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OBSERVATIONS OF THE WIND RESOURCE ACROSS THE DUBLIN URBAN AREA

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Abstract- **This paper presents an investigation of wind observations made at three (of a network of ten) stations in Dublin. Two of the stations are located over different parts of the urbanized landscape and one is located at Dublin Airport, which exemplifies a typical meteorological station. The purpose of the analysis is to evaluate the nature of the wind resource in the urban area. The potential output of a range of commercially available micro wind turbines at one of the stations is considered. At this location, an anemometer is mounted in a similar manner to international examples of building mounted domestic installations of micro wind turbines. Finally, the paper investigates the relevancy of the *Weibull* and *Rayleigh* probability density functions as a means to represent urban wind power density for this Network.**

***Index Terms*— micro/small-generation, probability density functions, Weibull distribution, wind energy, wind power density, Rayleigh distribution, urban wind speed/direction**

I. INTRODUCTION

There is significant research assessing the wind energy resource in 'rural' locations around the world [1-5], and in some research [4, 5], such work has been extended to apply to the potential for wind energy conversion systems. On the other hand, some of the research into the urban wind potential is somewhat biased prioritising instead the *performance* of wind turbines [6, 7]. As the wind resource is not the focus in such research, but rather the energy yield of the turbines, this leads to the potential for inappropriate installation locations where the energy potential can never be realised. In a context of renewable energy development, the inherent complexities associated with the urban terrain mean that the potential for a micro/small wind turbine market faces significant challenges. Notwithstanding this complexity however, if a renewable solution to increasing energy demand is to be achieved; wind energy - especially where civil populations are concentrated - must be captured.

The purpose of this paper is to present a statistical description of wind speed/direction data measured over a twenty week period for Dublin City. The wind data is acquired for selected stations associated with the *Weather Information Network of Dublin* (WIND) project and from a synoptic weather station at Dublin Airport, located 10 km north of Dublin City [8]. The latter represents the 'background' wind climate against which the urban effect can be judged. The urban sites consist of a number of stations that are located in different urban landscapes. At two sites, observations are made at two platforms: inexpensive, robust, cup anemometers positioned near roof-level and; vey high quality, precise instruments located well above roof height. The analysis is performed in three stages as described in Fig 1:

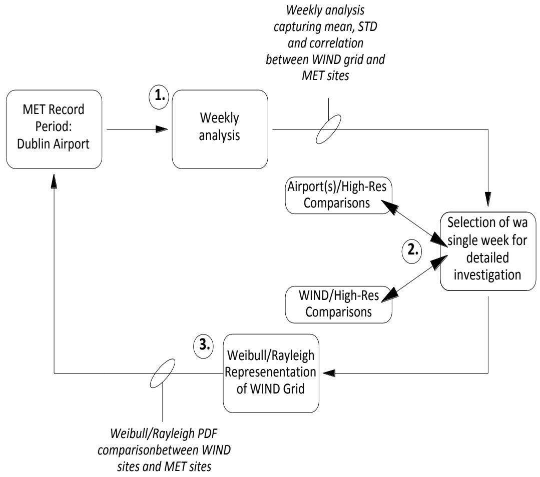

Fig. 1. WIND grid Analysis methodology

1. Comparing observations at the urban sites with the background Dublin Airport site
2. Selecting a period for more detailed investigations, which includes:
    - *Examining the relationship between observations at the background site and one of the urban sites that has instruments at two platforms*
    - *Establishing a statistical link between observations at the background site and the high-level platform and between the high-level and low-level platform. The latter is installed on a gable end wall of a house.*
    - *Investigating the potential for a micro wind generator at this site by considering a range of commercially available wind turbines*
3. Investigating the adequacy of the *Weibull* and *Rayleigh* probability distribution functions to represent the wind power density at station locations within the network.

