PERFORMANCE MONITORING AND MODELLING OF MICRO-, MIDI- AND MACRO-WIND TURBINES

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ABSTRACT

This thesis investigates the potential of using wind turbine to offset electricity demand for dwellings or public building. This work involves onshore small and large wind turbine implementation considering the suitability of the location to machine size, starting with wind resource assessment of a candidate site depending on reliable wind data. The present research can be divided into three main parts: modelling and monitoring of small wind turbine performance in built environment using detailed data which was measured on site, measuring long–term hourly data for the design of wind energy systems, and then comparing that annual energy output against four-second and minute by minute data. The third part presents a novel statistical tool developed to evaluate relative performance and overall accuracy of wind speed frequency distribution functions.

An exploration of the potential for using hourly- as opposed to minute-by-minute data for the utilization of large wind turbines was undertaken as the former set is much more widely available for a larger number of locations within the developing world. It was found that the difference between the annual energy outputs from the latter two data sets was in close agreement with only small differences. The results thus obtained can have significant effect on the capital cost related to purchase of data, since minute by minute data may be up to 60 times more expensive than hourly data.

Actual power curve was experimentally obtained for Zephyr Dolphin micro wind turbine, which was then compared to manufacturer's reported performance; this was done by using four-second data for two complete years. Significant differences were found between the two curves. On-site measured performance of mentioned wind turbine was found to be similar for other reported urban locations. In each case the measured output was only a sixth of the acclaimed output of 2 MWh/annum.Urban wind energy potential for Merchiston site in Edinburgh was investigated. The results are presented in the form of average wind speed, wind roses, and density distribution functions. The effect of sampling interval on wind energy production was also analysed. Finally local spatial variations of wind speed were also studied for the City of Edinburgh.

ACKNOWLEDGEMNETS

I would like to take the opportunity to thank my supervisors Prof. Tariq Muneer, and Prof. Naren Gupta for their support and guidance throughout the academic years. Furthermore, I am grateful for the assistance I have received from the technician Mr Ian Campbell. Further, I would like to give my appreciation to Dr. Peter Clarke for providing advice throughout my research. Finally, this research would not have concluded without the support of my friends, my family and Loubana.

DECLARATION

I hereby declare that the work presented in this thesis was solely carried out bymyself at Edinburgh Napier University, Edinburgh, except where due acknowledgement is made, and that it has not been submitted for any other degree.

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AHMAD MAKKAWI (CANDIDATE)

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Date

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Abbreviations

AC	Alternative Current
AD	Air-Dolphin
AEDB	Alternative Energy Development Board
AGM	Absorbed Glass Matt
AWEA	American Wind Energy Association
BADC	British Atmosphere Data Centre
BP	British Petroleum
BRE	Building Research Establishment
BWEA	British Wind Energy Association
CAT	Centre of Alternative Technology
CCL	Climate Change Levy
CDF	Cumulative Distribution Function
CO_2	Carbon Dioxide
DC	Direct Current
DECC	Department of Energy and Climate Change
DEFRA	Department for Environment, Food, and Rural Affairs
DTI	Department of Trade and Industry
DUKES	Digest United Kingdom Energy Statistics
EU	European Union
EWEA	European Wind Energy Association
FiT	Feed-in Tariff
GDA	Generic Design Assessment
GGSP	Gateway Gas Storage Project
GHG	Green House Gases
HAWT	Horizontal Axis Wind Turbine

IPCC	International Panel on Climate Change
ITC	Investment Tax Credit
LCBP	Low Carbon Buildings Programme
LPG	Liquefied Petroleum Gas
MTDF	Medium-Term Development Framework
MWT	Micro wind turbine
NIST	National Institute of Silicon Technology
NPPG	National Planning Policy Guide
OECD	Organization for Economic Co-operation and Development
Ofgem	Office of gas and electricity market
PC	Personal Computer
PCAT	Pakistan Council for Appropriate Technologies
PCRET	Pakistan Council for Renewable Energy Technologies
PDF	Probability Distribution Function
PPS	Planning Policy Statement
PV	Photo-Voltaic
RO	Renewable Obligation
ROC	Renewable Obligation Certificate
SCHRI	Scottish Community and Householders Renewable initiative
UK	United Kingdom
US	United States
VAWT	Vertical Axis Wind Turbine
VBA	Visual Basic Application
WECS	Wind Energy Conversion System
WT	Wind Turbine

Glossary of terms

P_w	Power available in wind stream [W]
ρ	Air density [Kg/m^3]
A	swept area of the turbine rotor
V	Wind speed [m/s]
P_T	Power harnessed by wind turbine [W]
C_p	Performance coefficient of wind turbine
RMSE	Root Mean Squared Error
MBE	Mean Bias Error
MBD	Mean Bias deviation
RMSD	Root Mean Squared Deviation
dB	Decibels
Γ	Gamma function
V_m	Mean wind speed
p/kWh	Pence per kilowatt hour
s	Slope
π	Pi=3.141592654
c	Scale parameter
k	Shape parameter
δ	Standard deviation
γ	Location parameter
μ	Mean of the natural logarithms of the times- to –failure
ω	Rotational speed (rad/s)

Chapter1

Introduction

This thesis investigates the performance of small wind turbines in urban and rural areas by producing the actual power curve of one of these turbines then modelling their energy output against the actual energy output for urban wind site. Critical wind resource assessment was performed for Merchiston campus wind test site and five statistical distribution functions were evaluated using detailed data measured on the test site. This research study also explores the potential for using hourly as opposed to minute-by-minute data in the simulation of large wind turbines within the developing world.

1.1 Environmental pollution

The use of conventional energy resources, although economical, is the prime source of greenhouse gas emissions. Coal, oil, and natural gas are being used to generate power emitting billion of tons of carbon dioxide (CO_2) and a range of other gases which have led to evident environmental degradation, the appearances of which have been classified by Ibrahim Dincer (Dincer 2000). Among these environmental risks, the most serious problem is the global climate change (greenhouse effect) because it leads to an increase in the surface temperature of the earth (Asif and Muneer 2007). Reports from International Panel on Climate Change (IPCC) show that during the last century, the Earth's surface temperature has increased by about 0.6°C (IPCC 2001). Much evidence exists which suggests that the future will be significantly compromised if humans keep degrading the environment. It is therefore of imminent importance to put these emissions under control and replace those fuels with renewable sources (wind, solar, biomass,.), and nuclear which produce considerably less CO_2 and others greenhouse gases (Kemal Hanjalic 2008). From Figure 1.1, wind energy appears to have the lowest contribution to GHG emissions and air pollution of all energy sources under consideration.

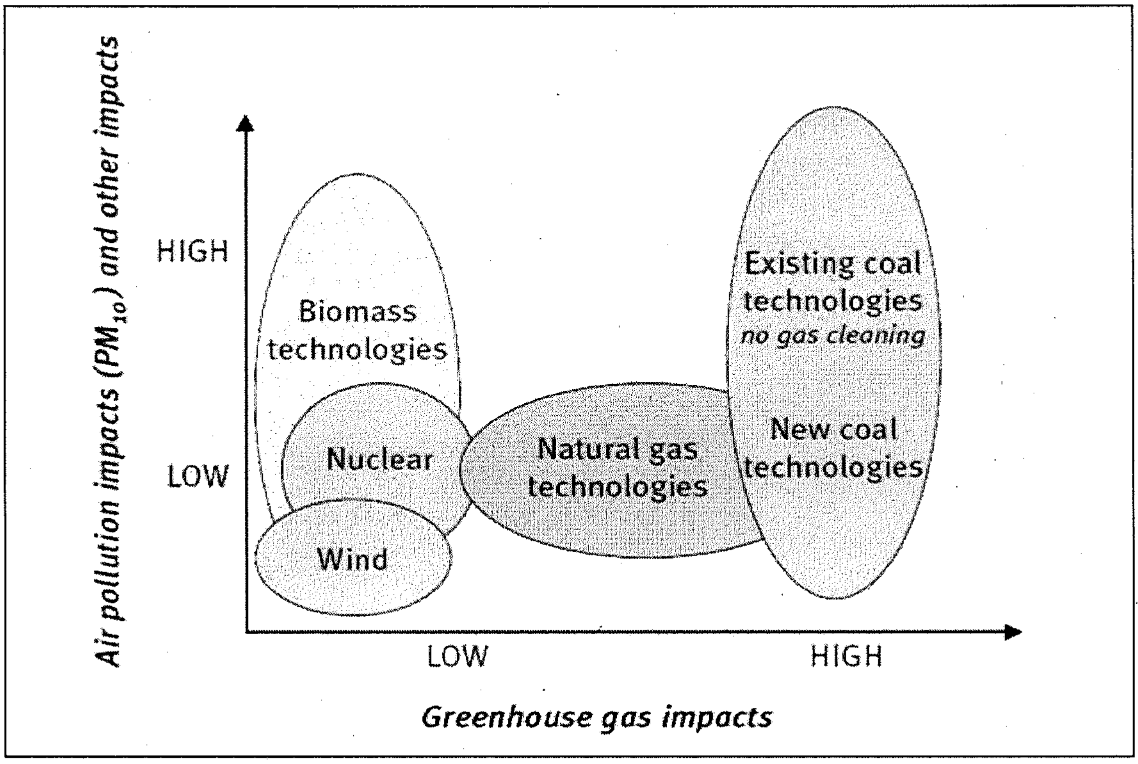

Figure 1.1 Comparison of energy sources with regard to air pollution and greenhouse gas emissions (Europian Commission Community Research 2003). Note: PM10 has become the generally accepted measure of particulate material in the atmosphere in the UK and in Europe.

1.2 Energy security

The energy security of United Kingdom is aimed to sustain the efficiency, diversity, and dependency in the way that best tackles climate change (Wicks 2009). Main motivation behind promoting energy efficiency is to reduce the quantity of energy consumed to provide products and services. Depending on fossil fuel as the main source of energy has a high rated risk regarding the high cost which is caused by increasing demand, and political complexity in the exporting countries that affect directly the global prices of oil and natural gas. From this prospective, diversity of energy resources is crucial element in future energy policy. In the last decade the UK reduced its dependency on oil and coal and replaced it with natural gas as a part of UK Kyoto commitment. As a consequence to this action electricity generation in great Britain became heavily dominated by natural gas (Grubb, Butler et al. 2006). Moreover, Britain has an ambitious policy for promoting renewable energy contribution in generating electricity and enhancing energy supply, since the change to low carbon technologies will decrease carbon dioxide emissions and will also improve diversity of energy sources (Skea 2010). The British government plans to enhance and support the change from fossil fuel economy to low carbon economy; so that the country will be less reliant on imported fossil fuel and more dependent on indigenous energy resources such as renewable and nuclear energy. The government has promised to accelerate this transition by: providing incentives for generating energy from renewable sources, starting to connect the accomplished off-shore wind farms to national grid, and introducing smart meters (Morris 2010).

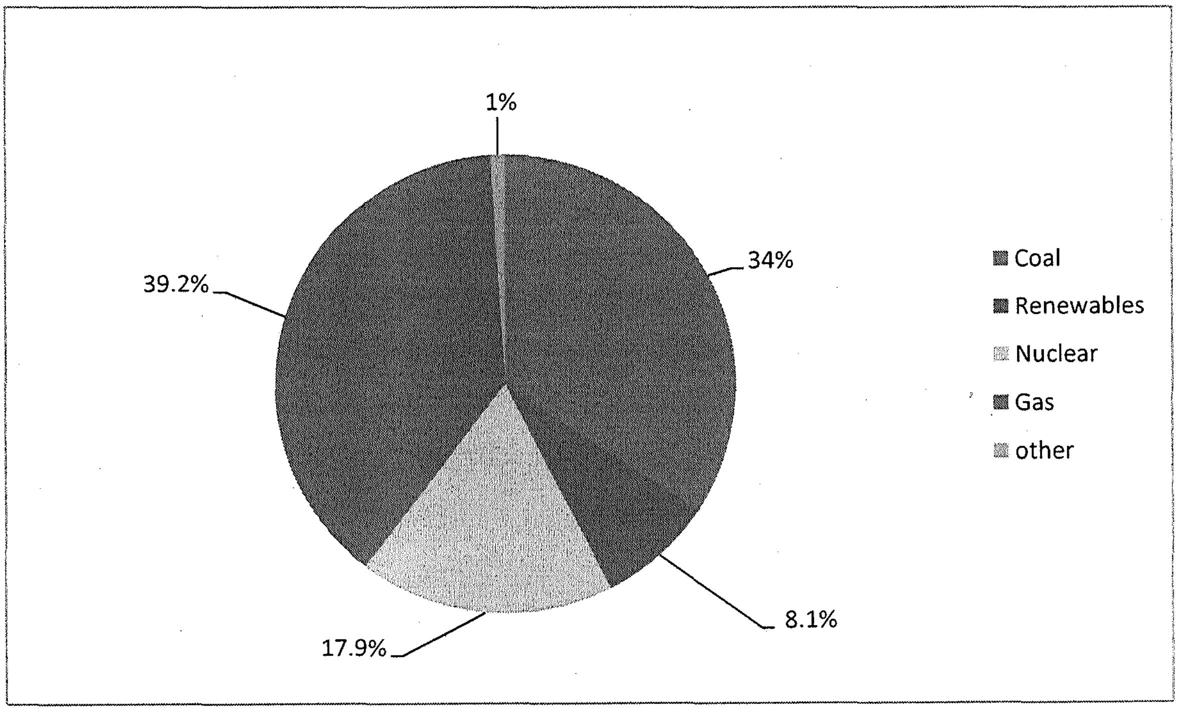

Figure 1.2 Percentage share of energy sources in electricity supplied in the UK for first quarter of 2011 (Department of Energy and Climate Change 2011)

1.3 Increasing energy prices

"Energy is the backbone of human development in every time, and wealth and stability of any society is dependent on how secure its energy supply is." (Muneer, 2010). Energy demand of both developed and developing countries (China, India, Brazil, and Russia) has increased continuously. Dealing with future energy requirements will be a big challenge faced by the global energy strategists. The main obstacle is the rising price of oil and natural gas, which increases as a result of soaring life expenses, such as products, services, electricity, and gas bills. There are many other influences on oil and gas prices in the global energy market. First of which is the growing demands from developing nations which have tremendous economic growths. The second influence is the recent political problems and civilian unrest in some oil-exporting countries in the Middle East (Williams 2011).

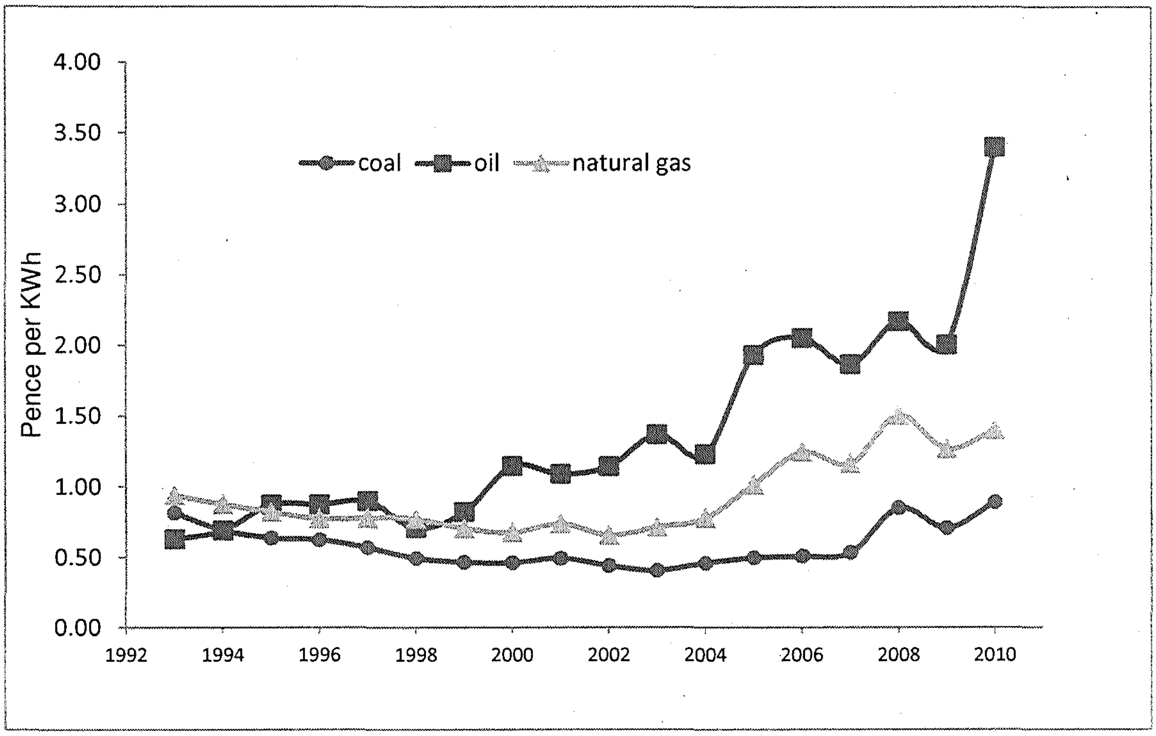

Figure 1.3 Average prices of fuels purchased by the major UK power producers (A National Statistics Publication 2011).

If fossil fuel continues to dominate means of electricity generation, then it will have substantial impact on the electricity prices, which is apparent in the increased gas and electricity prices in the UK. British main gas and electricity providers have announced tariff rise of 19 to 20 percent for electricity and 10 percent for gas increasing the burden on energy consumers (Evans 2011). Therefore the predicted average annual UK domestic electricity bill will rise by £ 91.2.

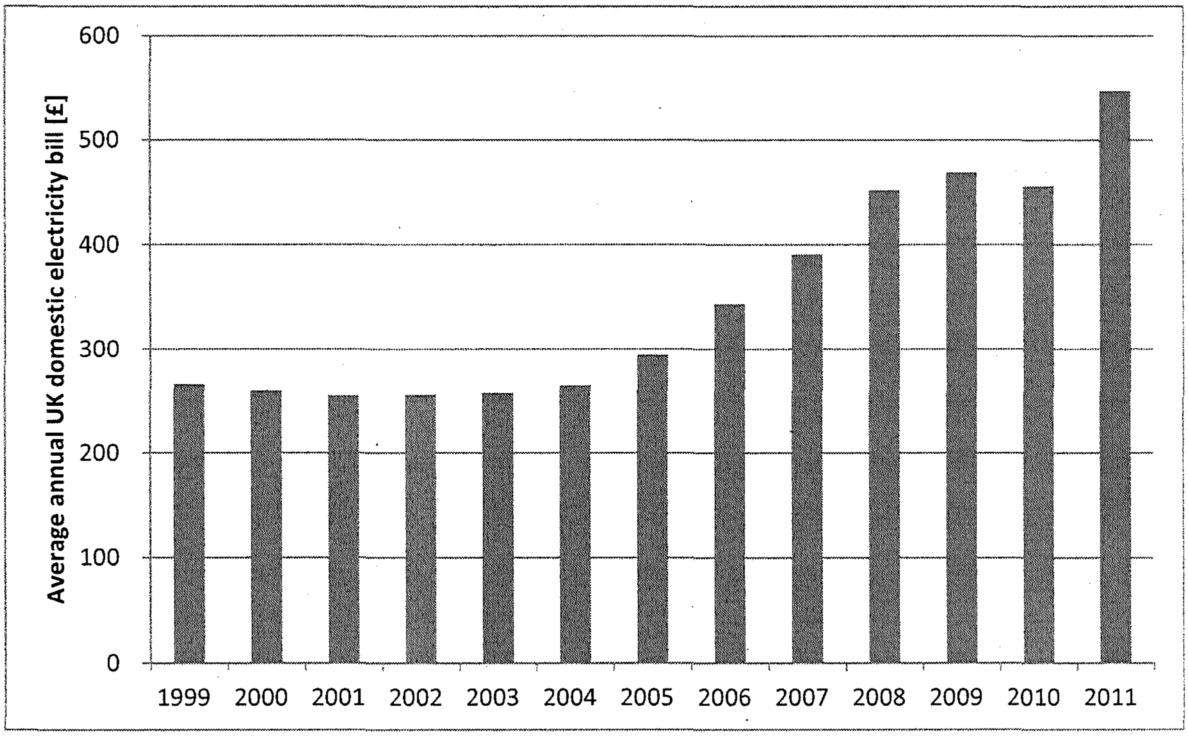

Figure 1.4 Average annual UK domestic electricity bills in Stirling pounds.

This state of inflation will persuade energy users to accept energy efficiency measures and consider alternative energy sources to reduce energy bills, and that action can be taken both on individual or community basis. Considering the situation in United Kingdom and referring to its geographical location, wind energy can be the most promising field to invest in:

1.4 Wind energy for electricity

Wind energy is considered the most sustainable energy source at par with the current electricity market price. Modern large wind turbines at high potential location can achieve a level of generation cost 0.04 to 0.05 €/KWh, which is considered economical compared with the price of electricity generated by fossil fuelled power plants (K. Hanjalic 2008).

Wind energy holds a key position in worldwide energy policies, since it produces energy with less GHG emissions and is the most widespread cost-competitive solution for the present global energy crisis. By 2020 global wind energy market will be expected to produce over 2000 TWH of electricity and supply about 20% worldwide power demand , and consequently is predicted to save CO_2 emissions by more than 1500 million tonnes a year (Jose 2011).

Table1.1 Typical available energy and corresponding CO_2 savings by a range of Horizontal Axis Wind Turbines (HAWTs) when annual wind speeds are 5.5 m/s at turbine hub height (Sinisa Stankovic 2009).

HAWT blade diameter [m]	Blade swept area [m2]	Energy capture			Carbon savings		
		Mean wind speed 5.5 m/s					
		Power in wind [KW]	Power from turbine [KW]	Annual turbine energy [KWh]	Coal-fired power station tonnes CO_2 /year	Current UK generation mix tonnes CO_2 /year	Gas-fired power station tonnes CO_2 /year
1	0.7854	0.1	0.02	374	0.4	0.2	0.1
2	3.14159	0.3	0.09	1496	1.5	0.6	0.4
5	19.635	2.0	0.56	9350	9	4	3
10	78.5398	7.8	2.24	37401	37	16	10
15	176.715	17.6	5.03	84153	82	36	23
20	314.159	31.4	8.94	149605	147	64	40
25	490.874	49.0	13.97	233758	229	101	63
30	706.858	70.6	20.12	336611	330	145	91
35	962.113	96.0	27.38	458166	449	197	124
40	1256.64	125.4	35.77	598420	586	257	162
50	1963.5	196.0	55.88	935032	916	402	252
60	2827.43	282.2	80.47	1346446	1320	579	364
70	3848.45	384.2	109.53	1832662	1796	788	495
80	5026.55	501.8	143.06	2393681	2346	1029	646

Small wind turbines can play a key role in generating electricity for domestic use in the urban and remote areas. Depending on the accessible wind resource in the candidate location and the size of wind turbine, the householder is at a double added advantage , especially after the issuance of renewable feed-in tariff on 1st April 2010, thus shortening the payback period of small wind systems and maximizing the financial profit. Electricity suppliers can then pay up to 34.5 pence per KWh depending on the capacity of the system (Department of Energy and Climate Change 2010) The other obvious benefit is mitigating domestic CO_2 emissions by using less of fossil fuel generated electricity .

1.5 Aims, Objectives, and Outline of the Project

The main aims and objectives of this project are addressed as following:

Aims

1. Observing and modelling the performance of wind turbines to investigate the feasibility of their application in compensating electricity demand for building.

2. Investigating the effects of location and wind data intervals on the projected energy output of designed wind turbine system, and finding statistical parameters for evaluating wind speed probability distribution functions.

Objectives

1. Installing micro wind turbines in a typical urban location; using detailed measured wind data for assessment of wind resources; and evaluating potential of wind energy in the candidate location.

2. Assessing in-depth current l micro and midi wind turbines operating in England and Scotland.

3. Indentifying problems associated with micro-wind turbines stemming from their use in urban areas on roofs of buildings. To this affect, micro wind turbine performance is monitored by recording its output second by second then concluded with actual power curve.

4. Modelling observed wind speed probability density distributions using the main body of models found in the literature, namely, Rayleigh, Lognormal, two-parameter Weibull, three-parameter Weibull, and bimodal Weibull probability distribution functions. One of the important steps in the evaluation of different functions is the interpretation of the statistical parameters, namely, slope, R^2, mean bias error, and root mean squared error, as are presently used in this research. A novel statistical tool is developed in the present work using these four statistical parameters. This tool is used to evaluate the relative performance of models when more than one model is involved or to determine the overall accuracy of a particular model for a specific site. The calculations are made based on the long term wind speed data collected at 4-s interval at the experimental site at Edinburgh Napier University.
5. Exploring the potential for using hourly- as opposed to minute-by-minute data for the design of wind energy systems, the former set being much more widely available for a larger number of locations within the developing world.

Project Outline

This thesis is organised into following chapters:

Chapter 1 introduces the context of the project, addressing the importance of wind resource and technology in the energy market.

Chapter 2 reviews world energy situation and focuses on the United Kingdom energy consumption, production, and its actions to tackle climate change and reduce Greenhouse gases emissions.

Chapter 3 describes the installation of micro wind turbines, anemometer, and data logger on the roof of Merchiston campus at Edinburgh Napier University, and explains the main failures which had been recorded with wind machines. It provides samples of the collected data of wind turbine and wind anemometer.

Chapter 4 presents the processing and analysis of all data sets used in the study, with explanation about modelling of wind turbine.

Chapter 5 discusses the principles of the technology along with their current state of development. It reviews the current policy and regulatory framework surrounding the technology and looks at barriers, incentives and future direction. It also describes the specifics of small-scale wind power; its challenges and limitations. Several case studies about small wind turbines are reviewed. The performance of Zephyr Air-Dolphin Micro wind turbine is monitored and modelled, its actual power curve is produced, and wind resource assessment is carried out for Merchiston campus site at Edinburgh Napier University using 4s detailed data for wind speed and direction.

Chapter 6 presents a novel statistical tool for evaluation of suitability and accuracy of wind speed probability distribution functions for specific sites.

Chapter 7 discusses the results of wind energy system design relying on two 4 year datasets with different sampling rates for Gharo location in Pakistan.

Chapter 8 concludes the thesis work by discussing the main findings and suggesting scope for future work.

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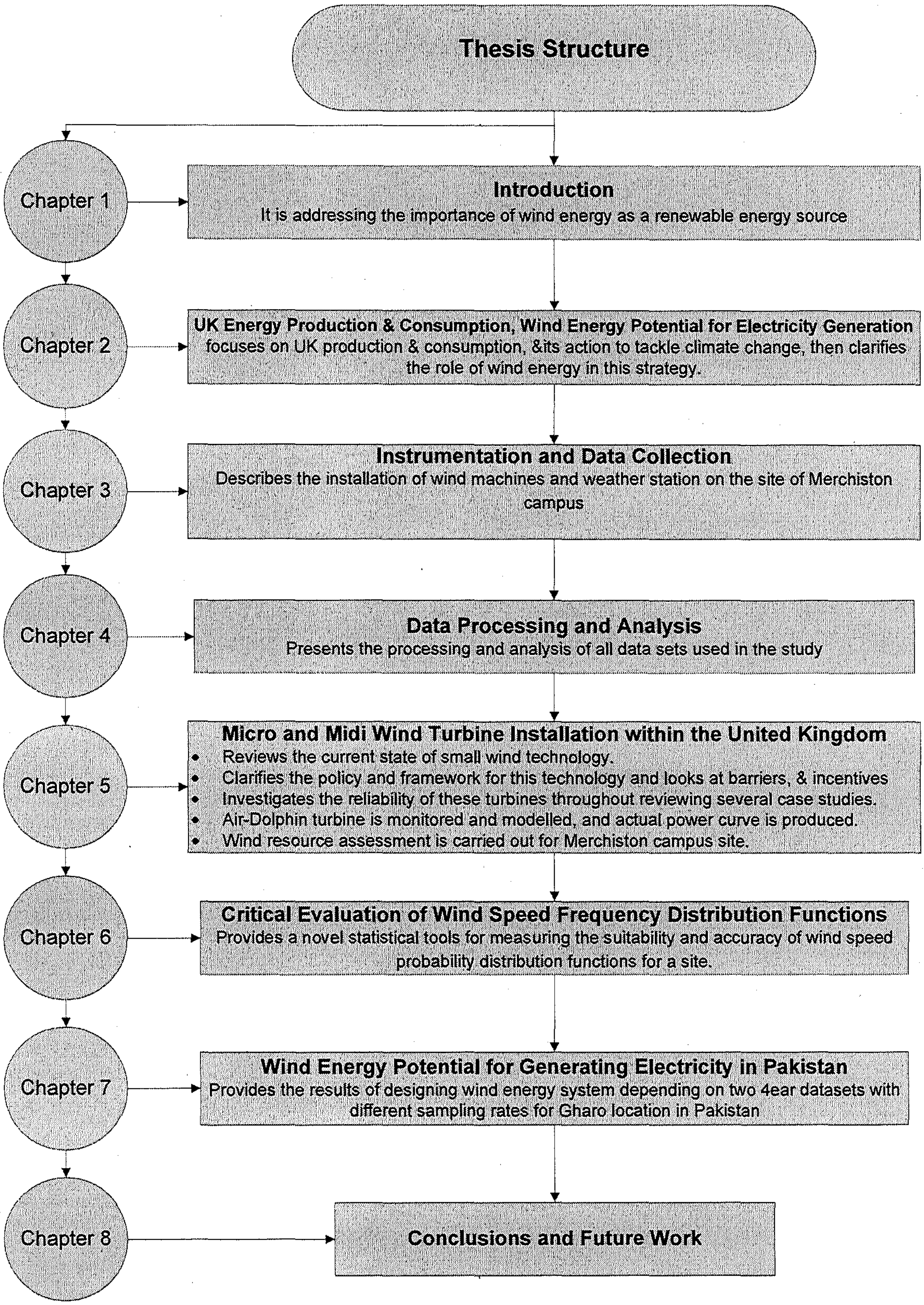

Figure 1.5 The flow chart of the thesis structure

Chapter 2

UK Energy Production and Consumption and Wind Energy Potential for Electricity Generation

2.1 Introduction

This chapter describes in brief world energy situation in the last two years, and focuses in more details on the United Kingdom's energy consumption, production and its actions to tackle the climate change and mitigate Green House Gases (GHG) emissions by investing in nuclear power and renewable resources.

Since UK is the richest wind power resource in Europe, this chapter also presents a renewable energy solution by harnessing wind energy to generate electricity. Towards this end, a feasibility study is conducted through installing small wind farm in one of the two candidate sites in the Scottish borders to offset electricity demand for Merchiston campus of Edinburgh Napier University.

2.2 Current global energy situation

Fossil fuels, contributing to 88% of our world energy requirements, are the primary bedrock of human being's life. Figure 2.1 demonstrates that Middle East still plays the most important role in oil market and Saudi Arabia alone possesses 20% of the total world's proven reserves, estimated to be at 1331.1 billion barrels (BP 2010).

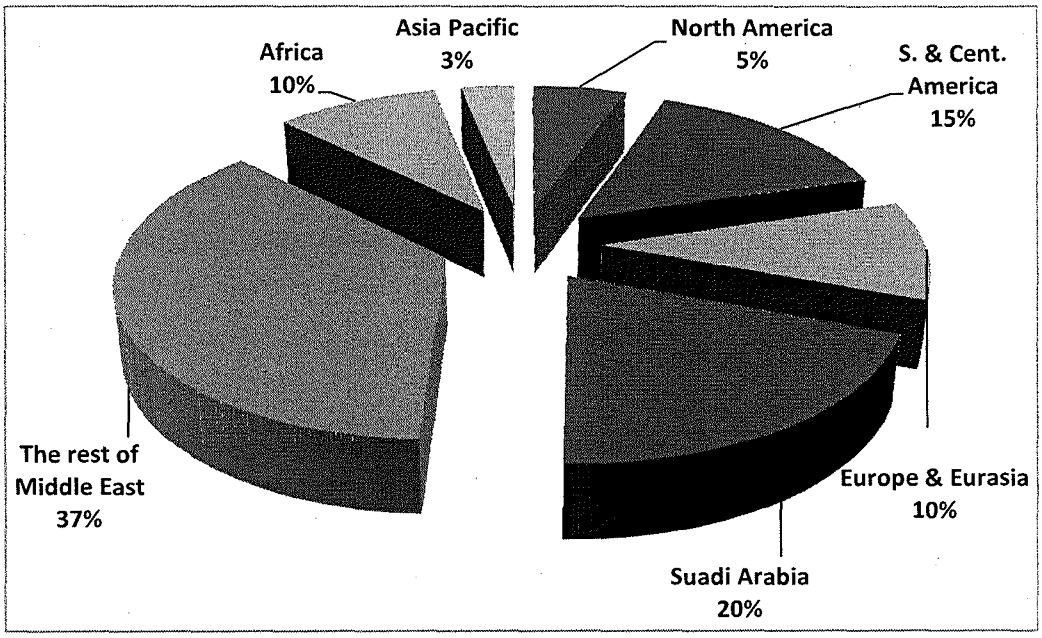

Figure 2.1 The world proven oil reserves in the end of 2009 (BP 2010)

This new awareness of importance of energy has led to re-evaluation of both the role of energy in our economy as well as the forecasts of the likely future demand. World primary energy consumption – including fossil fuel (oil, natural gas, coal), and nuclear and hydro power – decreased by 1.1% in 2009, the first decline since 1982 and the largest decline (in percentage terms) since 1980. Consumption in Organization for Economic Co-operation and Development (OECD) countries fell by 5%, the largest decline on record and the lowest level since 1998. Energy consumption declined in all regions except the Middle East and the Asia Pacific, in particular, Chinese energy consumption growth accelerating to 8.7%. Hydroelectric power generation increased by 1.5%, and was the world's fastest-growing major fuel for a second consecutive year.

The entire energy consumption in the (OECD) economies witnessed a negative growth in 2009. On the other hand, non-OECD countries achieved positive growth which affected their energy consumptions. However, with the global economy expected to recover in 2010, energy consumption in the OECD economies is predicted to witness a positive growth in 2010 (Commodity online 2009).

In June 2008, the Brent crude oil barrel reached the highest ever price, 144.95 US dollars, In consequence of credit crunch and recession, oil prices dramatically dropped down to around 40 US dollars by end of 2008. They started to increase gradually in 2009 affected by optimisation of economic recovery and positive economic growth of developing countries. In August 2010 oil price hit 82 US dollars (Live oil prices 2010).

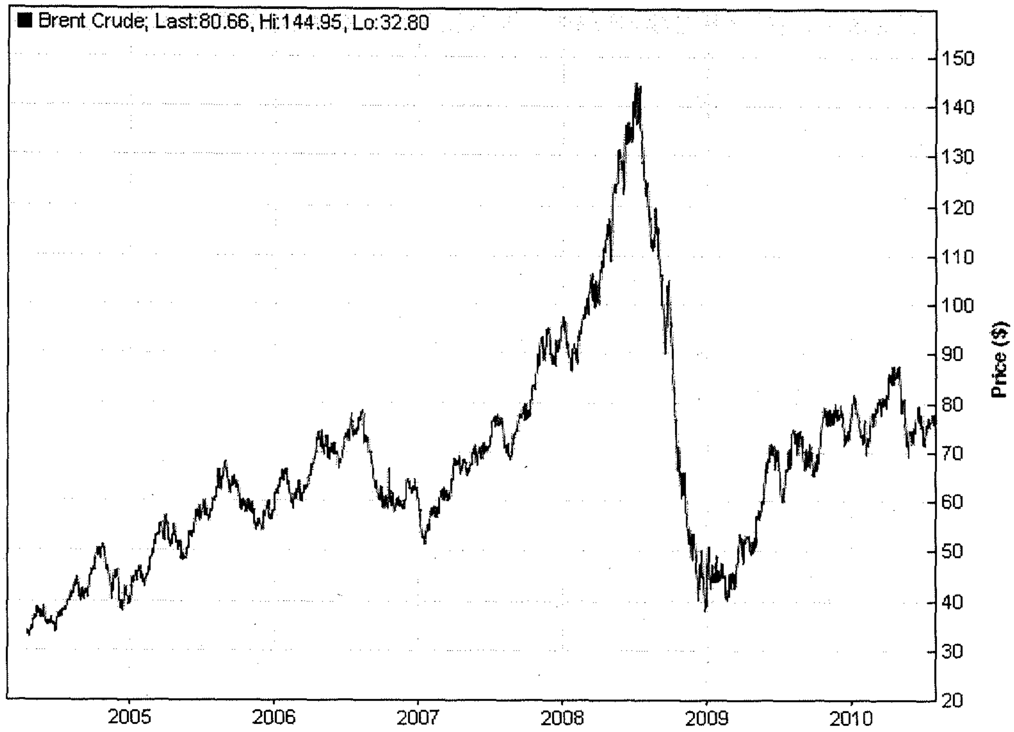

Figure 2.2 Brent Crude oil's prices in the last five years (Live oil prices 2010)

2.3 Current energy production and consumption in the UK

According to the UK Department of Energy and Climate Change, the total energy production in UK by March 2010 fell to 42.3 million tone oil equivalents, a decrease of 6.5 percent compared to March 2009. Whereas, the UK energy consumption was 214.1 million tone oil equivalents in 2010, reduced by 1.1 percent compared to last year (IFandP 2010).

In UK, the emphasis was on increasing natural gas use rather than coal and oil with a view to reduce CO_2 emissions. So in keeping with the trend, consumption of coal and other solid fuels fell by 13.8 per cent. Oil consumption dropped by 6.8 per cent, while gas consumption increased by 9.6 per cent. Primary electricity usage dropped by 0.1 per cent in 2010.

2.3.1 Coal

UK coal production has declined gradually and significantly over the last forty years (Hicks.J & Allen.G 1999). The Department of Trade and Industry (DTI) reported a decrease in coal production from 126 Mt in 1970 to 34 Mt in 1999

(MBendi 2010). National statistics publication (Department of Energy and Climate Change) reported lowest level 17.9 Mt of UK coal production in 2009.

UK coal consumption also decreased from 175.9 Mt in 1970 to 68.7 Mt in 2003, as issued by DTI. Moreover, coal consumption in 2009 was recorded the lowest level 56.1 Mt, and 86% of this consumption was just for electricity generation as reported by national statistics publication, Department of Energy and Climate Change. Figure 2.3 depicts the UK coal consumption and percentage of power generation from it since 1980.

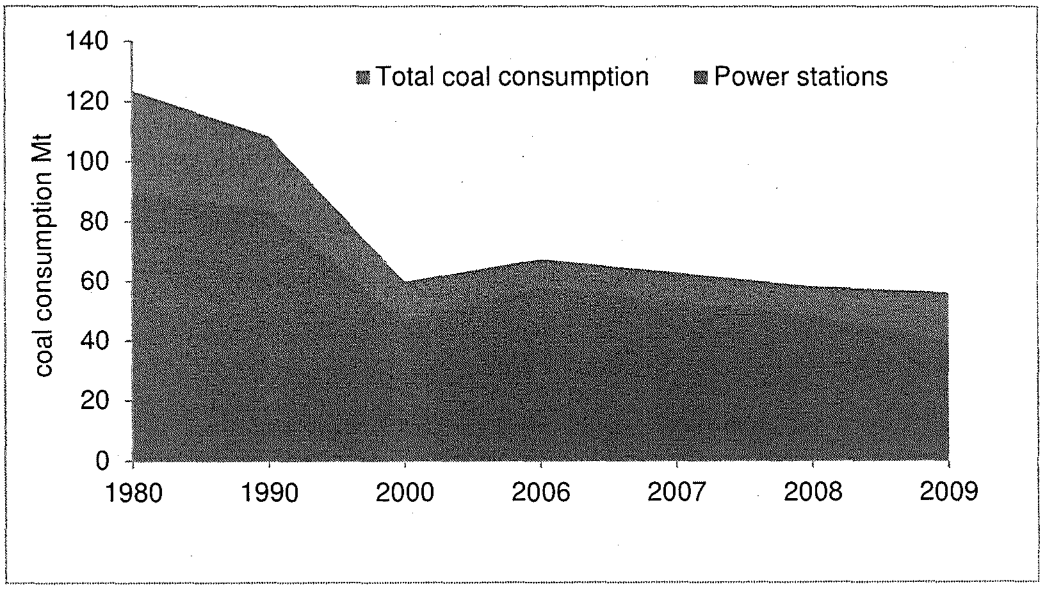

Figure 2.3 UK coal consumption and the percentage of electricity generation

This decline in coal production and consumption in the UK can be attributed to following key factors (Clough.L.D 2008):

- Replacement of coal with natural gas as energy resource for domestic use.
- Reliance on low cost imports, mainly from South Africa and Australia.
- Commitment to Kyoto protocol to reduce coal consumption and production as coal has high CO_2 emission factor.

2.3.2 Petroleum

Most of the British oil fields are located in North Sea waters to the north and east of the mainland of Scotland. With far north oil field discovered to the east of Shetland and Orkney islands, Aberdeen became the British oil industry centre (Wikipedia 2005). The UK started to produce oil from the North Sea fields in 1975. Consequently, British imports from oil fell and its exports increased. By 1981 first time in its history, the UK became a net exporter of crude oil when its surplus of oil recorded 20 thousand tonnes (Adams.K 2007). Figure 2.4 shows off-shore platform of oil well in the North Sea.

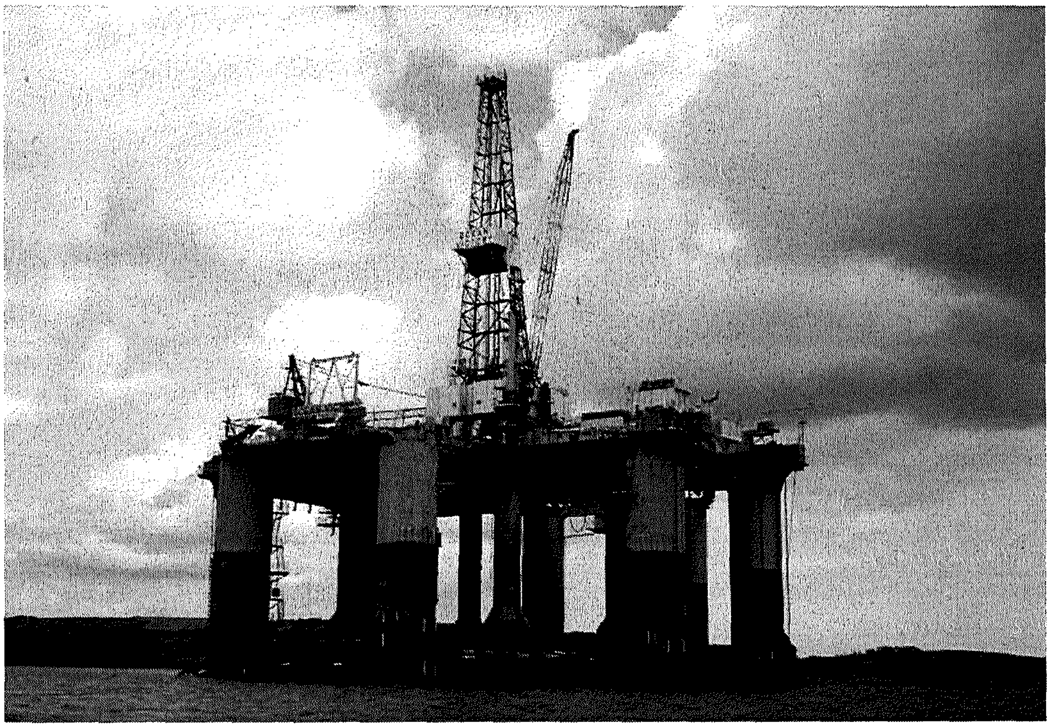

Figure 2.4 Oil exploration rig on the Cromarty Firth, north of Scotland (The Energy Situation in the UK 2005)

In 1984, miner strike enforced the British government to deal with instant risen demand for fuel oil, consequently increasing crude oil imports. The refineries had to be operated in full load to meet the indigenous energy demand.

