow u(z) = \frac{u_*(z^*)}{\kappa} \times \int_{z_0+d}^{z^*}\left[\frac{\sqrt[3]{\sin\left(\frac{\pi}{2}.\frac{z-z_d}{z^*-z_d}\right)^{1.28}}}{(z-z_d)}\right]dz$$

Linearly approximating $\sin x = \frac{2x}{\pi}, 0 < x < \pi/2$,

$$u(z) = \frac{u_*(z^*)}{\kappa} \times \sqrt[3]{c_1} \times \int (z-d)^{0.42667-1}dz \qquad (4)$$

$$\text{with } c_1 = \frac{2}{\pi}\left(\frac{\pi}{2(z^*-d)}\right)^{1.28}$$

V. ANALYSIS

This research uses wind data acquired from *Dublin Airport* and the *Focus Research Centre* (Dublin Institute of Technology), over one year (2008). Focus Research Centre is located in the south inner city and the meteorological station at Dublin Airport is located 15km north west of The focus Institute and is located in North county Dublin. A selection of months (with consideration applied over three consecutive days per month) was used to provide profiles in terms of:

- Wind speed
- Wind direction
- Modelled wind speeds (COST (Simplistic), [10], COST (Detailed), MacDonald [9])

From these profiles, analysis was performed in terms of:

- Statistical accuracy
- Energy profile of a selection of readily available micro wind turbines.

Wind speeds/directions were examined and analysed in Table 1. As would be expected, the correlation between the mean wind directions at both sites is inconsistent. This can be widely explained by the prevalence of turbulence at the inner-city site (Focus Building)

Table 1: Wind Resource Summaries

	Dublin Airport		**Focus Building**	
	(ms^{-1})	**Degrees**	**(ms^{-1})**	**Degrees**
January	4.7	(180-240)	2.62	(150-240)
March	5.45	(180-240)	2.15	(210-360)
May	3.24	(30-90)	2.04	(60-150)
July	7.63	(210-300)	2.99	(210-330)
September	3.22	(210-330)	1.82	(210-330)
November	7.46	(210-330)	2.72	(120-270)

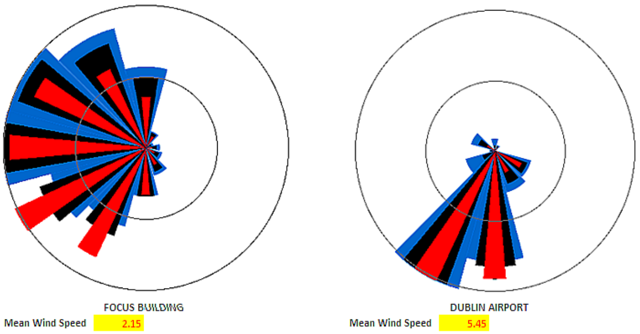
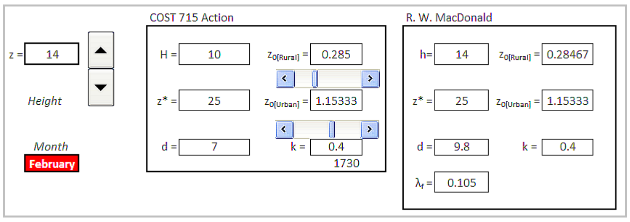


Fig. 4: Wind measurement comparison (*March 2008*) [12]

The analysis was undertaken in terms of the following parameters (as per EXCEL tool):



COST 715 Action

R. W. MacDonald

z = 14

Height

Month: February

H = 10

$z_{0[Rural]}$ = 0.285

z* = 25

$z_{0[Urban]}$ = 1.15333

d = 7

k = 0.4

1730

h= 14

$z_{0[Rural]}$ = 0.28467

z* = 25

$z_{0[Urban]}$ = 1.15333

d = 9.8

k = 0.4

λ_f = 0.105

Fig 5: System Parameter selection in the EXCEL Wind appraisal Tool

The height, z, was chosen to be 14m due to the Focus Building being three storeys and the wind measurement equipment is on the roof. An estimate of the average building height being 10m (in the urban environment) was then applied. The month is selected from the drop-down menu and for each month, a comparison of the modeled wind speeds with the wind speed measured on the roof of the Focus building is attained. The rural and urban roughness lengths were chosen based on literature [11]. λ_f, the frontal area density (to which the wind will be exposed) is chosen to be 0.105. This choice is based on the fact that at λ_f=0.2, this would represent skimming flow (over the obstacles) [13]. The analysis shows that for the COST methodologies, good correlation is achieved for each of the selected months other than November. The MacDonald uses the Focus building height and reference wind speed so there is direct correlation in all example months.