II. *WIND* DATA

The typical station in the WIND network is comprised of Davis^{TM} *Vantage Vue* and *Vantage Pro 2* wireless weather stations (Table 1). Each station is located in distinct Local Climate Zones of the urban landscape characterized by different building forms and layouts as described in [9-12]. The instruments at these sites are positioned near roof-level. At two stations, precise instrumentation is also located at a higher level, well above building height. Thus, for two locations, data is available for observation platforms positioned well-above and near the same level as the building (roughness) elements.

TABLE I

WIND NETWORK WEATHER STATIONS

Station ID	Model	Location	Elevation
GPEP #1	VUE	**UCD CAMPUS**	4.0m
GPEP #2	VUE	**DOMINICAN CONVENT, DUN LAORGHAIRE**	4.5m
GPEP #3	VUE	**ST. DOMINICS, TALLAGHT**	7.0m
GPEP #4	VUE	**ST. PATRICK'S, CORDUFF**	4.0m
GPEP #5	VUE	**ST. PIUS X GIRLS, TERENURE**	5.00
GPEP #6	VUE	**KINSELAY**	9.0m
GPEP #7	VUE	**ST. COLUMBA, NORTH STRAND**	5.0m
GPEP #10	Pro2	**MARYLAND, D8**	8.0m
Marrowbone	CSAT-3D	**MARROWBONE LANE, D8**	17.0 m
St. Pius	CSAT-3D	**ST. PIUS X GIRLS, TERENURE**	12.0 m

These shaded stations are facilited with high-resolution

At the low level platform stations, the instrumentation (VUE and Pro2) has a wind speed resolution of 0.1m/s and the wind direction is captured with respect to 22.5^0 sectors. Each of these instruments is connected via wireless technology to the web [13]. At the two sites where these is a high-level observation platform the instrumentation (CSAT 3D) measures wind speed along three orthogonal axes at resolution between 0.5 – 1 mms^{-1} [14].

In the discussion that follows, emphasis is placed on one station in particular, the Marrowbone site. At this station, the wind flow above the roughness elements is acquired. In addition, low-level platform observations from a nearby site (Maryland) are employed for comparison. Here, the instrumentation is located just above the gable end of a two-storey house, typical of the placement of micro-generators within the urban environment.

Initially, observations from the WIND network are compared with those acquired at Dublin Airport, a conventional meteorological site located near the edge of the city. Here, instrumentation and exposure follows meteorological standards and is maintained by the Irish Meteorological Services. This airport data is taken to represent the 'background' wind climate, which would be present across the Dublin area in the absence of the city itself. The high-level observations represent the influence of the underlying urban 'surface' and the low-level observations represent the micro-scale effects of buildings at or near roof top.

III. *WIND* ANALYSIS

There are two Airport sites located on the outskirts of Dublin (Dublin Airport to the North and Casement Aerodrome to the south west) and records over the 20 weeks were acquired for both.. Table 2 and Fig. 2 summarise the weekly summary of the MET station records. There is generally good consistency between the records taken from both sites and highlighted row in Table 2 was selected for more detailed analysis on this basis that the correlations between the sites was sufficient to exclude other weather interference. Dublin Airport is subsequently employed as the background for the urban.