Four years later, in 1988 Piper Alpha disaster took place causing the UK oil industry to reduce its oil exports and increase oil imports until in 1991-1992 UK became net importer for the first time since 1980.

After this short decline the oil production exports started to recover and increase gradually to reach its peak in 1999. Since then the production has been declining, but imports maintained steady increase till 2006 when the UK started to switch to gas reducing CO_2 emissions. Figure 2.5 shows the oil production and consumption pattern over a ten year period.

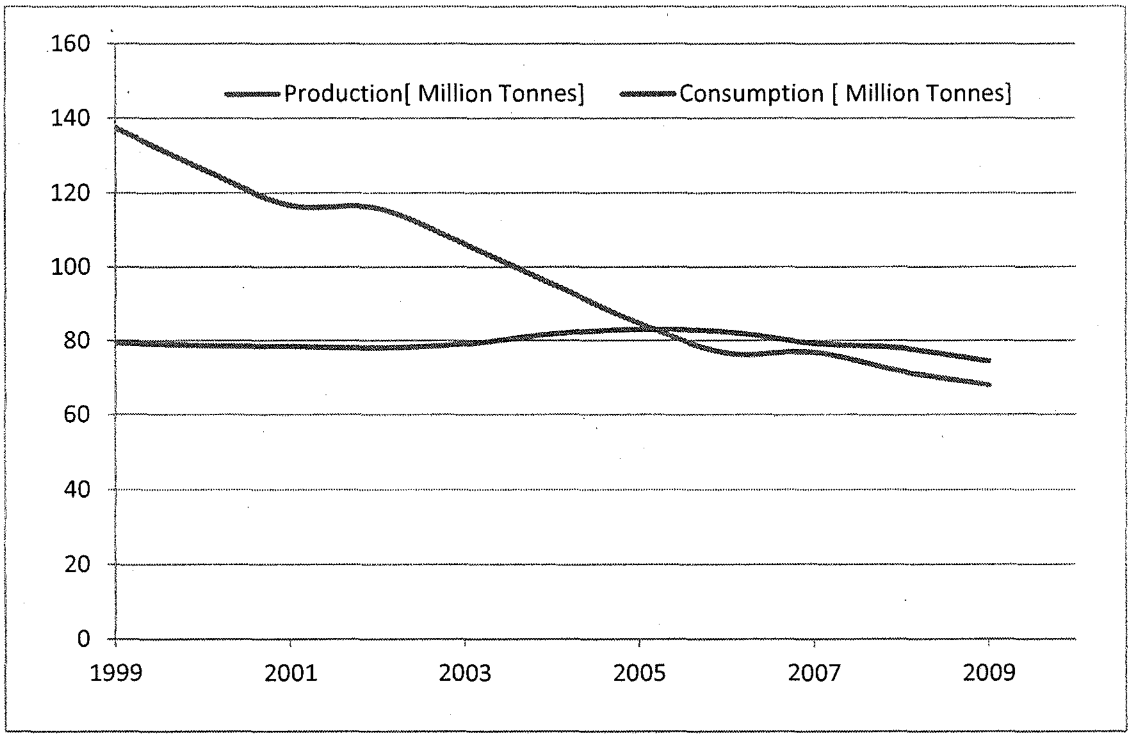

Figure 2.5 The UK consumption and production of petroleum (BP 2010)

The main supplier of crude oil to UK from 1950 to1980 was the Middle East, however, since 1990 UK started to import oil mainly from Norway. Petroleum products are more appropriate for transport due to their high energy intensity in medium capacity storage which cannot be currently replaced with any other fuel.

2.3.3 Natural Gas

The UK relies primarily on gas for heating and electricity generation. In 2004, the country was a net exporter for gas and self-sufficient in gas supply (Postnote 2004). However, later the situation changed and it became net importer of natural gas as shown in Figure 2.6. The estimated proportion of gas from the overall primary energy consumption for 2010 is 42% compared with 34.5% from oil, 11.5% from coal, and 7% from nuclear, and 5% from renewable.

The British government plans to increase gas storage capacity of the UK from 4% of its average annual demand into 30%. This 4% secures only 14 days of supply for Britain, against 90 and 77 for France and Germany, respectively. Likewise, the Gateway Gas Storage Project (GGSP) will increase the gas storage capacity of Britian by 1.5bn cubic meters through the construction of 19 underground caverns which equals five days of gas demand in Britain. The gas supply security and storage are extremely vital and essential for the UK , because in 2015 , UK will have to import about 80% of its gas consumption owing to North sea gas production decline and ever-increasing consumption for generating electricity (Webb.T 2009).

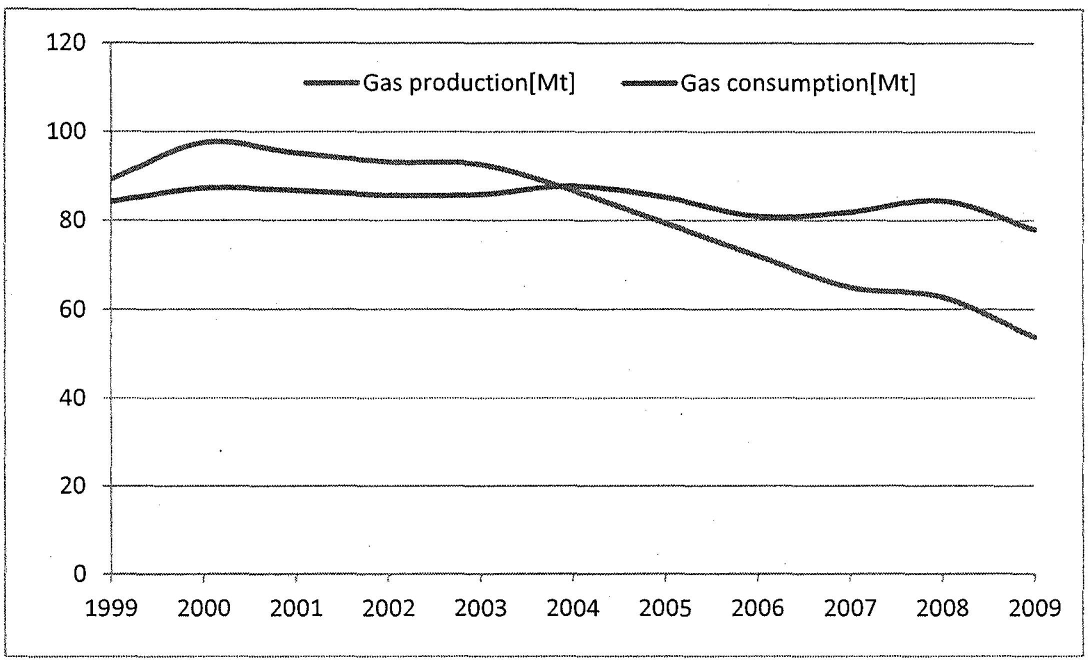

Figure 2.6 The UK natural gas production and consumption in the last ten years (BP 2010)

2.3.4 Nuclear energy

The nuclear energy proportion of the total electricity generation is 19% produced by 11 GWe British installed capacity if all plants operate in their full capacity. In addition, about 3% of UK electricity supply is covered by French nuclear power (World Nuclear Association 2010). But in case one, or more, of these stations are under maintainence, that precentage will be reduced. Table 2.1 provides the details of nuclear reactors currently operating in the UK.

Table 2.1 Nuclear power stations operating in the UK (World Nuclear Association 2010)

Reactors	Type	Net capacity each	Start Operation	Expected shutdown
Oldbury 1 & 2	Magnox	217 Mwe	1968	2011
Wylfa 1 & 2	Magnox	490 Mwe	1971-72	2010
Dungeness B 1 & 2	AGR	545 Mwe	1985-86	2018
Hartlepool 1 & 2	AGR	595 Mwe	1984-85	2014(2019?)
Heysham 1 & 2	AGR	615 Mwe	1985-86	2014(2019?)
Heysham 3 &4	AGR	615 Mwe	1988-89	2023
Hinkley Point B 1 & 2	AGR	620 & 600 Mwe	1976-78	2016
Hunterston B 1 & 2	AGR	610 &605 Mwe	1976-77	2016
Tornees 1 & 2	AGR	625 Mwe	1988-89	2023
Sizewell B	PWR	1196 Mwe	1995	2035
Total (19)		11,035 Mwe		

Magnox comes from the alloy used to clad the fuel rods inside the reactor. **AGR** is an Advanced Gas-cooled Reactor. **PWR is** Pressurized Water Reactor

Renewable and nuclear energy are the contributing key factors towards any hope of achieving 80% target reduction in GHG emissions by 2050. Due to concerns about mitigation of greenhouse gases and reliability of energy security replacement of the existing fleet of nuclear stations is put back on the government schedule. The total installed capacity will be 16 GWe with different reactor designs to be employed after completing the Generic Design Assessment (GDA) process regarding safety environmental, security, and waste management. The table below shows the planned and proposed plants to be installed by 2025 in the UK

Table2.2 Planned and proposed power reactors in the UK (World Nuclear Association 2010)

operator	Location	Type	Proposed capacity Mwe	Grid connection agreement Mwe	Start – up
EdF /BE	Sizewell, Suffolk	EPR x 2	3300	3300	2011
EdF /BE	Hinkley Point, Somerset	EPR x 2	3300	3300	2017
Horizon (RWE + E.On)	Oldbury, Gloucestershire	EPR or AP1000*	2500-3300	1600	2020+
Horizon (RWE + E.On)	Wylfa, Wales	EPR or AP1000*	2500-3300	3600	2020+
Iberdrola + GdF Suez+ Scottish & Southern	Sellafield, Cumbria	?	3600		2020+
Total planned and proposed			**15,200-16,800**		

Note: * is awaiting completion of GDA before decision.

2.3.5 Renewable energy

In Europe, UK has the most abundant renewable resources and its government realizes the key role renewable energy can play in securing the energy supplies and reducing GHG emissions. By the end of 2008 renewable energy provided 5.5% of electricity demand of the UK. In renewable energy strategy 2009, a challeging target for sustainable energy has been placed by British government in that, renewable resources (wind power, wave, tidal, biomass, biofuel, and solar energy) could provide 30% of the UK elelctricity supply, 12% of the heat, and 10% of the road and rail transport. Figure 2.7 depicts the growth in renewable technonlogies generating electricity since 1990. Obligation trend line represents Renewable Obligation (RO), which is a support scheme for generating electricity from renewable resources. Under this scheme British government enforces the companies supplying electricity to generate an increasing porportion of their electricity from renewable sources (Kew 2009).

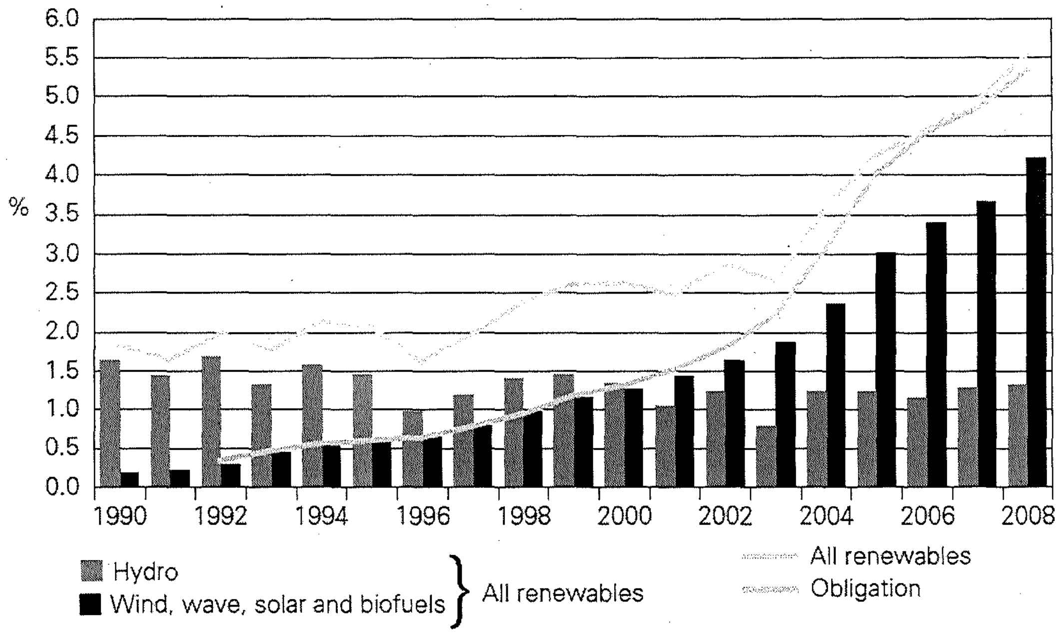

Figure 2.7 Growth in electricity generation from renewable sources(Kew 2009)

In UK Energy in Brief July 2010, reported 16.9% increase in electricity generation from renewable sources between 2008 and 2009, thus providing 6.7% of the total UK electricity production in 2009.

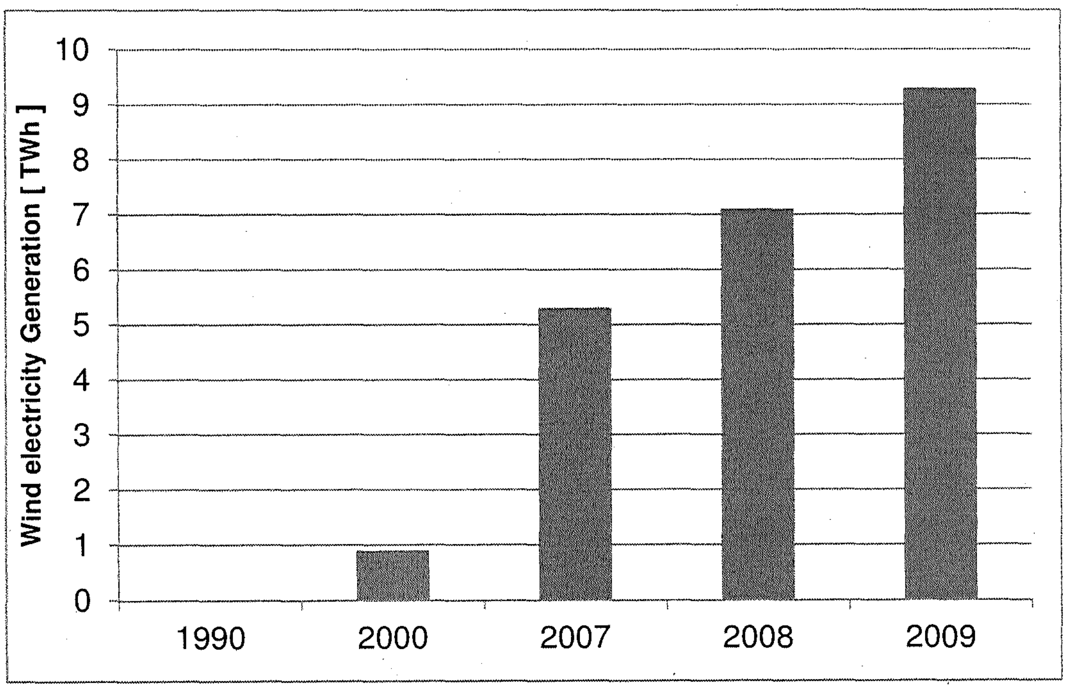

Figure 2.8 Electricity generation from wind power since 1990 (DECC 2010)

Wind energy contribution to national electricity generation grew 31% in 2009 compared to 2008 (UK Energy in Brief 2009), as shown in figure 2.8. On-shore and off-shore wind turbines in the UK together provided 9.3 TWh of energy in 2009. In July 2010, European Wind Energy Association (EWEA) reported UK to have installed in the first half of 2010 over half of all the newly installed off-shore wind turbines in Europe. One hundred forty seven wind turbines have been installed in the British water at eight different off-shore wind farms with a total capacity 455 megawatt. British off-shore wind power achieved 1GW capacity in April 2010. According to the most recent statistical data of British Wind Energy Association (BWEA), the overall installed capacity for both on-shore as well as off-shore wind farms is 4.6 GW. Table 2.3 provides the details of all these installations.

Table 2.3 Operational wind farms in United Kingdom (BWEA 2010)

	On-shore [MW]	No. Farm	Off-shore [MW]	No. Farm	Total [MW]
England	737.24	93	881.2	9	1618.44
Scotland	2127.27	100	10	1	2137.27
Wales	379.75	32	150	2	529.75
Northern Ireland	294.73	27	0		294.73
Total capacity					4580.19

2.4 Climate change and CO_2 target of Great Britain

Greenhouse gases are primarily responsible for climate change phenomenon, whose impact on planet earth is apparent through rising global temperatures, changing weather patterns (floods, drought, and weather extremities), and increasing sea level, putting the life of millions of people inhabiting the islands under risk. Hence, serious action needs to be taken to mitigate the emission of greenhouse gases and ensure that further climate change is stalled (DEFRA 2009).

Kyoto Protocol is an international agreement, signed in 1997 by more than 180 countries, suggesting actions against the rising concentration of Greenhouse gases' (GHG) emissions in the earth's atmosphere. This protocol has a goal of stabilizing GHG concentration at a safe level that would obstruct continuing rise of earth temperature. Thirty seven industrial countries have taken actions to reduce their emissions of greenhouse gases (carbon dioxide, nitrous oxide, methane, and per fluorocarbons) emitted by their plants and factories to meet the Kyoto protocol (Wikipedia 2010).

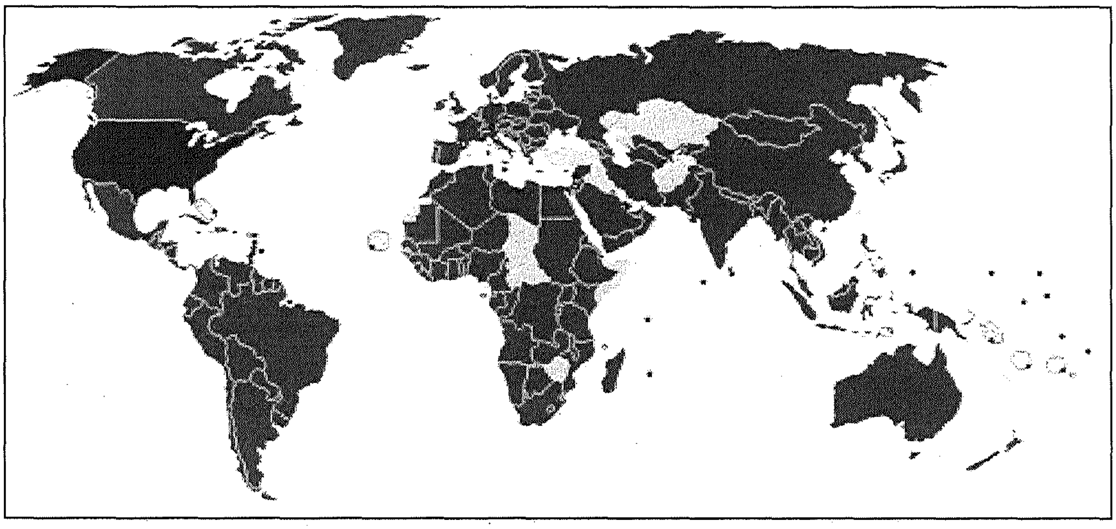

Figure 2.9 World map: Kyoto Protocol participation (December 2007).

- green – signed and ratified
- yellow – signed, ratification pending
- red – signed, ratification declined
- gray – no position

The GHG emissions in UK reduced from 628.3 in 2008 to 574.6 million tonnes CO_2 equivalent ($MtCO_2e$) in 2009. The portion of CO_2 of the total UK emissions for GHG was 85 percent in 2008 i.e. 532.8 $MtCO_2e$. However, CO_2 emissions in 2009 were estimated to be 480.9 $MtCO_2e$; a 9.74 percent reduction compared to 2008 (DECC NATIONAL STATISTICS 2010).

According to G8 climate scorecards 2009, UK achieved the Kyoto protocol target of GHG emissions, ranking only second after Germany. Figure 2.10 shows the emission trends of the UK from 1990 to 2020 (real and forecasted) compared to Kyoto target (Ecofys 2009).

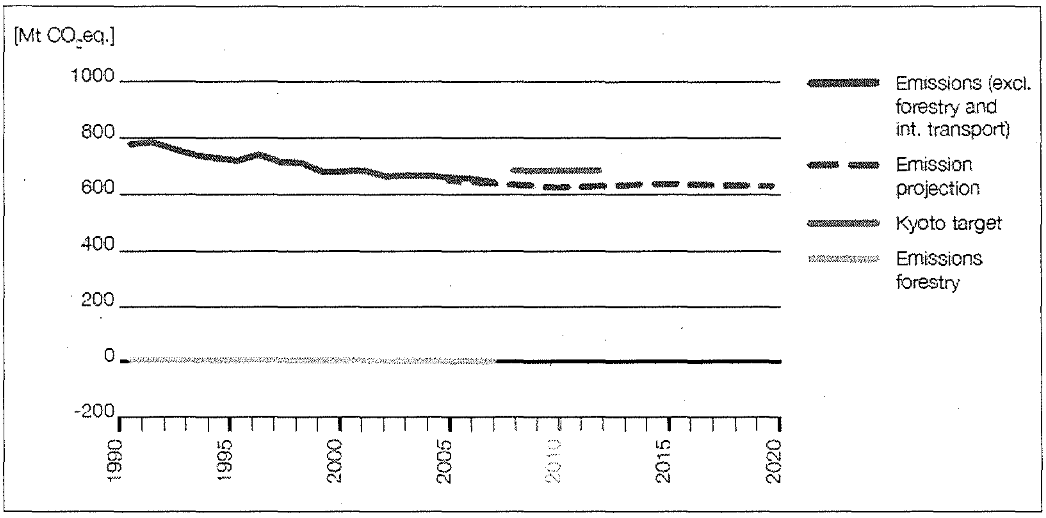

Figure 2.10 GHG emission trends in the United Kingdom (Ecofys 2009).

United Kingdom aims to limit its greenhouse gas emissions by taking several inventive and effective measures such as the following :

- Setting carbon budgeting system to limit GHG emissions in all sectors over short-time period (every 5 years).
- Planning to achieve the final target of 80% reduction in CO_2 emissions by splitting it in three stages: 10% by 2010, (20-30) % by 2020, and 80% by 2050, considering 1990 emissions level as reference.
- Investing in renewable energy to increase its national share to 15% and cut the energy consumption by 20%.
- CO_2 capture and storage technology consideration in any future planning for coal-fired added power stations.
- Planning to add a new generation of nuclear power plants.
- Planning to integrate international shipping and aviation in the climate change protocol.

2.5 Wind energy potential for generating electricity in Scotland

This part investigates the feasibility of the application of wind turbine as a means of offsetting the electricity demand for public buildings like Universities within Scotland. The hourly wind data of two locations in the Scottish borders have been critically analysed. In particular, the turbines' capacity factor, the annual energy output and payback period are presented herein.

2.5.1 Electrical energy and peak power requirements for Scotland

The Energy White Paper 2007 suggests that renewable energy should contribute 20% of the UK's electricity supply by 2020 with much of this expected to come from Scotland (DTI 2003). A study commissioned by the Scottish Executive in 2001 estimated that Scotland would be capable of supporting just over 59 GW of installed capacity across a range of renewable technologies (Snodin.H 2001). This resource would be expected to deliver around 214TWh of energy per year, exceeding Scotland's domestic demand of around 30TWh by a factor of seven (DTI 2007). In fact, the potential for the generation of renewable energy in Scotland is so large, that if fully exploited, it could satisfy over half of the total UK electricity demand of 406GWh in 2006 (MacLeay.I 2007).

2.5.2 Public opinion within Britain with respect to energy supply

A survey conducted on behalf of 'The Independent' newspaper in Britain showed that the majority of people think that the concept of offsetting the greenhouse gas emissions generated by fossil fuel combustion via tree-planting schemes was flawed (The Independent newspaper 2008). Furthermore, in excess of 90 per cent of the sampled population were in favour of renewable sources of energy. Table 2.4 summarises the details of this opinion poll.

Table 2.4 Public opinion is (per cent of sampled population) with respect to the question 'in which energy sources should the (UK) Government invest?' Poll conducted on behalf of 'The Independent' newspaper on 10 January 2008.

Energy Type	Yes	No	Not sure
Nuclear	35	32	33
Wind	90	4	6
Tidal	91	2	7
Solar	91	3	6
Biomass (wood, straw etc.)	49	13	38
Gas	21	48	31
Oil	12	65	23
Coal	15	57	28

2.5.3 Capacity factor and wind turbine installations within the EU

The capacity factor of a wind turbine expresses the output of the generator over a given time period (typically one year) as percentage of the theoretical maximum output of the generator over the same time. In the UK the annual capacity factor for wind power varies from 24% to 31% with a long-term average of 27% (DUKES 2005) for onshore locations. These figures compare more favourably than those for Denmark (around 20%) and Germany (around 15%). In contrast the end-of-year 2009 installed wind power capacities (MW) show a lack of serious commitment on the part of UK, i.e. 4,051 for UK, 3,465 for Denmark and 25,777 for Germany. The per capita installed wind power (W/person) capacity shows an even more skewed picture with UK indicating a figure of 154 compared with 642 and 312, respectively for Denmark and Germany. Figure 2.11 provides complete information with regards to the per capita installed wind power, and the low performance for the rest of EU may be referred to many reasons for instance poor wind resource, economic situation, and technical problems . Note that UK is at the very bottom of the league figure for developed EU countries (GWEC 2009).

UK performs poorly not only on the wind power front but also on other renewable and sustainable energy technologies. For instance, the number of currently installed solar thermal panels for hot water in UK is 81,000 as opposed to a million units in Germany. Likewise, the solar PV and Ground Source Heat Pump installations are in the following proportions: 1,300 and 500 for UK, while 300,000 and 40,000 for Germany.

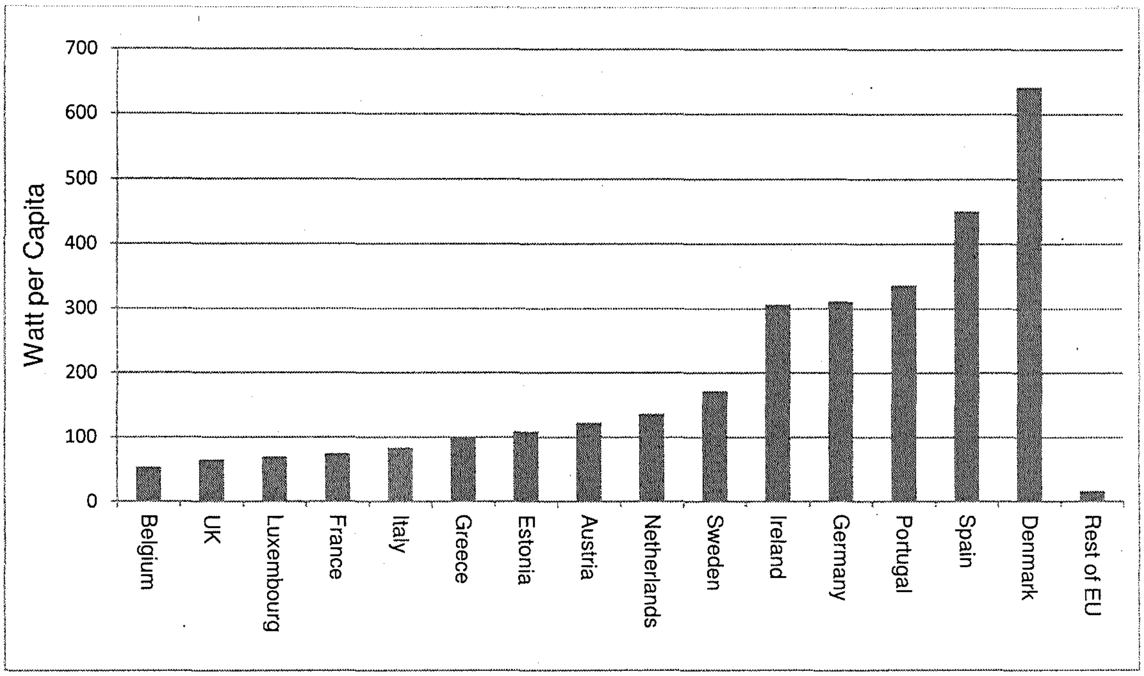

Figure 2.11 Wind turbine installed capacity in EU till end of 2009 per capita (EWEA, 2009)

2.5.4 Proposed macro wind turbine for Edinburgh Napier's Merchiston campus

This work shall explore the potential for supply of renewable electricity to one of the larger universities within Scotland. Owing to access by public at large and their independent research base and character, universities within Europe are well placed to demonstrate the application of sustainable energy solutions that are so expressly needed to arrest climate change. Towards this end it is hoped that Napier University's example of large-scale exploitation of wind energy will lead other members of higher education sector to join such an act of good practice.

2.5.4.1 Energy budget for Edinburgh Napier University Merchiston campus

Napier University's Merchiston campus provides accommodation for over 2000 students and 650 staff. It is located some 2.5 km south-west of Edinburgh city centre. A group of high-rise buildings offer teaching and office space along with study areas and catering. The majority of the buildings date from the 1960s, and have been refurbished and modified many times since they were built. The external shell of the buildings has however remained largely unchanged over time. This urban building complex, situated within Edinburgh's Greenhill conservation area is located 3km from city centre. The large, 160 m^2, solar PV façade may be seen on the extreme right (six-storey wall) in figure 2.11.

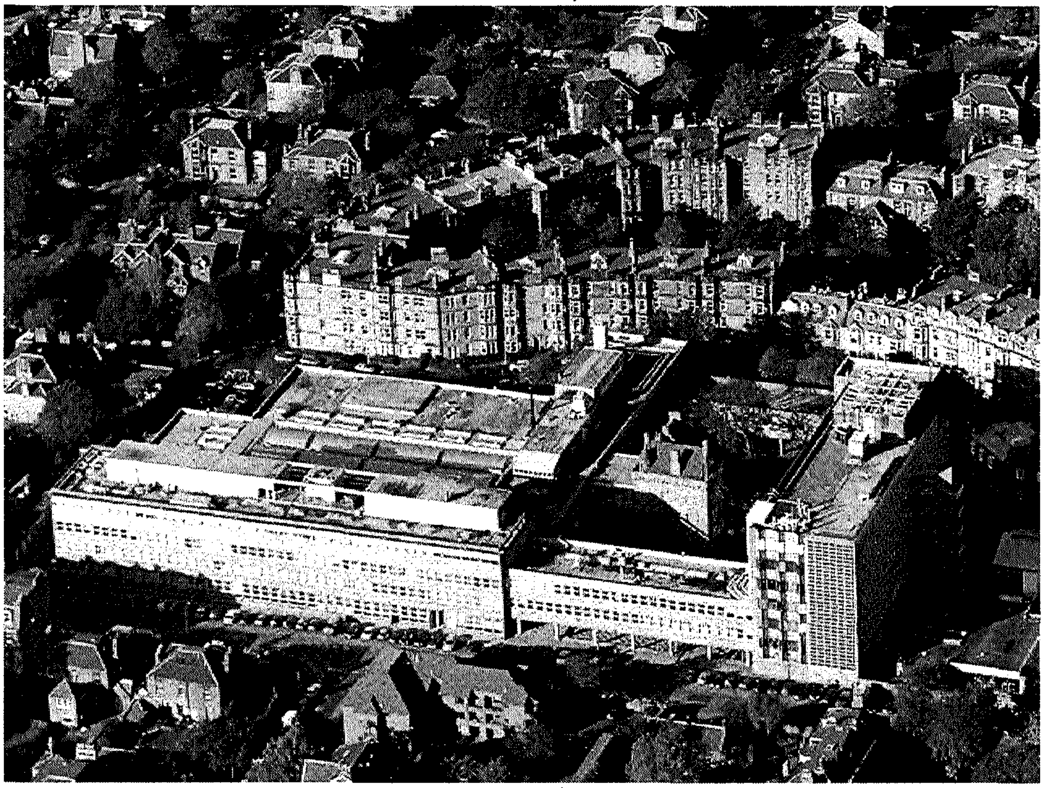

Figure 2.12 Edinburgh Napier University's Merchiston campus (Test site).

Presently, the energy requirements of the campus are met primarily from traditional sources. Gas is used for catering, hot water and space heating, while electricity for lighting and other appliances is delivered through a standard grid connection. Table 2.6 provides the monthly breakdown of the electrical energy requirements. On an average, over 3.7GWh/annum of energy is consumed. Bearing in mind the recent price rise for electricity within Britain, this represents an annual cost of around £400,000.

In April 2005, a 160m^2 photovoltaic (PV) array was added to the façade of one of the buildings producing AC power which is fed into the University grid (Muneer, 2006). Although this array might be expected to deliver around 14MWh of electrical energy per annum at its optimum orientation, the position of the building, and restrictions placed on the installation by the local planning authority have led to compromises on both the aspect and the tilt angle of the PV modules. The study by Muneer *et al.* concludes that the array is currently delivering 11MWh per annum.

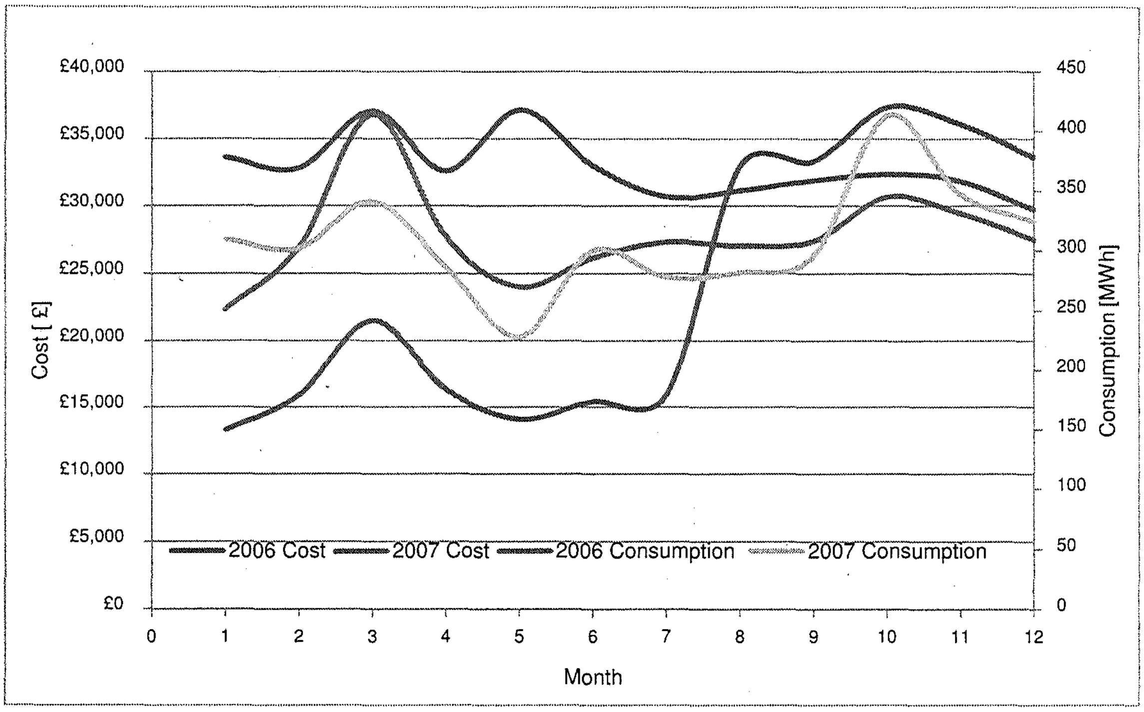

Figure 2.13 Electricity consumption and cost for Merchiston campus for 2006 & 2007

There is a long track record of renewable energy research and teaching at Napier University with UK's first ever BEng (Honours) academic programme that has been on offer since 1980.

Some of the key actions undertaken at Napier University to promote sustainable generation and use of energy are:

- A 160m^2 solar-PV array installed on 6 April 2005. Total energy produced to date has exceeded 33MWh and 27 tonnes of carbon dioxide saved.

- Local, roof top wind speed and direction measurements undertaken since 27 February 2007 on a per second basis, 7-hours per day, then on 24-hours per day with a sampling frequency of 4-s from 31 July 2007 onwards (Figure 2.11). That part of the work was in collaboration with Herriot-Watt University.

- Micro-wind turbines: Zephyr Air-Dolphin Mark 0 Z-1000 (1kW nominal, 24V DC), installed on 21 January 2007 and Ampair, Micro wind 600-230 (600W nominal, 240V) installed on 20 November 2007 (Figure 2.11).

- Solar-wind-hydrogen laboratory established on February 2008.

2.5.4.2 Modelling performance of chosen machines for two sets of data

There are a very large number of factors that affect the price and rent for large-scale wind turbine facilities. The basis of payment is developing and changing as the technology establishes itself. For the present feasibility study of erecting a wind turbine for Napier University, advice was sought from a professional land surveyor (Mr I Murning) who has estimated a basic rent of £1,000 to £5,000/ annum per turbine with an additional payment to the landlord (farmer) of 5% to 10% of the gross revenue produced from the sale of electricity to the national grid. Presently within Scotland there are wide variations in the payments of rent and or royalty to a landlord depending on the location, windiness, access, infrastructure costs, negotiating strengths of the parties and so on. For the purpose of the present study the higher figures of £5,000 per annum rent per turbine and 7.5% of gross estimated annual revenue from the sale of electricity to the grid have been assumed.

In 2007 the German wind energy market was the biggest in Europe. Two wind turbine manufactures control the market - Enercon and Vestas with a market share of 50% and 24%, respectively. In this study the economics of four potential machines have been explored – two German makes Enercon E 48 and Fuhrland FL1250 machines and two Danish designs, the Vestas V52 and V90 wind turbines.

Furthermore, hourly wind speed data measured by the UK Meteorological Office was acquired from two sites: Blackford Hill which represents locations closer to the river Forth valley and Drumalbin located more inland in South Lanarkshire. The results of the present analysis are summarised in Tables 2.7 and 2.8. The Fuhrland 1.25MW machine seems to provide the fastest payback and therefore from an economic point of view that would be the logical choice. The following assumptions have been made with respect to the economics presented in Table 2.8 electricity sold to grid at 7 pence/kWh, present day costs, with an expected inflation of 40% in the next 3 years; royalty payment to farmer of 7.5%; and maintenance contract payments of 0.095 pence/kWh from electricity sales.

One point that may be of relevance in the final choice of the machine is the torsional vibration and fatigue of the generator. In this respect, Enercon has come up with an innovative solution. The Enercon's low-speed synchronous gearless wind generator is directly connected to the rotor. The generator output voltage and frequency vary with the speed and are converted via grid management system to be fed into the grid. This allows rotational speed control to be optimised. The electrical power produced by the annular generator passes through a rectifier, a DC link and modular inverter system. The inverter system defines the essential performance characteristics for output to the grid specifications. In the inverter system, voltage, frequency and power are converted accordingly. The transformer inverter voltage is then stepped up to the appropriate voltage required by the grid or the wind farm network. Enercon have estimated that their annual generator undergoes the same number of rotations in 20 years as generators in conventional wind turbines do in three months.

Table 2.5 Performance of the chosen machines for the two sites under consideration.

	Rated power, MW	Blackford Hill, MWh produced/annum	Capacity Factor	Drumalbin, MWh produced/annum	Capacity factor
Enercon Model: E48	0.81	1282	0.18	956	0.14
Vestas Model:V52	0.85	1386	0.19	1046	0.14
Fuhrland Model FL 1250	1.25	1546	0.14	1078	0.10
Vestas Model:V90	3	4701	0.18	3530	0.13

Table 2.6 Economics of wind energy for the chosen machines.

Type of wind turbine	Enercon E 48	Vestas V52	Fuhrland FL1250	Vestas V90
Machine cost, million Euro	1.1	1.25	0.9	3.5
Machine cost, million £	0.87	0.99	0.71	2.8
Number of machines	2	2	2	1
MWh produced/annum	2564	2772	3092	4701
Electricity sales revenue	£251,272	£271,656	£303,016	£460,698
Site rent to farmer	£10,000	£10,000	£10,000	£5,000
Royalty to farmer from electricity sales	£18,845	£20,374	£22,726	£34,552
Maintenance to wind turbine manufacturer from electricity sales	£34,101	£36,868	£41,124	£62,523
Net savings/annum	£188,325	£204,414	£229,166	£358,622
Payback, years	12.5	13.2	7.4	10

2.6 Conclusions

Universities within Europe are well placed to demonstrate the application of sustainable energy solutions that are so expressly needed to arrest climate change by reducing our dependence on fossil and exploiting renewable energy sources. Towards this end it is hoped that Napier University's example of large-scale exploitation of wind energy will lead other members of higher education sector to join such an act of good practice. The solution for the bulk supply of electricity is the macro-turbine. Presently, it was found that the Fuhrland 1.25 MW machine provides the fastest payback (7.4 years) from an economic point of view. The capacity factor for the latter machine, to be located 35km west of university campus will be around 0.14. The machines will be able to offset 84% of the total electrical load for Napier University's Merchiston campus.

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Chapter 3

Instrumentation and Data Collection

3.1 Micro wind turbine installations at Merchiston campus

A micro wind turbine (MWT) study was undertaken to investigate its performance within the urban area. For this purpose three different designs of MWTs were chosen to be installed, monitored, and their data analysed. The three MWTs used are as follows: the Windsave WS1000, Air-Dolphin Z1000 and Ampair 600-230V with a nominal rated power of 1, 1, and 0.6 KW, respectively. Table 3.1 provides their specifications.

Table 3.1 Micro wind turbines installed at Edinburgh Napier University for the present study

Turbine	Air-dolphin Z1000	Ampair 600-230V	Windsave WS1000
Rated power, W	1000	600	1000
Rotor diameter, m	1.8	1.7	1.75
Mass, kg	17.5	16	25
Cut-in wind speed, m/s	2.5	3	4
Cut-out wind speed, m/s	50	n/a	35
Rated wind speed, m/s	12.5	11	15
Generator	Synchronous type, permanent magnet	Synchronous type, permanent magnet	Asynchronous type

Figure 3.1 shows the relative positions and heights (with reference to ground level) of the three MWTs installed on Merchiston campus rooftop.

