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Jonathan Blackledge

Technological University Dublin, jonathan.blackledge@tudublin.ie

Eugene Coyle

Technological University Dublin, Eugene.Coyle@tudublin.ie

Derek Kearney

Technological University Dublin, derek.kearney@tudublin.ie

See next page for additional authors

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Authors

Jonathan Blackledge, Eugene Coyle, Derek Kearney, and Eamonn Murphy

INVERTER PERFORMANCE FOR SMALL WIND TURBINES WHEN CONNECTED IN PARALLELED WITH THE LOW-VOLTAGE DISTRIBUTION SYSTEM

By

JONATHAN BLACKLEDGE *

EUGENE COYLE **

DEREK KEARNEY ***

EAMONN MURPHY ****

* Stokes Professor, Dublin Institute of Technology.

** Head of External Research, Dublin Institute of Technology.

*** Lecturer, Dublin Institute of Technology.

**** Technician, Dublin Institute of Technology.

ABSTRACT

Small wind turbines have been installed in urban and turbulent locations with surprisingly poor performance and this has been backed up by data from a trial at the Dublin Institute of Technology. In order to develop the small wind turbine industry a careful examination of assessment methods for the wind resource is required. Small wind turbines connected in parallel with the grid use inverters. As the wind turbine is not always at max output, a Weighted Average Efficiency for wind inverters is proposed. Pitfalls associated with developing an accurate weighted average efficiency for an inverter are identified and this will enable a more accurate sizing of the inverter for the turbine. The methodology for determining the performance of inverters and small wind turbines can be applied to any location.

Keywords: Inverter Efficiency, Micro-Wind Turbine, Weighted Average Efficiency, Sizing of Inverters, Wind Resource.

INTRODUCTION

World total primary energy demand is increasing annually and this has had a big effect on the availability and cost of fossil fuels. Investment in renewable technologies is increasing rapidly to meet this demand. As part of the renewable energy mix wind turbines smaller than 10 kW are being installed. Performance of these turbines has been disappointing due primarily to the difficulty is assessing the wind resource in an urban or turbulent environment.

In an urban or turbulent environment the output of a small wind turbine <10 kW will vary considerable and in many cases will never reach the nominal (full) power output of the device. By assessing the wind resource accurately and dividing it into the weighted averages for the power output of an inverter an accurate picture of the expected performance of the small wind turbine can be established with a reasonable degree of accuracy. In order to complete this process a number of key objectives must be met. They are (1) to establish a weighted average efficiency of data from National Meteorological Weather Stations nearby (2) Develop a Weighted Average Efficiency (WAE) of wind speed for the site (3) Plot the WAE against the

power performance curves of the turbine (4) Size the inverter to suit the chosen turbine and site wind resource (5) Determine the capacity factor for the small wind turbine to establish commercial viability of the project.

The approach using the WAEs is already in use for Photovoltaic (PV) systems but in this case a similar methodology is being employed for the small wind turbines (EN50530, 2010). Experience from weather stations, PV systems, and a small wind turbine installed at the Dublin Institute of Technology (DIT) point to potential pitfalls in this process. This article will serve as a guide for engineers looking to install wind turbines in urban and turbulent conditions.

1. Literature Review

A World Meteorological Organization (WMO) report on the assessment of the wind resource in the urban environment points to the difficulties in assessing the wind resource in the urban environment (Oke, 2006). The reason given is that most urban sites make it impossible to conform to the standard guidelines for site selection and instrument exposure that are outlined in the Guide to Meteorological Instruments and Methods of Observation (WMO, 2008). This

is due to the obstruction of airflow and radiation exchange by buildings and trees, unnatural surface cover and waste heat and water vapour from human activities.