TABLE 2

WIND GRID WEATHER STATIONS

	Dublin Airport				Casement					
Week Starting	U_{mean}	U_{STD}	θ_{mean}	θ_{STD}	U_{mean}	U_{STD}	θ_{mean}	θ_{STD}	R_{wind}	R_{θ}
01/09/2010	4.13	2.17	135.2	42.86	3.79	2.13	127.3	44.07	0.729	0.477
08/09/2010	5.79	2.17	230.1	40.59	6.23	2.6	224	31.12	0.804	0.83
15/09/2010	5.96	2.25	247	46.14	5.36	2.29	228.2	42.06	0.883	0.887
22/09/2010	3.98	1.57	225.4	95.23	3.05	1.66	188.6	100.3	0.552	0.502
29/09/2010	5.05	2.22	204.1	40.1	5.51	2.27	199.8	34.29	0.776	0.71
06/10/2010	5.39	2.5	116.5	74.25	5.27	2.17	105.9	54.04	0.764	0.556
13/10/2010	4.48	2.07	264	92.45	3.38	2.16	206.2	104.6	0.919	0.451
20/10/2010	5.33	1.92	252.9	52.44	5.36	3.06	223.1	51.23	0.742	0.455
27/10/2010	6.23	2.71	231	67.81	6.63	3.38	193.7	63.3	0.837	0.836
03/11/2010	6.69	2.89	213.4	83.47	6.03	3.18	196.9	81.63	0.833	0.81
10/11/2010	6.86	4.25	228.9	44.75	6.34	4.14	212.2	36.85	0.898	0.675
17/11/2010	4.86	2.73	186.5	110.3	3.81	2.9	161.9	97.82	0.846	0.621
24/11/2010	4.68	2.11	259.5	96.96	2.76	1.55	228.1	86.79	0.819	0.698
01/12/2010	4.5	1.49	220.9	106.1	3.09	1.77	219.2	94.16	0.551	0.052
08/12/2010	***4.57***	***1.54***	***236.3***	***78.5***	***3.1***	***1.71***	***202.9***	***62.53***	***0.807***	***0.84***
15/12/2010	4.8	2.35	261.1	77.62	3.33	2.38	235.8	56088	0.918	0.331
22/12/2010	4.2	1.81	230.5	78.66	3.77	3.44	203.3	60.39	0.373	0.499
29/12/2010	3.75	2.23	184.2	99.29	2.97	2.31	161.6	93.5	0.868	0.739
05/01/2011	5.8	2.34	227.5	81.2	4.96	2.54	193.6	77.19	0.716	0.46
12/01/2011	6.83	3.24	228.5	24.88	7.48	3.37	217.8	14.95	0.884	0.77

where U_{MEAN}, U_{STD} represent the mean and standard deviation of the wind speed and Θ_{mean} and Θ_{STD} represent the mean and standard deviation of the wind direction. R_{WIND} and R_{Θ} represents the correlation (wind and direction respectively) between the two sites.

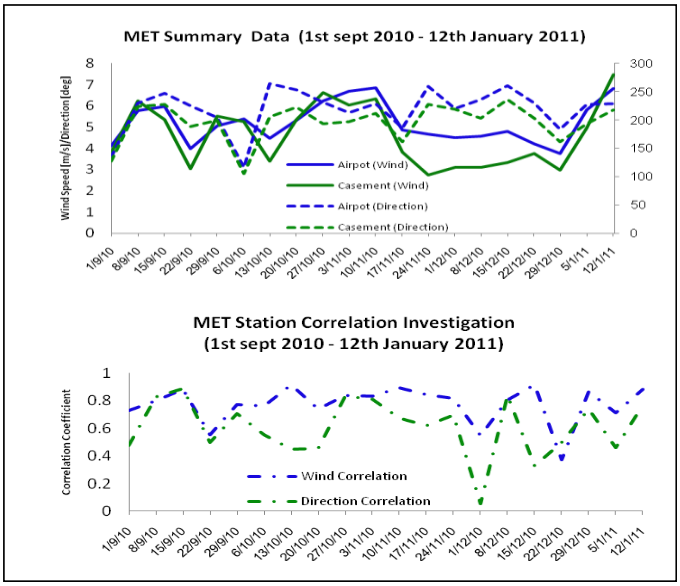

Fig. 2. MET station comparison over twenty weeks

A. Data Analysis: Airport vs. Marrowbone (high-level platform)

For the purposes of the paper, the Marrowbone high-resolution/high-level platform station and the station at Maryland (low-level platform) will be employed for comparison against the background of Dublin Airport. From Table 2, the week commencing the 8th of December was identified as the time period to make the comparisons:

***Airport** (Background)*
*→ **Marrowbone** (high-level platform)*
*→ **Maryland** (low-level platform).*

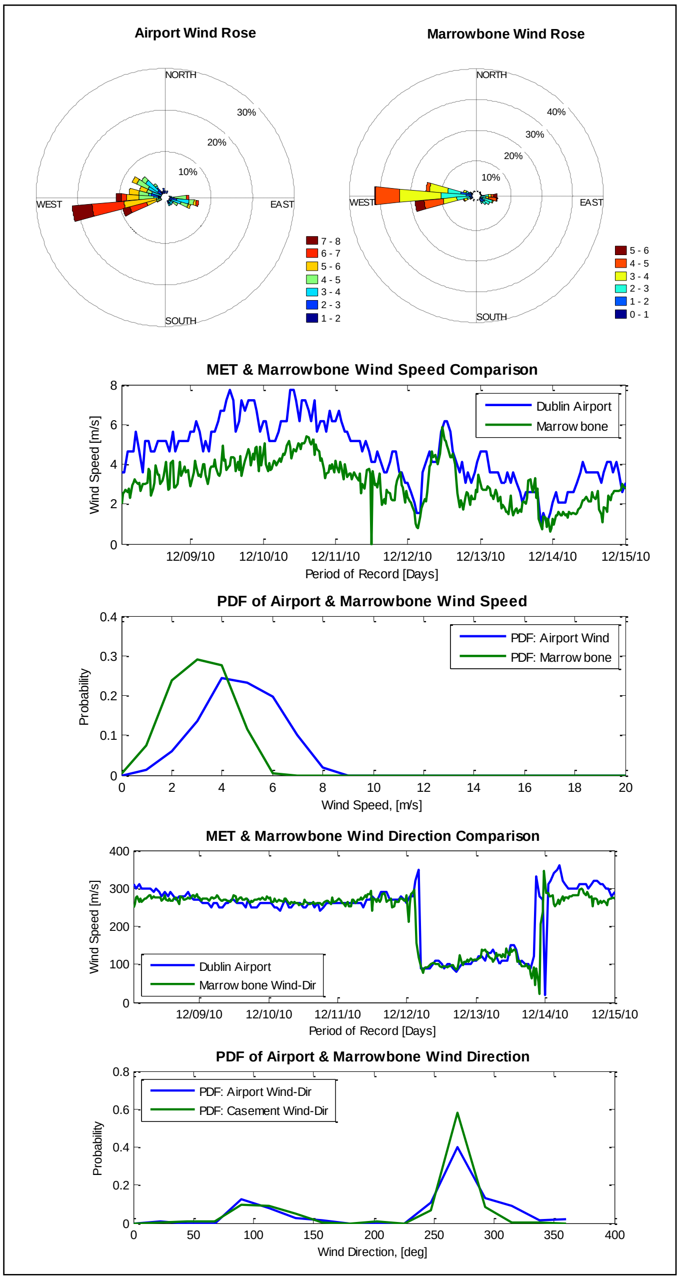

Fig. 3. MET and High-Res Data comparison

Fig. 3 illustrates that there is good consistencies between Dublin Airport and the Marrowbone station. There is good correlation between the two sites with respect to both wind speed and particularly direction with the magnitude being lower at the Marrowbone site.

B. Data Analysis: Marrowbone (high-level platform) vs. Maryland (low-level platform)

A summary of the findings at the Maryland installation in context with both the Airport and the installation at Marrowbone is provided in Table 4 with Fig. 4 illustrating the relationship of wind speed and direction between the two sites.

TABLE 3
MARROWBONE/MARYLAND SUMMARY

Week Commencing 8th December 2010					**Airport**	
	U_{mean}	U_{STD}	θ_{mean}	θ_{STD}	R_{wind}	R_{dir}
Maryland	1.56	1.04	259.87	78.8	0.6139	0.6846
Marrowbone	*3.09*	*1.13*	*228.35*	*73.07*	*0.8479*	*0.8437*
Airport	**4.57**	**1.54**	**235.77**	**78.01**		