Figure 3.1 Edinburgh Napier University Merchiston Campus rooftop test site. (From the left, Windsave turbine, wind monitoring station, Air-Dolphin turbine, Ampair 600 turbine and anemometer).

3.1.1 Air-Dolphin wind turbine

This turbine was assembled within a day and installed on 9/10/2006. For the main body of Wind Turbine (WT), that includes the generator and control board, no screws were needed. The rotor consists of three light blades made from carbon-fibre material. The Air-Dolphin turbine has an innovative tail that was inspired from owl feather. This tail has a number of thin grooves on its surface, resulting in major reduction of air flow drag and noise.

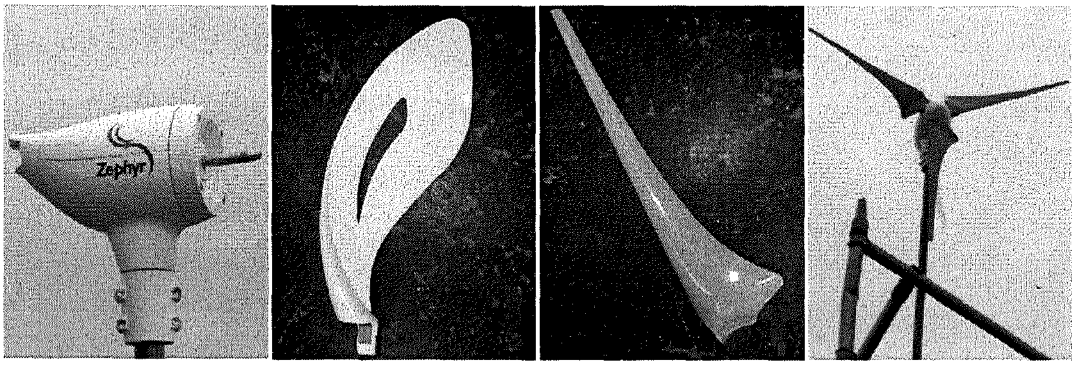

Figure 3.2 Main parts of an Air-Dolphin wind turbine at the installation site

The wind turbine was mounted on a 4 m high mast. All connection wires were made to go down through a tube. The data was recorded via an RS-485 link to a personal computer/ data logger.

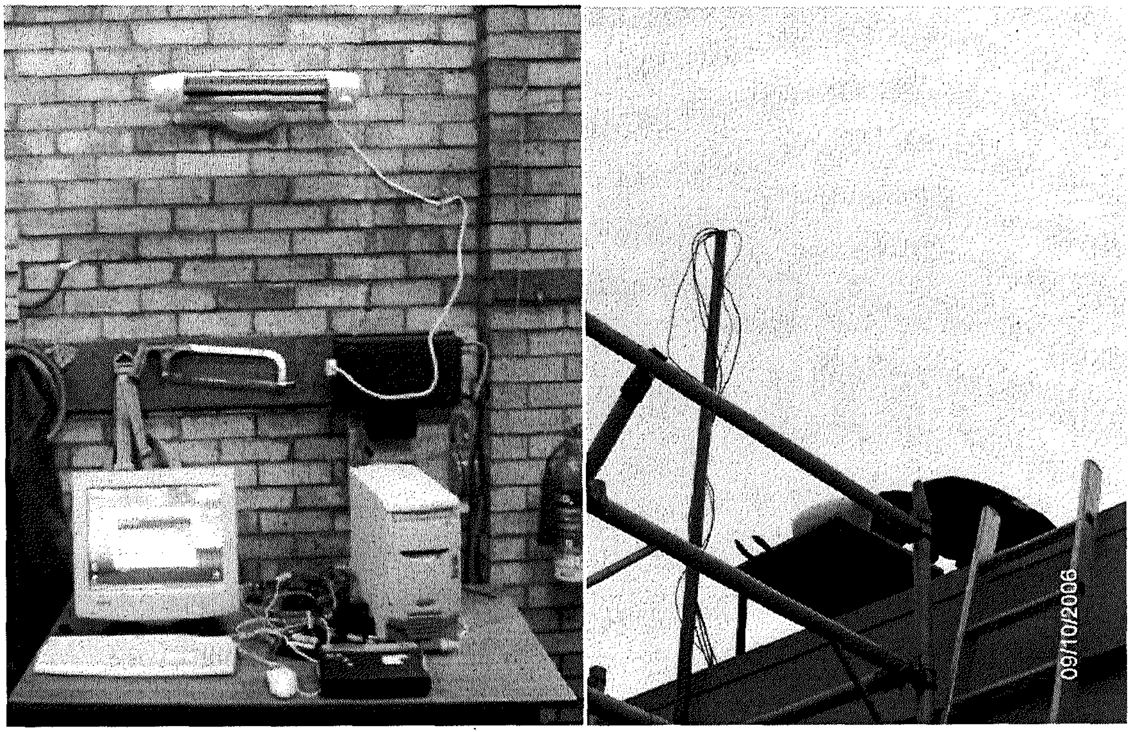

Figure3.3 Technician installing wind turbine (right) and the laboratory room

3.1.2 Air-Dolphin stand-alone system

As the name suggests, this wind energy conversion system (WECS) does not connect to the main grid. It has the following main components: the Air dolphin wind turbine, inverter, batteries, load (heater) and charge controller.

A stand-alone system is installed in rural areas where grid connection is not reliable or is too expensive to extend. Voltage conditioning equipment is used to regulate charge voltage and turbine load in order to optimise battery performance. Batteries are used for energy storage when the wind resource is not available, or when short-term demand is greater than the available wind resource. In times of low demand they act as buffer absorbing surplus energy. Stand-alone systems are usually low-voltage direct current systems, and electrical loads can either be drawn off as low voltage DC or mains voltage AC equipment supplied with inverters can be used. These systems are generally smaller (typically under 3kW in size) than the grid-connected systems. Larger (island) systems are possible, which may use 3-phase high voltage transmission (CAT Organization system), if there is high power demand or long distance power transmission required, to reduce transmission losses. Typically these systems are below 100kW in size. Figure 3.4 shows a typical layout of a stand-alone energy system.

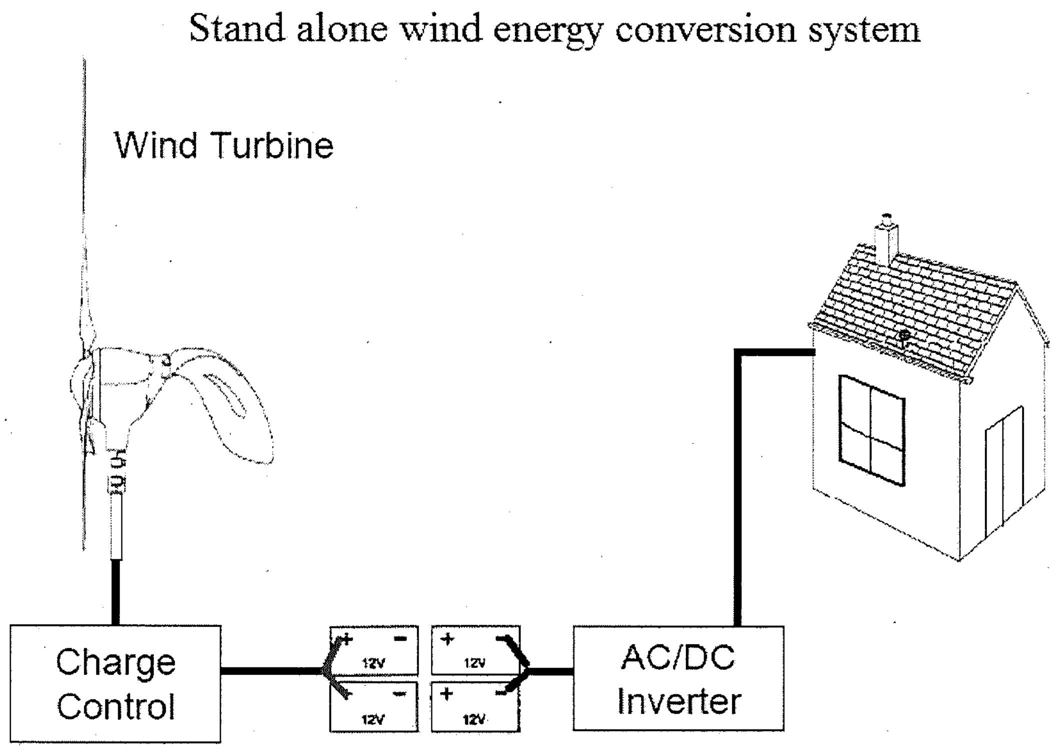

Figure 3.4: Layout of Edinburgh Napier University wind energy stand-alone system

3.1.3 Batteries

Batteries are the most vulnerable part of a stand-alone system. They store energy and are usually specified as voltage and capacity in Amp-hours, as follows:

E = V x capacity e.g. A 12V 100Ah battery stores up to 1200Whrs enough to run a 10W light bulb for 120 hours. Choosing batteries for any stand-alone system depends on the following four factors: cost, application, maintenance, and life expectancy.

Air-Dolphin wind turbine has a built-in battery charge management system which is used to charge lead-acid deep cycle Absorbed Glass Matt (AGM) batteries. The batteries used here are sealed (refer to Figure 3.5). They are considered cheap and reliable for rural area as they have long cycle life and require no maintenance.

In Napier stand alone system, the battery bank consists of four 150Ah 12-volt batteries wired in series/parallel configuration providing 300Ah at 24 volts.

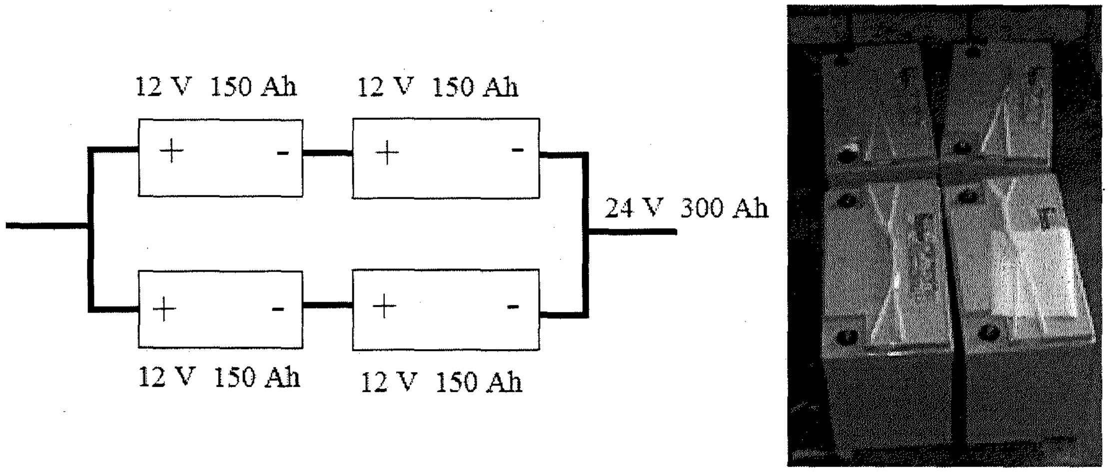

Figure3.5: The batteries bank used in Napier stand-alone system

3.1.4 Inverter

A 2kW modified sine wave 24VDC to 230VAC inverter is employed to supply power to the dump load. It was decided that a high voltage load would be used as this reduces the switching current required to operate the dump load air heater which in turn will help reduce the over-all cost of the system.

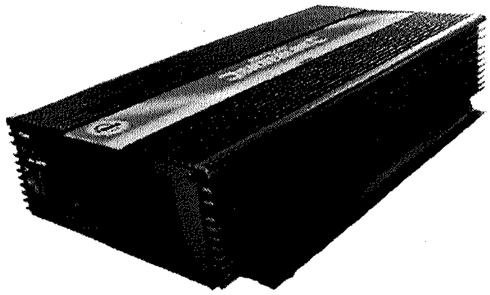

Fig 3.6 The inverter is connected to the batteries with the load connected on its AC output.

3.2 Data collection and sampling rate

This wind energy conversion system produced two sets of data: first one related to wind regime (wind speed and direction), and the second one related to the wind turbine performance (power output, voltage, current, rotational speed, and cumulative energy).

3.2.1 Wind turbine data

The wind turbine is provided with software to record the power output in daily files, with a possibility for changing the sampling rate. Wind turbine was connected to a PC via RS-485 link providing values for the following variables: voltage, current, power, energy, and rotational speed of the rotor with 1second resolution.

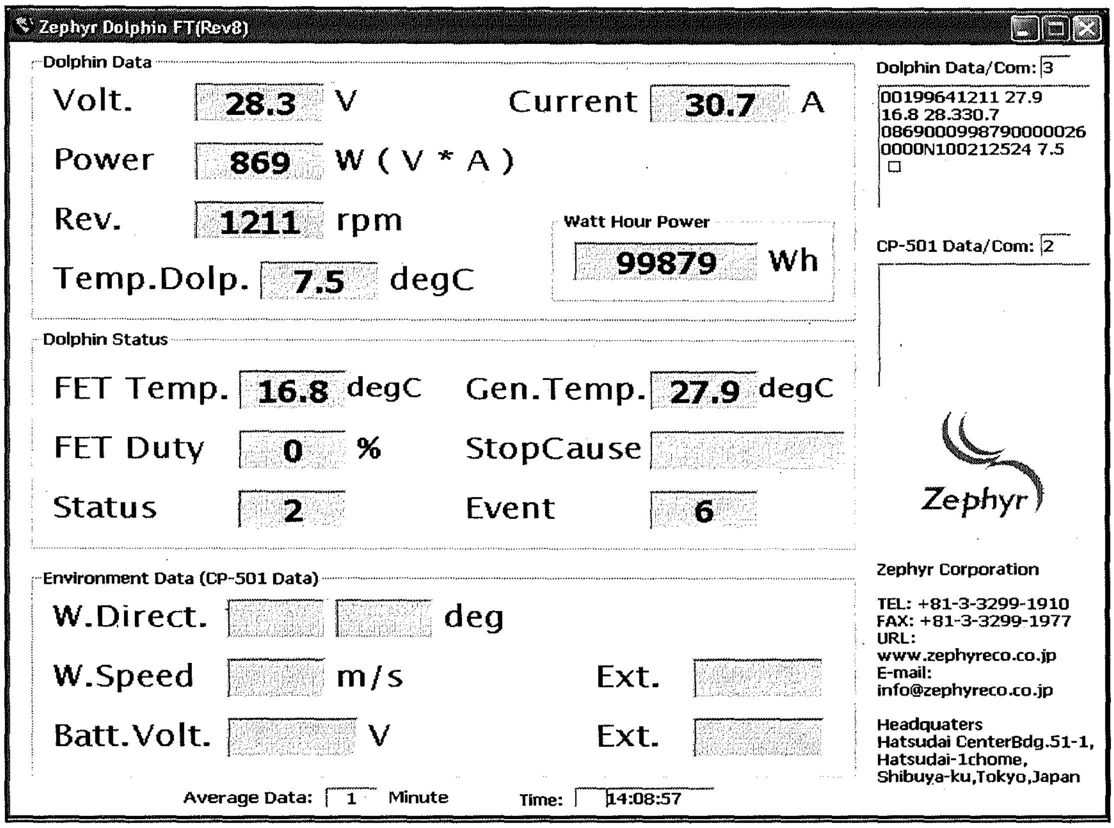

Figure 3.7 The software interface for Zephyr Air- Dolphin wind turbine

3.2.2 Anemometer calibrations:

Two anemometers and wind vane were installed to measure wind speed and wind direction at Merchiston campus. Prior to setting them up on the mast, the instruments were tested and calibrated against ultrasonic anemometer in the energy laboratory by using the small wind tunnel installed there. The two anemometers were then tested by comparing the recorded data for each of them. Wind vane was calibrated by using the spectrometer shown below in

Figure 3.9.

Figure3.8 Installation of Vaisala WM302 and NRG #40H anemometers on the roof of Merchiston campus

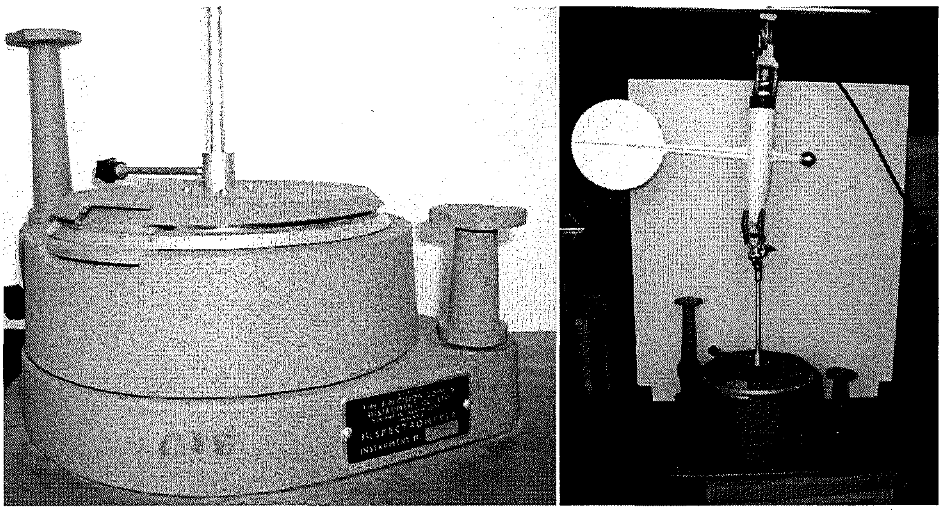

Figure 3.9 Calibration process of wind direction vane by using spectrometer

The principle of measuring wind direction in Vaisala WMS302 anemometer is ascertained using a variable resistance device, called potentiometer. The circuit has two variable resistances, each determining the direction of the wind, either

North-South or East-West, as the case may be. For example, the first one has the domain from 1 to 11 KΩ where minimum value signifies south blowing wind while maximum value indicates the wind direction towards north. Likewise, when the value on second resistance is 1 KΩ the direction of wind is towards west and when it is 11KΩ the direction is towards east.

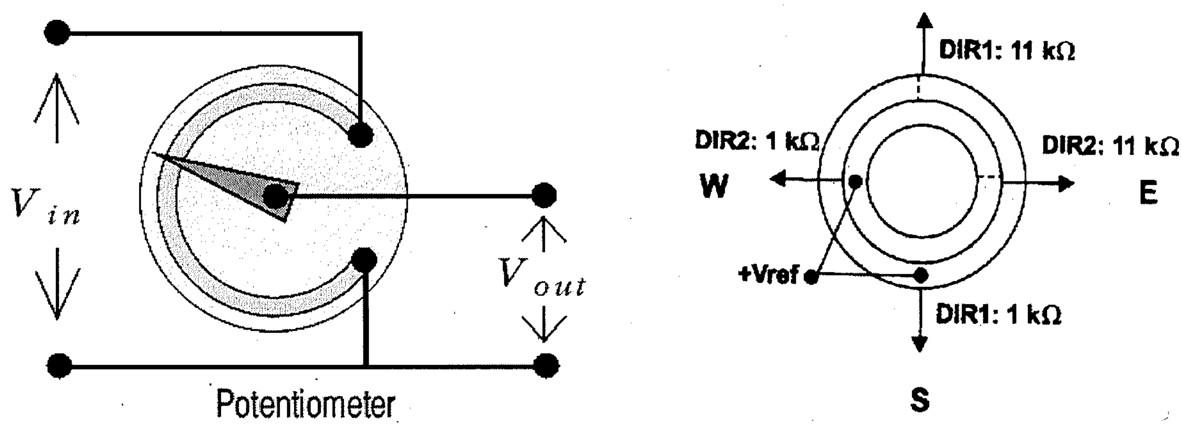

Figure 3.10 Schematic diagram shows the measurement of the resistances for evaluation of wind direction

3.3. Setting up the Squirrel data logger

The data logger used in this project to record the wind speed and direction signals is Squirrel 2020-1f8 model from Grant Instruments.

It can either work as a stand-alone system (comes with an SD memory card for data storage) or can be connected to a computer through USB and RS232 connections. It is equipped with both internal (6*1.5v Alkaline batteries) and external power supply (DC power supplier). Three channels were used to connect the two anemometers and wind vane output signals to the data logger.

Figure 3.11 Grant squirrel 2020 series data logger is used to record wind data for test site

3.4. Sampling rate for recoded data:

The data, thus obtained, generates two sets. The first set of data includes the following three variables: wind speed from the first anemometer (ws_1), wind speed from Vaisala WMS302 anemometer (ws_2), and the wind direction (dir). The sampling rate for recorded data is 4-second. Table 3.2 illustrates the data format.

Table 3.2 The wind speed-direction data file format

Date	Time	Space	dir	ws1	ws2
27/08/2008	11:24:56	Interval	338.8	34	10
27/08/2008	11:25:00	Interval	382.5	24	6
27/08/2008	11:25:04	Interval	367.1	25	6
27/08/2008	11:25:08	Interval	360.9	20	6
27/08/2008	11:25:12	Interval	238	16	4
27/08/2008	11:25:16	Interval	292.6	16	5
27/08/2008	11:25:20	Interval	223	22	9

The second set of data is recorded from the Zephyr wind turbine through its software. This software produces daily files with second by second sampling rate. Table 3.3 illustrates this data format.

Table 3.3 The wind turbine data file format

Date	Time	RS [rpm]	Temp1	temp2	Voltage [V]	Current [A]	power meter W/h
07/09/2008	00:00:15	533	17.7	13.3	26.6	5.7	3775
07/09/2008	00:00:16	505	17.7	13.4	26.7	4.4	3775
07/09/2008	00:00:17	469	17.8	13.4	26.6	3.3	3775
07/09/2008	00:00:18	445	17.9	13.5	26.5	2.2	3775
07/09/2008	00:00:19	365	17.8	13.5	26.4	1.3	3775
07/09/2008	00:00:20	291	17.9	13.4	26.2	0.7	3775
07/09/2008	00:00:21	277	17.6	13.6	26.2	0.4	3775
07/09/2008	00:00:22	266	17.9	13.5	26.2	0.2	3775

The sampling rate of wind turbine data set was averaged from 1 to 4 second to make it compatible with wind speed-direction data set. The two data files were then merged into one for further processing.

3.5 Installation of Ampair 600 wind turbine

This small wind turbine is British made. It was installed on 11/10/2007 at Merchiston campus. The system is grid-connected and consists of the wind turbine, anemometer, control system, and inverter. On 01/11/2007 the inverter failed. It was repaired within a week only to be broken again on 11/12/2007, and remained out of order until 16/01/2008.

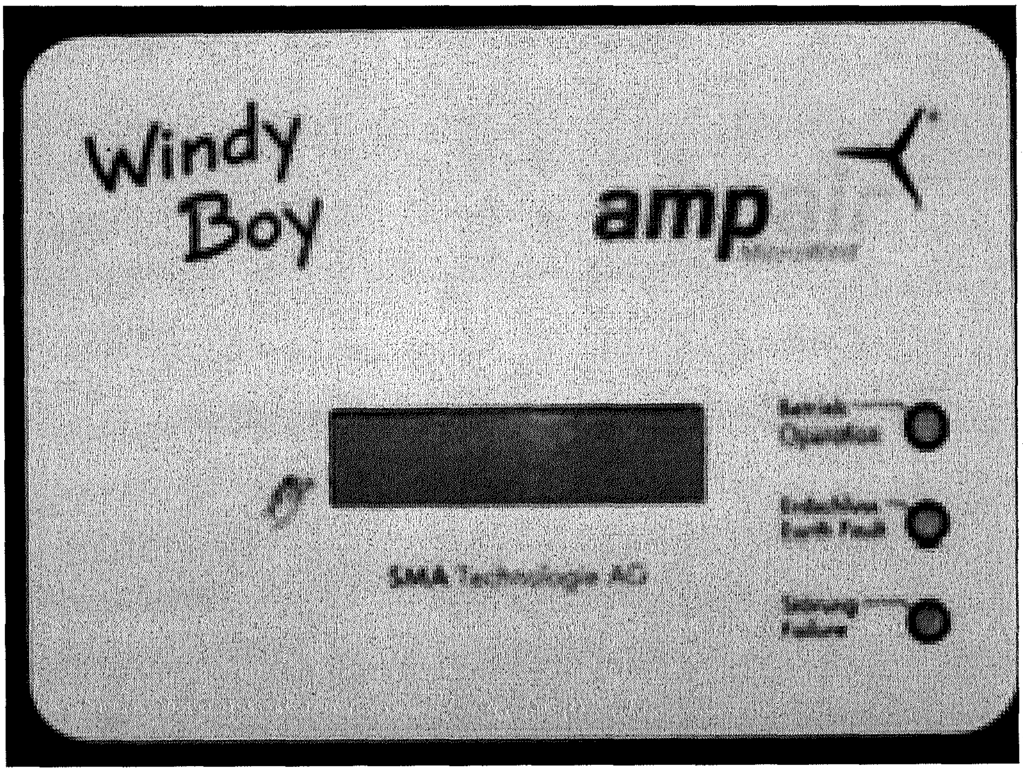

Figure 3.12 Windy boy inverter is connecting Ampair wind turbine to the grid

On 08/02/2008, since the weather was windy, the blades' structure could not withstand the wind speed. Consequently, the wind turbine and tail rotor were seriously damaged (refer to Figure C.1).

On 17/06/2008, the wind turbine was replaced with an improvised version designed to be more robust and durable against the variation and turbulence of the local wind (refer to Figure. 3.13).

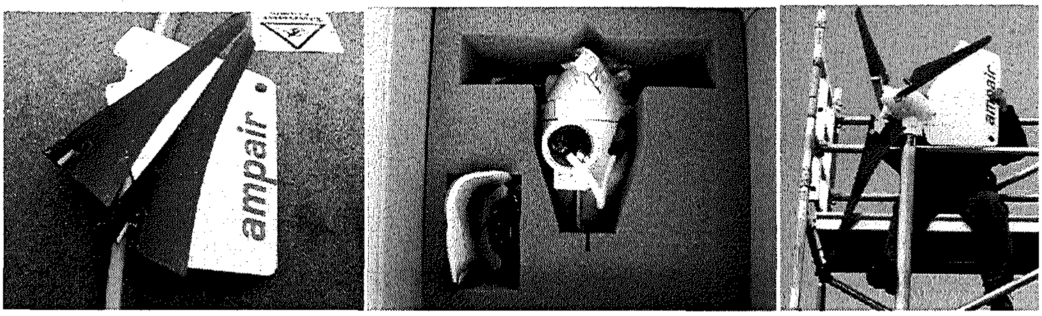

Figure 3.13 The installation of new design of Ampair wind turbine is shown

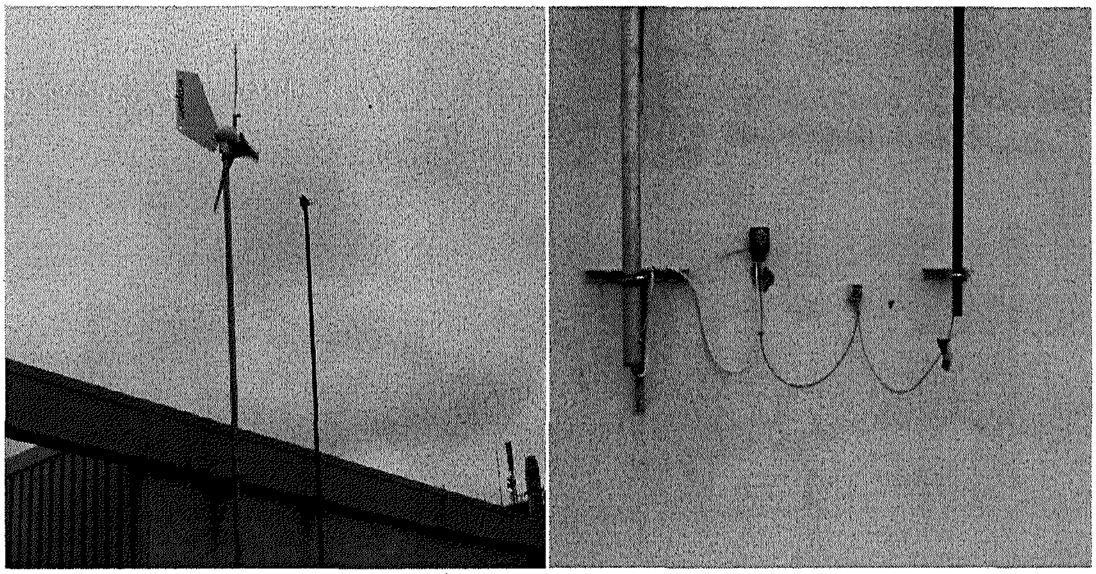

Figure 3.14 The Ampair 600 turbine with its anemometer and infra red data logger is displayed

3.6 Windsave WS1000

The Windsave WS1000 was installed on15 /06/2008. It was supplied only as grid-connected system with a rated power of 1kW at rated wind speed 12.5m/s. It was designed and improved to perform in the urban areas and for domestic applications.

The Windsave WS1000 uses a smart controller system which consists of an inverter and a G-83 protection unit. When the wind is very high the turbine applies mechanical control to furl the turbine out of the wind. It has a permanent magnet asynchronous generator, producing 3-phase electricity.

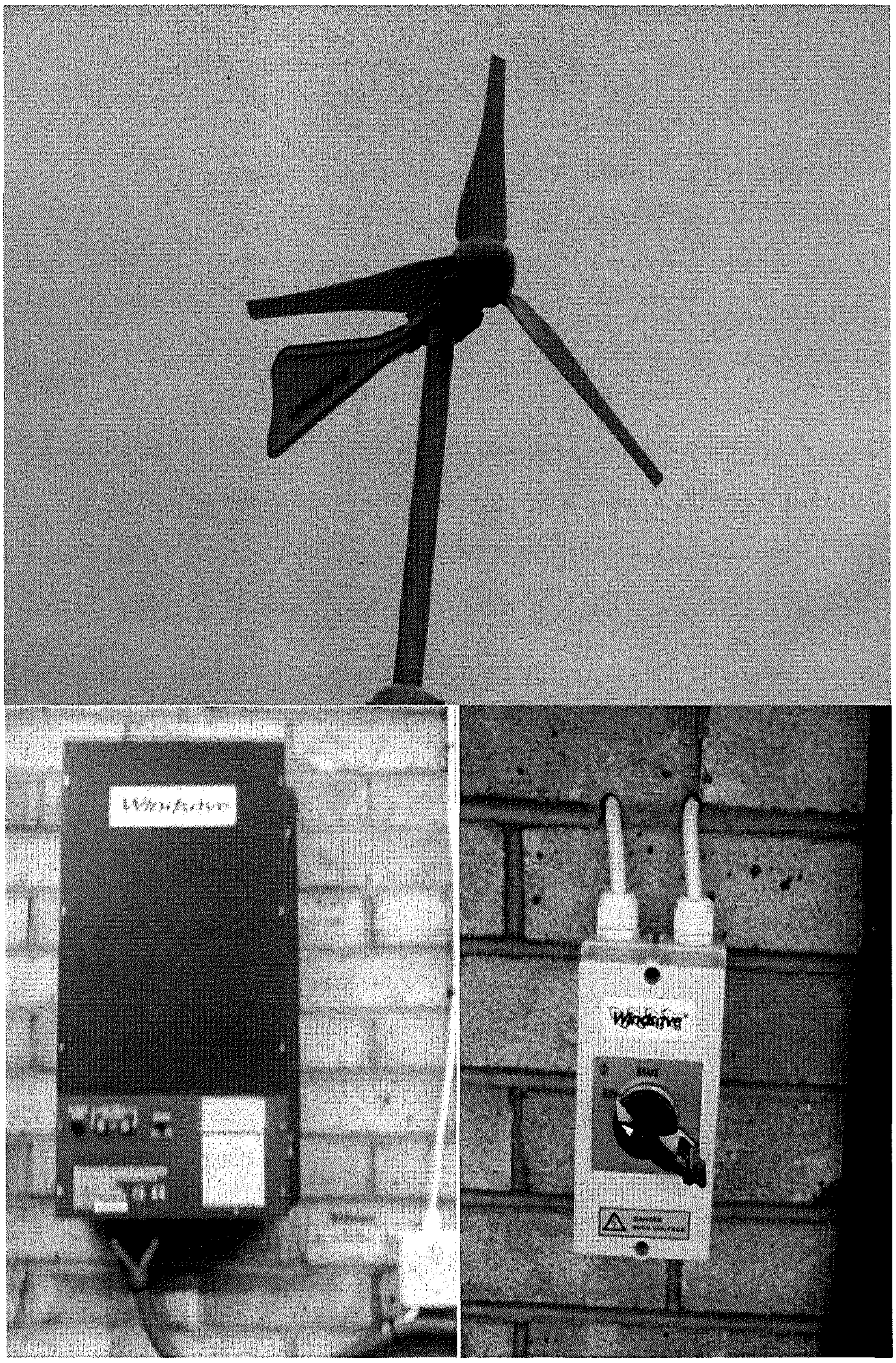

Figure 3.15 The main components of the conversion system of Windsave WS1000 Turbine

Subsequent chapter deals with the processing of collected data.

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Chapter 4

Data Processing and Analysis

4.1 Introduction

Before considering a prospective wind turbine project for any site, a detailed and comprehensive analysis of the existent wind regime is required. If the location is in open rural area a basic assessment of the wind regime may be obtained from local meteorological data or NOABAL wind data. However, any local obstructions such as properties or trees in neighbourhood of proposed site may have a considerable effect on the wind-velocity characteristics which will not be accounted for in a basic estimation. Therefore, locations in built-up areas require a precise knowledge of wind speed and direction that can be achieved by recording these parameters using anemometer and wind vane at the proposed location of wind turbine. Typically, a year's data is recorded to take into account the effects of seasonal changes.

4.2 Data sources

Present research work uses five wind data sets from different locations. First set is obtained from Edinburgh Napier University wind monitoring station, and it is combined with wind turbine performance data recorded via manufacturer supplied software. Second set is 17 years data from Edinburgh airport weather station. The third and forth data sets are extracted from British Atmospheric Data Centre (BADC) for two weather stations within Scotland; one at Blackford hill in Edinburgh city and the other in the Scottish border. Fifth data set is from Pakistan comprising of 4 years data for Gharo location.

4.2.1 Wind data collection of Edinburgh Napier University, Merchiston Campus site

Monitoring instruments were installed on the roof of Edinburgh Napier University Merchiston Campus in January 2007 which can be seen in Figure 4.1. The project was initiated with the view to precisely monitor the wind regime and examine micro wind turbine performance in such typical urban location. Wind speed and direction were recorded on 4 seconds intervals. Two 3-cup anemometers and two wind vanes were mounted on 4 m mast on the laboratory roof at Merchiston campus, 120m above sea level. Data has been recorded continually since 2007 on a four-second basis, apart from a two-week period in January 2008 when data was recorded at two-second intervals. In Chapter 3, Tables 3.2 and 3.3 provide the format for wind and turbine data files, respectively.

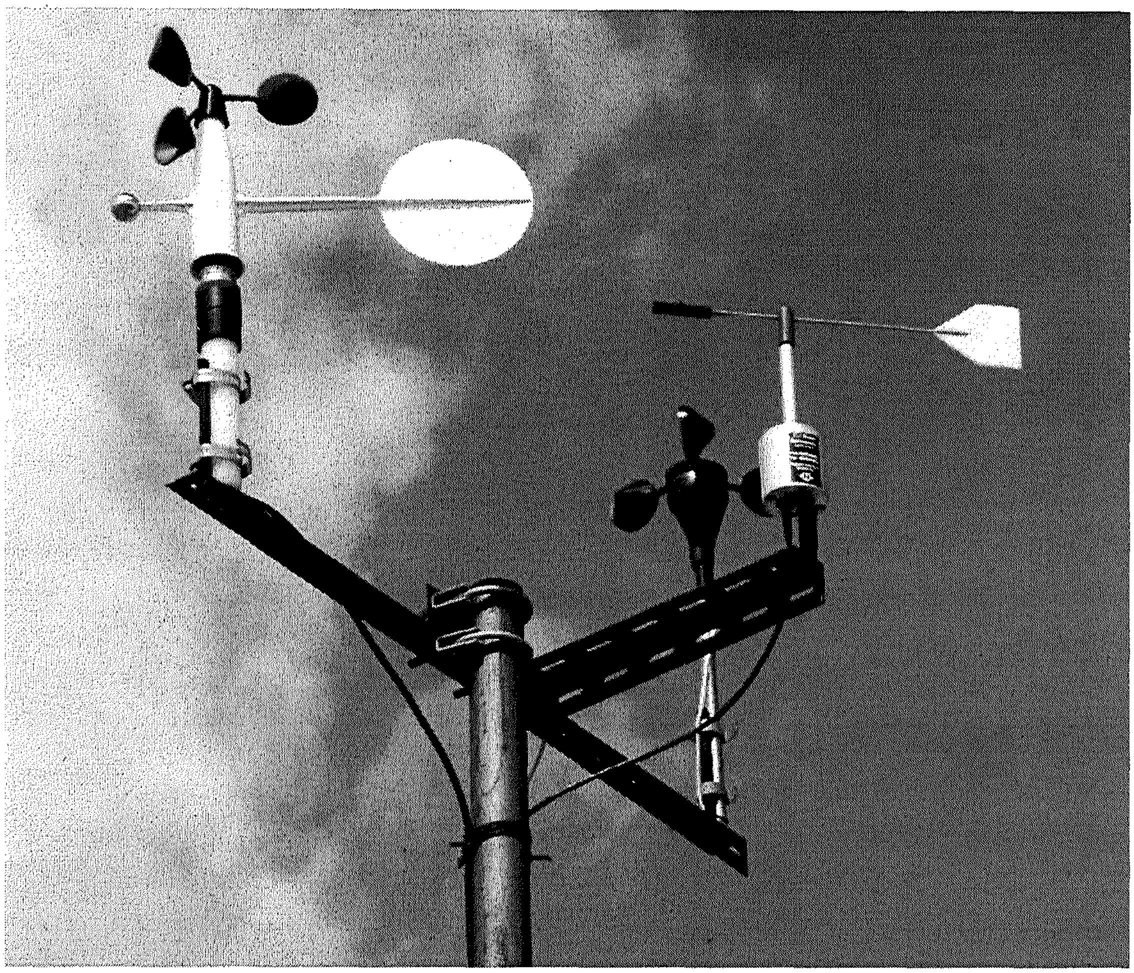

Figure 4.1 Two wind velocity anemometers and two wind direction vanes (Wind monitoring station, Edinburgh Napier University).

Most of the micro wind turbines are designed and manufactured according to conditions observed in rural locations where mean wind speeds are much higher than in urban areas, consequently resulting in low performances when installed in latter sites. Although wind stream in urban areas are obstructed by buildings and trees, high surface roughness creating turbulent flow applies extra strain on structure and equipments of the turbine causing increased premature failures. Table 4.1 displays the features and accuracy of the installed sensors.

Table 4.1 Installed wind monitoring equipment (Wind monitoring station Edinburgh Napier University)

	Vaisala WM30 Wind Sensor	**NRG #40H Anemometer**
Wind speed		
Measurement range Starting threshold Distance constant	0.5 to 60m/s 0.4m/s 2m	1 to 96m/s 0.78m/s 3m
Accuracy		
Wind speed up to 10 m/s Wind speed over 10 m/s Characteristic transfer function	± 0.3m/s ± 2% m/s = -0.24 + 0.699 × Hz	 0.1m/s 0.1m/s m/s = 0.35 + 0.765 x Hz
Wind direction		**W200P Potentiometer Wind Vane**
Measurement range Potentiometer Starting threshold Damping ratio Delay distance Accuracy	 0 to360° 1.0m/s 0.3m 0.6m ±3°	 360° 0.6m/s 0.2m 0.51m ±3°

4.2.2 Edinburgh airport weather station data

Edinburgh airport is situated in the western part of Edinburgh; 10.4 miles from Merchiston campus (Google maps). Wind data, there, was recorded for 17 years in the period between 1976 and 1992 on hourly basis. It is a reliable and detailed data set that also includes sun and weather data.

Table 4.2 Turnhouse airport weather station data file format

STNO	YEAR	MM	DD	HH	DBT	WBT	ATPR	WS	WD	RA	RD
4	1992	1	1	1	8.8	6.5	1011.3	14.92	230	0	0
4	1992	1	1	2	9.3	7.2	1009.4	15.43	220	0	0
4	1992	1	1	3	8.1	7.8	1009.1	15.43	220	0.3	0.8
4	1992	1	1	4	9	8	1008.9	14.92	230	0.6	1
4	1992	1	1	5	8.9	8.8	1009.4	13.89	230	1.2	1
4	1992	1	1	6	8.4	8.3	1011.5	10.29	260	2.7	1
4	1992	1	1	7	8.6	7.7	1012.2	9.77	250	0.2	1

The data has been filtered to derive the lowest and highest months in terms of monthly average wind speed which were October and January, respectively. Then a comparison is made between these, representing rural wind regime, and those that belonged to urban location (Merchiston site).

4.2.3 British Atmospheric Data Centre (BADC) data sets

One year hourly wind data has been extracted for two locations from two different weather stations via BADC web site using registered account. First set is from Blackford hill location, where weather station is setup on the hill which is 134 m above sea level with high wind energy potential. Figure 4.2 refers to the Blackford hill station mounted on 10 m high lattice tower.