The report: The Feasibility of Building Mounted/Integrated Wind Turbines (BIWTs): Achieving their Potential for Carbon Emission Reductions was funded mainly by the Carbon Trust in the UK (Dutton, Halliday, & Blanch, 2005). This report evaluated the energy generation potential and technical feasibility of siting wind turbines in the built environment. This study focused mainly on urban areas: from turbines situated next to buildings, through to turbines mounted on buildings, to turbines fully integrated into buildings. The report concluded that wind energy could make a significant contribution to energy requirements in the built environment but a more detailed evaluation of the resource is required. Building mounted or integrated wind turbines are currently an under developed area of technology and there exists significant potential in this area for development. Section 3 of the report identifies the technical hurdles that exist and reviewed them in terms of whether potential solutions exist or further research and development is required. The main research area identified was in the assessment of the wind regime in urban areas and around isolated buildings. This section was further sub-divided as follows:

- Carry out resource assessments for wind energy potential in a range of urban environments.
- Develop an improved understanding of local air flows around and over buildings through a combination of computational fluid dynamics modelling and in situ measurements.

The report highlights the implications of high turbulence levels and of veering or swirling winds, on the performance of wind turbines. In particular there remains a lot of uncertainty relating to atmospheric boundary layer flows in the urban environment and the design implications for wind turbines. Importantly the report could not identify any means currently used to work around the problem of the assessing the effect of turbulence on the performance of turbines within the built environment.

The wind turbines in the Warwick Field Trials conducted in the UK had an average capacity factor of 1.5% and this is

compared with an average capacity factor of 35% for the larger scale turbines installed in the open (Encraft, 2009). This reinforces the view that there is a lack of understanding with regard to the assessment of the wind resource in the urban environment.

2. Inverter Performance

The EN 61683:2000 (Photovoltaic Systems – Power Conditioners - Procedure for Measuring Efficiency) provides a methodology to determine the intrinsic efficiency of inverters by measuring directly their input and output power in the factory (EN61683, 2000).

The power efficiency of the inverter is expressed in Equation 1.

Equation 1 Power efficiency of inverter

$$\text{Efficiency} = \frac{\text{AC Output Power}}{\text{DC Input Power}} \times 100\% \quad (1)$$

Indirect items such as Maximum Power Point Tracking (MPPT) are outside the scope of this particular standard. This standard covers only Photovoltaic (PV) systems and it is not specifically for wind. It is often quoted by manufacturers of wind inverters and particularly with inverters, which are advertised as applicable for solar and/or wind. Many other manufacturers do not reference any standard specific to wind inverter efficiency.

The later EN 50530:2010 (Overall Efficiency of Grid Connected Photovoltaic Inverters) does look in detail at the European Weighted Average Efficiency for inverters connected to PV systems (EN50530, 2010).

Equation 2 European Weighted Average Efficiency

$$\eta_{\text{Euro}} = 0.03 \times \eta_{5\%P_n} + 0.06 \times \eta_{10\%P_n} + 0.13 \times \eta_{20\%P_n} + 0.1 \times \eta_{30\%P_n} + 0.48 \times \eta_{50\%P_n} + 0.2 \times \eta_{100\%P_n} \quad (2)$$

An explanation of the formula is as follows: The first term indicates that for 3% of the time a PV system will operate at 5% of nominal or full power capacity; and the same follows for the other terms. This formula takes into account the variation in solar energy throughout the year. California has also produced a WAE for grid connected PV systems with values slightly higher to account for the sunnier conditions there (Bower, 2004).

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The European Weighted Average Efficiency (EWAE) is not always accurate for individual countries as the solar resource varies considerably across Europe and indeed any continent so this efficiency would need to be checked against local solar irradiation data to obtain an accurate picture of the performance of an inverter for a PV system (Blackledge, Rivas, Kearney, & Murphy, 2012). A study of the measured data from two PV systems installed at the DIT has confirmed that there is a significant deviation in overall inverter efficiency from the EWAE formula for Ireland (Duarte, 2011). The difference can be seen by comparing Equations 1 to Equation 3.