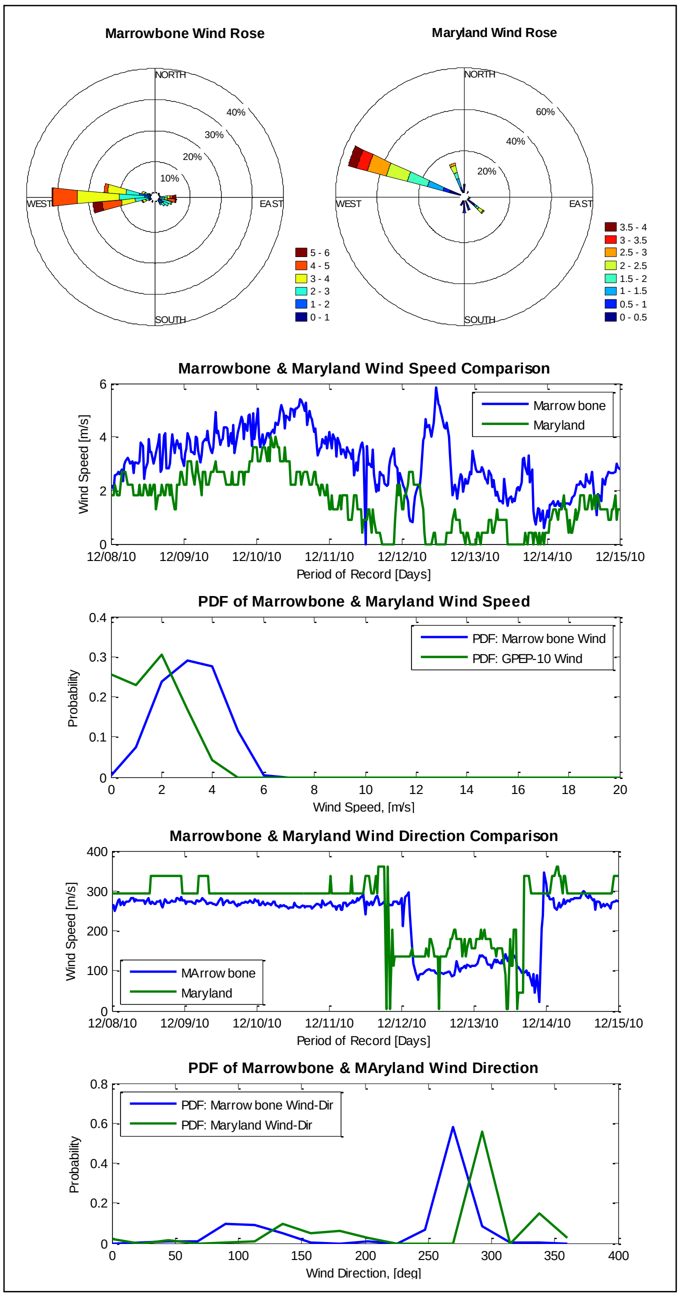

Fig. 4. Marrowbone (High-Res.) and Maryland (Standard-Res.) Data comparison

Comparing between the two sites in Fig. 4, the following is observed:

- The average wind direction is displaced by 30^0
- The wind direction variations are more chaotic at the Maryland site.
- There are a considerable amount of calm periods prevalent at the Maryland site. This could be indicative of the geographical location of the station or it could relate to the installation/positioning of the weather station itself. This station is installed at the gable-end wall of a private residence.

C. Performance of a micro-generator technology

Wind turbines extract kinetic energy from moving air, converting it into mechanical energy via the turbine rotor and then into electrical energy through the generator. The mechanical energy P_{mech} that is taken by the wind is equal to:

$$P_{mech} = \frac{1}{2} . c_p . \rho_{air} . A_{blades} . \left(v_{wind} \right)^3 \qquad (1)$$

Where:

- P_{mech} = Mechanical output power of then turbine [W]
- c_p = Performance coefficient of the turbine – i.e. the fraction of the kinetic energy of the air captured as rotational energy by the turbine blades
- ρ_{air} = Air density [$kg.m^{-3}$]
- A_{blades} = Turbine swept area [m^2]
- v_{wind} = wind speed [$m.s^{-1}$]

A sample of three micro wind turbines as illustrated in Table 4 were scrutinized in terms of manufacturer guidelines against the wind speed measured at the Maryland site. The turbines were chosen on the basis of their outputs and relative physical size and ability to be installed at the domestic installation at Maryland.