Fig 6 illustrates the comparison of the Focus wind speed (recorded) with the modeled wind speed against the wind speed record for Dublin Airport. Fig. 7 and Fig. 8 illustrate the best examples of correlation (January) and the worst case (November).

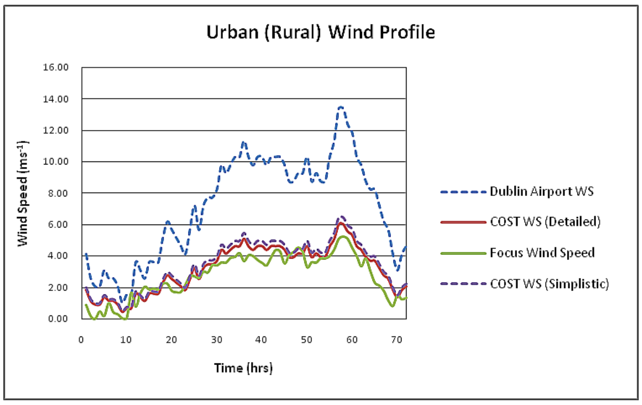


Fig. 6: Comparison of modelled wind speeds with the Dublin Airport reference wind speed (January)

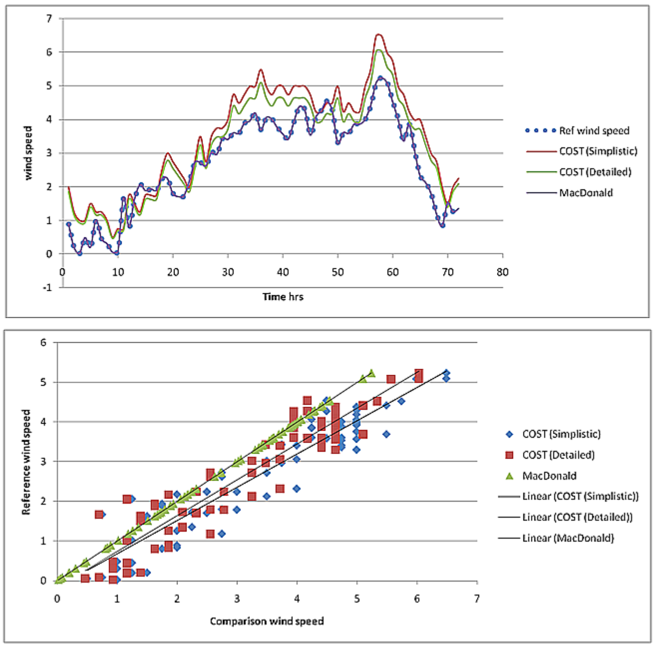


Fig 7: Wind Speed comparison (January, 2008) with good physical comparison and associated correlation

The correlation achieved between the wind speed recorded at Focus against both COST methodologies is 0.88 for January and 0.005 for the month of November.

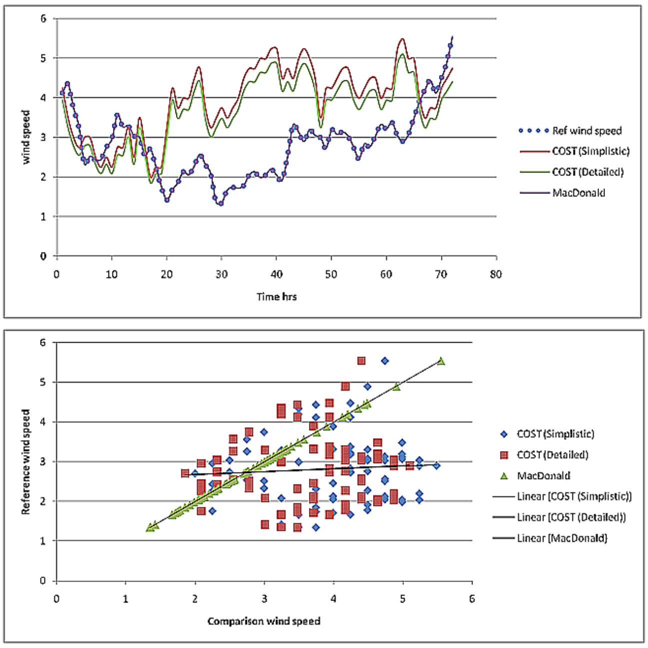


Fig 8: Wind Speed comparison (November, 2008) with poor physical comparison and associated correlation