Equation 3 Weighted Average Efficiency of Inverters for photovoltaic systems in Ireland

$$\eta_{\text{Ireland}} = 0.30 \times \eta_{5\%P_n} + 0.12 \times \eta_{10\%P_n} + 0.18 \times \eta_{20\%P_n} + 0.14 \times \eta_{30\%P_n} + 0.23 \times \eta_{50\%P_n} + 0.03 \times \eta_{100\%P_n} \quad (3)$$

This variation in efficiency will have an effect on the overall economic viability of a PV system, especially in the megawatt range. This variation in WAE for wind inverters is far more pronounced because of the local variation in the wind resource due to obstructions, surface roughness, etc.

In order to develop a formula for the weighted average efficiency for a wind inverter consideration must be given to the resource measured at lower levels i.e. less than 50 metres in the earth's atmosphere.

3. Developing a Weighted Average Efficiency Formula for Wind Inverters

Extensive research on the internet, exhaustive searching of standards databases, and also with phone calls to manufacturers has shown that there is no systematic methodology used for the determination of a weighted average efficiency for the performance of wind turbines. The methodology used for developing the WAE of inverters in the EN 50530 (*Overall Efficiency of Grid Connected*

Photovoltaic Inverters) can be applied to developing a WAE for wind inverters. The WAE will give an indication of the expected performance of the turbine and ultimately help in sizing the inverter.

3.1 Wind Data Analysis

Wind data is generally not available over a long term period for an urban location so it is best to use data from local meteorological stations as shown in Figure 1 to develop a long-term profile for wind on a site.

In Figure 2, the data is shown for weather stations in Ireland over a two-year period January 2008 – December 2009 (ME, 2010).

Knowing the long-term wind speed of a region will give an indication of the suitability of a site for wind generation. Power production is the ultimate objective of the installation of wind turbines. For practically all of the small scale wind turbines, an inverter is used to connect turbines in parallel with the grid. So the next stage of analysis is to develop a weighted average efficiency formula from the analysis of the data.

Figure 1. National meteorological service weather stations – Ireland (ME, 2010)

Figure 2. Average wind speed for weather stations in Ireland Jan 2008 – Dec 2009

The parameters of the WAE formula need to be determined. Data supplied by Met Éireann was analysed to determine the probability density of wind speed as shown in Figure 3 (ME, 2010).

What affects the parameters selected for the WAE is the power rating of the turbines. For the purposes of this assignment the EN 50438 Requirements for the Connection of Micro-Generators in Parallel with Public Low-voltage Distribution Networks definition for micro-generation will be used (EN50438, 2007). This varies from country to country in the single-phase range but the maximum power output for three-phase is 17.3 kVA for three phase equipment. An assessment of turbines available in the market indicates the characteristics in Table 1.

Table 1 is a compilation of small wind turbine manufacturer's power curve data. There is currently no universally accepted standard for measuring the power outputs for small wind turbines and this is compiled from general power curves from manufacturers. The cut-out wind speed is shown as 14.5 m/s which is not the case for all

Figure 3. Probability density of wind speed for weather stations in Ireland

Turbine	Rated Power Output (kW)	Cut in wind speed (m/s)
Ampair 600-230	0.6	3
Swift	1.5	3.5
Skystream 3.7	2.4	3.5
Siliken 3.4	3.8	3.5
Evanco R9000	5	3
Proven 11	6	2.5
ARI Green Energy	7.5	2.5
RWC Excel	10	3.5

Table 1. Operating characteristics of micro-wind turbines

turbines. However in locations where micro-wind turbines are generally installed, speeds above this level are quite rare.

A plot of wind speed probability against the percentage of full power output for micro-wind turbines is shown in Figure 4.

3.2 Weighted Average Efficiency for Wind Inverters in Ireland

The methodology found in EN 50530:2010 to determine the WAE for inverters can be used to determine the WAE of wind inverters for Ireland or indeed any location. Figure 5 shows the cut-in, peak power, and cut-out wind speeds for the WAE of wind inverters. This is based on the average power output of a sample of micro-wind turbines based on manufacturer's data as shown in Table 2.