TABLE 4
SAMPLE OF COMMERCIALLY AVAILABLE (MICRO)WIND TURBINES

Model	**U_{Cut-in} (ms^{-1})**	**U_{Rated} (ms^{-1})**	**P_{Rated} (W)**	**$P_{rated-Speed}$ (W)**
Jetstream II	3.5	10	750	790
Ampair 600	3	11	600	698
Swift	3.4	12	1500	1500

The Maryland site was selected for investigation as it represents a similar context to domestic building installations internationally [6, 7], where it is permissible to install micro wind on to the gable ends of such buildings. Current planning regulations in Ireland preclude such opportunities [15] and as Fig. 5 suggests, such installations are not ideal. From Fig. 5 the Airport site might be conducive for a micro wind turbine installation but based on the wind records over the week being investigated and the power output results illustrated, Maryland should not be considered at all. However, it is important to point out that the records accumulated at Maryland could be affected by the proximity of the measuring equipment to the building itself. Also requiring further clarification is the relative position of the station with respect to the local geography. Whilst the station has an elevation of 8m, it is still relatively embedded into the urban complexities and therefore a higher positioning could be warranted. The proximity of the station's anemometer could also be experiencing interference from the roof of the residence.

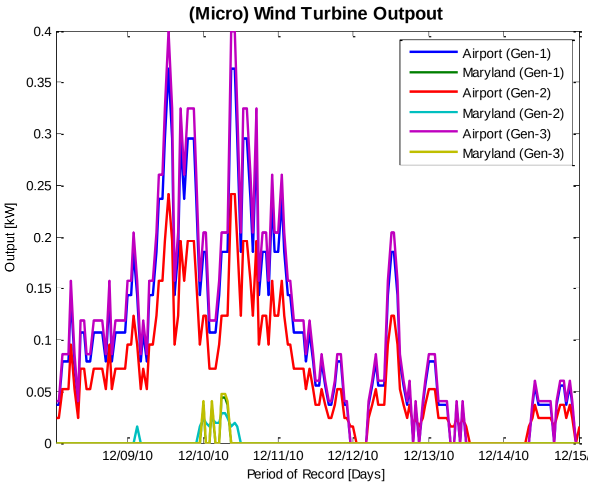

Fig. 5. Potential output for a sample of (micro) wind generators at the Dublin Airport & Maryland sites

IV. STATISTICAL ANALYSIS

A. Frequency Distribution

The Weibull distribution is commonly used to describe wind [1-5] and this function has been shown to give a good fit to measured wind speed data [16] The Weibull distribution function is described in (1).

$$P(u < u_i < u + du) = P(u > 0)\left(\frac{k}{c}\right)\left(\frac{u_i}{c}\right)^{k-1} e^{\left[-\left(\frac{u_i}{c}\right)^k\right]} du_i \qquad (2)$$

The Weibull scaling factor, *c*, has the same units describing wind speed, k, represents the Weibull shape parameter, u_i is a particular wind speed, du is an incremental wind speed. $P(u<u_i<u+du)$ is the probability that the wind speed is between *u* and *u+du* [17]. The Rayleigh distribution is a special case of the Weibull distribution in which the shape parameter, k, has a value of 2.0 [18].

The Weibull parameters can be derived in a number of ways [19], but the approach in this paper is to employ the *maximum likelihood method* [17] to compile fitted Weibull distributions of the WIND (and MET) weather stations.

It is important to point out that while the most common probability distribution describing wind is the Weibull, it has been shown that Weibull does not fit well when the wind regimes present bimodality of if there are high percentages of calm [2]. In [20] Bivona et al conclude that when the Weibull does not represent the wind regime in an area, the statistical properties of the wind data are affected by the surface roughness or geographical location.