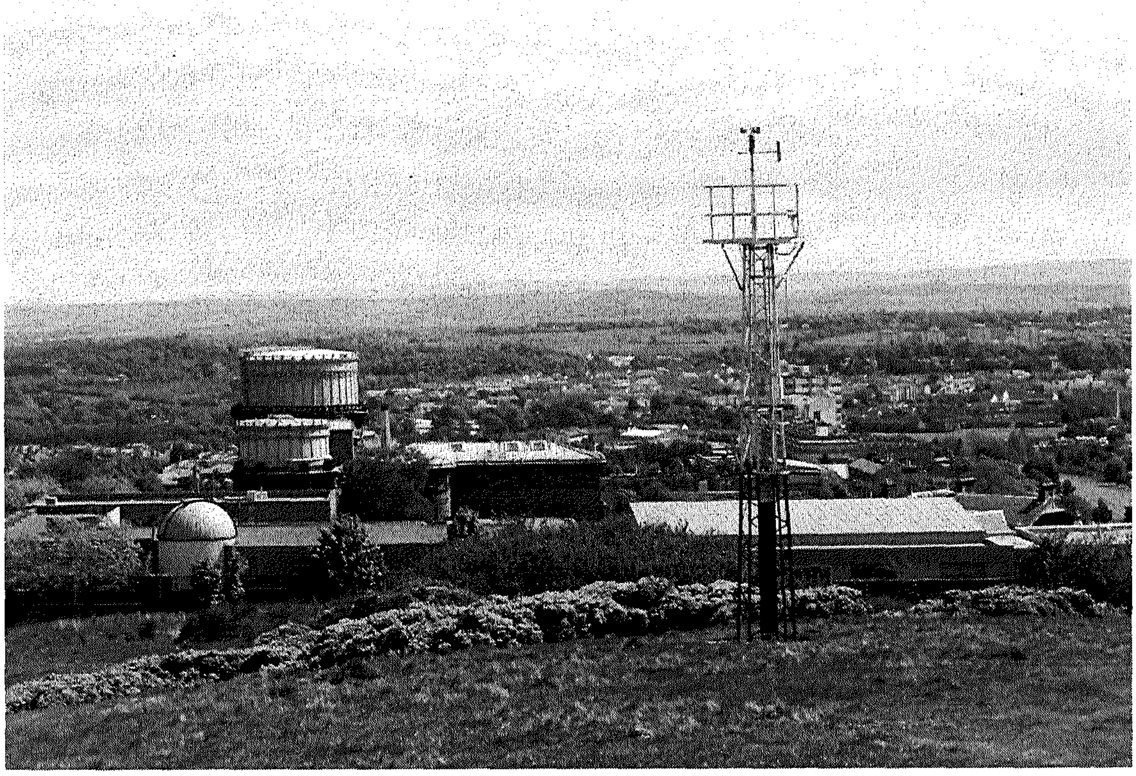

Figure 4.2 Blackford hill weather station mounted on 10 m high metal tower

Table 4.3 Description of Blackford hill weather station position and elevation

Name:	EDINBURGH: BLACKFORD HILL
src_id	251
Geographic area:	MIDLOTHIAN (IN LOTHIAN REGION)
Latitude (decimal degrees):	55.923
Longitude (decimal degrees):	-3.188
Grid ref:	NT 258706
Grid ref type:	OS
Postcode:	EH9 3 View all stations in EH9 postcode
Elevation:	134 meters
Drainage stream:	FIGGATE
Hydrological area ID:	190
Station start date	01-01-1861
Station end date	Current

The second data set is from Drumalbin weather station, 30 miles from Merchiston campus, positioned to the western south of Edinburgh with elevation of 245 m high above sea level and far from the coast

Table 4.4 Description of Drumalbin weather station position and elevation

Name:	DRUMALBIN
src_id	987
Geographic area:	LANARKSHIRE
Latitude (decimal degrees):	55.627
Longitude (decimal degrees):	-3.735
Grid ref:	NS 907384
Grid ref type:	OS
Postcode:	ML11 9 View all stations in ML11 postcode
Elevation:	245 meters
Drainage stream:	DOUGLAS
Hydrological area ID:	840
Station start date	01-01-1984
Station end date	Current

Data files contain hourly basis wind parameters from 1/9/2007 to 31/8/2008, including wind speed, wind direction, maximum and minimum gust speed, along with date, time and station number. Table 4.5 illustrates the data format for both files.

Table 4.5 Blackford hill and Drumalbin weather stations data file format

ob_end_time	src_id	mean_wind_dir	mean_wind_speed	max_gust_dir	max_gust_speed	mean_wid_dir_q	mean_wind_speed_q	max_gust_dir_q
01/09/2007 00:00	251	250	12	250	23	6	6	6
01/09/2007 01:00	251	260	11	250	20	6	6	6
01/09/2007 02:00	251	250	12	250	23	6	6	6
01/09/2007 03:00	251	250	14	250	22	6	6	6
01/09/2007 04:00	251	250	15	250	27	6	6	6
01/09/2007 05:00	251	240	13	250	23	6	6	6

4.2.4 Gharo wind data set

Gharo is a coastal city situated on the Arabian Sea in south-west Pakistan with promising wind energy potential. Wind data was obtained at minute by minute interval for a long term period from May 2002 to June 2006 with high accuracy and continuity. This data consists of date, time, wind direction, wind speed, temperature, and solar irradiation. Note that wind speeds are recorded for two heights 30 ft, and 100 ft (10 m and 30 m). Table 4.6 shows the format of data file.

Table 4.6 Gharo weather station data file format

LOCATION	DATE	TIME	WS30	W100	WD	TEMP	SRD
			MPS	MPS		C^0	
Gharo	01/05/2002	00:00	5.98	8.86	254	25.99	611
Gharo	01/05/2002	00:01	6.43	9.47	253	-	-
Gharo	01/05/2002	00:02	5.67	8.71	254	-	-
Gharo	01/05/2002	00:03	6.43	7.95	255	-	-
Gharo	01/05/2002	00:04	5.67	9.47	254	-	-
Gharo	01/05/2002	00:05	6.43	8.71	251	25.99	613
Gharo	01/05/2002	00:06	7.19	9.47	254	-	-
Gharo	01/05/2002	00:07	6.43	9.47	251	-	-
Gharo	01/05/2002	00:08	7.95	9.47	251	-	-
Gharo	01/05/2002	00:09	7.19	9.47	254	-	-
Gharo	01/05/2002	00:10	6.58	9.17	253	25.99	610

4.3 Processing data tools

Several Visual Basic Application (VBA) programs were written to examine the accuracy and continuity of the above data sets. Those codes were also programmed to perform all the mathematical operations of averaging data, calculating energy, and producing power curve.

DOS environment was both effective and beneficial in merging wind and turbine data files to produce monthly text files. Five or six files of wind data, with a 4 seconds interval resolution, had to be merged in one file. Consequently, merged data files exceeded 35 Mb and 145 Mb capacities for wind data and turbine data, respectively. Since Microsoft Excel has its limitation of 66567 rows, such large amount of data had to be processed as text files.

Data processing was done through standard functions in Microsoft Excel. This included calculating the statistical parameters, such as mean wind speed, standard deviation, first quartile, interquartile range, third quartile; R^2, slope, mean bias deviation (MBD), and root mean squared deviation (RMSD). Majority of tables and plots were drawn using Excel commands and environment. Furthermore, all statistical distribution functions were evaluated using statistical parameters from Microsoft Excel.

SPSS software package was effectively employed in filtering operations, like extracting specific data from a large set of data or retaining data for a certain time period. SPSS was also used to draw histograms of different variables. It can give large range of flexibility to modify bins width of frequency distribution, and its output files can be saved in various formats.

4.4 Wind turbine modelling technique

The power curve plot, figure 4.3, shows the relationship between wind speed and power output of Suzlon 950 wind turbine. Below cut-in (3 m/s) wind speed there is insufficient energy in the wind for the wind turbine to generate electricity. In the operating region between cut-in and rated wind speed (11 m/s) the wind turbine will attempt to maximise the energy capture from the wind. In the operating region between rated wind speed and cut-out (25 m/s) the machine is required to limit the energy capture from the wind, such that the rated power is not exceeded. Above the cut-out wind speed the wind turbine must stop and park the rotor in order to protect itself.

Modelling wind turbine performance is a tedious procedure that involves the following steps.

1. Drawing wind turbine power curve (see appendix c) on excel sheet.
2. Dividing the plot's area into four or five sections, depending on cut-in and cut-out wind speed .
3. Using trendline function from Excel to display R^2 and equation of the best-fit curve.
4. After obtaining the equations and determining initial conditions, code is devised to calculate power for each wind velocity of recorded data. According to that the generated energy is projected for the wind turbine in the proposed location.

The following figures demonstrate the three stages of generating equations from the power curve.

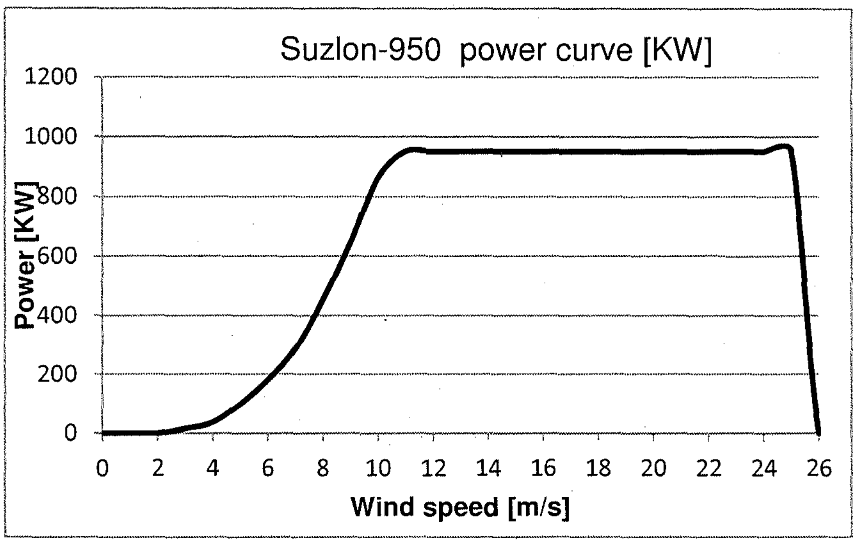

Figure 4.3 Wind turbine power curve based on data appendix C.1

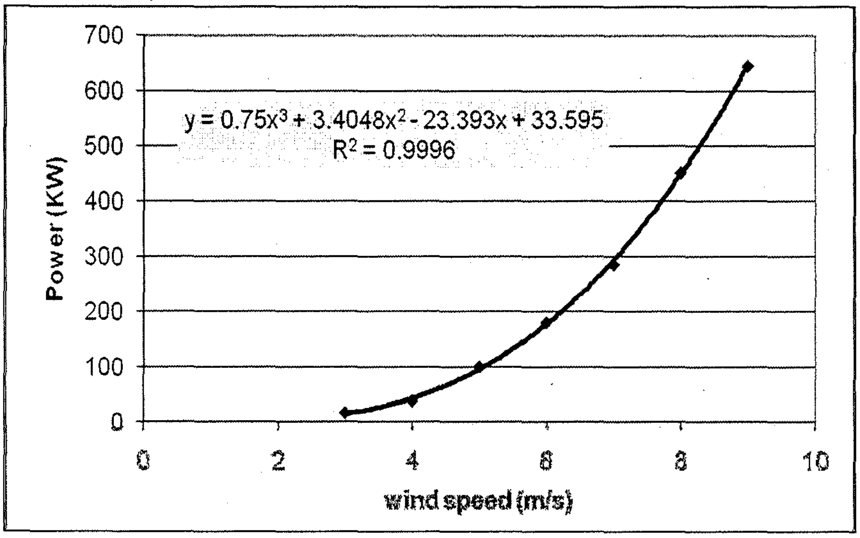

Figure 4.4 First part of the power curve fitted with a third degree equation

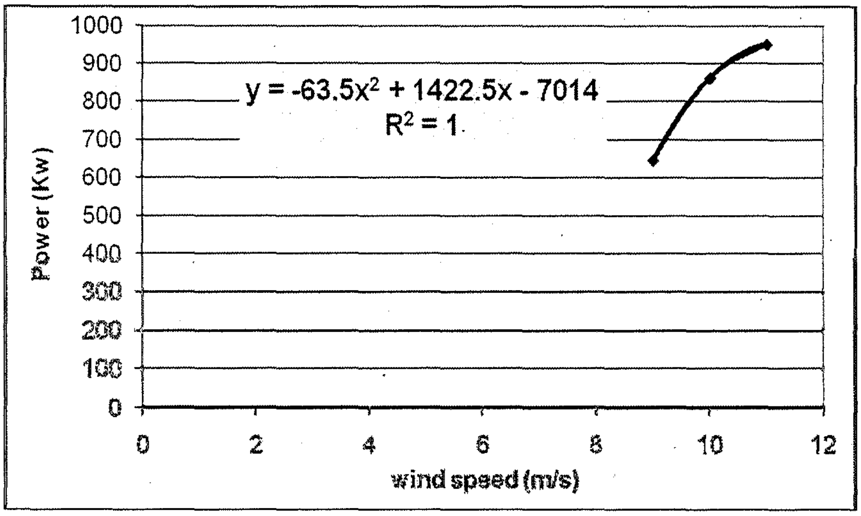

Figure 4.5 Second part of the power curve fitted with a second degree equation

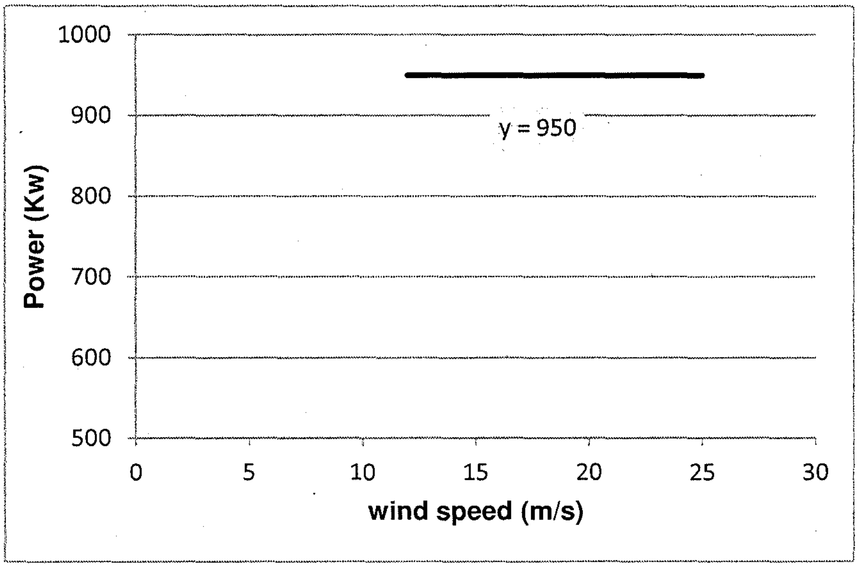

Figure 4.6 Third part of the power curve fitted with a constant value of 950

The equations may be used as following (P=Power, W=wind speed):

- If (X=W) =<3; Y=P=0.
- If 3 <(X=W)=< 9 ; Y=P= $0.75x^3 + 3.4048x^2 - 23.393x + 33.595$
- If 9 <(X=W)=<11 ; Y=P= $-63.5x^2 + 1422.5x - 7014$
- If 11 <(X=W)=<25 ; Y=P= 950
- If (X=W)>25 ; Y=P= 0

4.5 Edinburgh Napier data analysis

Data analysis of Merchiston site is including process of two data sets. The first one is wind data of 4-sec intervals for wind speed and direction, and the second one wind turbine data which consists of 1 sec intervals for rotational speed, currant, voltage, power, and energy. The analysis process starts with investigating the accuracy and continuity of the data sets to determine the missing data, and then averaging wind turbine data set to be 4-sec intervals. After that, the data are gathered in monthly files, then from wind turbine data files the actual monthly energy output is obtained. Wind roses, wind speed monthly average, and wind speed monthly probability distribution are determined using wind data monthly files. Visual Basic Application (VBA) code has been constructed to produced actual power curve using the measured data sets then that curve has been modelled to compute energy output. Monthly wind data files have been processed by SPSS software to generate observed wind speed frequency distribution, and then it has been fitted five different statistical distribution functions, which are Weibull, 3- parameter Weibull, D-Weibull, Lognormal, and Rayleigh respectively. Figure 4.7 shows the flow chart of analysis process of Edinburgh Napier University wind site.

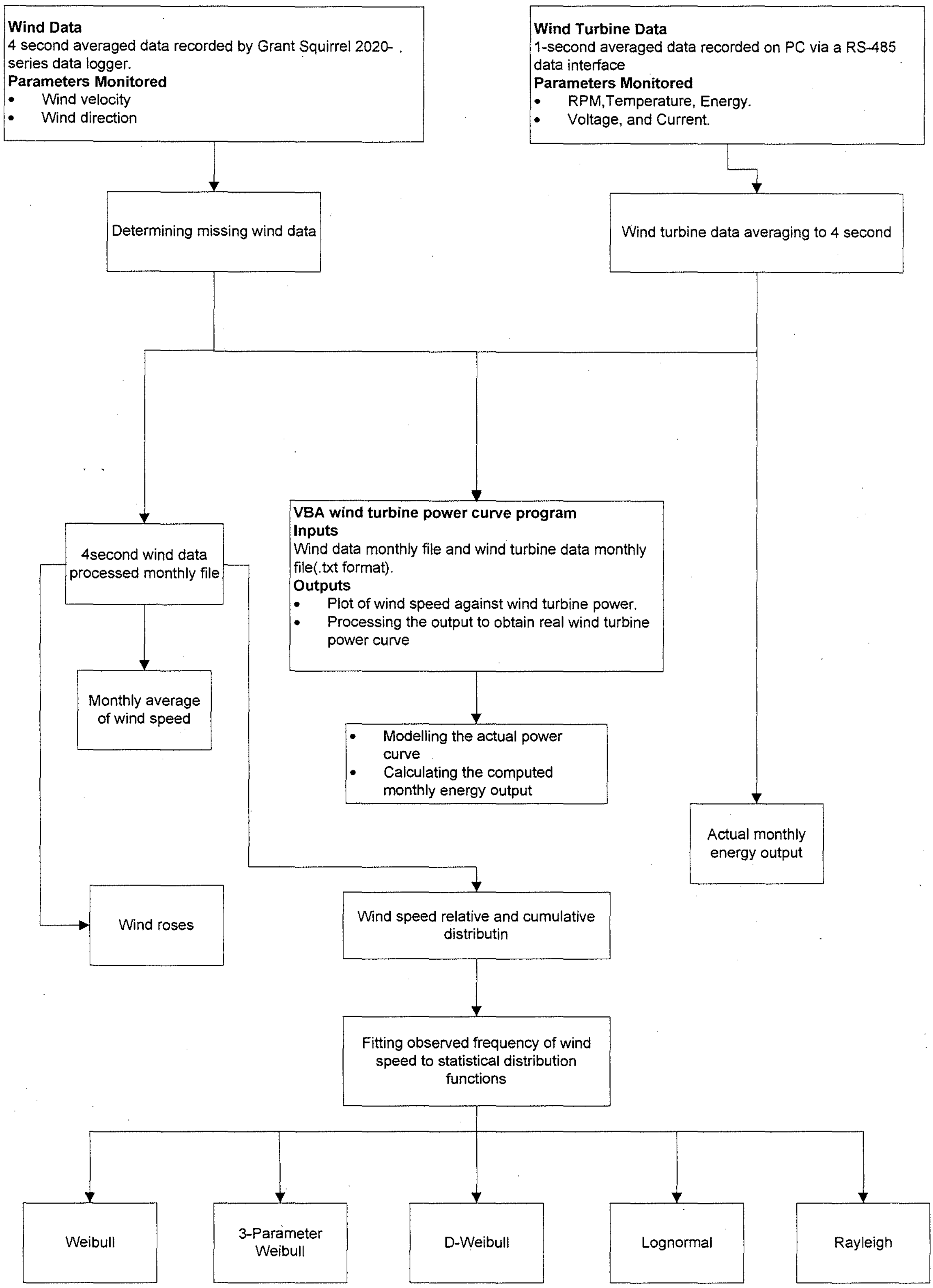

Figure 4.7 Flowchart illustrating Edinburgh Napier University wind data analysis

4.6 Temporal and spatial variation of wind speed analysis from two Edinburgh sites

This analysis process has two data sets 17 years of hourly wind data for Edinburgh airport, and 2 years 4-sec wind data for Merchiston campus wind site. Temporal variation analysis has been involved processing the second data set in three different intervals 4-sec, minute by minute, and hourly. VBA code has been constructed to average 4-sec monthly wind speed files into minute by minute, hourly monthly wind speed files, and then those files have been employed as input for SPSS14 software package to produce probability wind speed cumulative distributions, consequently every monthly file of those two years data has three cumulative wind speed distributions with different intervals. Mean Bias deviation (MBD) and Root Mean Squad Deviation (RMSD) have been employed to achieve statistical analysis considering the 4-sec cumulative distribution as reference. The analysis of spatial variation is including a comparison between hourly monthly cumulative wind speed distributions of two data sets, and that has been performed for two months January and October.

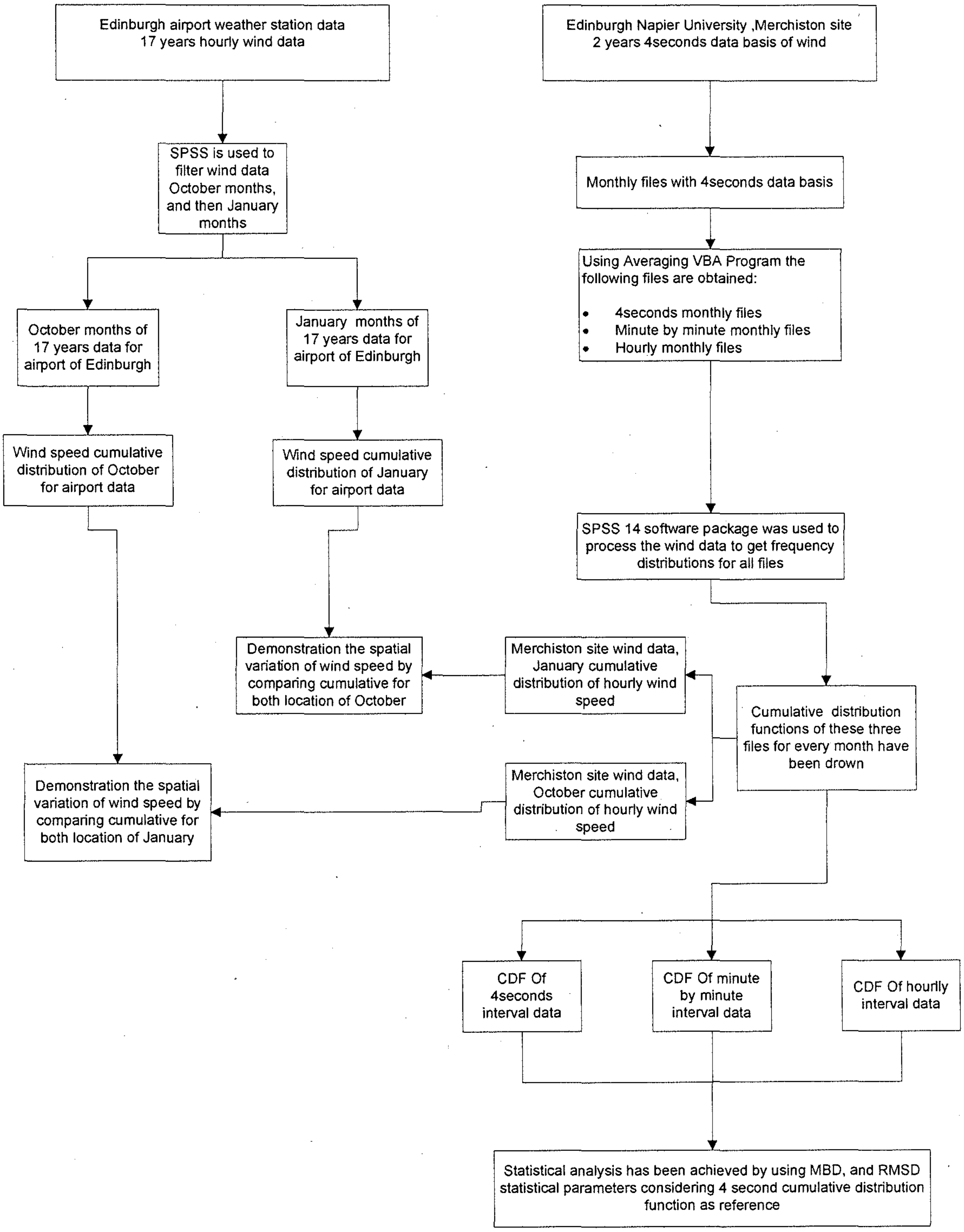

Figure 4.8 Flowchart illustrating temporal and spatial wind speed variation analysis of Edinburgh airport and Napier University (Merchiston) data

4.7 Gharo wind data analysis

Gharo wind data set has 4 years minute by minute intervals data which was measured at two different heights 10 m and 30 m high in all analyses and calculations the recorded data at 30 m high has been used since it has more potential for wind energy. Minute by minute monthly files have been averaged into hourly monthly files. Every file has been statistically analysed by determining the following statistical parameters: Data accuracy, mean wind speed, standard deviation, first quartile, inter-quartile range, third quartile, and energy output. In modelling of wind turbines process, three different machines were been chosen (Suzlon 950, Suzlon 1250, and Vestas 1500) to project energy output for the candidate site. Using projected energy output an inter-comparison of machine performance has been carried out which leads to best performing machine for the project.

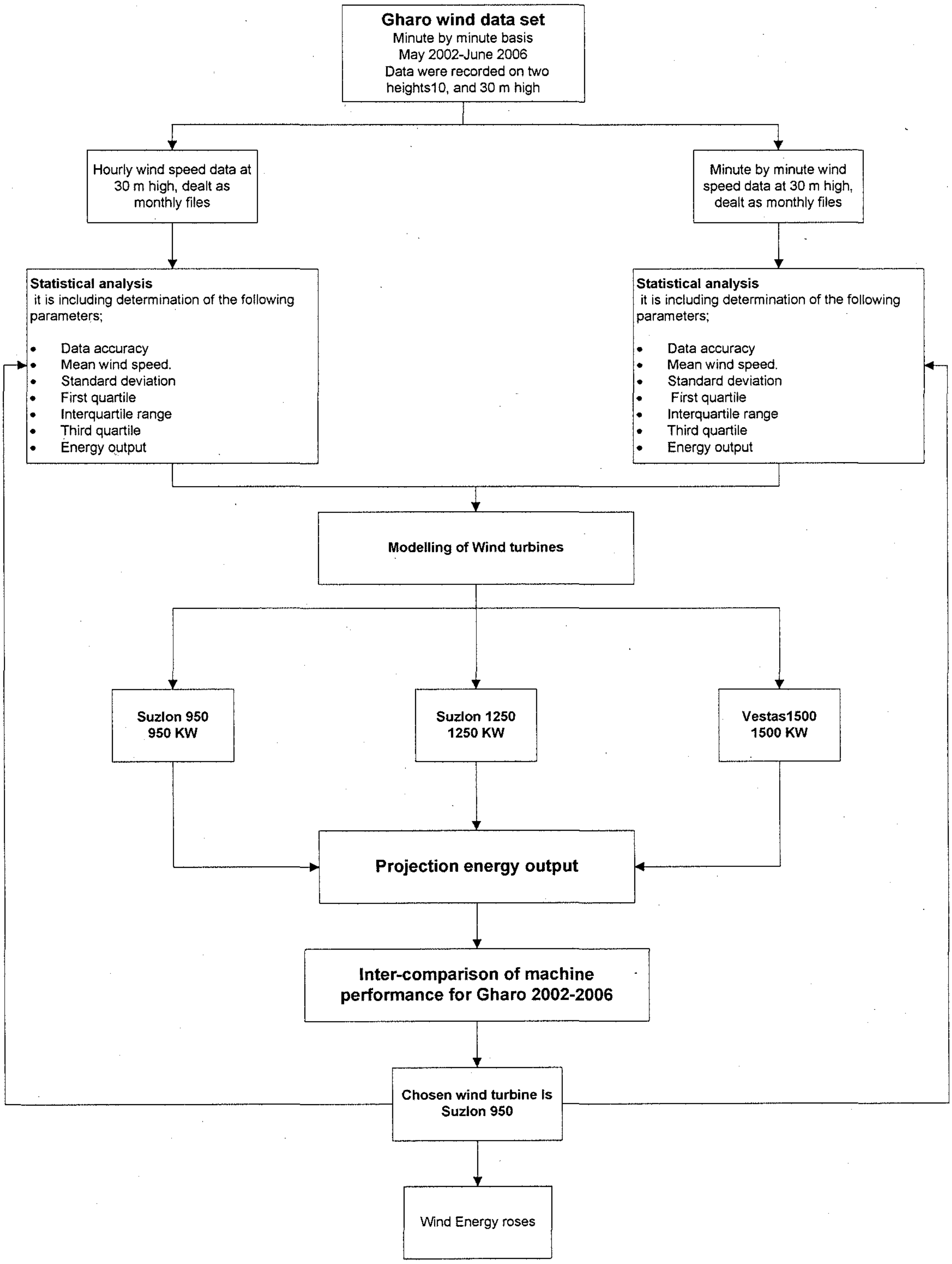

Figure 4.9 Flowchart illustrating the Gharo wind data analysis

4.8 Feasibility analysis of wind energy potential in Scotland

The analysis process for this feasibility study has been started with extracting one year hourly wind data for two different locations in Scotland depending on British Atmospheric Data Centre (BADC) database, thus in one hand is two wind data sets from two different weather stations, and on the other hand is the annual electricity demand for Merchiston campus and the annual electricity bill for this campus. The previous mentioned wind data sets have been adapted to hub heights of candidate wind turbines. The four candidate machines are made by three different manufacturers (Vestas, Fuhrland, and Enercon) with diverse power capacity; therefore modelling those machines against the available wind data have given different energy outputs and capacity factors. Economic analysis has been carried out to help in choosing the right wind turbine with minimum payback period. Consequently, three crucial values were required: The first one is the cost of land lease per wind turbine, then the second one is the cost of wind turbine including the delivery and installation, the third one is the cost of operation and maintenance contract. After those stages by using projected energy outputs, sales revenue of produced electricity can be calculated, then as results payback periods for all machines are determined. Since Fuhrland FL1250 has given the best payback period, so it has been chosen to be installed, and 84% annual electricity demand for Merchiston campus can be compensated by setting up two wind turbines.

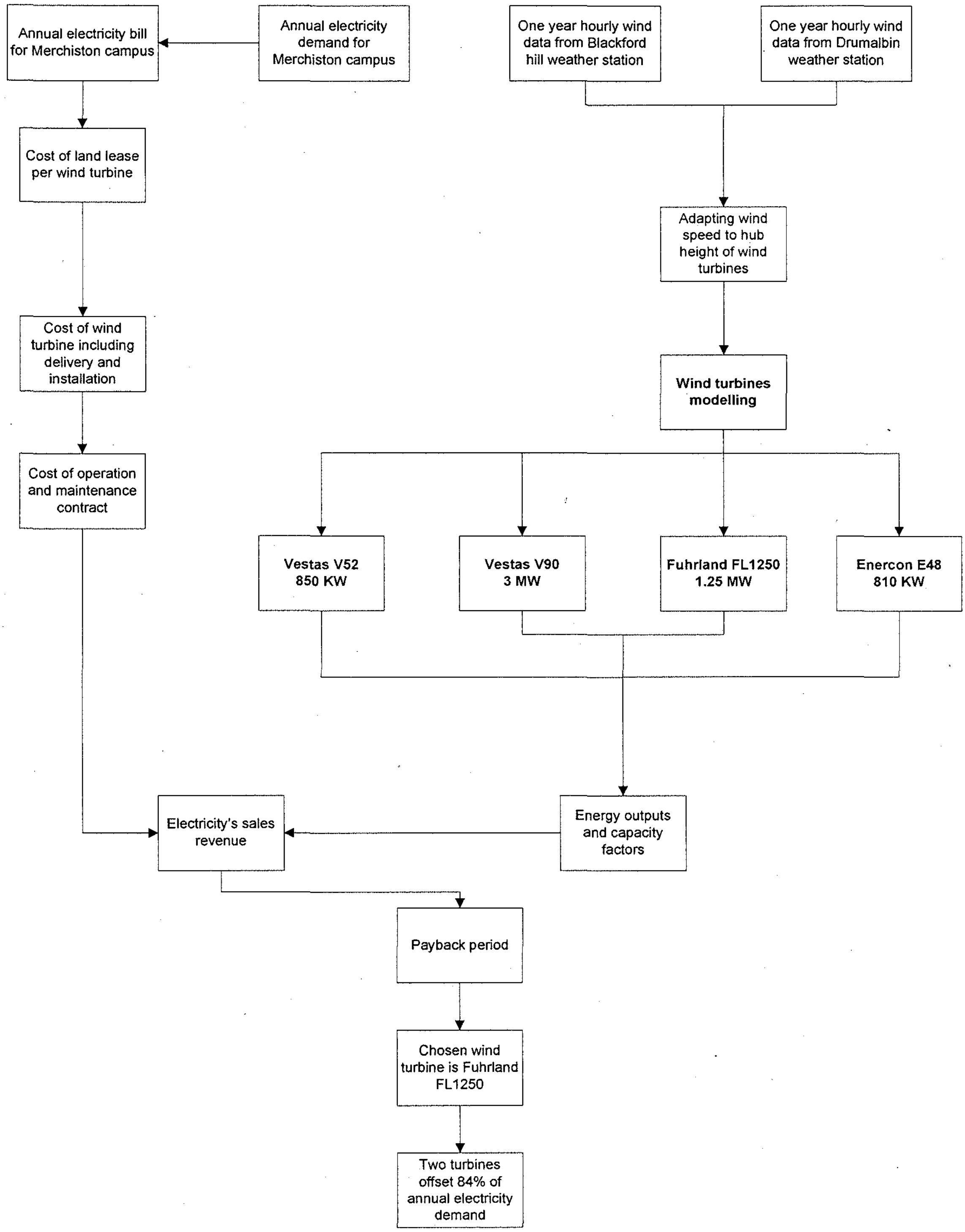

Figure 4.10 Flowchart illustrating feasibility analysis of wind energy potential in Scotland

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Chapter 5

Micro and Midi Wind Turbine Installation within the UK

5.1 The accessible power in the wind

Power extracted from wind stream by wind turbine basically depends on wind speed and the swept area of turbine blades. The wind turbine harvests the power from wind flow when the blades reduce velocity of the air flow converting that kinetic power into spinning shaft connected to generator producing electricity . Power in the wind (P_w) is calculated from the kinetic energy equation:

$$P_w = \frac{1}{2}\rho A V^3 \quad [W] \quad (5\text{-}1)$$

Where:

P_w= Power available in wind stream [W].
ρ = Air density [Kg/m^3].
A = Swept area of the turbine rotor [m].
V= Wind speed [m/sec].

The performance coefficient of wind turbine varies for different wind speeds. A typical value is around 0.3, and it can be as high as 0.5 in a well designed-blade rotor of lift type, or it can be as low as 0.1 in the drag type of wind turbine. Theoretically, the maximum harnessed power is ruled by the Betz limit (16/27= 0.59259): theoretical maximum value of the performance coefficient. Thus, extracted power by wind turbine is calculated by the following equation (Stankovic.S 2009):

$$P_T = C_P \frac{1}{2}\rho A V^3 \quad [W] \quad (5\text{-}2)$$

Where

P_T= Power harnessed by wind turbine [W].
C_P = Performance coefficient of wind turbine.

In the above equation each variable has its own significance. For instance, if the swept area of rotor is increased to double, the power output will be doubled. However, the wind speed variable (V) has a more viable and sensitive role since the power (P) is proportional to the cube of wind velocity. Air density (ρ)

can be an important variable to consider since it depends on the climatic conditions of a particular wind turbine location. Its value is decreased in the warm weather and increased in the cold weather. Moreover, the height of the turbine with reference to sea level also affects the air density; the higher the altitude, the lower the value of air density.

5.2 Fundamental wind turbine designs

There are many different designs for wind turbines but all of them rely on two basic principles, according to which they can be classified in one of the two categories. When the wind stream is parallel to the rotational axis of turbine rotor, it is called Horizontal Axis Wind Turbine (HAWT). When the wind direction is perpendicular to the above, it is called Vertical Axis Wind Turbine (VAWT). In each design, the rotor can either utilize aerodynamic lift forces to spin the rotor, or aerodynamic drag forces which employ the momentum change of the wind deflection as it beats the blades to rotate the rotor. Each category has its implementations and limitations.

5.2.1 Horizontal Axis Wind Turbine (HAWT)

HAWTs employed to generate electricity require high tip speed ratio. Therefore, the rotor consists of lift-type blades, unlike the drag-type blades which are used when torque is rather required. HAWTs have two different designs upwind and downwind turbine. In first design, the rotor faces the wind stream with a substantial advantage that it avoids wind shade behind the tower. So majority of horizontal axis wind turbines have this design.

The limitations of these turbines are as follows: the rotor needs a yaw mechanism to keep it facing the wind direction, the blades have to be made rather inflexible, and the rotor is to be placed at some space from the tower, thus incurring higher manufacturing costs (Manwell.F.J 2009).

In second design, the downwind turbines have the rotor mounted on the far side of the tower and they do not need to be provided with yaw mechanism as rotor and nacelle have such aerodynamic design that makes the nacelle follow the wind passively. However, noise emissions in this type of turbine are higher than the previous one due to the approaching airflow being disturbed by the tower and consequently inducing low-frequency noise as the blades are in the wind shade of the mast. The downwind machines are unsuitable for setting up in urban areas where wind regimes are turbulent and unsteady. Hence, they are mainly installed in rural areas (Danish Wind Industry Association 2010).

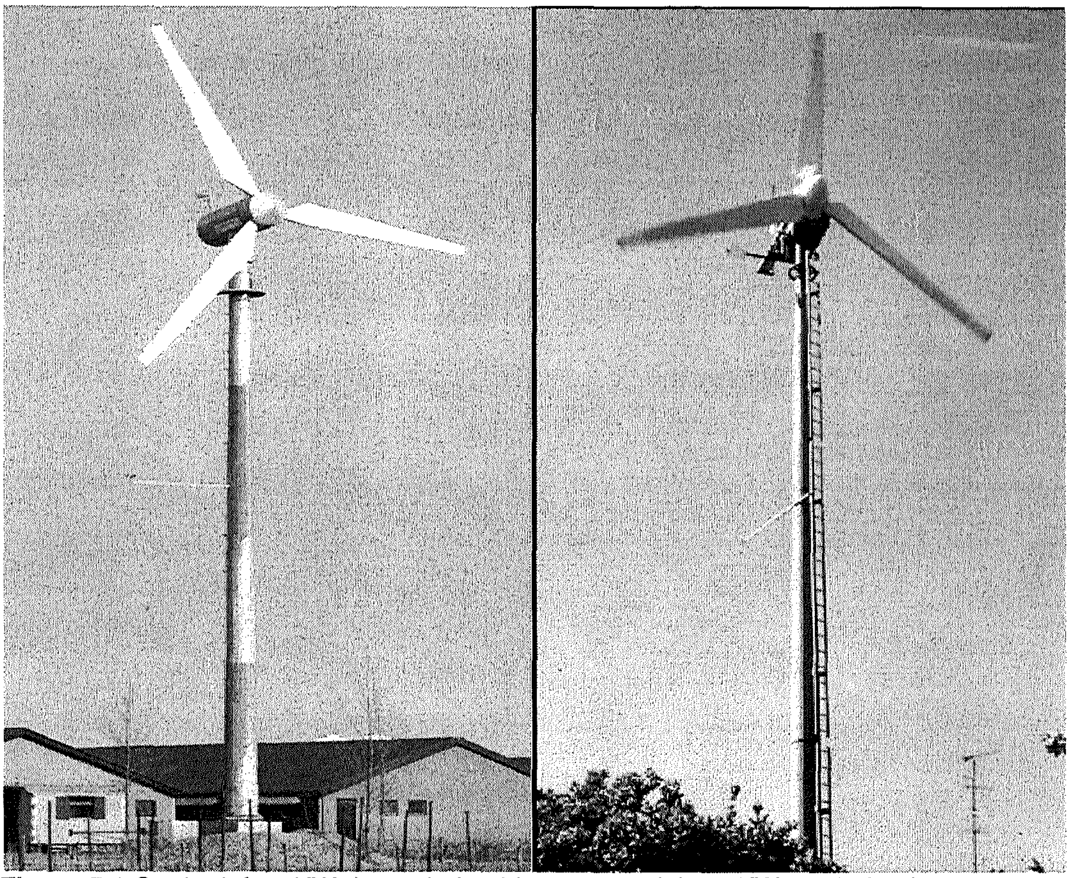


Figure 5.1 On the left 15KW downwind turbine and on right 22KW upwind turbine (Winds of change 2010)

5.2.2 Vertical Axis Wind Turbine (VAWT)

VAWTs come in two different designs depending on the structure of blades, the lift and drag-based design. The most important advantage of vertical axis wind turbines is that they accept wind from any direction. So, the need for complex yaw mechanism is eliminated. The ease of their maintenance is another advantage. Location of gearbox and generator is at the ground level which leads to economical and simple design of the tower (Mathew 2006).

Major drawback of some vertical axis wind turbines is the need for an auxiliary mechanism to start the rotor after every stop. As the rotor does not generate torque when it passes the aerodynamic dead zone, it reduces the efficiency of the machine. Another disadvantage could be seen when the wind is stronger in that the VAWTs have difficulty controlling rotor over-speed.

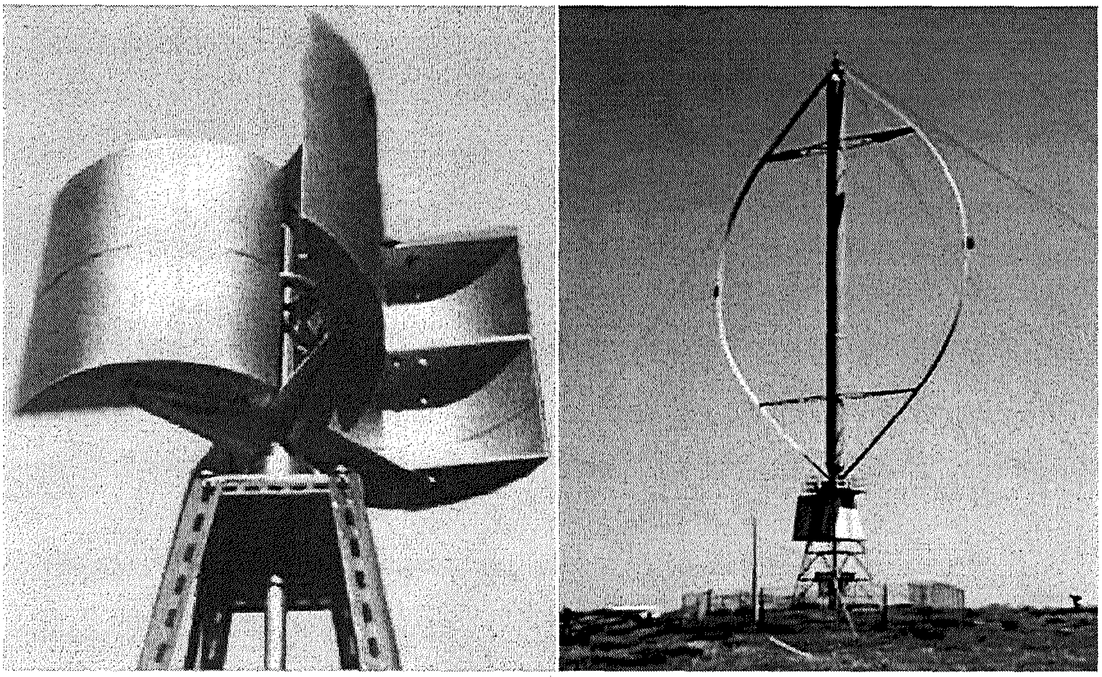


Figure 5.2 The two conventional vertical turbines (from left to right): Savonius and Darrieus (The Green Technology Blog 2010), (Wikipedia 2010).

Primary designs (Savonius and Darrieus) had some weaknesses. However, the most recent designs of vertical axis wind turbines like Aerotecture, Quietrevolution, and Turby overcame these limitations. VAWTs can present an efficient alternative option to generate electricity for urban and rural areas with the capability to operate in low wind speed without noise (Energy Beta 2010). Moreover, in harsh climate characterized by wind fluctuation, high wind turbulence, and directional variability, HAWTs cannot perform well to deliver high efficiencies. Whereas, VAWTs display maturity and capability to operate effectively in such tough conditions (Pope, Dincer et al. 2010).