The cut-in wind speed for micro-wind turbines is 3 m/s and the cut-out wind speed for turbines is above 15 m/s; peak power occurs at approximately 10 m/s. The average wind speed from the weather stations in Ireland is shown in Table 3.

Figure 4. Average power output curve for micro-wind turbines

Figure 5. Micro-wind turbine performance plotted against wind speed probability in Ireland

Wind Speed (m/s)	1	2	3	4	5	6	7	8	9	10-14	15-18
Turbine Power Output %	0	0	2	6	13	22	36	55	78.3	100	0

Table 2. Average power output of micro-wind turbines versus wind speed

The inverter performance gleaned from manufacturer data is shown in Figure 6. The parameters for developing a WAE formula for wind inverters can be based on the parameters as outlined in Table 4.

Table 5 shows the probability density of wind speeds, and the turbine power output at the wind speeds identified; this is necessary to develop a WAE formula for Ireland.

Using the values in Table 5 a WAE formula for wind inverters

Wind Speed (m/s)	Malin Head %	Belmullet %	Valentia %	J'Town Castle %	Gurteen %	Airport %	Overall %
1	2.5	6.9	8.3	10.2	8.6	2.4	6.5
2	4.2	5.4	11.2	21.9	15.4	7.0	10.8
3	6.0	7.7	13.3	20.4	20.0	11.2	13.1
4	9.5	12.9	14.1	16.9	16.9	14.3	14.1
5	8.4	11.2	14.0	12.4	13.4	15.2	12.4
6	10.8	10.2	10.6	8.3	10.0	12.5	10.4
7	10.5	11.6	8.9	5.3	6.9	10.6	9.0
8	10.1	10.1	6.6	2.5	4.1	8.6	7.0
9	10.2	8.2	5.2	1.3	2.3	6.3	5.6
10	6.5	4.6	2.9	0.6	1.2	4.7	3.4
11	4.8	3.0	2.2	0.2	1.1	3.1	2.4
12	4.2	3.1	1.3	0.0	0.0	1.8	1.7
13	4.3	2.0	0.7	0.0	0.1	1.0	1.4
14	2.5	1.3	0.4	0.0	0.0	0.5	0.8
15	2.0	0.8	0.2	0.0	0.0	0.3	0.5
16	1.1	0.4	0.1	0.0	0.0	0.2	0.3
17	0.7	0.3	0.0	0.0	0.0	0.1	0.2
18	0.5	0.1	0.0	0.0	0.0	0.0	0.1

Table 3. Breakdown of the wind speed for the weather stations in Ireland

Figure 6. Inverter efficiency versus power output for typical inverter with transformer

% Rated Power	3%	9%	22%	32%	80%	100%
Inverter Efficiency	83%	89%	93%	94%	95%	94%

Table 4. Efficiency of inverter at each % rated power

Wind Speed (m/s)	1	2	3	4	5	6	7	8	9	10-14	15-24
Probability Density (%)	6.5	10.8	13.1	14.1	12.4	10.4	9	7	5.6	10	1.4
Turbine Power Output (%)	0	0	3	6	13	22	36	55	78	100	0

Table 5. Weighted average efficiency formula based on probability density of wind speed and turbine power output

was developed using the power output for the turbine for each m/s wind speed.

Equation 4 Weighted Average Efficiency formula for inverter efficiency in Ireland

$$\eta_{Irl} = 0.3 \times \eta_{3\%P_n} + 0.14 \times \eta_{6\%P_n} + 0.13 \times \eta_{13\%P_n} + 0.11 \times \eta_{22\%P_n} + 0.09 \times \eta_{36\%P_n} + 0.07 \times \eta_{55\%P_n} + 0.06 \times \eta_{78\%P_n} + 0.1 \times \eta_{100\%P_n} \quad (4)$$

Equation 4 shows that there is a concentration of terms in the lower power regions. This will have the effect of reducing the overall efficiency of the inverter as it is not as efficient in the lower power regions as shown in Table 6. When this formula is used in conjunction with the inverter data in Table 4 and Figure 6 then the actual efficiency for an inverter used in Ireland can be calculated by multiplying the inverter efficiency with the probability density of wind speed in Ireland.