B. Wind Power Density

The average power density per period of time can be calculated by using the probability density function of the measured wind data using (3).

$$P_{\text{Measured}} = \sum_{j=1}^{n} \frac{1}{2}.\rho.u_{m.j}{}^{3}.f(u_j) \qquad (3)$$

Chang in [21], as discussed by Jamil et al in [22], further describes how wind power density can be described by a Weibull probability density function (4).

$$P_{\text{Weibull}} = \frac{1}{2}.\rho.c^3.\Gamma\left(1+\frac{3}{k}\right) \qquad (4)$$

where Γ(x) is the gamma function. The wind power density can also be described by the Rayleigh probability distribution, where k=2 and the mean wind speed is approximated by (5)

$$u_m = c\sqrt{\pi/4} \qquad (5)$$

Therefore the Rayleigh probability distribution describing the wind power density, as discussed by Celik [23], is obtained by (6)

$$P_{\text{Raylleigh}} = \frac{3}{\pi}.\rho.u^3{}_m \qquad (6)$$

The average error factor in calculating the power density (4,6) by both the Weibull and Rayleigh functions is found using (7).

$$\text{Error}(\%) = \left[\frac{P_{\text{Weibull / Rayleigh}} - P_{\text{Measured}}}{P_{\text{Measured}}}\right] \qquad (7)$$

C. *Evaluation of Weibull and Rayleigh Distributions*

The Weibull/Rayleigh distribution performances over the 20 week period are evaluated through:

- Mean root-square error (RMSE)
- Chi-square Test (χ^2)
- The correlation coefficient (R^2)

The RMSE parameter (11) describes the deviation between the predicted and modelled values and should be as close to zero as possible [3].

$$\text{RMSE} = \left\{\frac{\sum_{i=1}^{N}(y_i - x_i)^2}{N}\right\}^{0.5} \qquad (8)$$

The χ^2 test returns the mean-square of the deviations between the experimental and calculated values for the distribution (12).

$$\chi^2 = \frac{\sum_{i=1}^{N}(y_i - x_i)^2}{N-n} \qquad (9)$$

In both RMSE and χ^2 tests, y_i represents the i-th actual measured wind datum and x_i represents either the Weibull or Rayleigh modeled values; N is the number of observations and n is the number of constants [3, 4]. The smaller these two values, the better-fit the respective curves envelope the frequency distribution of measured wind speed. The R^2 coefficient shows the ability of the model and has a maximum value of 1.

$$R^2 = \frac{\sum_{i=1}^{N}(y_i - z)^2 - \sum_{i=1}^{N}(x_i - y_i)^2}{\sum_{i=1}^{N}(y_i - z)^2} \qquad (10)$$

In (10), y_i represents the i-th actual measured wind datum, z is the mean value of the Weibull/Rayleigh modeled data, x_i represents the i-th value of the Weibull/Rayleigh modeled data and N represents the number of observations [21].