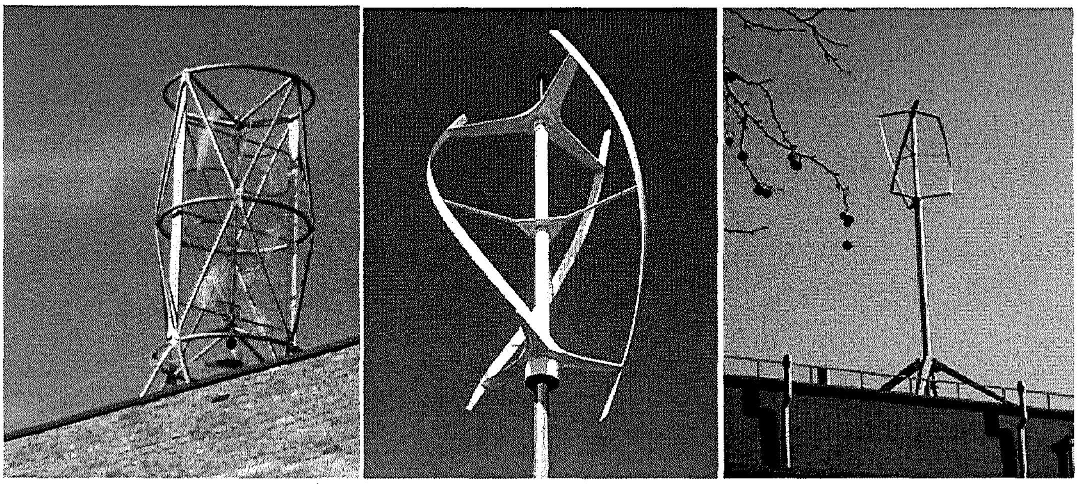


Figure 5.3 The new designs of VAWTs (from left to right): Aerotecture, Quietrevolution, and Turby (Energy Beta 2010)

5.3 Wind energy in United Kingdom

Wind energy contributed slightly fewer than 3% of the electricity generated in the UK in the end of year 2009. This contribution is considerably low compared to the rest of Europe, since Britain has the best wind resource in Europe both for on and offshore wind energy (DECC 2010). In terms of offshore wind alone, Britain has enormous wind energy potential that equals to the third of Europe's offshore wind potential. If this energy could be exploited, it would provide three times over the UK's current electricity demand. The UK wind energy target is 5% by 2010, which requires 6 GW of installed wind capacity (Grimes 2008). Britain had 4616 MW of installed capacity from 264 projects by the end of 2009. Figure 5.4 demonstrates Britain's annual mean wind speed and topographic maps, showing high potential for wind energy capture, especially in Scotland (BWEA 2010). Regarding to UK Renewable 65% of UK electricity generated from onshore wind energy will be coming from Scotland, since Scotland is rich in mountains, hills, and valleys, which are optimal locations where wind stream is strong and stable. Figure 5.5 shows that Scotland has plan to install more than 4GW capacity of onshore wind farm projects in the near future.

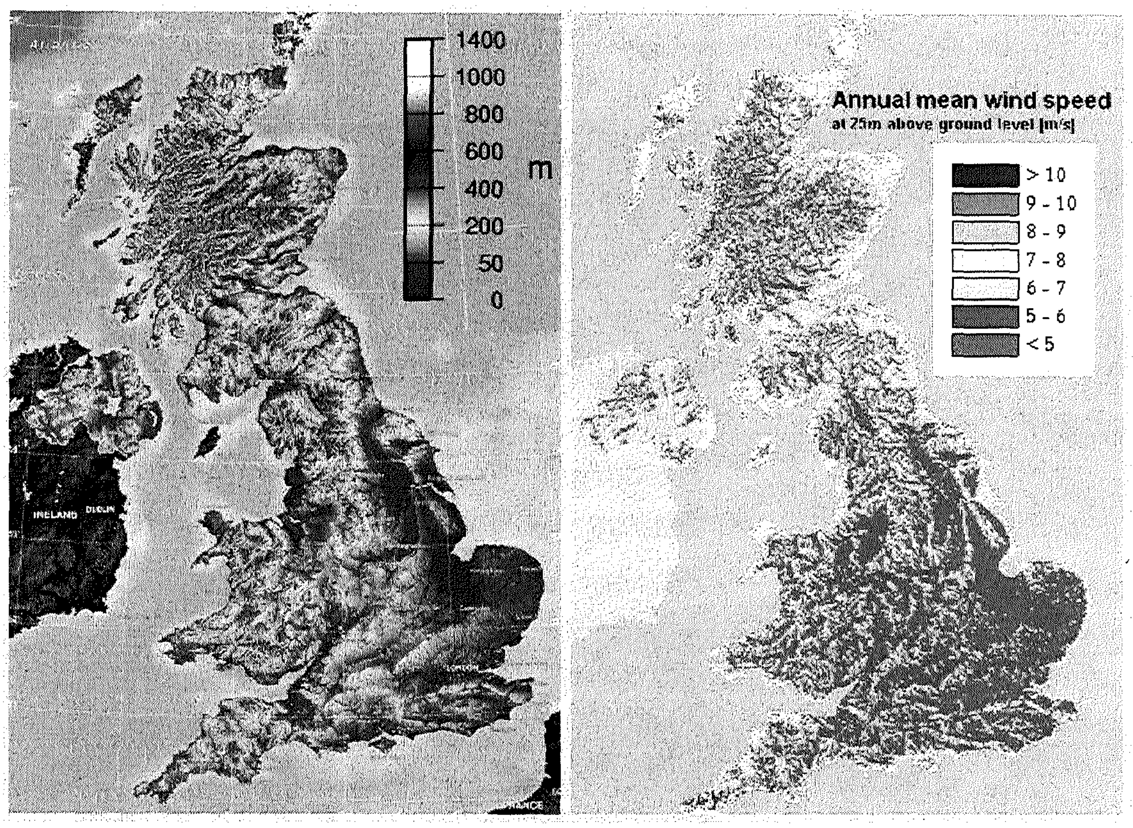


Figure 5.4 UK map showing annual mean wind speeds at 25 m above ground level [m/sec] on right and UK mountains map on left (Renewable UK 2010)

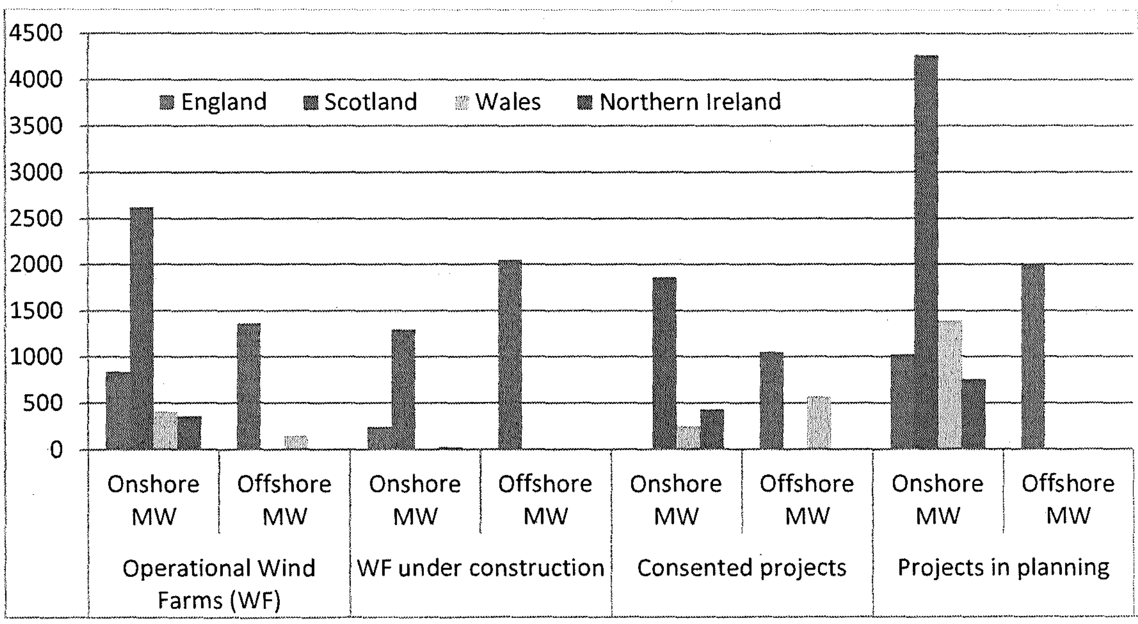


Figure 5.5 Current and future installed capacity of wind farms in United Kingdom(BWEA 2011)

According to the report of UK Energy in Brief 2010, the contribution of renewable sources in the generated electricity by 2009 was 6.7 %, and 42% of this value came from wind energy. Figure 5.6 demonstrates the development of renewable energy in general and wind energy in particular from 2004 to 2009, with annual growth was ranged between 20-25%. In 2009 UK generated 9.592 TWh from wind energy, which is ensured annual electricity demand for more than 3.2 million homes in Great Britain (AEA report to DECC May2010)

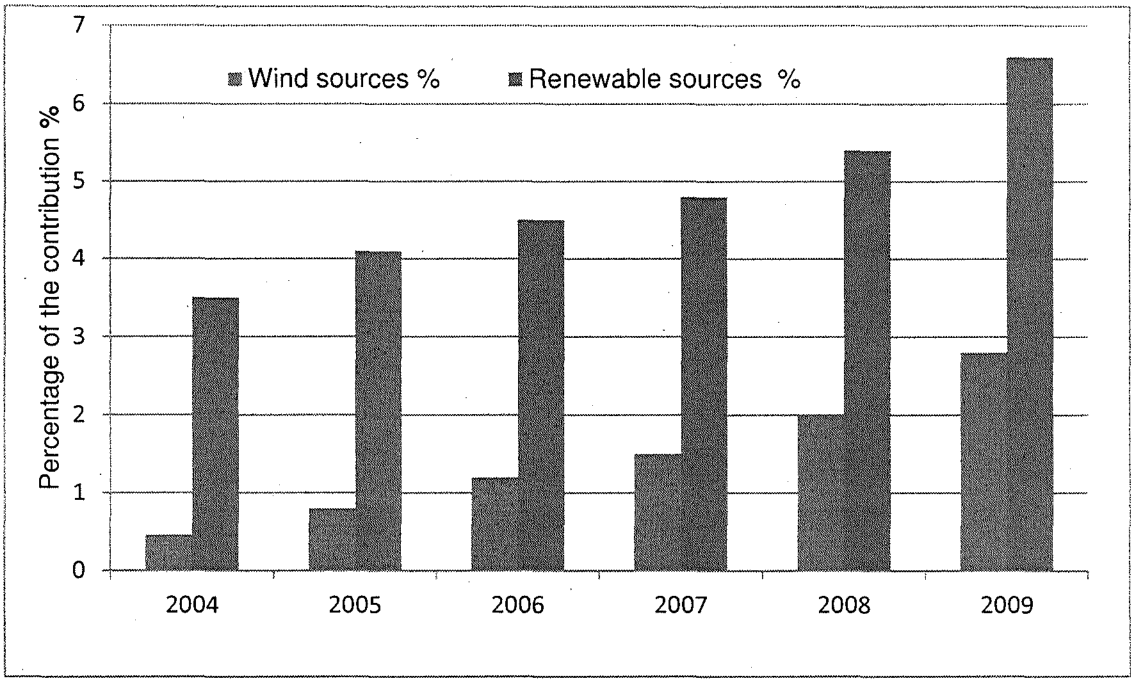


Figure 5.6 Contribution of renewable vs. wind sources to electricity generated in UK (DECC 2010; Wikipedia 2010).

Offshore wind energy market is still in its incipient stage compared to onshore wind, since the industrial attention is being paid to the mature onshore wind market as it has more profitable and less risky investment. Offshore wind energy is more expensive than onshore energy, but capacity factors of offshore wind turbines are higher (up to 40%) than the onshore wind turbines (up to 30%), resulting in higher energy output (Clarke 2009) from the former. Offshore wind has a promising future in Europe with 100 GW of offshore wind projects already in various stages of planning. This will provide up to 10% of European electricity demand while reducing 200 million tonnes of CO_2 emissions a year. The recent total installed capacity and grid connected is 2063 MW in European countries (EWEA 2010). In 2009 the UK became the world leading country for offshore installed wind capacity of over 1GW. However that is considered low capacity comparing to what Britain has from massive potential of offshore wind resources: Irish Sea alone has more than 5 GW offshore potential. The projected 28 GW of offshore wind generating capacity (by 2020) would be producing some 94 TWh annually, almost 26% of 2006 UK electricity demand (Boyle 2006)

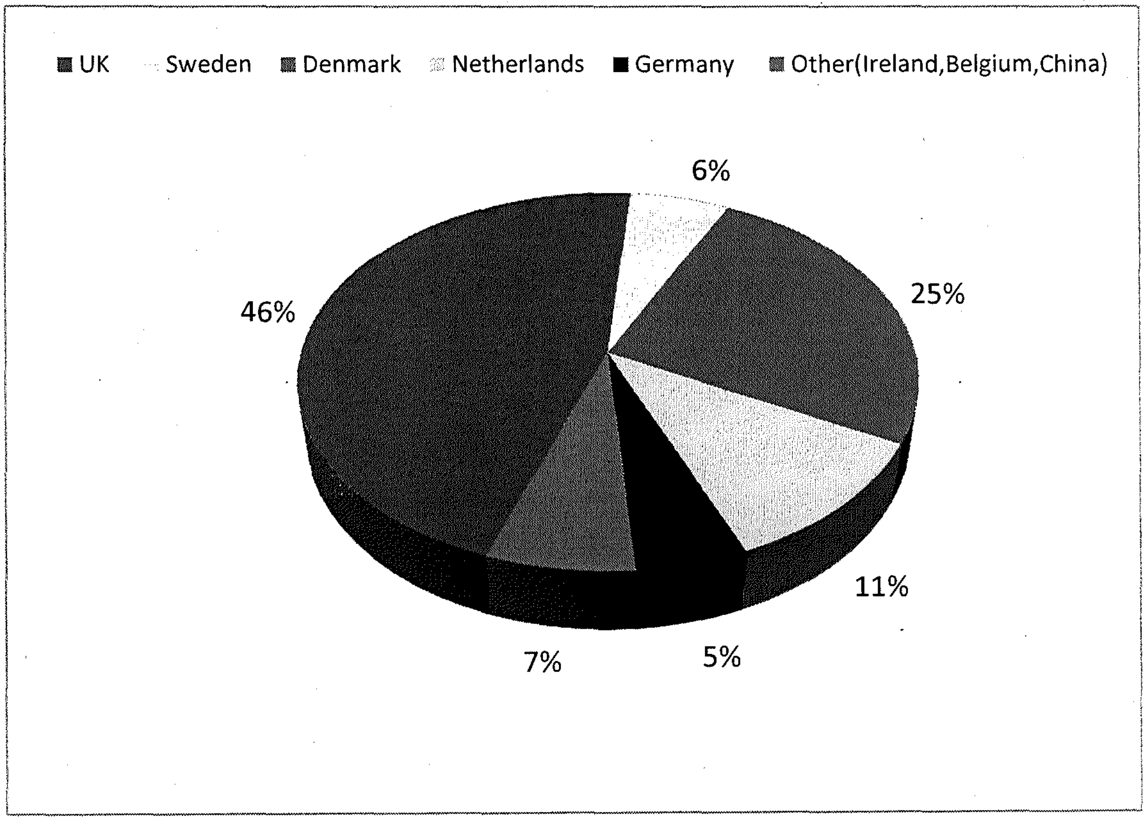


Figure 5.7 World's offshore wind capacity at the end of 2009 (BWEA 2010)

Figure 5.8 Wind turbines at the operational Burbo Bank offshore wind farm (Trine Hoffman Sørensen 2010)

5.5 Small wind turbines

According to British Wind Energy Association (BWEA), depending on the power capacity, small wind turbines can be divided into following three categories:

1. Micro wind turbines (0-1.5 KW)
2. Small wind turbines (1.5-15 KW)
3. Small-medium wind turbines (15-100 KW)

5.5.1 Current global small wind turbine overview

United States of America is the leading producer of small wind turbine globally as per the American Wind Energy Association's (AWEA) 2010 survey. The U.S. small wind market sustained positive growth in 2009 supported by following factors (AWEA 2010):

- US federal incentive, the Investment Tax Credit (ITC), for small wind technology provided financial support for consumers enabling them to purchase qualified small wind systems with rated power capacities of 100 KW and less. The ITC has been restricted by a maximum of 30% of the capital budget allotted to any project. Consequently, the small wind industry will be provided with stable and long-term policy by this federal legislation.

- In 2009, around 80 billion US Dollars were pumped into the market. This external private investment provided the companies with capital to increase production, improve quality, reduce cost, and sustain demand.

- In December 2009, a technical standard to test small wind turbine was prepared by AWEA, whereby a third-party organization can certify that the system in question conforms to the AWEA standard requirements of reliable performance and safety criteria after an average field monitoring period between of 6-12 months. This certification enables manufacturers to supply proved information about reliable performance of the product and its safety issues. The certification process is, therefore, considered as a strong and obvious indicator of improvement and maturity of small wind technology.

- Zoning codes or planning permission to fix this challenge, nine states of USA enacted laws to ensure wind turbine's owner and community have benefited by making the permitting streamlined, affordable, and accountable is increasing awareness of the consumer, environment, and community(AWEA 2008).

- The most important factor in estimating performance of a wind turbine is the average wind speed prevailing on the candidate site. Hence, many companies in private sector have produced an improved resource assessment technology to identify the geographic regions with best wind energy potential. Traditionally, wind resource assessment of any location typically relied on wind maps at a height of 50 m above the ground level. This type of assessment, though useful for large-scale wind turbines, is not helpful for small wind turbines which operate at a lower height. Therefore, wind resources in specific locations are now being evaluated industrially to help in choosing the right wind turbines for those sites.

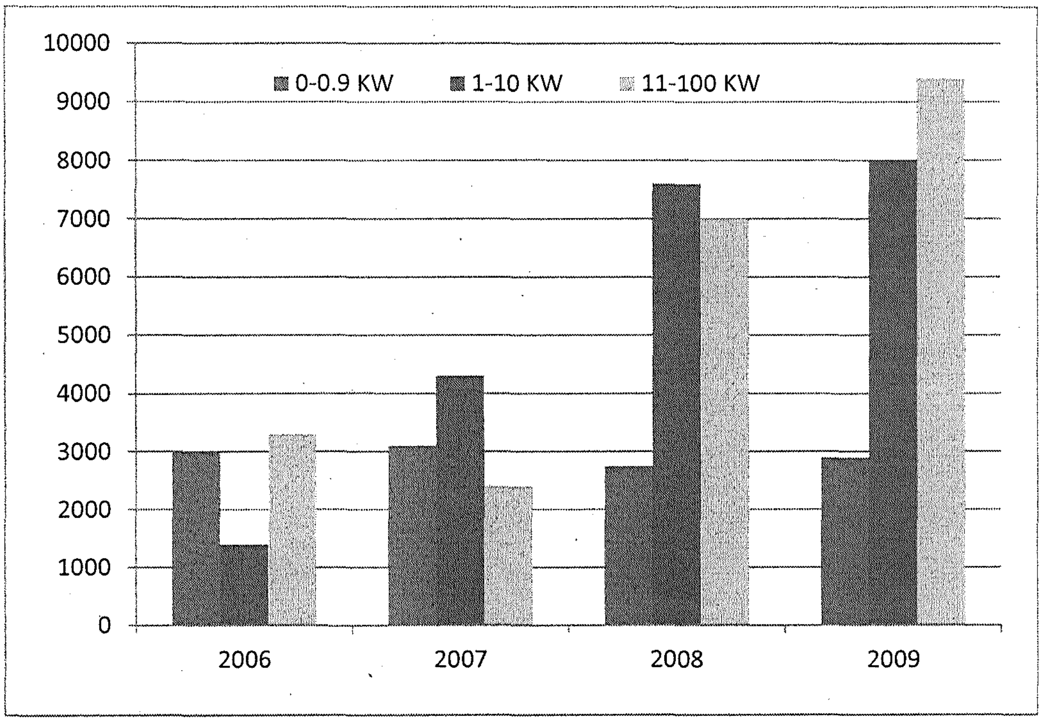


Figure 5.9 Comparison of US annual small wind turbine market growth by segment

The aforesaid factors thus led to positive growth in the small wind turbine market with 2009 seeing an increase of 15 % in the USA installed power capacity compared to 10 % in the rest of the world. However, it is to be noted that the number of sold systems declined by 6%. Figure 5.9 shows the small wind turbine market growth in USA during 2006-2009 that demonstrates an upward market trend toward small and small- medium capacities of wind turbines, grid-tied systems. Since 2007 picture started to change when customers gradually shifted toward on-grid systems which also became a dominant option for commercial/ light industrial market, while sales of off-grid turbines (micro wind turbines with capacity < 1KW) remained flat. It should be mentioned here that 95% of US production of small wind turbine units were sold in the local market. Hence, USA is not a chief exporter of small wind turbines.

Table 5.1 Installed Small wind turbine - global market Shares 2009 and 2008(Ekopolitan 2010)

Manufacturer	Capacity sold globally in 2009 (kW)	Global Share 2009 (%)	Capacity sold globally in 2008 (kW)	Global Share 2008 (%)
Southwest Wind power (US)	11700	27%	10000	26%
Northern Power (US)	9200	22%	4300	11%
Proven Energy (UK)	3700	9%	4800	12%
Wind Energy Solutions (NL)	3700	9%	n/a	n/a
Bergey WindPower (US)	2100	5%	1700	4%
Entegrity Wind Systems (CAN/US)	n/a	n/a	3500	9%
Others	12100	28%	14400	38%
Total	42500	100%	38700	100%

After USA, the next largest global producers are Canada and Great Britain. The annual range of small wind systems installed in Canada is 600-800 units (Canadian Wind Energy Association 2010). In United Kingdom over 3000 units under different segments were installed in 2009 (UK renewable 2010). In-depth analysis of British market is elaborated in the following section.

5.5.2 Market of Small wind systems in United Kingdom

Optimal local wind resource, economic incentives and international competitive manufacturing companies of small wind systems are helping Great Britain to emerge as the pioneer of small wind turbine technology (New Energy Focus 2010). According to RenewableUK, three quarters of local small wind turbine market is provided by 22 British manufacturers. Moreover, UK small wind market has witnessed continued growth. In 2008 local producing exports increased by 45% compared with 2007, and they grew by a further 25% in 2009 (UK renewable 2010). Furthermore, this market is expected to benefit from government motivations and a weaker currency in expanding its growth. Figure 5.10 refers to continuous growth of installed power capacity of small wind systems in Britain since 2005 and predicts the growth in 2010 and 2011.

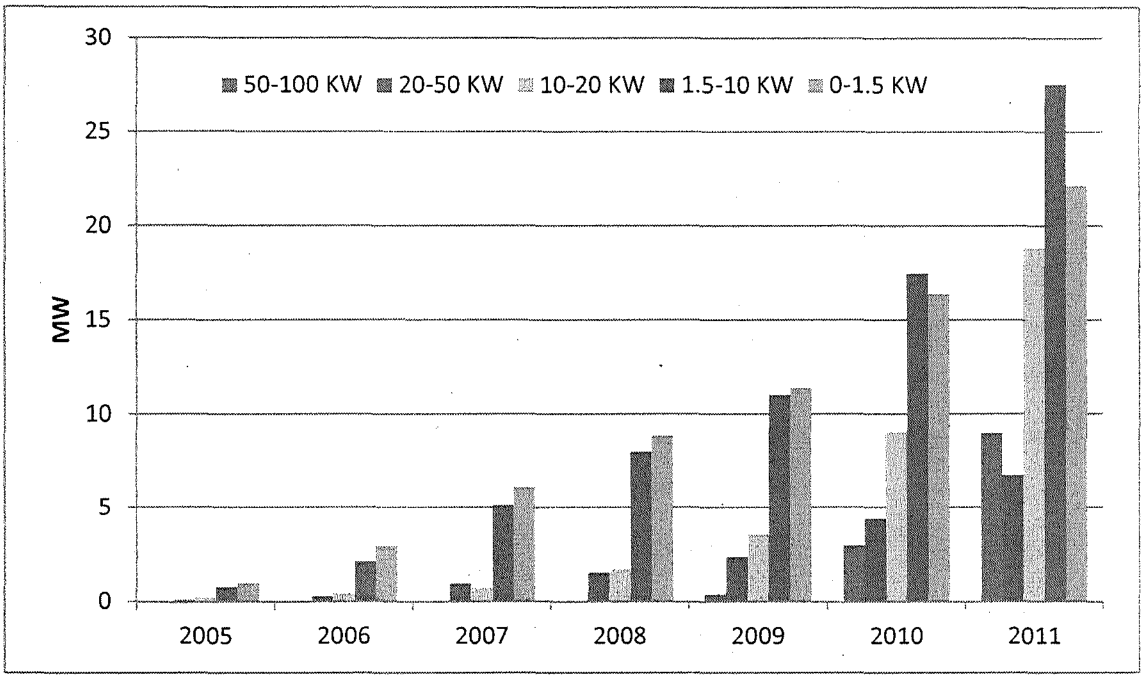


Figure 5.10 Cumulative installed power capacity small wind systems (MW) by segment in UK

5.6 Micro wind turbine systems

There are a large number of wind turbine manufacturers worldwide producing small wind turbines, but only a few companies are manufacturing micro wind turbines for building mounted turbine market. These producers are mainly based in Japan, United Kingdom, Spain, Italy, Netherland, and Finland. While British and Japanese manufacturers are mainly focusing on the development of horizontal axis wind turbine technology, other countries are concentrating on vertical axis wind turbine technology development.

The following section discusses the growth of British micro wind turbine market, and then reviews the results of installation of small wind turbine from individual, industrial and academic perspectives.

5.7 United Kingdom micro wind turbine market overview

The building mounted-wind turbines (MWTs) market has been witnessing increased growth through the last 5 years. In 2005 only two systems were installed, however now there are more than 2432 existing systems in the UK (Renewable UK 2010). Figure 5.10 demonstrates the UK market growth of MWTs since 2005.

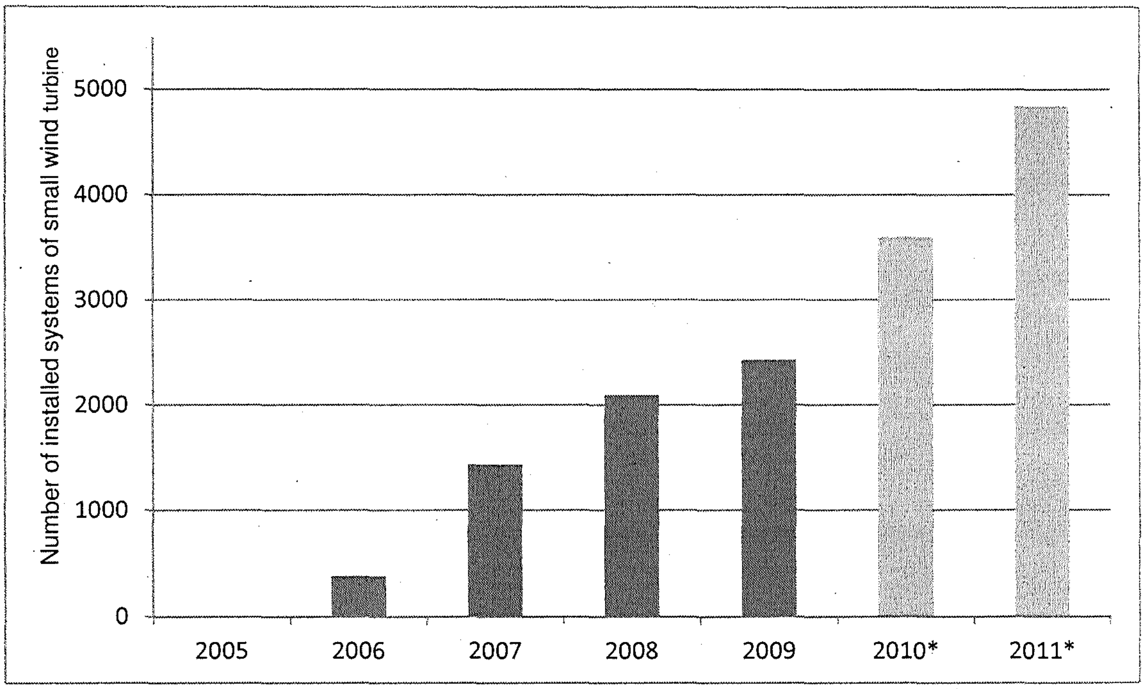


Figure 5.11 Cumulative number of building mounted wind systems installed in the UK (Renewable UK 2010)

In the beginning systems were mostly designed for rural sites with sufficient wind resources. However, the majority of domestic homes are located in built environments where the wind energy potential is greatly decreased owing to obstruction. Moreover, only 19.3% of the UK population lives in rural areas while the rest (80.7%) are urban-dwellers (DEFRA 2005).To increase the potential market size, manufacturers have now developed turbines targeting the urban market. Such systems are positioned on roof of buildings which are light enough to install on domestic homes. Manufacturers devised this solution to overcome the obstacle of limitation and high value of land in urban areas. Roof-mounted wind system technologies can either be connected directly to the grid (on-grid systems) or they may be used to generate electricity for immediate consumption or to charge batteries (stand-alone systems). The on-grid system is expected to have a considerable growth in the near future. The off-grid system of domestic wind turbine is predicted to experience steady growth in the upcoming years. Figure 5.12 depicts the total number of small wind systems installation under both types in the UK since 2005, in addition to extrapolated forecast for 2010 and 2011.

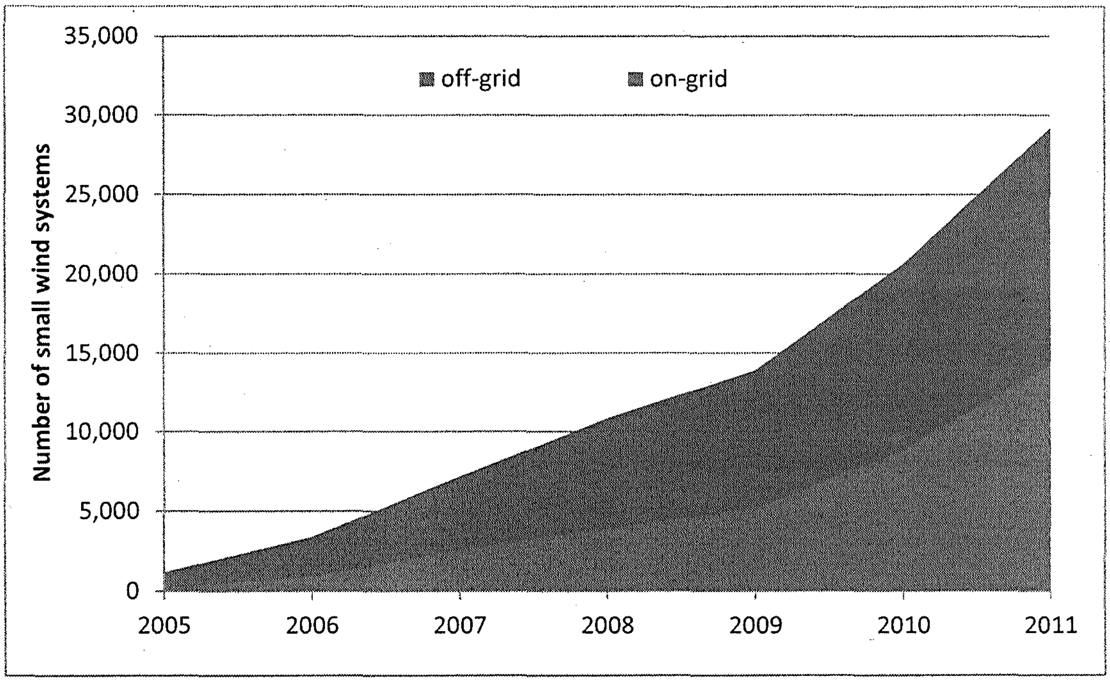


Figure 5.12 Cumulative number of on-grid/off-grid connection system of wind turbine (Renewable UK 2010).

5.8 Case studies for roof-top mounted micro-wind turbines within UK

5.8.1Building Research Establishment (BRE) study

The Building Research Establishment (BRE) is an independent (previously government) laboratory. Their report (BRE, 2007) on micro-wind turbines examined the carbon and financial payback times that can be expected from typical domestic micro-wind turbine installations in a range of representative locations in Manchester, Portsmouth and Wick. The report describes the financial and carbon costs of manufacturing, installation and maintenance and compares them with the likely carbon and cost savings made by the electricity generated during their useful life.

The results show that, in windy locations such as the outskirts of Wick and parts of Portsmouth, domestic micro-wind turbines can generate sufficient energy to pay back their carbon costs within a few months to a few years and then go on to make a positive contribution to combating global warming. However, in less windy urban areas such as Manchester they are very unlikely to ever pay back their carbon costs. Even when optimally sited outside of major conurbations, financial payback is unlikely for all but the most efficient, low maintenance, low price turbines.

The report shows that performance is highly sensitive to relatively small changes in local wind conditions (standard performance calculations are usually based on wind speed databases, which don't account for surface roughness and local effects), installation and maintenance regimes (including associated transport costs) and expected service life.

The report also highlights the need for manufacturers to develop more efficient turbines with low maintenance and a long reliable life and for those planning to install them to first take account of local wind conditions.

5.8.2 Roof-top mounted micro-wind turbine on a London home

Mr McCarthy (2007) has enumerated his experience of urban, roof-top turbine in an article in *The Independent*. He lives in a Victorian house in London. About four years ago he installed a micro-wind turbine with a nominal rated power of 1kW. Having spent a total of £2,700 on the machine he found that the 'output was barely enough to supply an energy-efficient light bulb – about £2 worth per year'.

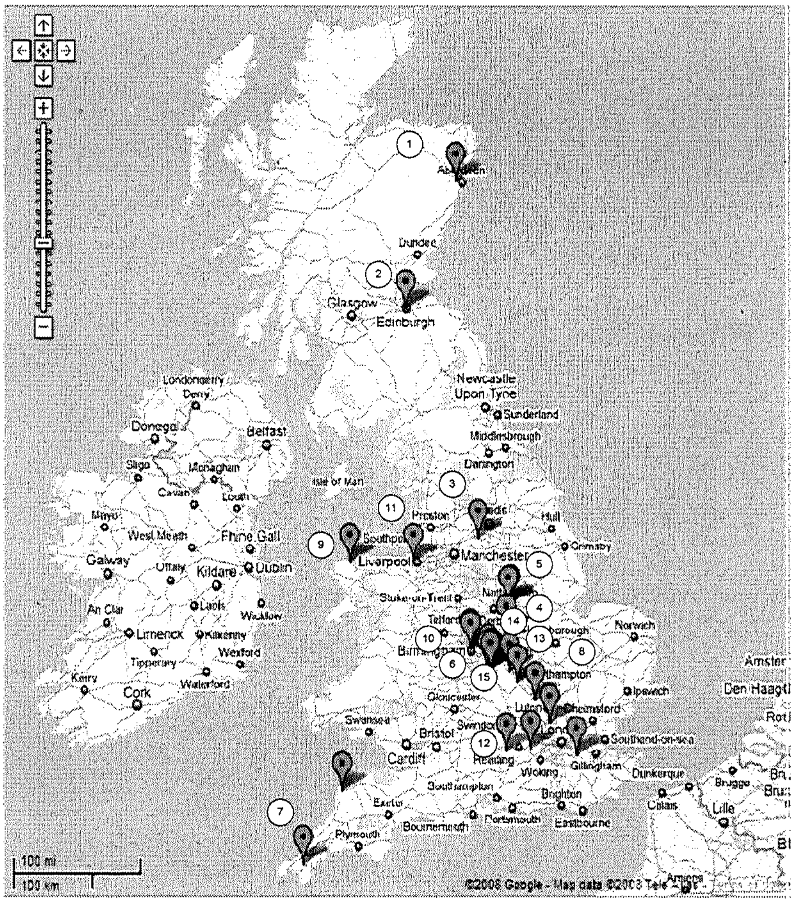
5.8.3 Warwick micro wind turbines study

'Warwick micro-wind turbine trials' represented a collection of test results from a total of 26 building mounted wind turbines, including the Edinburgh Napier University installation, from local manufacturers within Britain during 2007-2009. A general summary and findings of the report, concluded in mid of 2009, are as follows:

- First large scale multi-turbine / multi-site trial in the world of wind turbines in the 0.5-1.5kW range
- Open field, urban and suburban housing, high-rise building installations investigated
- Wide range of mounting systems
- All turbines installed for real clients
- So far the general marketing hype is widely ahead of actual technical deliverability
- Some companies are grossly over-representing the potential for energy delivered from urban wind
- Most low-rise sheltered urban & suburban sites make no economic sense at current grid energy costs
- Building mounting concerns, i.e. structural integrity can be overcome but at a cost

Figure 5.13 shows the location map for Warwick study and the average energy output in Wh/day.

It is to be noted that the annual outputs range between 18 and 657 kWh. In contrast the average electricity demand for a typical dwelling house in the UK is 3,000 kWh/ annum.



No.	Site name
1	Aberdeen
2	Napier
3	Huddersfield
4	Leicester
5	Nottingham
6	Lillington Road
7	Hill Close Gardens
8	Daventry Civic Centre
9	Princes Drive
10	Eden Court
11	Delta Court
12	Thatcham
13	West staddon
14	Sumerfield Crescent
15	Tannery Court

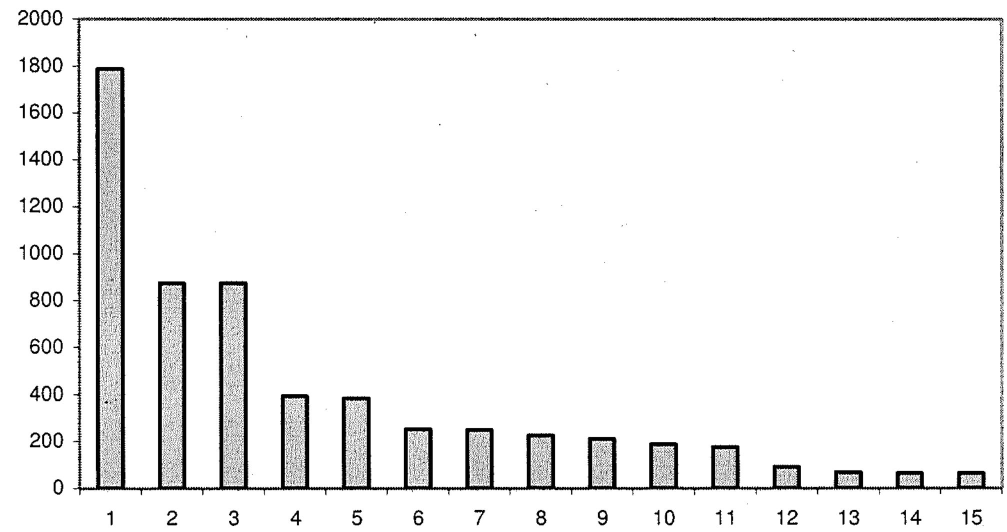


Figure 5.13: Micro-wind turbine trials within Britain: average energy generated per day, Wh for the 15 locations shown on the map (top).

5.8.4 Edinburgh Napier University case study

Figure 5.14 shows the results from author's own measurement of the Air-Dolphin micro wind turbine output. Note that the expected annual energy output is 331kWh which substantially falls short of required domestic demand of 3,000 kWh. Note also that the predicted output from locally measured wind-speed data is 18% lower. The capacity factor for this machine is 4%.The clear differences between produced and computed energy output in the Apr2009,May09,and Jun2009 are referred to technical problem in the wind turbine system as load was broken which affected electricity dumping. Turbulent nature of wind stream and fast wind direction variations have substantial role on the wind turbine productivity and efficiency.

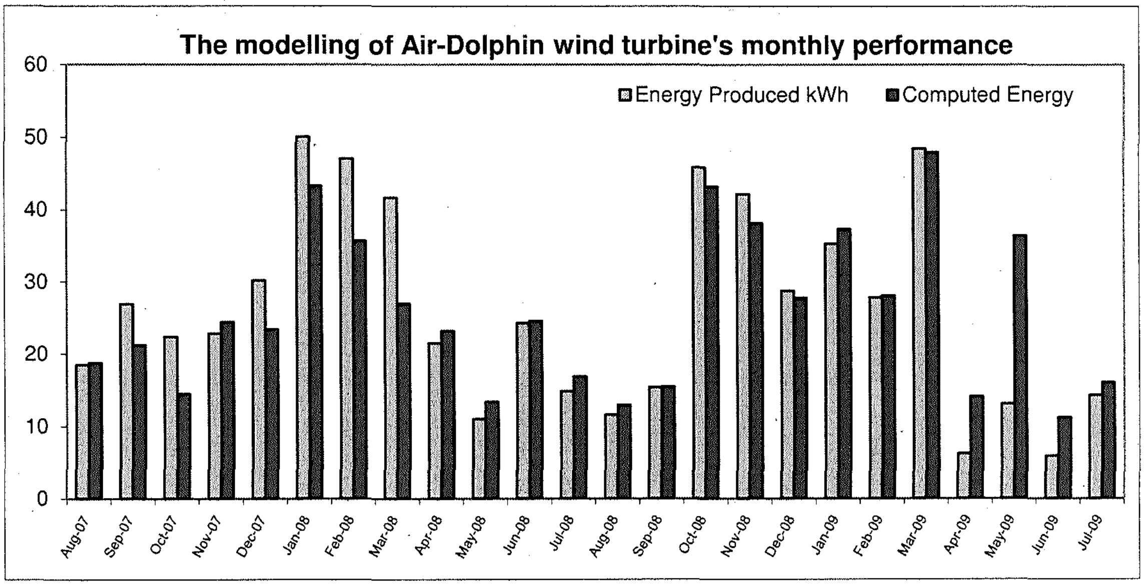


Figure 5.14 Napier University Air-Dolphin micro-wind turbine monthly energy production profile

The performance of Air-Dolphin (AD) micro-wind turbine in built environment for three different locations, namely Leicester, Edinburgh, and Nottingham, is compared against the manufacturer power curve. The actual power curves are created using measured wind speed and energy output from each site. As can be noted from Figure 5.15, there is a considerable discrepancy between the manufacturer claim and the urban area production of wind turbine. However, there is only a slight difference among the sites' actual power curves. Edinburgh has the best wind resource among the three cities, therefore, its wind turbine performed slightly better than the others. Also, as mentioned above the capacity factor for this wind turbine in Edinburgh Napier University is 4%, while for

Leicester and Nottingham sites it is 3% and 2.6%, respectively. The large difference between the actual power curves, presented in Figure 5.15, and manufacturer's one can be referred to producer power curves usually are achieved in controlled conditions (e.g. in wind tunnel), where the local effects of wind speed and direction variations, presence of turbulence, and overall dynamics of wind turbine are regularly not totally represented. Accordingly, if the manufacturer power curve is employed for estimation of energy projection that will usually result in overestimated energy outputs.