3.3 Weighted Average Efficiency for a Urban Location in Ireland

The overall efficiency of an inverter in Ireland at 92.86% is not entirely accurate. The WAE needs a correction factor for specific locations to obtain an exact figure for the WAE of an inverter. The WAE formula for a wind inverter in Ireland includes Malin Head and Valentia weather stations, which are some of the windiest places in Europe and indeed with the exposure to the Atlantic Ocean they are some of the windiest places in the world inhabited by humans. Data from anemometers installed at the Dublin Institute of Technology (DIT) will reveal a more realistic probability density for local level wind resource. Figure 7 shows the probability density of wind data from Monthly average of

Inverter Efficiency	83%	89%	93%	94%	95%	94%
Probability Density of Inverter Output when Connected to a Micro-Wind Turbine	3%	14%	24%	36%	13%	10%
Overall Efficiency of Inverter in %	2.49	12.46	22.32	33.84	12.35	9.4

Table 6. Weighted Average Efficiency of a wind inverter in Ireland

Figure 7. Monthly average of wind speed data from Church Lane, Focas Institute and Met Éireann weather stations

wind speed data from Church Lane, Focas Institute and Met Éireann weather stations over a six-month period from January to June 2009.

It can be seen from Figure 7 that the Church Lane site has a very poor wind resource. The mounting height of the anemometer is six metres above ground level and the site is surrounded by trees and buildings with a slight opening to the North. The output from a small 240W wind charger installed at this site was just 2-kWh over a six-month period so it will not be considered as it is not a suitable for a wind turbine. The Focas building is a four storey building which is the highest building in the area with the exception of the five storey main DIT building about 100 metres to the south. Data from this site was collected over a six-month period and it is shown in Table 7.

The same methodology used to determine the WAE for Ireland can be used to determine the WAE of an inverter for an urban location. Using the values in Table 8 a WAE formula for wind inverters in urban locations was developed using the power output for the turbine for each m/s wind speed. Equation 5 Weighted Average Efficiency formula for inverter efficiency in urban locations

$$\eta_{\text{Urban}} = 0.72 \times \eta_{3\%P_n} + 0.15 \times \eta_{6\%P_n} + 0.06 \times \eta_{13\%P_n} + 0.03 \times \eta_{22\%P_n} + 0.02 \times \eta_{36\%P_n} + 0.01 \times \eta_{55\%P_n} + 0.005 \times \eta_{78\%P_n} + 0.0 \times \eta_{100\%P_n} \quad (4)$$

Wind Speed (m/s)	Jan	Feb	Mar	Apr	May	Jun	Overall
0.0	12.4	11.2	8.8	17.3	7.5	15.4	12.1
1.0	13.4	17.4	12.6	18.5	10.4	19.0	15.2
2.0	22.2	30.0	23.1	26.5	21.6	30.0	25.6
3.0	15.7	21.6	19.6	17.8	20.0	18.8	18.9
4.0	14.0	13.8	18.5	11.8	19.8	11.1	14.8
5.0	7.6	3.8	8.3	6.2	9.3	3.2	6.4
6.0	5.9	1.5	5.1	1.0	5.7	1.5	3.4
7.0	3.8	0.5	2.4	0.4	3.0	0.6	1.8
8.0	1.8	0.2	1.0	0.2	1.4	0.2	0.8
9.0	1.0	0.0	0.4	0.2	0.6	0.1	0.4
10.0	0.9	0.0	0.2	0.1	0.4	0.0	0.3
11.0	0.8	0.0	0.1	0.0	0.2	0.0	0.2
12.0	0.3	0.0	0.0	0.0	0.1	0.0	0.1
13.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0

Table 7. Probability Density of wind speed from Focas Building, Dublin Institute of Technology