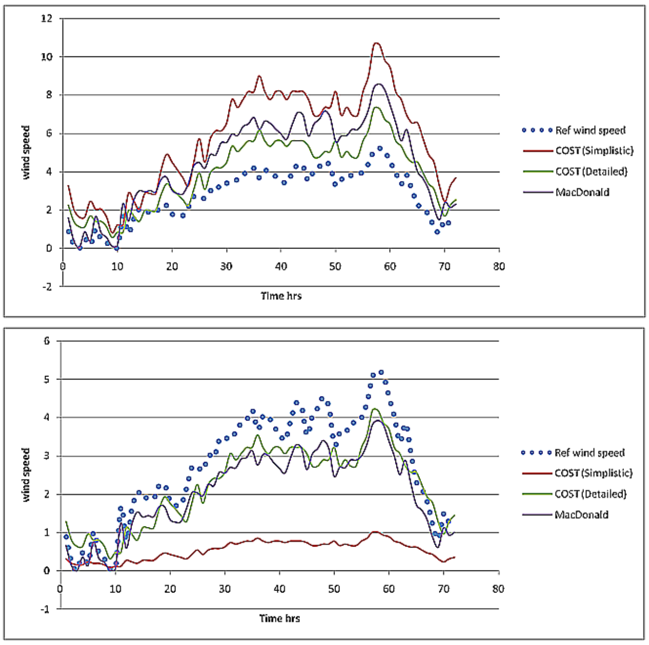


Fig 9: Wind Speed comparison (November, 2008) with poor physical comparison and associated correlation

Figure 9 illustrates the comparison between the two COST methodologies and the MacDonald approach at z > z* (@18m) and z < H (@z=10m) during January. There is physical correlation even though there are magnitude deviations between the respective approaches.

Wind Turbine Application

A sample of micro wind turbines as illustrated in Table 2 were scrutinized in terms of manufacturer guidelines against the wind speeds with a summary of results presented in Table 3.

Table 2: Micro wind Turbine Sample

Model	Cut-in (ms^{-1})	Rated (ms^{-1})	Cut-out (ms^{-1})	Rated Power (W)	Output at Rated Speed
Jetstream II	4	10	60	750	790
Espada	3	17	55	800	950
Passaat	3	10	35	1400	950
Whisper 200	3	12	55	1000	1000
Whisper 500	3	11	55	3000	3000
Proven 2.5	3	12	65	2500	2200
WES Tulipo	3	9	20	2500	2100
Skystream 3.7	4	9	63	1800	1800
Swift	4	14	65	1500	1000
Inclin 1500	4	12	35	1500	1500

Table 3 summarises a comparison, for a range of micro wind turbines, the respective energy yields in terms of CER acquired load data and the modeled (and measured) urban wind speeds. The standard load profile data is representative of a domestic consumer over the course of one year, with a peak demand of 1.73kW and an annual consumption of 6000kWh Wind resource implementation is also considered in terms of capacity factor measurement for the range of technologies.

Table 3: Energy Yield/ Load Comparison and respective Capacity Factors for a range of micro wind turbines with respect to 2008