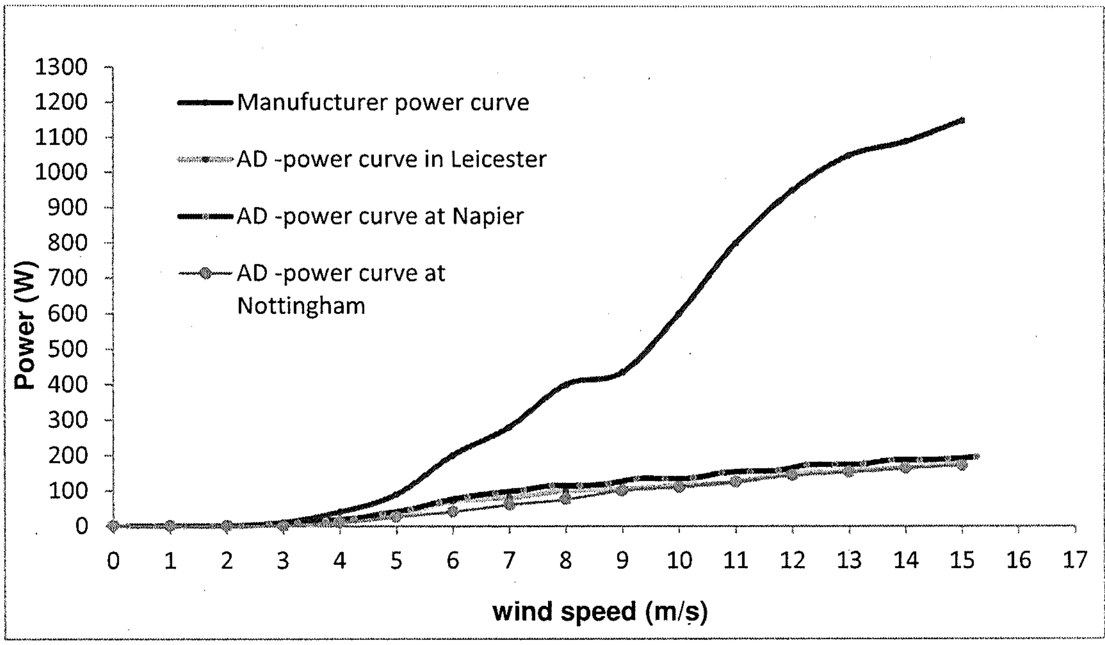


Figure 5.15 Actual power curves of same wind turbine for three different locations compared with manufacturer power curve.

5.9 Case studies for midi-wind turbines

5.9.1 The Nenthead (Alston, Cumbria) turbine

This proven, 6kW (WT6000) machine located at Nenthead (Longitude N54.79879°, Latitude: 2.35369°, Altitude: 490m) has a 9.5m mast and an SMA windy boy 6kW inverter. Between 13/02/2007 and 19/02/2008 (total number of hours = 7195hours) it produced a total of 14,208 kWh of energy. The turbine came off line 6-8 times due to grid failure and hence was off line for 6 days. This project received a 'Clear sky' grant of £5,000. An additional contribution of £15,000 was made by the owners. This turbine's capacity factor is 33%.

Figure 5.16 Proven WT6000 turbine is at Nenthead, Cumbria

5.9.2 The Cockermouth eco-school wind turbine case study

A Proven 6kW machine was installed at the Cockermouth School's eco centre in late 2006. The turbine, mounted on a 9m high mast has operated for the past 18 months and produced 7MWh/annum of energy with a capacity factor of 13%. The mast is lower than what the supplier had wished and this was due to the local Planning Authority restrictions. Furthermore, although the turbine is located on a slight rise above the general level of its environs, there are several school buildings in close proximity that are likely to cause turbulence. This may account for the lower capacity factor. However, this situation may not be far off from most suburban environs.

Figure 5.17 proven WT6000 turbine at Cockermouth

5.9.3 The Higher Meadow Head Farm (Lancashire) turbine

Situated in rural Lancashire on a farm within a valley, this 6kW Proven turbine is also an example of good performance as can be seen from Table 4. This machine, owned by Chris Driver, was commissioned on September 21st, 2006 but started producing power from October 2nd of the same year. In the year and a half of operation the machine had two downtimes of three weeks each: in November 2007 the generator coil was burnt followed by a cracked magnet during Christmas season. The capacity factor for this machine is 25%.

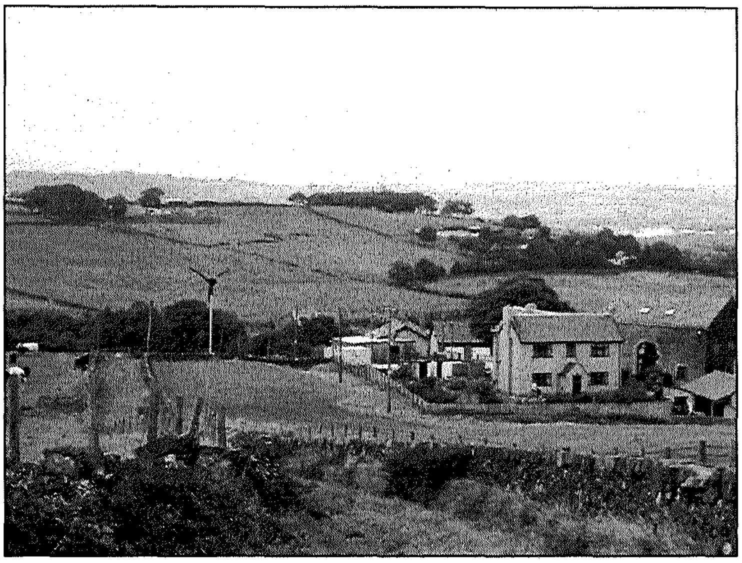


Figure 5.18 proven WT6000 turbine at Lancashire

Table 5.2 Performance of the wind turbine at Higher Meadow Head Farm, Lancashire

Date	Import @ night-rate	Import @ day-rate	Total import	Energy produced KWh
Oct 2, 2006	0	0	0	0
Oct 31, 2006	223	186	409	888
Dec 1, 2006	292	193	485	1630
Jan 1, 2007	330	319	649	1611
Feb 1, 2007	271	198	469	2098
Mar 1, 2007	371	346	717	836
Apr 1, 2007	306	163	469	1344
May 1, 2007	337	162	499	657
Jun 1, 2007	266	208	474	784
Jun 20, 2007	203	154	357	187
May 2, 2008	3075	2492	5567	10469
Totals	**5674**	**4421**	**10095**	**20504**

5.9.4 The Kirklees Town-Council turbine case study

The turbines at Civic 3 building, located within Huddersfield town centre, are the first roof mounted wind turbines on a local authority building in the UK. The whole demonstration project is part of a European-funded project called 'ZEN' (Zero Emissions Neighbourhoods). A large array ($143m^2$) of solar PV panels and two 6kW wind turbines are providing 94MWh of the total required electricity of 1175MWh/annum.

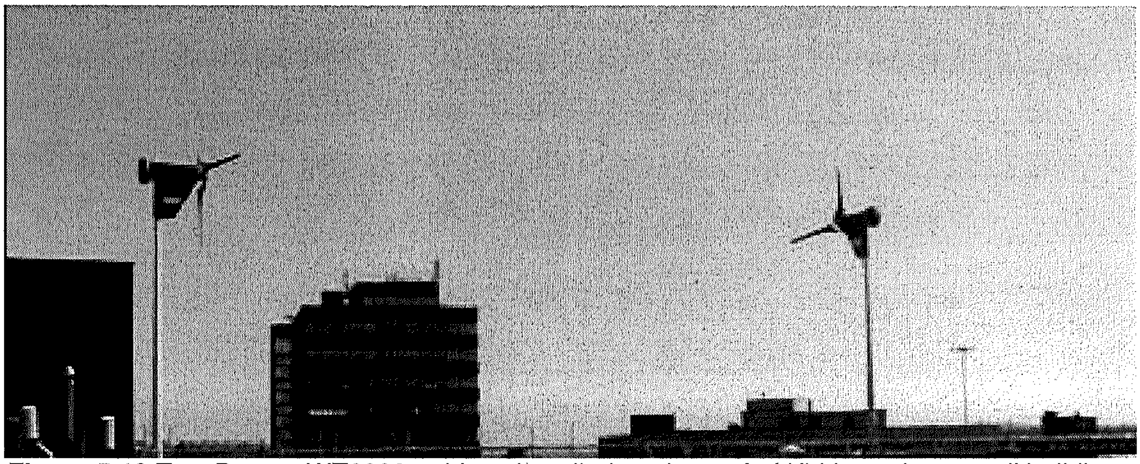


Figure 5.19 Two Proven WT6000 turbines installed on the roof of Kirklees city council building

5.10 Obstacles facing implementation of small wind turbine in urban areas

The most important problems facing the development of small wind turbine technology in built environment are technical hurdles relating to assessment of wind regime at set up location, suitability and reliability of wind turbine design itself, maintenance considerations, and impact of conversion wind system operation on the building and neighbourhood, likes noise level and vibration transition. In addition, there are non-technical barriers, which are not less important than the former ones. Those hurdles are related to the development of GIS system providing more dependable data to determine wind and solar energy potential in the built in areas, in addition to planning, permission and capital cost (Dutton.G.A 2005).

5.10.1 Technical Obstacles restricting building mounted turbines

5.10.1.1 Assessment of wind regime in urban area

Evaluation of wind resources could be done through obtaining mean wind speed for any location within UK NOABL database, which can be accessed via British wind energy association web site(www.bwea.com/nobal). The required user input is only the post code of the location, since NOABL model provides the average wind speed for a square kilometre (Syngellakis.K;Traylor.H 2007). The method of NOBAL model is not effectively beneficial for wind resource assessment in urban areas, due to its non-inclusion of the local topographical features for instance, the building intensity, forests, hills or valleys, which could have considerable effects on wind regime.

There are topographical models available; models that use computer programs such as WAsP, WindFarm or WindFarmer, which consider the effect of elevation of location to sea level, and roughness of ground surface. The above-mentioned computer programs must be supplied with local data for candidate location, that could either be from the nearest metrological station measurements or from other related wind recorded data. This kind of computer packages, without carrying out actual wind measurement, can provide higher accuracy level for wind resource estimation compared to NOBAL model. However this method is not an alternative to direct measurement, it only gives on-site suggestions where direct measurement would offer effective results. Furthermore, using some wind turbine computer programs can enable user to estimate the annual energy output of the wind turbine, noise level, and visual impact at certain location.

The most reliable option to perform accurate site wind resource assessment is to measure the wind speed on the candidate location at the optimal hub height of the proposed turbine in order to eliminate any suspicion arising from predicting wind shear. Measurement at a lower and higher height on the mast is also recommended, as it supplies clearer vision about the development of wind shear, and the combination between height and energy output. Measuring instruments are mounted on booms sticking out laterally form the mast to avoid the aerodynamic effect of the mast on the performance of the instruments. The standard apparatus for measuring wind speed is the vigorous and cheap cup anemometer. Figure 5.20 shows the development of wind speed profile in urban, suburban or rural, and open areas.

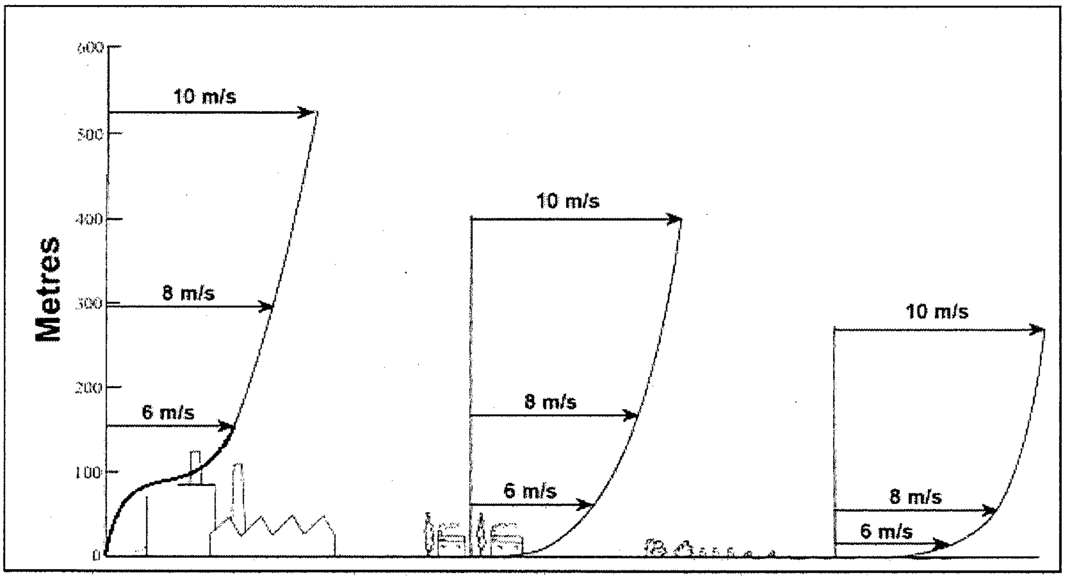


Figure 5.20 mean wind speed profiles over different terrains

5.10.1.2 Reliability of wind turbine performance

The reliability of micro wind turbine is a crucial issue in evaluating the success of any wind turbine project. Low reliability mainly affects revenue of the project, and raises the operation and maintenance costs, in addition to reducing the availability of wind turbine to generate electricity. Warwick MWTs project highlighted a group of reliability issues and three of these cases have been experienced with Edinburgh Napier MWTs research project. The technical reliability problems of micro wind turbines can be summarized in the following points:

- Lack of durability testing of micro wind turbine body including blades, tail hub, and nacelle, as mention in Chapter 3. Ampair 600 turbine was completely damaged at its blades and tail on that gusty and turbulent day; At Merchiston site, even the air-Dolphin turbine had tail failure once.
- Occasional failure of inverter and control systems in vulnerable working conditions, like in urban areas or under gusty and turbulent wind regimes.
- Noise emanating from some of MWTs led to these machines being permanently switched off as a result of complaints by the neighbourhood

residents. According to council health and safety officer statement the turbines' noise level exceeded the maximum allowed limit (Encraft 2009).

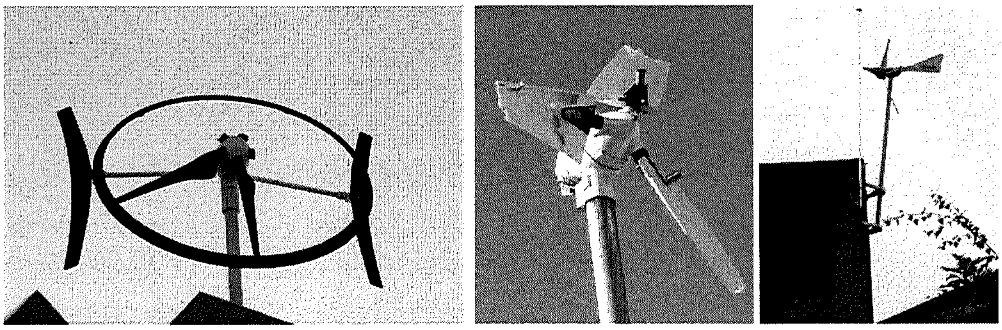


Figure 5.21 Structural failures for turbines in the Warwick wind trial (Hailes 2008).

Both the manufacturers as well as installers are responsible for reliability issues. In other words, it may not always be a manufacturing defect. Sometimes, mistakes are made during installation which affects the turbine reliability. Most of these problems occurred when UK micro wind turbine industry was still in its immaturity. However, the manufacturers' response to those issues was acceptable and positive. British Wind Energy Association set a performance and safety standard for small wind turbines on 29th February 2008 as a guide for manufacturers and installers. Performance testing, acoustic noise testing, durability and safety testing are covered by this standard.

5.10.1.3 Noise emissions and vibration transition

Noise is a critical issue in public acceptance of wind turbine installation in built environment. The noise emitted is essentially a function of tip speed and blade shape; therefore it depends on aerodynamic structure of the wind turbine. In many cases of urban environment projects the ambient background noise is louder than the turbine's standard operational noise (which tends to be around 40dB), such as in Zephyr Air Dolphin (Chris Johnson 2008).However, during Warwick trial of micro wind turbine negative experiences happened due to noise, vibration, and collapse by strong and turbulent wind (Cace.J 2007); in three cases turbines had to be switched off over night due to noise levels. Figure 5.22 graphically represents the acoustic test of Whisper 0.9 KW wind turbine during its operation compared with background sound. It provides a clear vision about noise emission of micro wind turbine, regarding to planning for renewable energy a companion guide to PPS22 (2004), "generally, the noise limits should be set comparative to the existing background noise at the nearest noise-sensitive properties and the limits should reflect the variation in both turbine source noise and background noise with wind speed." In the light of this practice the noise from wind turbine should be limited to 5dB above background noise for both day and night periods. It should be borne in mind that noise from wind turbine is not a part of background noise. Therefore, accordingly to British standard Whisper 900 wind turbine is considered fail, since wind turbine noise is exceeded the limit at low wind speed till 6 m/s.

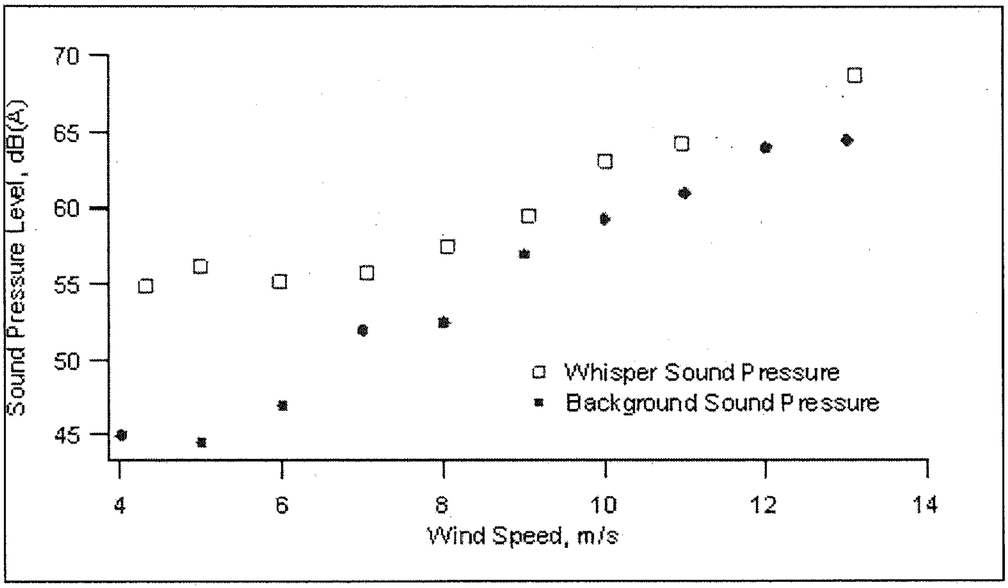


Figure 5.22 Measured sound power levels of a Southwest Whisper 900 wind turbine (Rogers.L.A 2006)

Vibration, generated by the high rotational speed of HAWTs, is another important issue for building mounted wind turbines. Vibrations are transmitted down the mast, through the support foundation and into the structure of the building that raise concern among the residences about their possible damage to the buildings. Therefore, several roof-topped micro wind turbines were stopped during windy night due to vibration transmittance. Manufacturers have taken this serious problem into account and have developed mechanisms to mitigate and absorb the vibrations. Either of the two methods can be employed to remove vibration transmittance from a building: first, by fastening anti-vibration mountings with mass dampeners along the mast, and second, by installing mast fastens alongside a house taking all vertical load and part of horizontal load away from the property (Chris Johnson 2008).

5.10.2 Non- technical obstacles restricting building mounted turbines

5.10.2.1 Development of GIS system providing detailed data for urban areas

Evaluation of local wind energy potential in urban location needs to taken into a designer's consideration along with spatial features of the site including building shapes, height and wall constructions (i.e. roughness degree and building density distribution). Developing a robust geographical information system that includes the area's topography, morphology, and construction can help in increasing the accuracy of estimating wind energy yield in built in environment. Such a system will be crucial in identifying the best wind potential sites for installing wind turbine (Dutton.G.A 2005).

5.10.2.2 Capital cost

The overall cost for small wind turbine system is an inhibiting factor in the widespread adoption of small wind technology. For instance, 1KW system positioned on a site costs around £3000, including wind turbine, mast, connection cables and all required accessories, and operation and maintenance contract. However, for a typically installed micro wind turbine in an urban location with annual average wind speed of 4 m/s and estimated energy output of 600 KWh, considering the lifetime tariff of UK new feed-in tariff 20p/KWh (Department of Energy and Climate Change 2010), the payback period will be 25 years. This cost is not taking into consideration the Scottish Community and Householder Renewables Initiative (SCHRI) grant, which provides grants for 30% of the installed cost (up to £4,000) and this could reduce the payback period by 7.5 years.

5.10.2.3 Planning permission

Local governments are responsible for planning permission of renewable micro generation development (such as wind, solar, biomass, and hydro) within their boundaries. When property owner applies for permission to install small wind turbine on roof of his house or on free stand, department of planning permission will take in account a number of issues including noise, vibration, and potential interference with radar and aircraft communications, visual impact and effects on ecology (RenewableUK 2010), for which they use the following statements as guideline:

- Planning policy statement 22(PPS22) in England (Office of Deputy Prime Minister 2004).
- National planning policy guideline 6 (NPPG6) for renewable energy developments in Scotland (Scottish Executive 2000).
- Planning policy Wales ,March 2002 (BWEA 2009).
- Planning policy statement 18 (PPS18) for Renewable Energy in Ireland (BWEA 2009).

The previous statements were mainly designed to deal with wind farms of large scale of wind power technologies. With respect to micro wind turbine the documents were poor and superficial. However, some local authorities (such as Merton council) produced their own framework, which became a part of national planning guideline committed to renewable energy in the built environment, providing other authorities a good example to follow (Merton Council 2010). Later the government revealed permitted development rights which announced exemption from planning permission for installing a range of micro-scale renewable technologies in urban area provided certain conditions are met. For instance, installation of a micro wind turbine in built environment is subject to maximum height (3 m), rotor diameter (2.2 m), noise limit (45 dB), and micro generation certification scheme (installed and certified).

5.11 UK small wind incentives

Incentives can be crucially vital in helping the achievement of renewable energy technologies. Government and small wind turbine companies are working along with other supportive organisations to stimulate economic support for people who are interested in generating their own electricity from wind turbines installed on their houses .Therefore, incentive systems are in operation in Great Britain throughout financial grants and feed in tariff.

5.11.1 Governmental grants

Governmental fund is provided for small scale renewable technologies by Low Carbon Buildings Programme (LCBP), which is managed by the Energy Saving

Trust. Grants towards installing small scale wind turbines are available for householders, community organisations, schools, the public and not-for-profit sector, and private businesses. In order to qualify for funding, applicants must first carry out a number of energy efficiency measures (Environmental Protection UK 2007). In 2008 approximately around 14% of LCBP budget (£1,500000 in funds) was committed to help in installation of all small wind turbines (BERR 2008).

5.11.2 Climate Change Levy (CCL) discount scheme

The Climate Change Levy (CCL) is a tax on energy delivered to non-domestic users in the United Kingdom. It aims to provide a motivation for industrial, agricultural, public, and commercial sectors to increase energy efficiency and to reduce carbon emissions of greenhouse gases. It came into force on1st of April 2001, according to which energy supplier pays the levy to Customs and Excise and passes the cost through to customers. The CCL is applied at different rates, depending on the energy content of the different sources: Liquefied petroleum gas (LPG) at 0.96 p/kg; natural gas at 0.15 p/kWh, and electricity at 0.43 p/kWh (Carbon Trust 2006). Only electricity generated from renewable resources is exempt from CCL.

5.11.3 Renewable obligation certificates

The Renewable Obligation Certificate scheme (ROC) is a major support mechanism for renewable projects generating electricity in United Kingdom. According to this obligation, all British electricity suppliers have to gradually increase the proportion of their electricity from renewable sources. Office of gas and electricity market (Ofgem) administrates the Renewable obligation. They have been issuing Renewable Obligation Certificates (ROCs) to renewable electricity generators, since ROC scheme came into effect in April 2002 (Mitchell, Bauknecht et al. 2006). When suppliers cannot meet their obligations they must pay an equivalent amount into a fund. The initial value of the ROC was £30, hence an ROC equals to 1000KWh or 1MWh, and the buy-out price for the 2009-10 obligation periods is £37.19 and will be £36.99 for the 2010-11 obligation periods (Ofgem 2010). A simple calculation shows an annual income of around £ 25 can be claimed from a 1 KW micro wind turbine connected to the grid and installed at a place with good wind energy potential producing 650 KWh. The ROC scheme is clearly designed to develop large scale renewable energy projects. There is only minimal incentive with respect to small scale systems and therefore, a real need to produce a feed-in tariff motivating renewable micro generation by minimizing the payback period.

5.11.4 Feed-in tariff (FiT)

The ROC was not created with small scale renewable technologies in mind; therefore the scheme failed to motivate investment in micro generators. Introduction of feed-in tariffs for small scale low carbon electricity generation was thus justified. By feed-in scheme, which came into effect on 1st of April 2010, government intends to encourage people to install more small scale low carbon electricity generators. Anyone generating electricity from renewable technologies with capacity under 5 MW is eligible to be paid for the energy that he generated (Department of Energy and Climate Change 2010). Table 5.3 provides the first year generated electricity rates for all technologies. It is useful to mention here that there is a digression rate of 9% per year.

Table 5.3 The generation rates of small-scale low carbon technologies according to FiT_s scheme (sustainable solutions 2010).

Technology	**Scale**	**Generation Rate Apr 2010 - Mar 2011**	**Tariff Lifetime (years)**
AD	≤500kW	11.5	20
AD	>500kW	9.0	20
Hydro	≤15 kW	19.9	20
Hydro	>15 - 100kW	17.8	20
Hydro	>100kW - 2MW	11.0	20
Hydro	>2kW - 5MW	4.5	20
Micro-CHP	<2 kW	10.0	10
Solar PV	≤4 kW new	36.1	25
Solar PV	≤4 kW retrofit	41.3	25
Solar PV	>4-10kW	36.1	25
Solar PV	>10 - 100kW	31.4	25
Solar PV	>100kW - 5MW	29.3	25
Solar PV	Standalone	29.3	25
Wind	≤1.5kW	34.5	20
Wind	>1.5 - 15kW	26.7	20
Wind	>15 - 100kW	24.1	20
Wind	>100 - 500kW	18.8	20
Wind	>500kW - 1.5MW	9.4	20
Wind	>1.5MW - 5MW	4.5	20
Existing generators transferred from the Renewables Obligation		9.0	to 2027

For wind energy 6 bands exist with highest generation rate (34.5 p/KWh) given to micro wind turbine under 1.5 KW power capacity. The FiT_s that are available for new installations will be reduced each year in accordance with the predicted technology cost reductions to ensure that new installations obtain the same approximate rates of payback as installations already sustained through FiT_s. Both on- and off-grid systems of renewable energy generation will benefit from this tariff scheme. Figure 5.23 shows the annual degression for the coming ten years for all wind turbine mentioned categories. The degression of tariffs is applied for new installation and it does not effect, therefore the earlier start is the higher price for tariffs. As response for several feedbacks about negative effects of early degression on new business setting up, it has been decided to delay the degression introduction until April 2012.

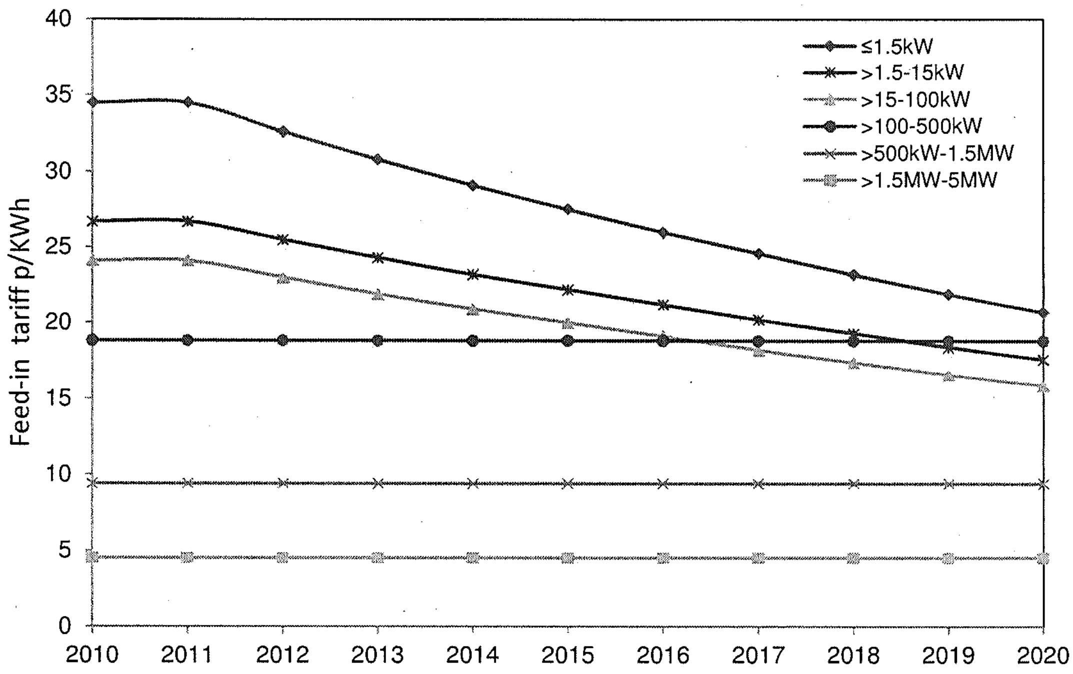


Figure 5.23 The degression of small wind FiTs rate over ten years with annual reduction rate of 9% (Department of Energy and Climate Change 2010).

5.12 Wind flow in urban areas: Merchiston campus's case study

Rooftop-mounted and building integrated wind turbines are generally installed within urban areas, where wind regime is turbulent, weak, and unstable in terms of wind speed and direction compared to open windy sites which are preferable for wind farms. The morphology and geography of any location in built up areas affect the wind stream there considering high-rise and average buildings, trees, hills as local obstructions when wind flow passes over that terrain (Wang[1], Bai et al. 2008; Wang[2], Bai et al. 2008). A building will cause sudden change in the flow and thus increase the intensity and size of the turbulent zone. Placing a turbine in a turbulent wind stream will result in both power output reduction and fatigue loads increase on the turbine. Merchiston wind site is an ideal example of wind regime behaviour in built up area. So, the high degree of turbulence monitored in the location due to the increased surface roughness of scenery can result in focused and dynamically changing winds. The wind is inclined to change speed and direction very rapidly resulting in high dynamic loads acting on the turbines and causing increased wear and fatigue of system's components, thus increasing the cost of maintenance and operation, and reduced energy output. That was exactly what happened in Edinburgh Napier

University micro wind trial at Merchiston campus. In February 2007, Zephyr Air-dolphin turbine required mast and trial vane replacement when they collapsed under strong and turbulent winds. In November 2007 and January 2008, Ampair 600 wind turbine experienced several electrical and mechanical failures: firstly load controller and inverter were substituted when load controller failed twice after being overloaded which damaged the inverter, then a month later as a consequence to extreme wind the tail fin and turbine rotor blades failed and were seriously damaged which required load controller replacement with modified controller and wind turbines replacement with stronger, more rigid versions than ones which were designed for rural areas.

5.13 Micro-wind turbine dynamics in built up areas

A distinctive purpose of small wind turbines is to frequently produce power over short periods, e.g. for battery charging, rather than to produce maximum power over extended periods, e.g. for income from exports to the grid. It is therefore important that small turbines generate in weak winds and respond quickly when harnessable winds occur. In both cases, the requirement is for rapid starting of the rotor before the generator cuts in. Most small turbines start rotating only when the aerodynamic torque acting on the blades exceeds the combined resistive torque of the drive train and generator. It is widely acknowledged that poor starting performance can be a major problem for small turbines (Clausen.P. D 2000). To exacerbate the problem, small turbines rarely have variable pitch and are often located in areas of unfavourable wind, simply because that is the location of the load. Starting is especially difficult for so-called micro-turbines, those around 1kW or less. The starting sequence of blades designed for optimal power extraction begins with, and is often dominated by, an extended 'idling' period during which the blades accelerate slowly as the angles of attack slowly
decrease (Wood 2001). This is often compounded by installing small turbines close to buildings and structures where the power is needed rather than where the average wind speed is large. It is clear that the starting and low wind speed behaviour is very important for the successful operation of small turbines (Wood 2004). An example of wind speed and power output measurements conducted at the Napier University's wind energy facility is shown in a time series format in Fig. 5.24. The figure shows 7 minutes of data measured at 2-s time interval.

The anemometer's dynamic response with 0.4 s is sufficiently rapid to have negligible effect compared to that of the rotor. The delayed response of the rotor can discernibly be noticed in Fig. 5.24. It should be noted that the very turbulent nature of the wind in this particular location contributes to the whole time delay of the rotor. However, it is beyond the scope of this research project to determine to which degree the turbulence contributes to the delayed response relative to the inertia-induced delayed response.

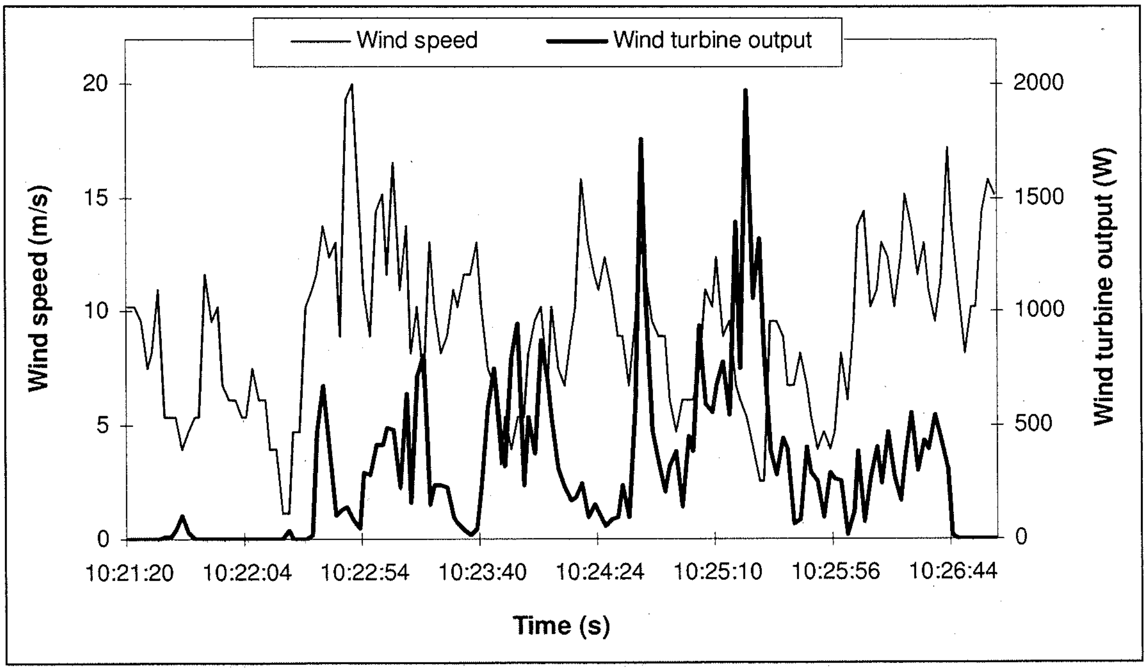


Figure 5.24 Wind speed and power output data collected at the Napier University's wind energy facility in a time series format on 23 January 2008

A number of articles have been published dealing with wind turbine starting mode (Ebert 1997) (Mayer. C 2001) (Wright.A.K 2004). Ebert, Wood, and Mayer presented starting sequences from experiments conducted using two separate machines but with the same 5 kW-rated blades. In both studies, the wind speed was in the range 5–8 m/s, which was considerably higher than the cut-in wind speed of the turbine. Both references describe 30–50 s 'idling' periods of slow rotation, with little acceleration after the initial start. In this condition the blades experience high angles of attack, are stalled, and are generating only a small amount of torque. When the angle of attack eventually decreases sufficiently to produce high lift-drag ratios, the rotor accelerates rapidly. Very few small turbines have pitch adjustment, so the angles of attack during starting are usually high and unfavourable. The starting sequences for varying pitch in (Mayer. C 2001) showed that increasing pitch (i.e. reducing a) decreases the idling period. Wright and Wood used a three-bladed, 2m diameter wind turbine, with a rated power of 600W at a rotor speed of 700 rpm and at 10 m/s wind speed. The turbine's rotor moment of inertia was 0.43 kgm^{-2} with the main contribution coming from the blades, and was determined at the same time as the resistive torque. The average start time (accelerated from rest up to 250 rpm), was 28 s, the minimum length 9 s and the maximum 101 s.

5.14 Wind sources assessment for urban location

Monitoring performance of micro wind turbines and determining wind regime characteristics in built up environment were the major drivers behind the set up of this wind trial. Due to turbulent nature of wind flow in urban area data sets with small sampling intervals were needed to evaluate the wind energy potential in the flow and wind turbines output.

5.14.1 Mean wind speed

Mean wind velocity is a key issue when characteristics of wind regime for any candidate location are needed to be assessed for individual wind turbine or wind farm installation. But assessment does not depend only on average wind speed, other factors also have to be considered before any judgement and decision can be made. The importance of wind velocity comes from cubic relationship between velocity and wind power. Relying on mean wind speed value, the available energy of wind flow passing through cross section of swept area can be estimated. So, careful concern of how wind speed data is averaged is also required. Set of two years data of 4 s sampling intervals has been processed to obtain monthly wind velocity average starting from August 2007 (refer to Figure 5.25). Maximum (5.52 m/sec) and minimum wind velocity (2.9 m/sec) were in January 2008 and June 2009, respectively. Annual average wind speed in Merchiston campus is approximately 4 m/sec.

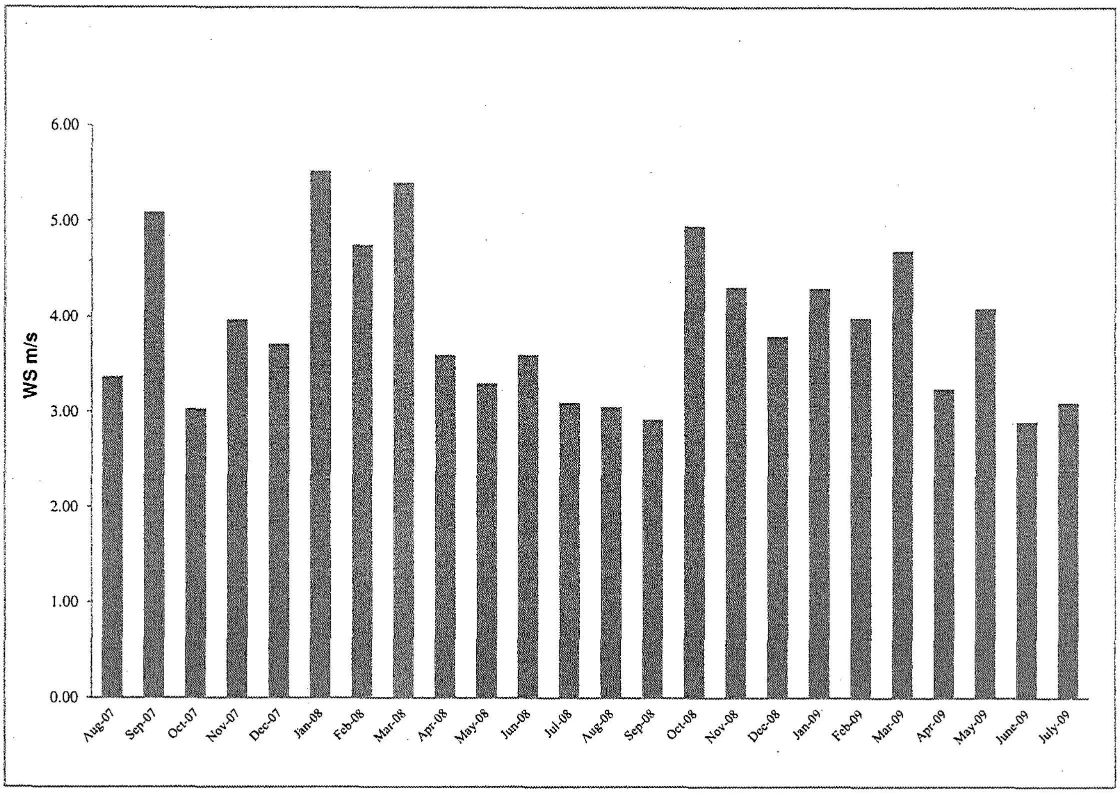


Figure 5.25 Wind speed average for Merchiston campus Aug07-Jul 09

5.14.2 Wind frequency roses

Wind roses demonstrate the occurrence of winds at a location, showing their strength, direction and frequency. Besides velocity, wind direction is also measured since it can play substantial role in determining energy output. Information on wind direction can be employed to determine the turbulence of wind at certain location. If wind direction changes with high frequency, the wind regime is likely to be turbulent and that can affect wind turbine operation in two manners. Firstly, due to the mass and inertia of wind turbine, there is a time delay hence wind turbine has to continuously change direction to keep on facing wind resulting in power output reduction. Secondly, the rapid change in wind direction causes fast variation in load forces acting on turbine system, and the frequency and range of forces increase fatigue failure rates. The prevailing wind direction for a location is the wind direction which is witnessed most frequently, but it may not yield the major energy from this direction. Figures 5.26 and 5.27 show monthly wind direction roses at Edinburgh Napier University Merchiston site for 24 months, as can be seen the most frequent direction of blowing wind is southern west. As oceanic depressions pass Scotland the wind usually commences to blow from the south west, but later comes from the west or north-west as the depression travels away. The scope of directions between south and north-west accounts for the majority of time and the strongest winds nearly always blow from this angle of directions. The penetration of westerly winds into eastern Scotland is dominated for a large extent by geography, with the Central lowlands assisting that. From the wind roses in figures 5.26, 5.27, spring time tends to have a maximum frequency of winds from the north east. This seasonal effect is due to a build of high pressure over Scandinavia. The effect of urban environment on the wind roses is obvious through the wide range of direction, since this is an indicator of turbulent nature of wind regime, further more turbulent wind stream decreases ability of wind turbine to capture the maximum energy from wind.

In winter months, it can be noticed form the prevailing direction of blowing wind is southern west , when wind draft to the west and northern west it becomes stronger and more productive as it can be noticeable from wind turbine energy output.