Wind Speed (m/s)	0	1	2	3	4	5	6	7	8	9	10-14	15-24
Probability Density (%)	12	15	26	19	15	6	3	2	1	0.5	0	0
Turbine Power Output (%)	0	0	3	6	13	22	36	55	78	100	0	0

Table 8. Weighted Average Efficiency of a wind inverter in Focas Building, Dublin Institute of Technology

Equation 5 shows that there is a further concentration of terms in the lower power regions; this is due to the turbulence in the urban environment. This will have the effect of further reducing the overall efficiency of the inverter. Again the overall WAE of a wind inverter can be calculated by multiplying the inverter efficiency at various power levels with the probability density of wind speed in urban locations, as shown in Table 9.

3.4 Capacity Factor of Turbines and its effect on the Sizing of the Inverter

The capacity factor of the turbine for each location can be calculated by multiplying the sum of the product of the WAE and the percentage of rated power for the turbine, as shown in Table 10.

Overall in Ireland the capacity factor for large-scale wind turbines > 1MW is in the region of 35%. This is because of the hub height, which is generally in the region of 50m. Weather stations are located closer to the ground and this gives a lower overall wind speed. This is why the capacity for turbines is lower at 26.3% for micro-wind turbines. This will have an effect on the sizing of an inverter. Most inverters can withstand an over-current but very few can withstand an over-voltage. If an inverter was sized to less than the rated power output of the turbine and not exceed its maximum input voltage this leads to greater efficiencies as

Inverter Efficiency	83%	89%	93%	94%	95%	94%	
Probability Density of Inverter Output when Connected to a Micro-Wind Turbine	72%	15%	6%	3%	2%	1%	
Overall Efficiency of Inverter in %	59.76	13.35	5.58	2.82	1.9	0.94	84.35%

Table 9. Weighted Average Efficiency of a wind inverter in urban locations

Wind Speed (m/s)	Probability Density (%)	Turbine Power Output (%)	Capacity Factor
1	6.5	0	0.0
2	10.8	0	0.0
3	13.1	3	0.4
4	14.1	6	0.8
5	12.4	13	1.6
6	10.4	22	2.3
7	9.0	36	3.2
8	7.0	55	3.9
9	5.6	78	4.3
10 to 14	9.7	100	9.7
15 to 24	1.4	0	0.0
Overall			26.3%

Table 10. Capacity Factor for turbine located in Ireland

a smaller inverter would be more efficient and cost effective for the project.

When installing wind turbines in the urban environment or in similar turbulent conditions there additional factor that needs to be considered. Local obstructions can cause turbulent mixing of wind that results in a reduced wind resource even on buildings that are higher than other buildings around them. This can be seen from the data in Table 11 where the overall capacity factor for a turbine located on this building would be 4.57% which means that it is unsuitable for a wind turbine installation. Generally an average wind speed greater than 6 m/s is required to make a turbine installation economically viable.

The low capacity factor calculated from wind data from the Focas Institute is in line with international experience. 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 best turbine in the trial had a capacity factor of 4.4%. 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%.

Conclusion

The WAE for a region can be determined once data from local weather stations is available. This will establish if the region is suitable for the installation of small wind turbines. If an anemometer is installed on a potential site for a wind

turbine for a period of six months a WAE for the site can then be determined. This can be compared to the WAE for the region to determine the quality of the site chosen for the wind turbine. Once the WAE for the site is known this can be plotted against the power curves of the turbine to be installed. This will predict will a reasonable degree of accuracy the expected power yield of the site. An additional benefit is that the capacity factor for micro-wind turbines installed on the site can be determined. Data has shown that a small wind turbine installed on an open site with low surface roughness, will have a capacity factor of approximately 26%, and in an urban environment this will drop to 4.7% or lower when one considers the Church Lane site. As the methodology to assess the wind resource could prevent the installation of small wind turbines in less than ideal conditions, such as the ones encountered in the Warwick field trials (Encraft, 2009). It will also give also encourage development of suitable sites.