D. *Weibull and Rayleigh Analysis*

TABLE 5:
STATISTICAL EVALUATION OF THE WIND GRID DATA IN TERMS OF THE WEIBULL AND RAYLEIGH DISTRIBUTIONS

Weather Station	**Recorded Data**		**WEIBULL**								**RAYLEIGH**							
	U_m [ms^{-1}]	***U_{PD} [Wm^{-2}]***	***U_{m-R} [ms^{-1}]***	***k***	***c***	***U_{PD-R} [Wm^{-2}]***	***U_{PD} [Error] [%]***	***R^2***	***χ^2***	***RMSE***	***U_{m-W} [ms^{-1}]***	***k***	***c***	***V_{PD-W} [Wm^{-2}]***	***U_{PD} [Error] [%]***	***R^2***	***χ^2***	***RMSE***
GPEP #1	2.00	12.417	2.01	1.43	2.21	14.536	17.060	0.9999	0.0004	0.0162	2.21	2.00	2.49	12.5410	1.0020	0.9995	0.0021	0.0373
GPEP #2	1.29	3.902	1.30	1.37	1.42	4.193	6.957	0.9992	0.0014	0.0302	1.46	2.00	1.65	3.6508	-6.8730	0.9994	0.0010	0.0262
GPEP #3	2.39	22.844	2.40	1.47	2.65	23.757	3.997	0.9996	0.0026	0.0418	2.59	2.00	2.92	20.3590	-10.8800	0.9997	0.0021	0.0372
GPEP #4	2.00	1.466	2.00	1.51	2.22	13.271	15.749	0.9998	0.0011	0.0271	2.25	2.00	2.43	11.6510	1.6190	0.9996	0.0018	0.0349
GPEP #5	1.84	7.919	1.85	1.51	2.05	10.338	30.546	0.9997	0.0010	0.0259	1.98	2.00	2.32	9.9048	14.2550	0.9991	0.0033	0.0471
GPEP #6	2.63	21.899	2.64	1.72	2.96	25.406	16.009	0.9997	0.0020	0.0367	2.73	2.00	3.08	23.7730	8.5540	0.9997	0.0025	0.0410
GPEP #7	1.38	3.799	1.39	1.62	1.55	4.027	6.013	0.9967	0.0068	0.0676	1.47	2.00	1.66	3.7070	-2.4200	0.9968	0.0066	0.0664
GPEP#10	2.29	16.808	2.30	1.57	2.56	18.882	12.341	0.9997	0.0020	0.0332	2.44	2.00	2.75	16.8440	0.4550	0.9997	0.0020	0.0366
Airport	5.10	149.330	5.10	2.15	5.76	145.230	-2.743	0.9999	0.0023	0.0390	5.03	2.00	5.68	149.0100	-0.2130	0.9999	0.0030	0.0446
Casement	4.46	137.890	4.48	1.62	5.00	134.200	-2.679	0.9999	0.0022	0.0387	4.71	2.00	5.32	122.2400	-11.3480	0.9999	0.0009	0.0240

Table 5 summarises (over the twenty week period) the statistical comparisons between the WIND stations with respect to the Weibull & Rayleigh functions, with U_m and U_{PD} being the recorded wind speed and the wind power density respectively and U_{PD-R} and U_{PD-W} are the power density approximated by the Rayleigh and Weibull models respectively..

With respect to approximations of the wind speed distributions, the data generally follows a Weibull/Rayleigh approximation, but the amount of calms prevalent at the WIND sites does have a detracting impact on comparison consistency.

The correlation coefficient (R^2), chi-square (χ^2) and the Root-Mean-Square-Error (RMSE) techniques were employed to make the statistical comparisons. The best comparisons will be decided according to the highest values of R^2 and the lowest values of χ^2 and RMSE.

V. CONCLUSIONS & FUTURE WORK

The aim of this paper was to investigate wind measurements from a rural background (Dublin Airport) against measurements from a network of weather stations positioned in the Dublin urban environment and to examine if any relationship exists. This was achieved by considering the Airport data in terms of a weather station at a relatively high elevation and then to investigate the reaction of the same wind regime at a point lower in elevation deeper into the urban environment. It is evident that with the right (weather stable) conditions, there is good correlation between the Airport site and the site relatively high above urban influence, but it is due to this influence that the wind regime deeper into the urban environment is significantly attenuated and chaotic in nature.

This process allows a context for analysing the performance of a potential wind turbine should it be installed within the urban environment on the gable end of a domestic installation.

Finally, the Weibull and Rayleigh distributions were employed to investigate their relevance as a means to describe urban wind. It is evident from the analysis and with respect to the subsequent accuracy assessments that some sites could be indicative of these distributions, but with the degree of wind calms recorded over a relatively short time period, there couldn’t be significant confidence that these distributions represent the optimal means of representing the wind resource within an urban environment.

The next stage for development in this research is to quantify the extent to which the surface topography and building morphology influences and affects the urban wind resource. This will be explored by considering a model of surface roughness across Dublin City.

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