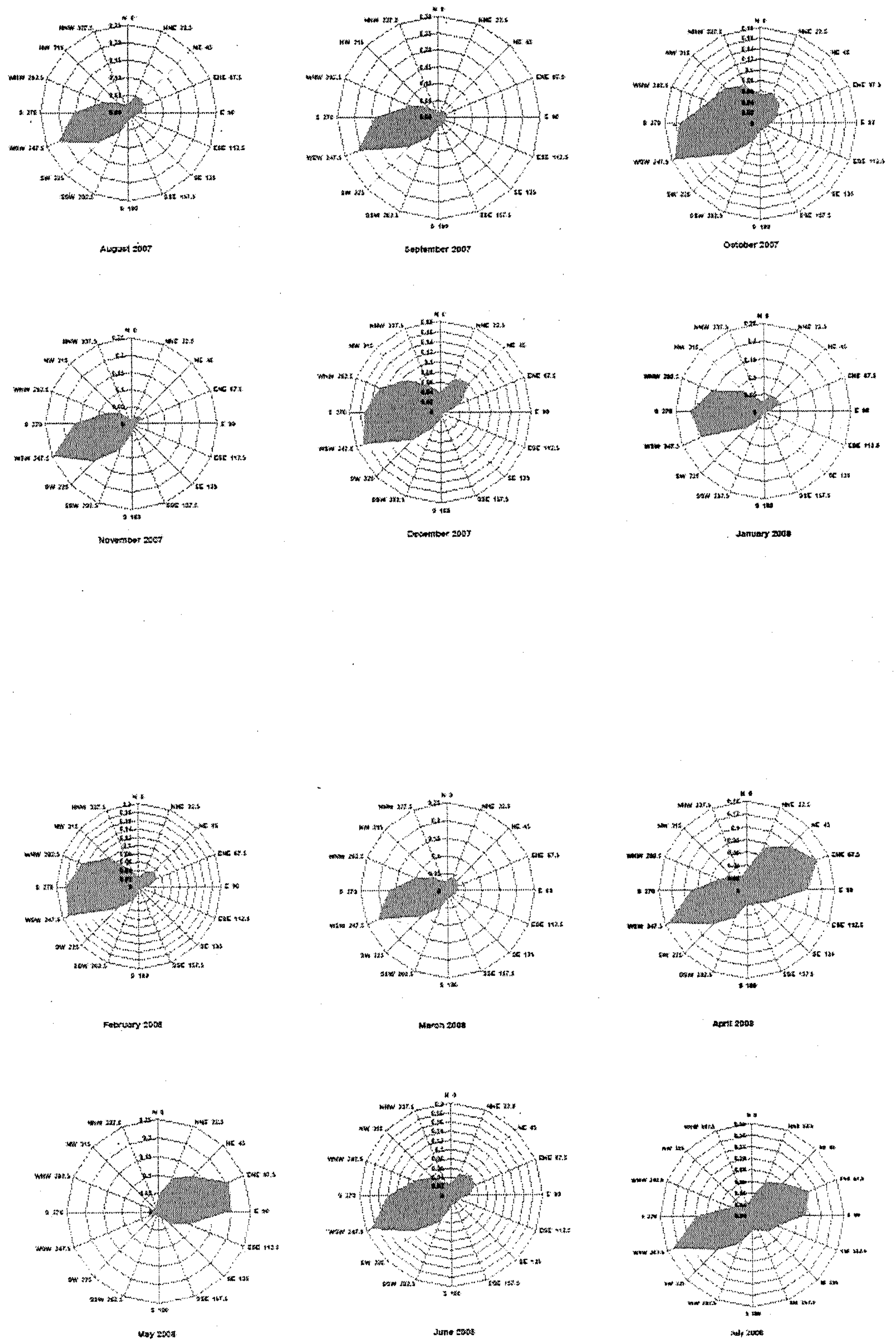


Figure 5.26 Monthly wind direction roses of Edinburgh Napier University, Merchiston campus (August 2007-July 2008)

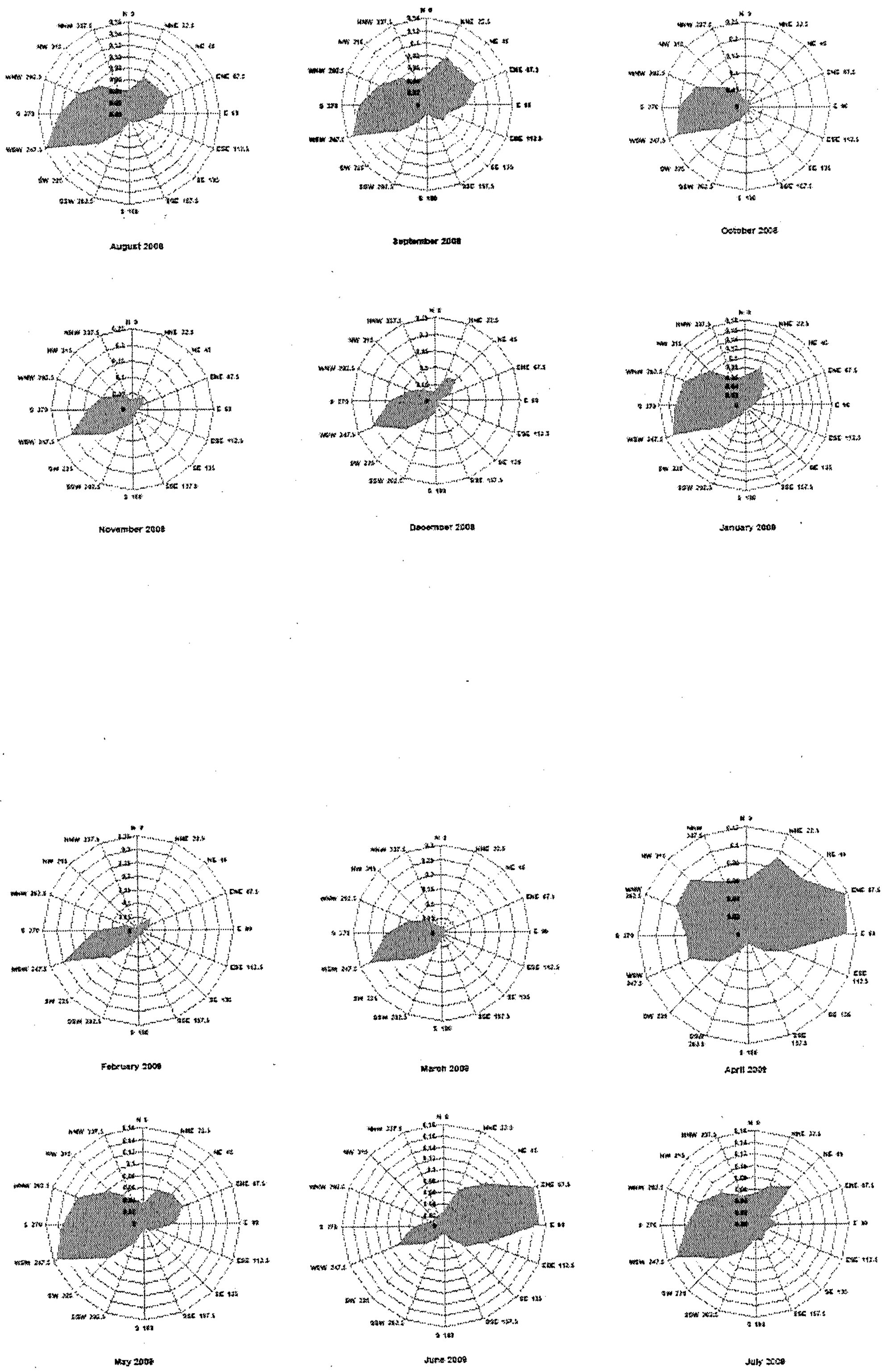


Figure 5.27 Monthly wind direction roses of Edinburgh Napier University, Merchiston campus (August 2008-July 2009)

5.14.3 Wind speed Distribution

Wind speed distribution is a key factor in wind resource assessment. Since it is deployed to illustrate the proportion of the time the wind blows at a given range of wind velocity. A turbine power distribution for a certain wind turbine at candidate location can be derived using power distribution in conjunction with power curve of candidate wind turbines. Designing two wind turbines for two different sites requires more than just the average wind velocity, especially if they have similar mean wind speed, but diverse wind regimes. Consider the following scenario: the mean wind speed in first location is 15 m/s throughout the day, while the velocity in second site is 30m/s for first 12 hours and it is zero for the rest of the day. If a wind turbine with cut-in wind speed 3.5 m/s and cut-off wind speed 25 m/s is installed in both locations, the wind turbine in the first case will work sufficiently and deliver satisfactory energy output, whereas the wind turbine in the second site will be idle throughout the day because all the time either the wind speed will be above cut-off wind speed or below cut-in wind velocity. Actual projects will be in between these two hypothetical cases. The above example, thus, demonstrates that wind speed distribution is a key element in wind energy assessment.

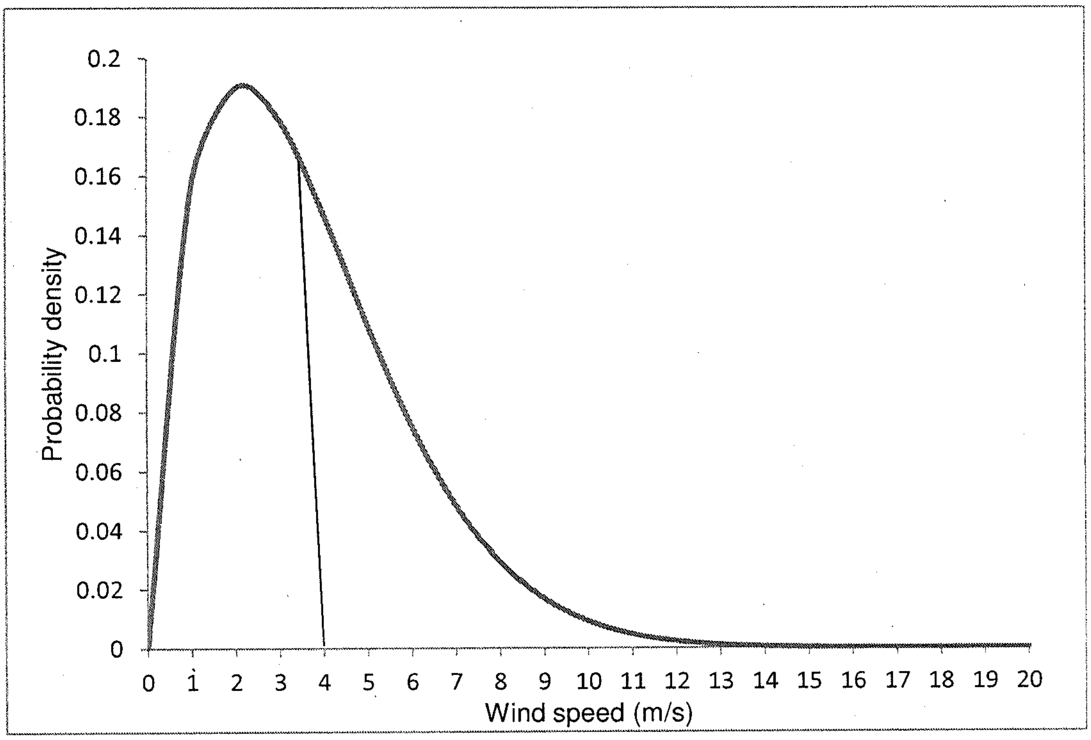


Figure 5.28 Probability density distribution of wind velocity and its median value.

As can be seen in Figure 5.28, the frequency of each wind speed in the range 0-20 m/s is described by velocity probability distribution. The area drawn under the curve of probability density function of wind speed is equal to 1. If this area is divided into two equal parts, then the vertical line splitting the two areas would occur at a wind velocity of 4m/s. This implies, 50% of the time the wind speed is below 4m/s, and 50% of the time the wind velocity would be above 4m/s. This value of wind speed is called the median of the distribution. The velocity with highest frequency (which in this plot is 2 m/s) is known as modal wind speed. The plot is positively skewed, i.e. skewed to the right, as a consequence of low frequency of high wind speed at the site.

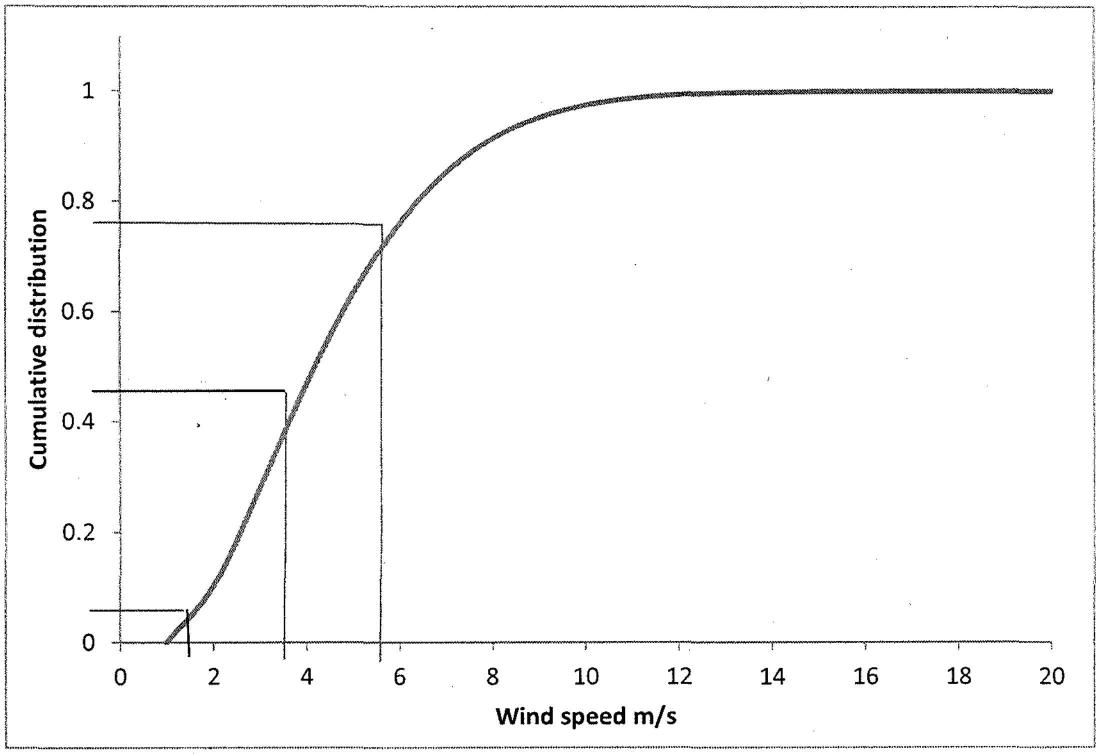


Figure 5.29 Cumulative distributions of wind velocity plot.

The cumulative distribution curve is constructed by plotting the time fraction that represents the wind speed which is smaller than or equal to given wind speed. It can be used to determine the frequencies of winds blowing within given limits. Figure 5.29 shows measured wind velocity observations in order of wind velocity, which are equal or less than the bin velocity. For example, 58% of wind velocities fall between 2m/s and 6m/s. The median wind velocity is also shown at 50% cumulative frequency, measuring 4m/s.

5.15 Statistical modelling of wind speed distributions

Statistical models of probability distribution are mathematical models describing the likelihood that how certain values of a random variable, such as velocity, will behave. Statistical techniques can be utilized to assess the wind energy potential of a suggested location, and to estimate the energy output from a wind turbine that would be placed on that site. Fitting statistical model to actual measured dataset has an advantage of substitution measured wind regime characteristics with few parameters. This research work focuses on five statistical models which were used to assess wind energy potential in different locations by other researchers. These statistical models are Weibull, Rayleigh, Lognormal, three parameter-Weibull, and double-Weibull. Chapter 6 presents critical evaluation of these models and that which of them offers best fit for observed wind data of typical urban location. Figure 5.30 demonstrates the five modelled distributions against the actual recorded data of October 2007 at Merchiston site. It can be shown that Weibull and Rayleigh distribution functions are not fitted the observed frequency distribution,and then lognormal and 3-Parameter Weibull are providing better fit since they have more parameters than the previous two,but D-Weibull is presented the best fit.

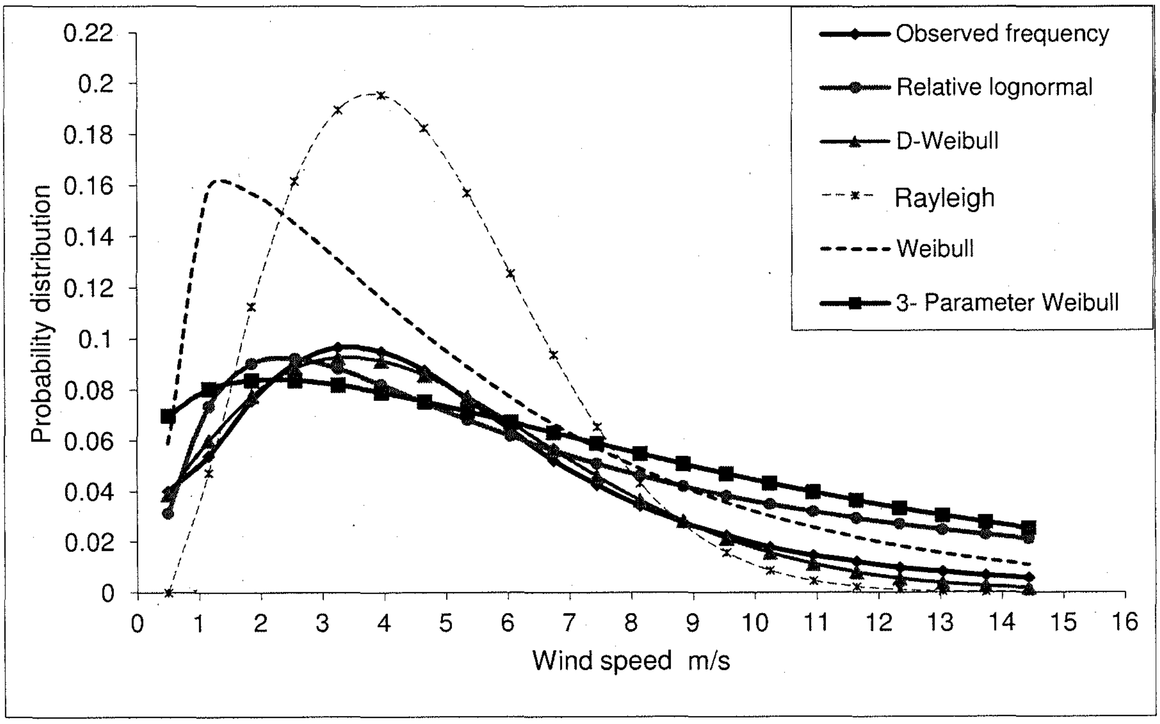


Figure 5.30 The observed frequency distribution is shown with Lognormal-Weibull, Rayleigh, Weibull, and 3-Parameters Weibull modelled distributions based on October 2007 data, Edinburgh Napier University.

5.16 Statistical analysis

The mean bias deviation (MBD) and root mean squared deviation (RMSD) are used in the following section to quantitatively evaluate different interval data. The 4-s data is used as the reference. MBD provides an indication between the two data sets, whether the data set has a tendency to return smaller or higher values relative to the reference values. MBD can be expressed either as a percentage or as an absolute value. The presently reported MBDs are based on absolute values. An MBD nearest to zero is desired. MBD is given by the following equation:

$$MBD = \frac{\sum(CFo - CFr)}{n} \tag{5.1}$$

where, CF_0 is the cumulative frequency value from either 1-min or 1-h data, CF_r the reference cumulative frequency value of 4-s data and n the number of data points.

The root mean squared deviation (RMSD) gives a value of the level of scatter that the 1-min or 1-h data produces. It provides a term-by-term comparison of the actual deviation between different data sets. Since it is a measure of the absolute deviation, RMSD is always positive. A lower absolute value of RMSD indicates a closer data set to the reference. Mathematically, it is given by the following equation:

$$RMSD = \sqrt{\frac{\sum(CF_o - CF_r)^2}{n}} \tag{5.2}$$

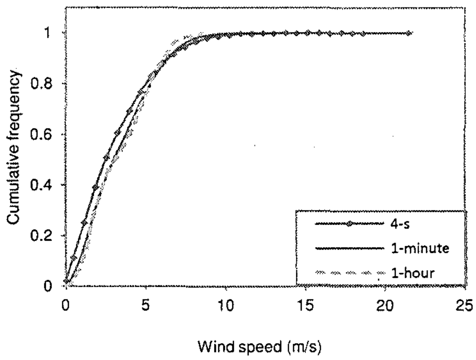
The calculated values of MBD and RMSD for the available data are presented in Table 5.4. As it will be shown later because the cumulative frequency curves for 1-min and 1-h data are very similar to each other, the MBD and RMSD values are also very similar. Overall, the RMSD and MBD values for 1-min data are slightly smaller than that for 1-h data.

5.17 Temporal variation of wind speed

Urban wind speed evaluation is based on the wind speed data measured at Merchiston Wind experimental site. The data was collected at the roof of School of Engineering's building, at a height of 30 m, at a 2-s interval and further averaged on a 4-s interval, minute by-minute and hourly basis. A total of 24 months of wind speed data were collected spanning from August 2007 to July 2009 inclusive. The monthly mean speeds vary approximately between 3 m/s and 5.5 m/s for the presently analysed data(see figure 5.25). The effect of sampling interval on the wind energy production has been studied in a recent research by Carta and Mentado. They calculated the annual energy output from a pitch regulated wind turbine generator for five different data sampling intervals namely, 5, 10, 15, 20, 30 and 60 min. (Carta and Mentado 2007) showed that the wind energy output decreases as the sampling interval time increases, from 8.56 GWh/ year at 5-min interval to 8.53 GWh/ year at 60-min interval. However, the decrease is almost exponential for the smaller time intervals. The 24 months collected data is presented in three time intervals in Figure 5.31.

Table 5.4 Statistics for the observed wind data

4-sec reference	***1-min***		***1-hour***	
Month	**MBD**	**RMSD**	**MBD**	**RMSD**
Aug-07	-0.028	0.053	-0.124	0.284
Sep-07	0.070	0.103	0.062	0.110
Oct-07	-0.026	0.038	-0.033	0.049
Nov-07	-0.023	0.050	-0.024	0.061
Dec-07	-0.031	0.040	-0.030	0.047
Jan-08	0.008	0.021	0.008	0.034
Feb-08	-0.035	0.044	-0.032	0.056
Mar-08	-0.033	0.054	-0.026	0.065
Apr-08	-0.030	0.058	-0.031	0.068
May-08	-0.030	0.061	-0.028	0.077
Jun-08	-0.033	0.053	-0.033	0.065
Jul-08	-0.035	0.057	-0.027	0.069
Aug-08	-0.035	0.060	-0.027	0.076
Sep-08	-0.038	0.053	-0.038	0.068
Oct-08	-0.021	0.024	-0.019	0.080
Nov-08	-0.021	0.043	-0.020	0.048
Dec-08	-0.115	0.142	-0.031	0.051
Jan-09	-0.045	0.062	-0.024	0.046
Feb-09	-0.029	0.037	-0.028	0.065
Mar-09	-0.027	0.028	-0.070	0.105
Apr-09	-0.069	0.078	-0.036	0.073
May-09	0.013	0.019	-0.028	0.084
Jun-09	-0.037	0.062	-0.035	0.082
Jul-09	-0.075	0.082	-0.045	0.082



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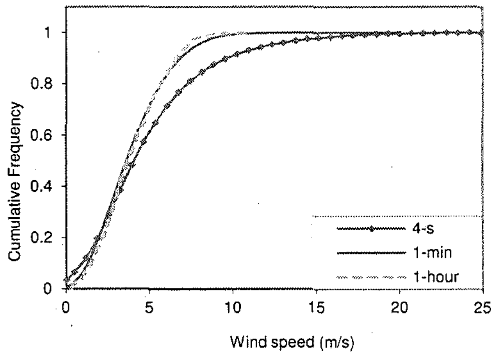

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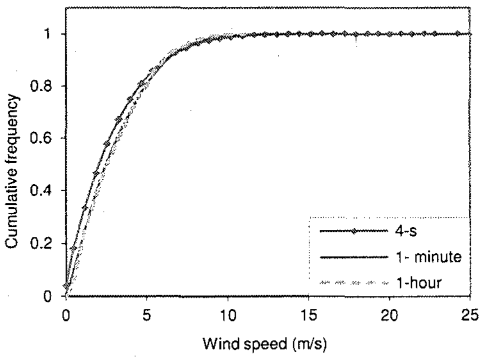

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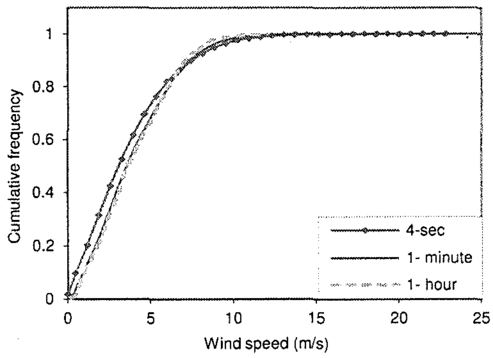

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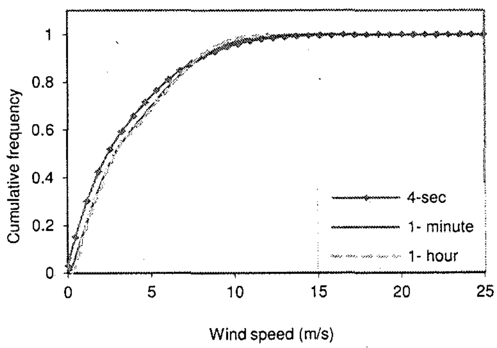

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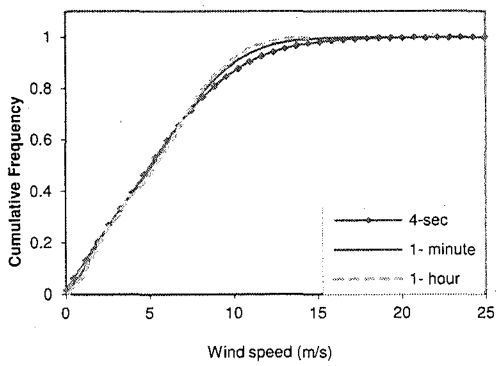

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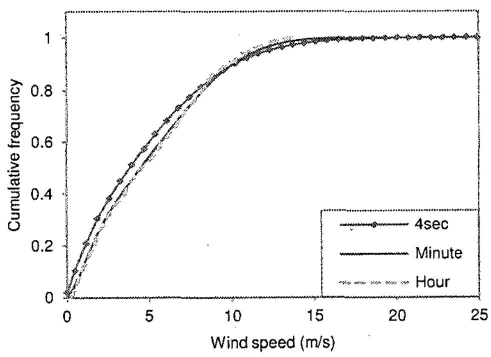

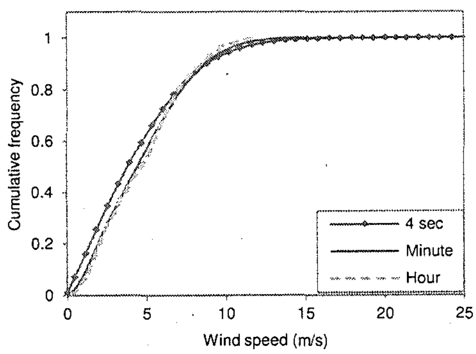

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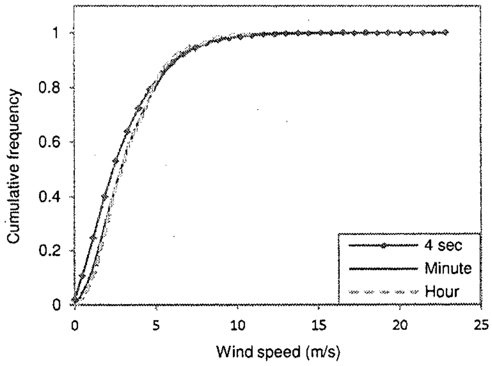

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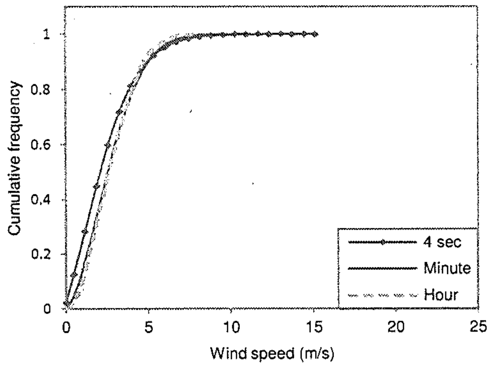

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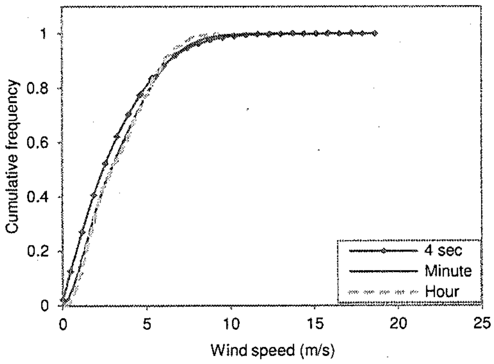

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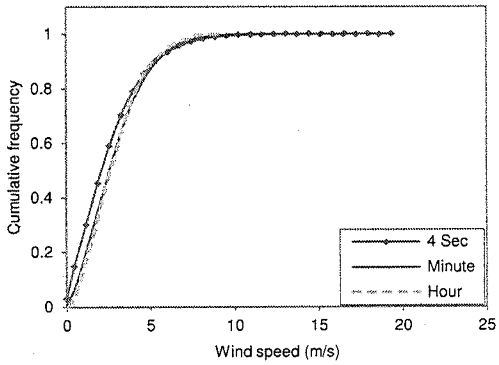

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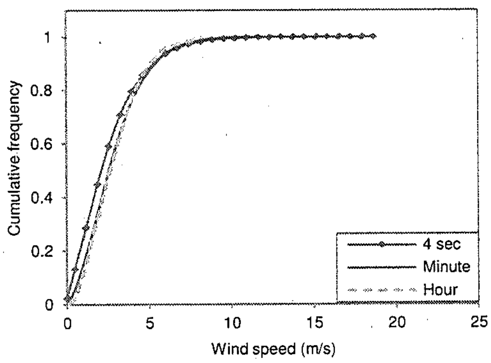

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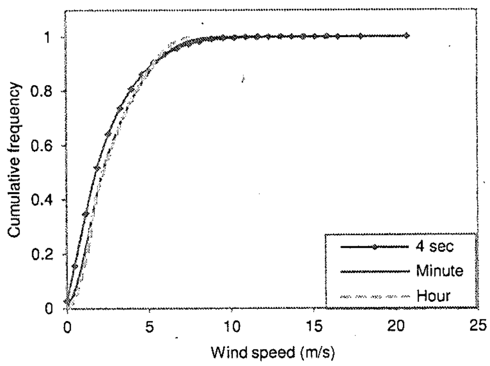

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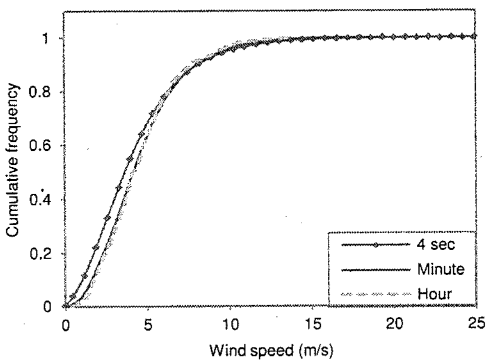

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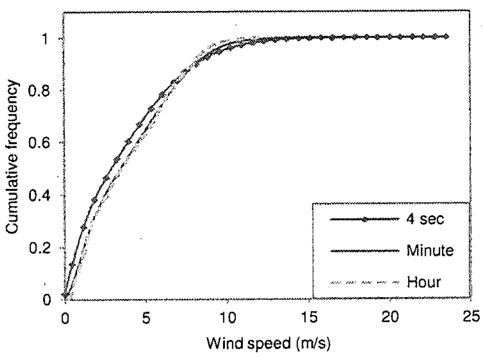

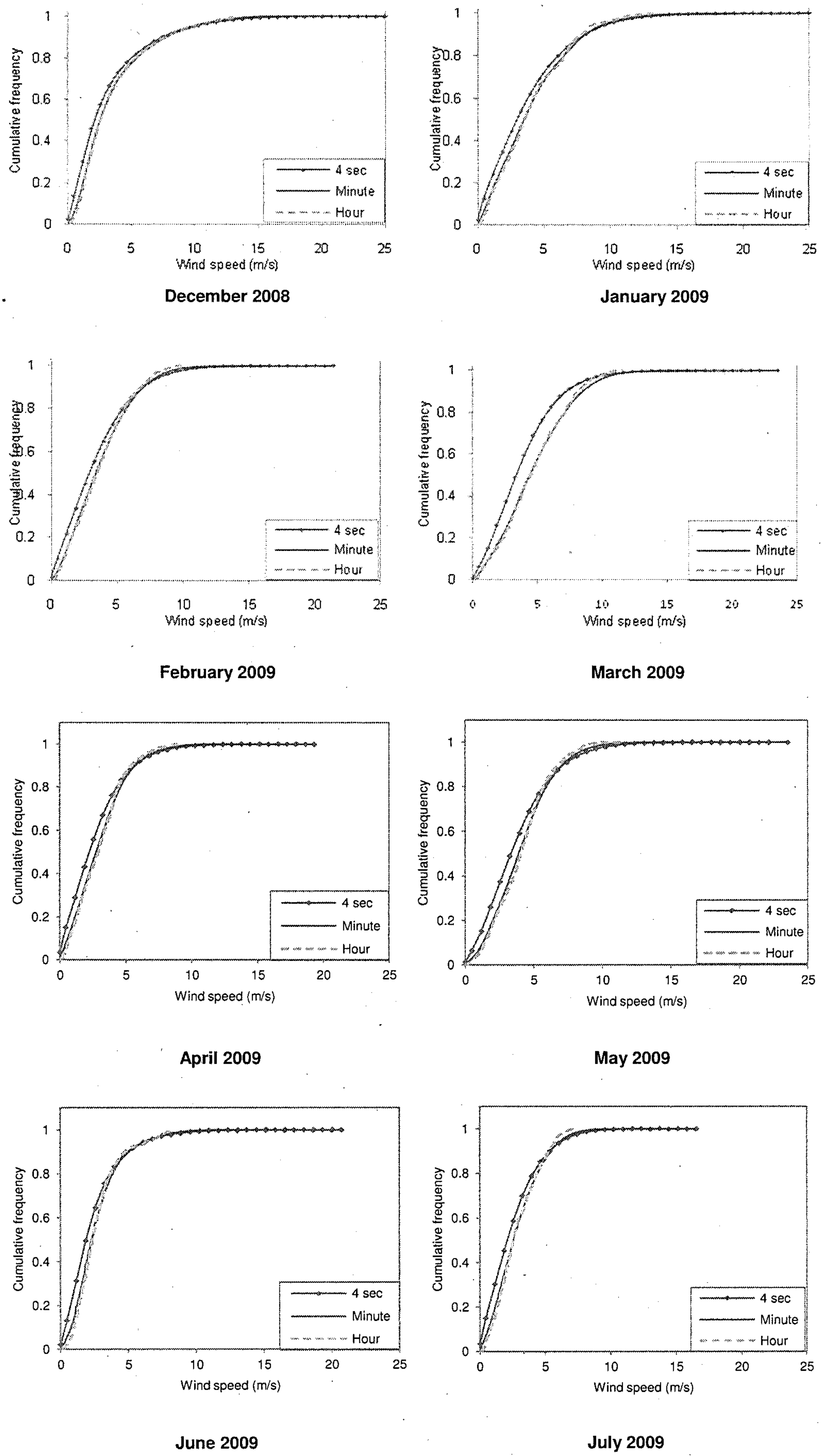

Figure 5.31 Effect of wind speed sampling interval using 4-s, 1-min and 1-h data for August 2007-July 2009

The difference between the 4-s, 1-min and 1-h data can be seen in the above plots (Fig. 5.31). For August, October, November and December, which have relatively lower mean wind speed, the cumulative frequency curves for the 4-s data present higher cumulative frequency values up to a certain wind speed level than those for the 1-min and 1-h data. This level differs slightly from 1 month to the next from 5.5 to 7.5 m/s. Up to this wind speed value, 1-min and 1-h data almost overlap. After this point, the curves of different time interval tend to overlap. For September and January, which have mean wind values higher than 5 m/s, the cumulative frequency curves for the 4-s data present higher cumulative frequency values up to a wind speed level of 2 m/s than those for the 1-min and 1-h data. After this point, for September, the curves representing the 1-h and 1-min data provide, by a large margin, higher cumulative frequency values than the 4-s data. However, for January, the curves are almost identical up to 8 m/s. After this point, the curves representing the 1-h and 1-min data provide slightly higher cumulative frequency values than the 4-s data. When there are clear differs between cumulative curves of several data intervals, that means using the big intervals data will result in overestimation for the energy outputs, especially when small intervals cumulative frequency shifts to the left. That fact is very frequent in built up areas ,where a large effect should be given to local obstacles such as building density, and trees, which makes wind stream turbulent and unstable, consequently fine detailed data sets are required for wind resource assessment and design of wind turbine system in urban areas, while the case is opposite when the site under study is in open area or on the coast where wind stream is strong and stable in this case hourly intervals for data will be sufficient and accurate.

5.18 Spatial variation of wind speed

The spatial variation of wind speed is studied presently by comparing the available data to that from a nearby location for October and January. It should, however, be noted that complex wind field analysis is avoided. The aim is to give an idea of error introduced in such extrapolations over the concerned distance. This is important when the measured wind speed data does not exist in a particular location, which is often the case for micro turbine applications. The curves representing the Napier data and the average of 17 years of

Edinburgh Airport data are given in Figures. 5.32 and 5.33 for October and January, respectively. For October, the mean wind speed of 17 years of Edinburgh Airport data (from 1976 to 1992) is 5.3 m/s while that of Napier data is significantly lower at 3.0 m/s. Therefore, for this month, the Edinburgh Airport data shows more variability as suggested by the flatter cumulative frequency curve and the greater range. In January, the mean wind speed of 17 years of Edinburgh Airport data is 6.0 m/s while that of Napier data, slightly lower, is 5.5 m/s.

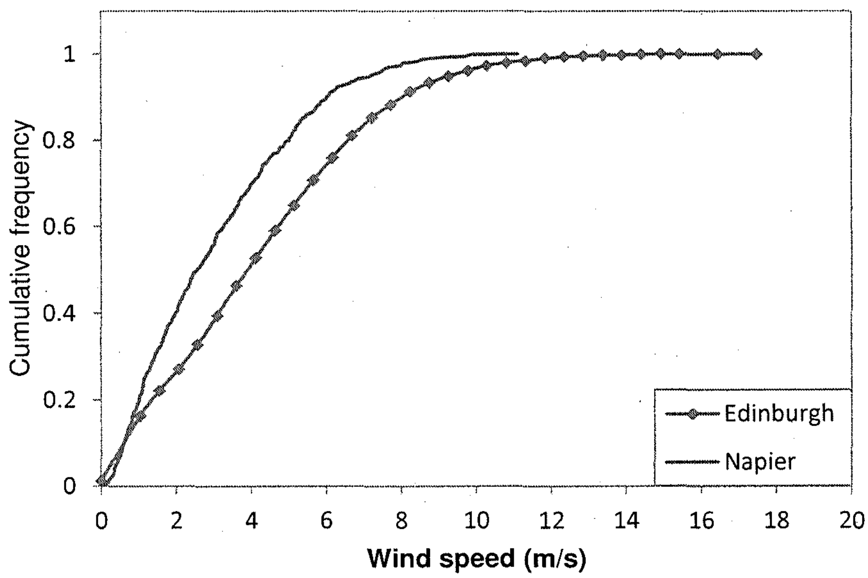

Figure 5.32 Spatial variation of wind speed, by comparing the available data to that from a nearby location for October 2007

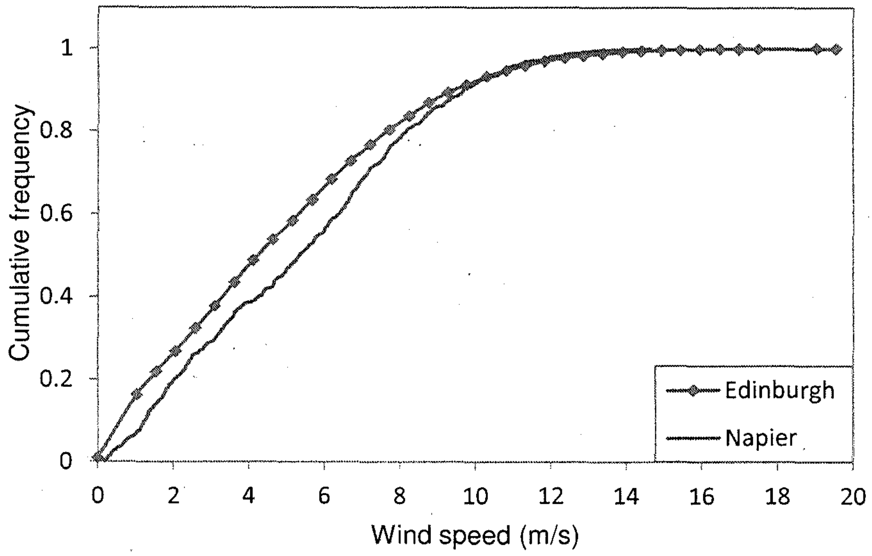

Figure 5.33 Spatial variation of wind speed, by comparing the available data to that from a nearby location for January 2008

5.19 Conclusions

The wind power basics were discussed with the view to implement wind turbine technology in the urban area. Present chapter also threw light on the technical and non-technical obstacles facing widespread application of small wind turbine technology in the built up environment. The UK small wind turbine incentives were investigated and reviewed. However, the market situation of small wind turbine in UK is studied considering its future direction.

This chapter provided an evaluation of the performance of some of micro and small wind turbines that are at present operating in England and Scotland. It has been shown here that urban, roof-top micro-wind turbines do not offer any good return on their investment and therefore are not serious candidates for future provision of electricity in the building sector. The midi-turbines do perform adequately, but only on rural farms.

The wind resource assessment of Merchiston wind site is concluded to have an annual average wind speed of 3.9 m/s, southern west prevailing wind direction with high wind shear and turbulent wind flow which results in low energy production.

This output harmonizes with many published works of similar sites throughout the United Kingdom which were members of the Warwick Wind Trials (Warwick Wind Trials, 2008). Merchiston wind test site is considered to be a promising location for capturing the wind in the built up areas. The site is the roof of five-floor building located on a hill-top within the urban environment. The weather station at test site is approximately 130 m high above the sea level. Low potential of wind energy could be attributed to two issues. Firstly, it can be due to high surface roughness, characteristic of urban locations, which magnifies the wind shear of flowing air stream, in turn, reducing the wind velocity close to the ground or roof surface level. High surface roughness also increases the turbulence of air stream. The second issue is the existence of buildings within the neighbourhood close to the turbines. Moreover, it is believed that poor aerodynamics of micro-wind turbines is also responsible for their underachievement. It was shown that different sampling interval of wind speed has an important bearing on the cumulative frequency curves; this will in turn lead to different wind turbine performances calculated based on these data. Furthermore, if local and topographic effects have been taken in account, wind resources outside Edinburgh city limit are stronger than the urban area.