This paper had to rely on manufacturer's data for the performance curves of wind inverters. What is needed is a laboratory where the conversion efficiency of the inverters can be verified independently across a range of power outputs. In addition the power curves of micro-wind turbines were supplied by manufacturers but there is no internationally agreed methodology for assessing the performance of wind turbines. Once installed the turbines are subject to local fluctuations in the wind resource due to obstructions. There is no internationally agreed methodology to assess the impact of the terrain roughness on the power performance of turbines. Power performance curves for small wind turbines would need to be assessed against the terrain in which they are to be installed. The capacity factor for turbines at a particular site could then be more accurately determined.

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Wind Speed (m/s)	Probability Density Focas (%)	Turbine Power Output (%)	Capacity Factor
0	12	0	0
1	15	0	0
2	26	0	0
3	19	3	0.57
4	15	6	0.9
5	6	13	0.78
6	3	22	0.66
7	2	36	0.72
8	1	55	0.55
9	0.5	78	0.39
10 to 14	0	100	0
15 to 24	0	0	0
Overall			4.57

Table 11. Capacity Factor for turbine located in the urban environment

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ABOUT THE AUTHORS

Jonathan Blackledge holds a PhD in Theoretical Physics from London University and a PhD in Mathematical Information Technology from the University of Jyväskylä. He has published over 200 scientific and engineering research papers including 14 books, has filed 15 patents and has been supervisor to over 200 MSc/MPhil and PhD research graduates. He is the Science Foundation Ireland Stokes Professor at Dublin Institute of Technology where he is also an Honorary Professor and Distinguished Professor at Warsaw University of Technology. He holds Fellowships with leading Institutes and Societies in the UK and Ireland including the Institute of Physics, the Institute of Mathematics and its Applications, the Institution of Engineering and Technology, the British Computer Society, the Royal Statistical Society and Engineers Ireland.

Eugene Coyle is Head of Research Innovation and Partnerships at the Dublin Institute of Technology. His research spans the fields of control systems and electrical engineering, renewable energy, digital signal processing and ICT, and engineering education and has published in excess of 120 peer reviewed conference and journal papers in addition to a number of book chapters. He is a Fellow of the Institution of Engineering and Technology, Engineers Ireland, the Energy Institute and the Chartered Institute of Building Services Engineers, was nominated to chair the Institution of Engineering and Technology (IET) Irish branch committee for 2009/10 and a member, by invitation, of the Engineering Advisory Committee to the Frontiers Engineering and Science Directorate of Science Foundation Ireland, SFI.

Derek Kearney graduated in 2007 from Ulster University with a First Class Masters Degree in Renewable Energy, and is currently working on a PhD in the area of wind energy. He is a lecturer in the College of Engineering and Built Environment at Dublin Institute of Technology and is programme manager for the MSc courses in Energy Management, Sustainable Electrical Energy Systems and Sustainability, Technology and Innovation. He is also programme manager for the BSc in Electrical Services and Energy Management. His principal area of specialty for both teaching and research is in the area of renewable energy and energy conversion systems. Recent achievements include winner of the 2006 President's Award for Teaching Excellence. He was chairman of the Honours Degree in Electrical Services and Energy Management for three years and previously worked on mainland Europe for a number of years.

Eamonn Murphy is a Technical Officer in the Department of Electrical Services Engineering, Kevin Street, Dublin 8. The Department of Electrical Services Engineering, this is one of the largest departments in DIT consisting of 41 whole-time staff and 10 part-time staff with a compliment of approximately 1500 students. The Department caters for Higher Certificate, Ordinary and Honours Degree programmes and in addition caters for the education and training of the Standards-Based Apprenticeship for the trade of electrician – phase 4 and phase 6. The Technical Office plays a very important role in terms of being a resource centre for all practical workshops, measurement, electronic, PLC and project laboratories. Technical Officers are responsible for the operation and maintenance of 11 such facilities in the department, which include solar research installations and wind energy installations.