			January [kWhr]		March [kWhr]		May [kWhr]		July [kWhr]		September [kWhr]		November [kWhr]	
			Gen kWhr	Capacity Factor %	Gen kWhr	Capacity Factor %	Gen kWhr	Capacity Factor %	Gen kWhr	Capacity Factor %	Gen kWhr	Capacity Factor %	Gen kWhr	Capacity Factor %
750W	Jetstream II	Focus	1.60	3.0%	0.04	0.1%	0.26	0.5%	1.51	2.8%	0.07	0.1%	0.69	1.3%
		COST (Simplistic)	3.29	6.1%	1.43	2.7%	0.08	0.1%	2.63	4.9%	0.00	0.0%	3.32	6.1%
		COST (Detailed)	2.58	4.8%	1.05	2.0%	0.00	0.0%	1.83	3.4%	0.00	0.0%	2.47	4.6%
		MacDonald	1.60	3.0%	0.04	0.1%	0.26	0.5%	1.51	2.8%	0.07	0.1%	0.69	1.3%
		Dublin Airport	26.73	49.5%	18.11	33.5%	6.97	12.9%	27.34	50.6%	2.99	5.5%	31.69	58.7%
	Cum-Load		58.36		49.39		43.36		41.77		46.13		54.99	
1kW	Whisper 200	Focus	1.49	2.1%	0.18	0.2%	0.46	0.6%	1.70	2.4%	0.13	0.2%	0.86	1.2%
		COST (Simplistic)	2.90	4.0%	1.44	2.0%	0.31	0.4%	2.47	3.4%	0.00	0.0%	3.06	4.3%
		COST (Detailed)	2.32	3.2%	1.05	1.5%	0.08	0.1%	1.89	2.6%	0.00	0.0%	2.40	3.3%
		MacDonald	1.49	2.1%	0.18	0.2%	0.46	0.6%	1.70	2.4%	0.13	0.2%	0.86	1.2%
		Dublin Airport	25.47	35.4%	15.63	21.7%	5.96	8.3%	23.42	32.5%	2.55	3.5%	28.37	39.4%
	Cum-Load		58.36		49.39		43.36		41.77		46.13		54.99	
1.5kW	Swift	Focus	1.12	1.0%	0.03	0.0%	0.14	0.1%	0.93	0.9%	0.03	0.0%	0.48	0.4%
		COST (Simplistic)	2.40	2.2%	1.04	1.0%	0.06	0.1%	1.92	1.8%	0.00	0.0%	2.42	2.2%
		COST (Detailed)	1.88	1.7%	0.77	0.7%	0.00	0.0%	1.33	1.2%	0.00	0.0%	1.80	1.7%
		MacDonald	1.12	1.0%	0.03	0.0%	0.14	0.1%	0.93	0.9%	0.03	0.0%	0.48	0.4%
		Dublin Airport	22.87	21.2%	13.34	12.4%	5.08	4.7%	19.98	18.5%	2.18	2.0%	24.20	22.4%
	Cum-Load		58.36		49.39		43.36		41.77		46.13		54.99	
2.5kW	Proven 2.5	Focus	3.57	2.0%	0.95	0.5%	1.38	0.8%	4.26	2.4%	0.45	0.3%	2.68	1.5%
		COST (Simplistic)	6.74	3.7%	3.83	2.1%	1.25	0.7%	5.94	3.3%	0.15	0.1%	7.15	4.0%
		COST (Detailed)	5.40	3.0%	3.07	1.7%	1.00	0.6%	4.76	2.6%	0.12	0.1%	5.73	3.2%
		MacDonald	3.57	2.0%	0.95	0.5%	1.38	0.8%	4.26	2.4%	0.45	0.3%	2.68	1.5%
		Dublin Airport	58.61	32.6%	35.53	19.7%	13.66	7.6%	52.88	29.4%	6.37	3.5%	64.06	35.6%
	Cum-Load		58.36		49.39		43.36		41.77		46.13		54.99	

The findings of the analysis presented in Table 3 can be summarized as follows:

1. The wind energy resource at the Focus site is significantly less than the site at Dublin Airport. With respect to the average over three days on a selection of months in the year, the average yield of the Dublin Airport site ranges from 14.61kWhr (SWIFT 1.5kW), to 38.52kWhr for the same considerations (Proven, 2.5kW). The Focus site on the other hand has an average yield (with respect recorded wind speeds) of 0.45kWhr (Swift 1.5kW) to 2.45kWhr (Proven 2.5kW)
2. The capacity factor associated with the micro wind turbines operating over the periods (and specific to the measured wind data collected at Focus) ranges from 0.4% (SWIFT 1.5kw) to 1.3% (Jetstream II, 750W). In comparison, the Airport site had an average capacity factor variation (again for the same period) ranging from 13.5% (Swift, 1.5kW) to 35.1% (Jetstream II, 750W)
3. With respect to yield comparison between the Focus (measured) wind speeds and the modelled wind speeds – and more specifically the COST methodologies described – the 'simplistic' implementation of the COST 715 action over estimates by an average of 137% whereas the 'detailed' approach again over estimates but by an average of 79%.

VI. CONCLUSIONS AND FUTURE WORK

The primary goal of this work was to develop the methodology proposed by Fisher et al [10] to include variability of the friction velocity with varying height in the derivation of the wind speed reference (3).

A summary of the findings are:

- The two sites under consideration (Dublin Airport and Focus Research Centre) had two considerably different wind resources as was evident in the wind rose analysis. This is explained by topographical differences and resulting turbulent winds associated with the urban environment.
- By extrapolating a rural reference wind speed into the boundary layer to acquire a value of friction velocity and then down to acquire the wind speed in the urban roughness layer provided good comparisons. When the analysis was carried out, correlation between both COST approaches ('simplistic' and 'detailed') ranged between 0.0053 for November to 0.88 for the sample in the Month of January. The MacDonald methodology uses the wind speed in the urban environment so direct comparison at the urban reference height is not helpful. As an attempt to cross validate, the methodologies were compared at
    - $h < z < z^*$, and
    - $d < z < h$

  The analysis proved that the 'simplistic' COST approach – in both contexts – did not trace the MacDonald waveform as well as the 'detailed' COST approach.
- Using the analysis as described above applied to a selection of micro wind turbines illustrated how variations in the measurement of the associated wind resource results in significant errors in estimation of yields.

It is hoped that this work can be applied to a number of sites within the Dublin urban area and through stochastic statistical analysis, a more generic application of the model can be developed and ultimately form the basis for the more accurate evaluation of the wind resource applicable to micro wind generation technologies.

VII. ACKNOWLEDGEMENTS

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