With regards to micro wind turbine dynamics, the turbine has to be designed to have a very low response time to enable it to react to any changes within the wind regime very rapidly. Due to the high intermittency of the urban wind regime, the power management system used to control the turbine must also have a very high response time to enable any energy generated to be used. Turbines have to be designed very robustly to be able to survive very high turbulent winds.

This increased turbidity of winds has been observed at Edinburgh Napier University to cause increased loading and stress on the wind turbines, resulting in damage caused by fatigue. Failure of components has caused both the Air-dolphin and Ampair turbines to stop working during the test survey. These findings are in conformation with those turbines taking part in the Warwick Wind Trials

Chapter 6

Critical Evaluation of Wind Speed Frequency Distribution Functions

6.1 Introduction

The probability distribution of wind speed is one of the important wind characteristics for the assessment of wind energy potential and performance of wind energy conversion systems, as well as the structural and environmental design and analysis. A thorough understanding of the characteristics of wind regimes in which a wind turbine is expected to work is a pre-requisite for the successful planning and implementation of any wind power project. Knowledge of wind velocity distribution at different time scales and quantum of energy associated with these wind spectra are essential for the proper sizing and sitting of a wind energy project (Mathew 2002).

Once the probability density distribution (alternatively known as relative frequency distribution) is known, the wind power density (and thus, wind energy output) can easily be obtained. Knowing the probability density distribution and the corresponding power density distribution, one can assess the economic viability of installing a wind energy conversion system at a particular location (Bhumralkar, Mancuso et al. 1980). Therefore, the probability distributions and the functions representing them mathematically have been the main tools used in the wind energy-related literature. As stated by Ramirez (Ramírez and Carta 2005), a large number of studies have been published that propose the use of a variety of standard parametric probability distribution functions to describe wind speed frequency distributions. This chapter involves the modelling of observed wind speed probability density distributions using the main models found in the literature, namely Rayleigh, Lognormal, two-parameter Weibull, three-parameter Weibull and bimodal Weibull probability distribution functions. The probability density and the corresponding cumulative distribution functions considered in the present research are presented in Table 6.1.

Table 6.1 Probability density and the corresponding cumulative distribution functions

Name	Type	Function	Equation	Parameters	References
Weibull	pdf*	$f_W(v)=\left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1}\exp\left[-\left(\frac{v}{c}\right)^k\right]$	(6.1a)	,	(Carta and Ramírez 2007a), (Alghoul 2007), (Celik 2003), (Pallabazzer and Gabow 1991), (Pashardes and Christofides 1995), (Burton 2001), (Jaramillo 2004), (Dorvlo 2002)
	cdf&	$F_W(v)=1-\exp\left[-\left(\frac{v}{c}\right)^k\right]$	(6.1b)		
Rayleigh	pdf	$f_R(v)=\frac{\pi}{2}\frac{v}{v_m^2}\exp\left[-\left(\frac{\pi}{4}\right)\left(\frac{v}{v_m^2}\right)^2\right]$	(6.2a)	$_m$ (≡) $v_m=c\sqrt{\frac{\pi}{4}}$	(Mathew 2002), (Lalas, Tselepidaki et al. 1983), (Nfaoui, Buret et al. 1998; Feretic, Tomsic et al. 1999)
	cdf	$F_R(v)=1-\exp\left[-\left(\frac{\pi}{4}\right)\left(\frac{v}{v_m}\right)^2\right]$	(6.2b)		
Lognormal	pdf	$f_L(v)=\frac{\exp\left[-\frac{1}{2}\left(\frac{\ln x-\mu}{\sigma}\right)^2\right]}{\sqrt{2\pi}v\sigma}$	(6.3a)	μ,σ	(Seguro and Lambert 2000), (Jamil 1989)
	cdf	$F_L(v)=Normal\ distribution\left[\frac{\ln x-\mu}{\sigma}\right]$	(6.3b)		
3-Weibull	pdf	$f_{3-W}(v)=\left(\frac{k}{c}\right)\left(\frac{v-\gamma}{c}\right)^{k-1}\exp\left[-\left(\frac{v}{c}-\gamma\right)^k\right]$	(6.4a)	, , γ	(Jamil 1989), (Garcia, Torres et al. 1998; Rankine 2006)
	cdf	$F_{3-W}(v)=1-\exp\left[-\left(\frac{v}{c}-\gamma\right)^k\right]$	(6.4b)		
bi-Weibull	pdf	$f_{bi-W}(v)=\omega\left\{\left(\frac{k_1}{c_1}\right)\left(\frac{v}{c_1}\right)^{k_1-1}\exp\left[-\left(\frac{v}{c_1}\right)^{k_1}\right]\right\}+$ $(1-\omega)\left\{\left(\frac{k_2}{c_2}\right)\left(\frac{v}{c_2}\right)^{k_2-1}\exp\left[-\left(\frac{v}{c_2}\right)^{k_2}\right]\right\}$	(6.5a)	$_1$, $_1$, $_2$, $_2$, ω	(Garcia, Torres et al. 1998), (Rankine 2006), (Corotis, Sigl et al. 1978), (Celik 2004), (Takle and Brown 1978), (Tuller and Brett 1984), (Xiao, Li et al. 2006), (Carta and Mentado 2007)
	cdf	$F_{bi-W}(v)=\omega\left\{1-\exp\left[-\left(\frac{v}{c_1}\right)^{k_1}\right]\right\}+$ $(1-\omega)\left\{1-\exp\left[-\left(\frac{v}{c_2}\right)^{k_2}\right]\right\}$	(6.5b)		

*pdf: probability density function &cdf: cumulative distribution function

Over the years, a large number of studies have been published that present the use of a variety of probability density functions to describe wind speed frequency distributions. At the present time, however, it is the two-parameter Weibull function that is the most widely used and accepted in the specialised literature on wind energy and other renewable energy sources [(Carta and Ramírez 2007a), (Alghoul 2007)]. The two-parameter Weibull function has experienced the widest use in the specialised literature on wind energy [(Celik 2003), (Pallabazzer and Gabow 1991), (Pashardes and Christofides 1995)]. The Weibull function has been widely used since the studies started on the modelling of wind speed probability distributions. Initially, the two-parameter Weibull function was used. This is due to its appeal of wide applicability, flexibility and usefulness for describing the frequency of occurrence of high wind speeds. Several authors have indicated that the Weibull function should not be used in a generalised way, as it is unable to represent some wind regimes, such as those which describe wind speed frequency histograms which present bimodality or bitangentiality [(Burton 2001), (Jaramillo 2004)].

The parameters *c* and *k* of the Weibull function have been studied for many locations [(Lalas, Tselepidaki et al. 1983), (Nfaoui, Buret et al. 1998), (Feretic, Tomsic et al. 1999)]. However, when there is no detailed measured data for a particular site except for the mean wind speed, some approximations may be used to assume a Weibull distribution; the scale parameter is usually slightly bigger (10%) than the mean wind speed, for values of shape parameters between 1.5 and 3.0, while the scale parameter is half of the mean wind speed for value of shape parameters close to 1.0. Also note that higher values of *c* indicate higher mean wind speeds while the value of *k* indicates the wind stability. There are several methods presented in the literature to identify the parameters of the Weibull function [(Jaramillo 2004), (Seguro and Lambert 2000), (Jamil 1989), (Garcia, Torres et al. 1998)]. The Weibull function relates the mean wind speed v_m to its scale and shape parameters thus,

$$v_m = c\ \Gamma(1+\frac{1}{k}) \tag{6.6}$$

where, the Gamma function Γ can be solved using the Stirling approximation given by,

$$\Gamma(x) = \sqrt{2\pi x}\ x^{x-1}\ e^{x} \left[1 + \frac{1}{12x} + \frac{1}{288x^2} + \ldots \right] \qquad (6.7)$$

(Note that equations 1-5 were included in the Table 6.1)

The Rayleigh and Lognormal functions were proposed as alternatives to the Weibull function (Garcia, Torres et al. 1998). The Rayleigh function is a special and simplified case of the Weibull function. It is obtained when the shape parameter *k* of the Weibull model is assumed to be equal to 2. One of the most distinct advantages of the Rayleigh distribution is that the probability density function and the cumulative distribution function may be obtained from the mean value of the wind speed and therefore offers a convenient and simple approach (Rankine 2006). The Rayleigh model has been widely used to fit the observed probability density distributions and its validity was shown for various locations by numerous researchers [(Mathew 2002), (Corotis, Sigl et al. 1978), (Celik 2004)].

In essence, the classic Weibull function is, theoretically, not a universal model or no single model could be expected to give good results at all stations since wind patterns are different due to various reasons. Modifications to the two-parameter Weibull function were therefore suggested for better results. Among those, the hybrid Weibull model, a slight modification to the Weibull function, was proposed to improve the modelling at low wind speeds (Takle and Brown 1978). A three-parameter Weibull function was also utilised in some studies and was found to provide improved fitness and flexibility than the classical Weibull function. Tuller and Brett (Tuller and Brett 1984) and Xiao et al. (Xiao, Li et al. 2006) suggested two alternative probability density functions to two-parameter Weibull namely, the Type I extreme value distribution and three-parameter Weibull function. Xiao et al. reported that although three of the probability density functions are all suitable for describing the probability distribution of the extreme wind speed data, the Type I and the three-parameter Weibull function are more appropriate compared to the two-parameter Weibull.

Regarding the bimodal distribution, there are hypothesis as to the cause of bimodal nature of the distribution. For La Ventosa, Mexico, Jaramillo and Borja (Jaramillo 2004) relate this to two different types of winds, namely mountain-gap generated wind phenomenon and that caused by local effects as sea breeze. Thus, the frequency distribution for that particular location is established by both mountain-gap wind phenomenon and sea breeze winds. The mountain-gap phenomenon produces exceptional wind speeds due to the effect of strong cross-mountain pressure gradient, constituting the second mode with an average wind speed of around 14.2 m/s. The sea breeze wind, however, caused by the temperature difference when the sea surface is colder than the adjacent land, constitutes the first mode with low wind speed potential. In recent years, some studies have shown that the classic two-parameter Weibull function may be inadequate in modelling the wind speed distributions that show such bimodal behaviour. Thus, alternate, more involved functions such as the two-component mixture Weibull distribution (bimodal Weibull) have been suggested to better model the bimodal behaviour of wind regimes (Jaramillo 2004). Jaramillo and Borja (Jaramillo 2004) showed that the wind speed distribution in La Ventosa, Mexico is not represented well by the typical two-parameter Weibull function. Therefore, they have also used bimodal Weibull to analyze the wind speed frequency distribution in that region. It is reported that the analysis of wind data showed that computing the capacity factor for wind power plants to be installed in La Ventosa must be carried out by means of a bimodal function instead of the typical Weibull function. Otherwise, the capacity factor is underpredicted. The bimodal Weibull model was also used for wind power density and wind turbine energy output estimations (Tuller and Brett 1984). Tuller and Brett (Tuller and Brett 1984) concluded that their proposed bimodal model was more realistic than the unimodal probability models fairly commonly used in scientific literature. The bimodal probability model's estimation of the annual energy generated by a pitch regulated wind turbine gives a closer result to the energy calculated from the sample data than estimations made through the unimodal probability models. Carta and Ramirez (Carta and Ramírez 2007a) analysed the statistical characteristics of hourly mean wind speed data recorded at 16 weather stations located in the Canarian Archipelago. As a result of this analysis, they showed that the typical two-parameter Weibull function does not accurately represent all wind regimes observed in that region. However, a Singly Truncated from below Normal Weibull mixture distribution and bimodal Weibull distribution provide very good fits for both unimodal and bimodal wind speed frequency distributions observed in that region and offer less relative errors in determining the annual mean wind power density. Carta and Ramirez (Carta and Ramírez 2007b) presented methods to calculate the five parameters of bimodal Weibull distribution, namely, method of moments, the maximum likelihood method and the least-square method. They applied these methods to the hourly mean wind speed data recorded at four weather stations located on the island of Gran Canaria (Canarian Archipelago-Spain). They concluded that the least-square method provides the highest degree of fit in all the stations analysed, though the difference with respect to the other two estimation methods is not significant. There is, in conclusion, no significant difference between the different methods employed in describing wind power probability density distributions.

Furthermore, more models were studied elsewhere, including three-parameter Lognormal, Generalised Extreme Value, variations of the Gamma family (Pearson Type, Log-Pearson, and the Generalised Gamma), Square-root normal, seeking either to find more accurate models or to improve the existing models [(Morgan 1995), (Chadee 2001)]. Note that the Weibull distribution itself is a special case of the generalized gamma distribution.

6.3 Data and methodology

6.3.1 Wind data used

The present model evaluations are based on the wind speed data measured at the experimental site at Edinburgh Napier University. The wind speed data has been collected at the experimental site at the top of the School of Engineering's building, at a height of 30 m, at 4-second interval. A total of twenty four months of wind speed data were collected spanning from August 2007 to July 2009 inclusive. These measurements were made possible by a grant provided under the Scottish Research Infrastructure Funding Programme. Some of the observed probability density distributions for the available data are given in Figure 6.1. The monthly mean speeds vary between 2.7 and 5.9 m/s for the presently analysed data. As can be seen in Figure 6.1 for January-2008, which is the windiest month with a mean value of 5.9 m/s, the observed probability density distribution shows a bimodal behaviour. For this particular urban site, the bimodal nature of the distribution is thought to be due to the prevailing turbulence caused primarily by the tall buildings nearby and also by the topography of the location. However, as the mean wind speed becomes smaller the curves become more-peaked, as can be seen for October-2007 characterised by a sharp peak indicating little wind potential with a mean value of 3.0 m/s.

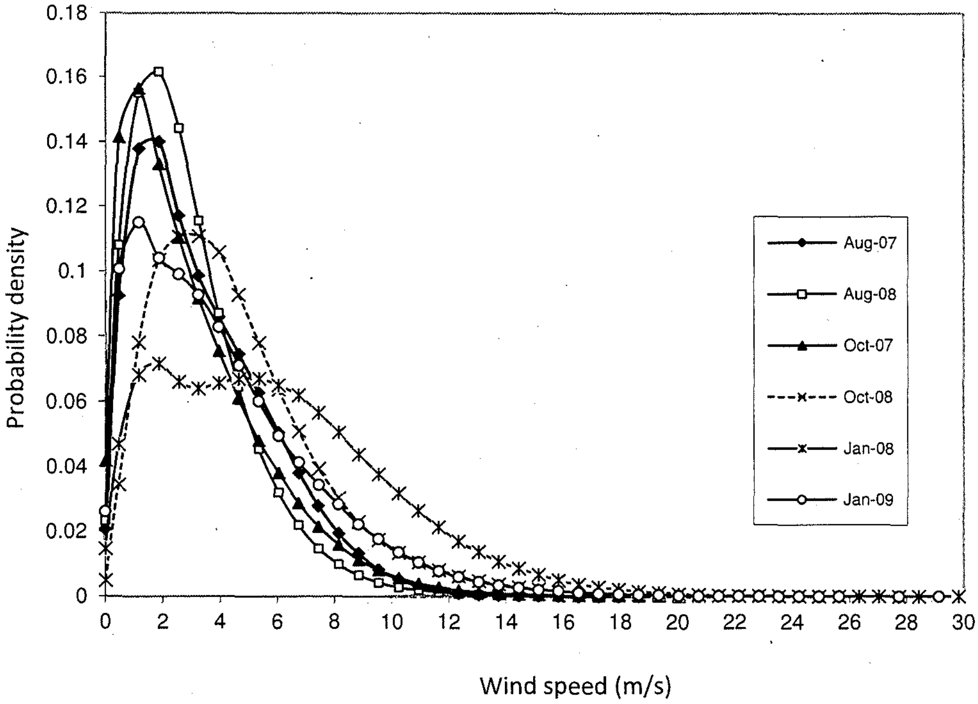

Figure 6.1. Observed probability density distributions for the available data

6.3.2 Statistical parameters used

The following statistical parameters are used in the coming sections to quantitatively evaluate the performance of each function presently used. The slope of the best fit line, given by Eq. (6.8), between the computed and measured variable is desired to be equal to one. Slope values exceeding one indicate over-estimation, while slope values under one indicate under-estimation of the computed variable.

$$s = \frac{\sum (PD_o - \overline{PD_o})(PD_c - \overline{PD_c})}{\sum (PD_o - \overline{PD_o})^2} \qquad (6.8)$$

Note that PD_c is the calculated probability density, PD_o the observed and $\overline{PD}$ the mean value of the given probability density (PD_c or PD_o) and n the number of data points.

The coefficient of determination (R^2) is the ratio of explained variation to the total variation given by,

$$R^2 = \left[\frac{\sum (PD_o - \overline{PD}_o)(PD_c - \overline{PD}_c)}{\sqrt{\sum (PD_o - \overline{PD}_o)^2 \sum (PD_c - \overline{PD}_c)^2}} \right]^2 \quad (6.9)$$

R^2 lies between zero and one. A high value of R^2, thus indicating a lower unexplained variation, is desirable. R^2 is often used to judge the adequacy of a regression model, but it should not be the sole criterion for choosing a particular model as in general terms, the value of R^2 increases with the number of coefficients in the model.

The root mean squared error (*RMSE*) gives a value of the level of scatter that the model produces. This is an important statistical test, as it highlights the readability and repeatability of the model. It provides a term-by-term comparison of the actual deviation between the predicted and the measured values. Since it is a measure of the absolute deviation, *RMSE* is always positive. A lower absolute value of *RMSE* indicates a better model. Mathematically, it is given by the following equation:

$$RMSE = \sqrt{\frac{\sum (PD_c - PD_o)^2}{n}} \quad (6.10)$$

The mean bias error (*MBE*) provides an indication of the trend of the model, whether it has a tendency to underpredict or overpredict the modelled values. *MBE* can be expressed either as a percentage or as an absolute value. Nevertheless, within a data set overestimation of one observation can cancel underestimation of another. An *MBE* nearest to zero is desired. It is given by the following equation:

$$MBE = \frac{\sum (PD_c - PD_o)}{n} \quad (6.11)$$

6.3.3 Accuracy score

One of the important steps in evaluation of different functions is the interpretation of different statistical parameters, namely slope, R^2, *MBE* and *RMSE*, as were used in the present chapter. Therefore, an overall accuracy score is required to facilitate a discrete comparison between different models. In the present work, a novel statistical tool is developed based on a similar tool developed earlier by Muneer (Muneer, Younes et al. 2007), deriving from the fundamental concepts to give an overall accuracy score for each function using the four aforementioned statistical parameters. Figure 6.2a shows a slope that has a large deviation from the ideally sought value of 1.0, but high value of R^2, whereas in Figure 6.2b the slope is very close to ideal value, but a low value of R^2 is realized due to large data scatter. Therefore case (b) would be preferable over case (a).

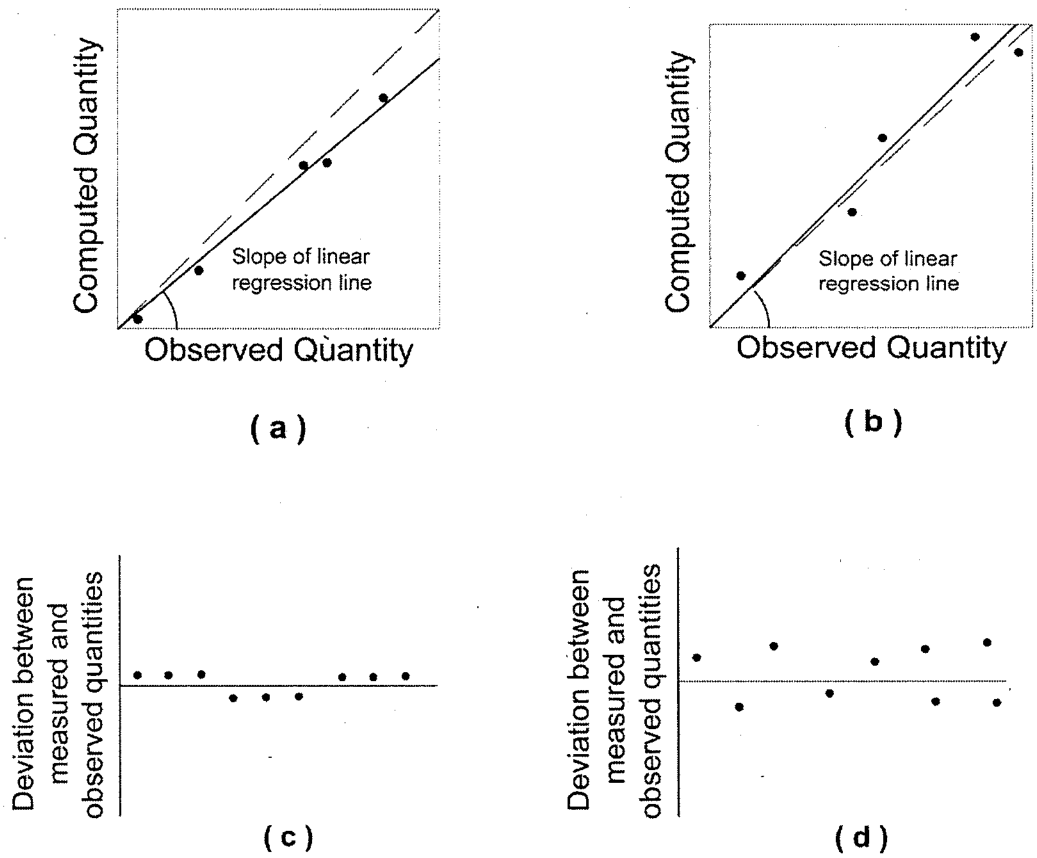

Figure 6.2 Basic concepts for the statistical parameters used (a) Slope has a large deviation but with a reduced data scatter about the fitted line (b) Slope is very close to ideal value but with an enhanced data scatter (c) Smaller, but a systematic trend of deviations, and (d) An almost equal spread of positive and negative, but larger deviations.

Similarly, Figure 6.2c presents a smaller, but a systematic trend of deviation: negative deviations in the middle range, with positive outcomes at the lower - placed on, and higher ends can be noted. In the case of Figure 6.2d, an almost equal spread of positive and negative, but larger deviations are noticed. Although case (d) would both provide a much higher value of *MBE*, case (d) would, however, be preferable over case (c). Overall, it can be concluded that the slope parameter provides a much more important indication of the validity of any given model. The R^2 of the line fitted between computed and observed data, *MBE* and *RMSE* for the given model's deviation provide second order information as higher values of R^2 or lower values of *MBE* and *RMSE* do not warrant a better model. Ideally, the latter three parameters ought to be examined only in conjunction with the value of slope. The following overall accuracy score is proposed with varying weighting factors of 3, 1, 1, and 1 for *s*, R^2, *RMSE*, and *MBE*, respectively.

$$\Psi = 3\left[1-|1-s|\right]+\left[R^2\right]+\left[1-\frac{RMSE}{RMSE_{\max}}\right]+\left[1-\frac{|MBE|}{|MBE|_{\max}}\right] \qquad (6.12)$$

Where:

s= Slope

R^2= Coefficient of determination

MBE= Mean bias error

RMSE= Root mean squared error

Ψ = Accuracy score

Note that *s* and R^2 are dimensionless unlike *RMSE* and *MBE*, and therefore the latter two are divided by the values of $RMSE_{max}$ and MBE_{max}. The latter are largest values amongst all models for a particular month. Ψ is a convenient index, by means of which it is possible to compare the performance of any suite of models. Therefore, for a perfect fit the overall accuracy score Ψ will be 6. The maximum obtainable score per statistical indicator is unity; therefore, overall, a model would have a maximum obtainable score of 6. Note that this is due to the fact that the slope parameter has been weighted with a factor of 3. It should be noted that obtaining the maximum score does not necessarily imply that the model is accurate and best performing; it only indicates that the model yields better results compared to the other models in the evaluation.

6.4 Results and discussion

In the present study, the suitability of the functions is assessed based on both probability density and cumulative distributions. The latter is particularly used as alternative to the former to try to improve the quality of the fits. Figure 6.3 presents the observed probability density distribution for October-2007, which is one of the least windy months, together with the distributions obtained from the probability density functions.

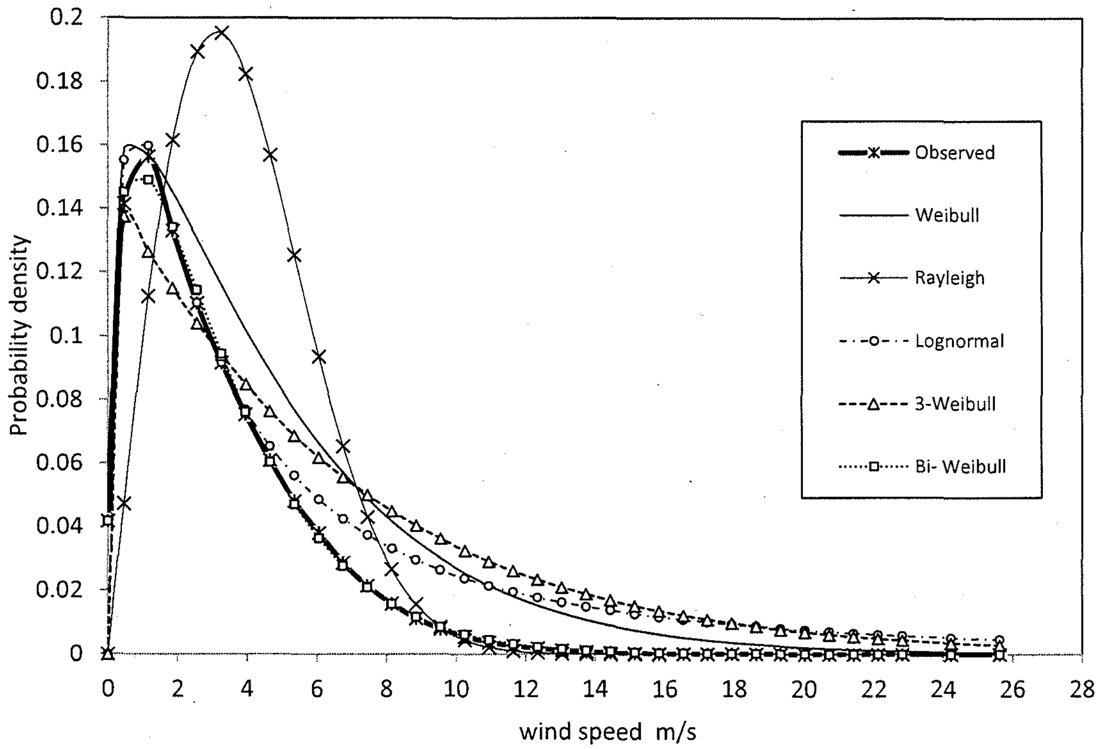

Figure 6.3 Observed probability density distribution for October-2007 with fitted distributions.

It is observed that the Rayleigh model leads to distributions that greatly over or underpredict the observed distribution while the Weibull, three-parameter Weibull and Lognormal functions highly overpredict wind speeds greater than 2 m/s, 4 m/s, and 5 m/s, respectively. Bimodal Weibull probability density function provides a close fit throughout the entire wind speed spectrum. The observed probability density distribution for January-2008, which is the windiest month, together with the distributions obtained from the probability density functions are presented in Figure 6.4. Note that the observed probability density distribution for this particular month is of bimodal nature. As can be expected, the models such as Rayleigh, Lognormal, Weibull, three-parameter Weibull models are unable to model this bimodal behaviour, leading to distributions that greatly over- or underpredict the observed distribution.

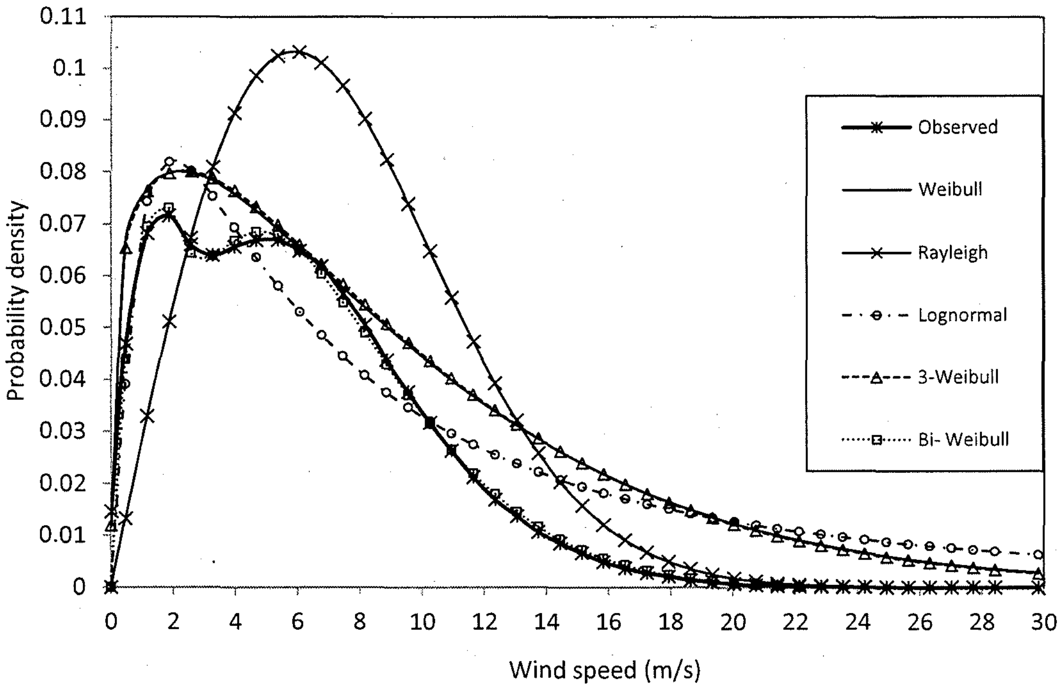

Figure 6.4 Observed probability density distributions for January-2008 with fitted distributions.

The Weibull and three-parameter-Weibull models lead to almost identical distribution curves. On the other hand, the bimodal Weibull function provides the best fit, producing very close distribution curve to the observed data. Note that the bimodal Weibull model provides the best fit regardless whether the distribution is of bimodal or unimodal nature.

The model parameters of the functions, obtained from the fit of probability density functions to the observed probability density distributions, and the corresponding mean wind speed values calculated from the probability density functions are given in Tables 6.2 and 6.3, respectively, for all the data currently studied.

Table 6.2 Parameters for probability density functions

	Rayleigh	Lognormal		Weibull		3-Weibull			bi-Weibull				
Month	c	μ	σ	c	k	k	c	γ	c_1	k_1	c_2	k_2	ω
Aug-07	4.71	1.50	1.14	5.39	1.17	1.17	5.37	9.9E-04	3.6	-2.3E+00	4.12	1.58	0.17
Sep-07	6.70	1.90	0.99	7.79	1.33	1.39	7.71	-1.0E-01	6.0	2.5E-05	5.58	1.74	0.35
Oct-07	4.38	1.45	1.31	4.92	1.13	1.02	6.57	1.0E-04	6.3	1.6E-05	3.36	1.23	0.32
Nov-07	5.47	1.68	1.16	6.22	1.20	1.19	6.26	7.8E-05	8.3	1.3E-05	4.53	1.44	0.31
Dec-07	5.65	1.63	1.38	5.82	1.11	1.09	5.90	1.0E-03	8.3	-2.7E-04	4.00	1.14	0.31
Jan-08	8.31	2.12	1.20	9.37	1.21	1.22	9.32	-1.0E-04	3.9	-1.9E+00	6.67	1.55	0.16
Feb-08	7.67	1.96	1.39	8.17	1.12	1.08	10.19	2.3E-01	6.2	-4.2E-06	5.84	1.16	0.29
Mar-08	6.55	1.85	1.17	7.34	1.22	1.15	5.16	9.9E-05	6.3	8.3E-06	5.46	1.43	0.30
Apr-08	4.29	1.42	1.08	4.99	1.22	1.15	5.00	1.0E-03	6.3	1.4E-05	3.52	1.51	0.33
May-08	3.70	1.28	1.03	4.23	1.28	1.29	4.20	1.0E-04	6.3	1.8E-05	3.12	1.61	0.32
Jun-08	4.63	1.49	1.18	5.21	1.18	1.15	5.16	9.9E-05	6.3	1.3E-05	3.73	1.36	0.31
Jul-08	3.90	1.35	1.12	4.55	1.19	1.17	4.60	8.6E-05	6.0	2.4E-05	3.22	1.47	0.32
Aug-08	3.79	1.31	1.07	4.41	1.23	1.23	4.41	9.9E-05	6.6	1.8E-05	3.16	1.54	0.33
Sep-08	3.54	1.24	1.12	4.16	1.18	1.14	4.11	9.9E-05	6.3	1.9E-05	2.82	1.43	0.34
Oct-08	5.66	1.69	0.95	6.26	1.42	1.42	6.26	-6.3E-04	6.3	4.0E-06	4.84	1.75	0.32
Nov-08	6.27	1.74	1.40	6.48	1.12	1.09	6.57	1.0E-04	7.1	-2.2E-05	4.63	1.12	0.29
Dec-08	3.98	1.40	1.19	4.93	1.16	1.09	5.90	1.0E-03	6.4	8.6E-05	3.01	1.41	0.37
Jan-09	5.72	1.73	1.30	6.48	1.14	1.09	7.00	9.9E-05	6.3	4.5E-02	4.56	1.31	0.34
Feb-09	5.12	1.61	1.15	5.76	1.23	1.12	6.88	1.0E-04	6.3	1.9E-02	4.26	1.46	0.32
Mar-09	6.40	1.85	1.12	7.18	1.27	1.27	7.17	1.0E-04	7.0	6.1E-02	5.43	1.61	0.34
Apr-09	4.20	1.43	1.17	4.82	1.20	1.20	4.83	9.9E-05	6.3	8.1E-02	3.46	1.52	0.37
May-09	5.37	1.65	0.99	5.90	1.39	1.39	5.90	-2.4E-03	6.3	3.1E-03	4.61	1.69	0.31
Jun-09	3.36	1.19	1.02	3.93	1.28	1.28	3.94	9.9E-05	6.3	-1.1E-01	2.78	1.53	0.29
Jul-09	3.97	1.37	1.14	4.54	1.22	1.21	4.55	9.9E-05	6.3	7.3E-03	3.27	1.46	0.32

As can be seen from Table 6.2, the Rayleigh parameters of *c* do not conform to the expected $v_m = c\sqrt{\frac{\pi}{4}}$ relationship due to the fact that the Rayleigh distribution proves too close to the observed one. However, they are quite close to those of the Weibull function. Overall, the shape parameters of the Weibull function are very close to 1. For the three-parameter Weibull function, the γ parameter is very close to zero in most of the months, meaning that it becomes equivalent to two-parameter Weibull function. In these cases, the *c* and *k* parameters of the former function are very similar to those of the latter. For the bimodal Weibull function, the first set of parameters c_1 and k_1 is somewhat different than usual *c* and *k* values. However, the second set of parameters is within the expected limits.

Table 6.3 Mean wind speed values calculated from the probability density functions

Month	Observed	Weibull	Rayleigh	Lognormal	3-Weibull	bi- Weibull
Aug-07	3.37	6.93	5.98	6.90	6.92	3.18
Sep-07	5.28	10.18	8.49	11.31	9.89	4.62
Oct-07	3.01	6.64	5.56	7.36	8.36	3.07
Nov-07	3.97	8.09	6.93	8.26	8.13	4.08
Dec-07	3.72	7.79	7.16	8.09	7.90	3.75
Jan-08	5.86	11.66	10.53	10.81	11.63	5.88
Feb-08	5.02	10.64	9.73	10.05	12.50	5.59
Mar-08	4.72	9.36	8.31	9.09	6.95	4.98
Apr-08	3.30	6.63	5.44	7.40	6.70	3.06
May-08	2.78	5.48	4.69	5.70	5.45	2.72
Jun-08	3.31	6.72	5.87	6.63	6.66	3.37
Jul-08	2.86	6.03	4.95	6.52	6.10	2.82
Aug-08	2.87	5.82	4.81	6.36	2.34	2.74
Sep-08	2.69	5.51	4.49	5.94	5.47	2.43
Oct-08	4.55	8.14	7.18	9.63	8.13	4.19
Nov-08	4.00	8.34	7.95	7.67	8.40	4.47
Dec-08	3.44	6.67	5.04	7.71	7.92	2.46
Jan-09	4.02	8.54	7.25	8.60	9.05	4.20
Feb-09	3.71	7.49	6.49	7.64	8.42	3.83
Mar-09	4.69	8.92	8.12	8.38	8.91	4.81
Apr-09	3.00	6.35	5.32	6.67	6.35	3.12
May-09	4.09	7.66	6.81	8.46	7.66	4.05
Jun-09	2.69	5.21	4.26	6.26	5.22	2.17
Jul-09	2.84	5.90	5.03	5.99	5.90	2.88

From Table 6.3, overall, the mean wind speeds calculated from the bimodal Weibull function parameters are closest to the observed ones, while the other models exceedingly overpredict the observed mean wind speed values. The statistical parameters for fits of probability density functions are presented in Table 6.4 24 months currently analysed. The fitness of Rayleigh, Weibull, 3-Parameter Weibull, lognormal, and D-Weibull functions has been testified against the observed distribution to find out the fittest model for urban mentioned data set. Four statistical parameters (R^2, slope, RMSE, and MBE) were been involved in this evaluation process. For Rayleigh model, it was overestimated as its statistical parameter values were far from optimal values, since the optimal values are R^2=1, slope=1, RMSE=0, MBE=0). Then the performances of Weibull and 3-Parameter Weibull were quite similar with advantage for Weibull from the tables 6.4(a,b) the values of R^2, and slope were

Table 6.4(a) Statistical parameters for probability density functions

Month	Var	Weibull	Rayleigh	Lognormal	3-Weibull	bi-Weibull
Aug-07	R^2	0.937	0.741	0.966	0.953	0.999
	Slope	0.938	0.604	1.050	0.955	1.013
	RMSE	0.018	0.037	0.013	0.032	0.009
	MBE	0.014	0.015	0.010	0.010	2.817E-04
Sep-07	R^2	0.883	0.873	0.916	0.915	0.994
	Slope	0.865	0.640	0.996	0.867	0.982
	RMSE	0.014	0.021	0.011	0.014	0.002
	MBE	0.009	0.009	0.007	0.010	-0.001
Oct-07	R^2	0.961	0.623	0.949	0.883	0.999
	Slope	0.899	0.550	1.019	1.097	1.000
	RMSE	0.016	0.042	0.013	0.019	0.002
	MBE	0.013	0.012	0.009	0.010	1.748E-04
Nov-07	R^2	0.961	0.785	0.955	0.958	1.000
	Slope	0.939	0.616	1.061	0.943	1.004
	RMSE	0.015	0.030	0.012	0.015	0.001
	MBE	0.012	0.012	0.008	0.012	1.974E-04
Dec-07	R^2	0.946	0.479	0.962	0.953	0.985
	Slope	0.901	0.513	1.033	0.918	1.000
	RMSE	0.005	0.013	0.003	0.005	0.002
	MBE	0.012	0.011	0.007	0.012	-2.61E-05
Jan-08	R^2	0.953	0.781	0.906	0.955	0.992
	Slope	0.996	0.631	1.112	0.990	0.991
	RMSE	0.011	0.021	0.010	0.011	0.002
	MBE	0.010	0.010	0.005	0.010	-3.37E-04
Feb-08	R^2	0.965	0.541	0.959	0.912	0.986
	Slope	0.956	0.545	1.067	1.141	1.014
	RMSE	0.011	0.028	0.008	0.014	0.004
	MBE	0.010	0.009	0.005	0.010	0.001
Mar-08	R^2	0.967	0.775	0.955	0.917	0.996
	Slope	0.964	0.622	1.088	0.681	1.010
	RMSE	0.013	0.026	0.010	0.021	0.002
	MBE	0.011	0.012	0.007	0.012	3.957E-04
Apr-08	R^2	0.939	0.814	0.970	0.929	0.995
	Slope	0.893	0.617	1.004	0.899	0.992
	RMSE	0.018	0.034	0.013	0.018	0.003
	MBE	0.013	0.013	0.011	0.013	-0.001
May-08	R^2	0.939	0.861	0.955	0.931	1.000
	Slope	0.922	0.644	1.036	0.901	0.997
	RMSE	0.024	0.041	0.019	0.024	0.001
	MBE	0.019	0.019	0.014	0.018	-2.39E-04
Jun-08	R^2	0.966	0.705	0.970	0.964	0.995
	Slope	0.954	0.587	1.058	0.944	1.003
	RMSE	0.018	0.040	0.013	0.018	0.003
	MBE	0.016	0.015	0.010	0.015	1.589E-04
Jul-08	R^2	0.949	0.802	0.949	0.945	1.000
	Slope	0.915	0.611	1.020	0.924	0.998
	RMSE	0.020	0.039	0.016	0.020	0.001
	MBE	0.015	0.015	0.012	0.015	-1.23E-04

Table 6.4(b) Statistical parameters for probability density functions

Month	Var	Weibull	Rayleigh	Lognormal	3-Weibull	bi-Weibull
	R^2	0.941	0.838	0.958	0.958	0.999
	Slope	0.905	0.626	1.014	0.898	0.995
	RMSE	0.021	0.039	0.017	0.039	0.001
Aug-08	*MBE*	0.016	0.015	0.013	-0.018	-4.22E-04
	R^2	0.936	0.740	0.962	0.936	0.986
	Slope	0.906	0.584	1.003	0.902	0.988
	RMSE	0.022	0.047	0.017	0.022	0.007
Sep-08	*MBE*	0.017	0.016	0.013	0.016	-0.001
	R^2	0.938	0.919	0.963	0.939	0.997
	Slope	0.856	0.679	1.000	0.857	0.991
	RMSE	0.015	0.022	0.011	0.015	0.002
Oct-08	*MBE*	0.010	0.010	0.009	0.010	-0.001
	R^2	0.946	0.471	0.951	0.956	0.972
	Slope	0.962	0.525	1.062	0.981	1.015
	RMSE	0.015	0.038	0.011	0.015	0.006
Nov-08	*MBE*	0.013	0.012	0.006	0.012	0.001
	R^2	0.910	0.702	0.959	0.881	0.981
	Slope	0.867	0.548	0.984	0.994	0.975
	RMSE	0.019	0.040	0.013	0.019	0.006
Dec-08	*MBE*	0.012	0.011	0.009	0.011	-0.002
	R^2	0.969	0.664	0.954	0.962	0.998
	Slope	0.931	0.567	1.051	0.997	1.004
	RMSE	0.013	0.032	0.010	0.013	0.002
Jan-09	*MBE*	0.011	0.011	0.007	0.011	1.022E-04
	R^2	0.966	0.784	0.956	0.937	0.999
	Slope	0.935	0.616	1.063	1.115	1.005
	RMSE	0.016	0.033	0.013	0.017	0.001
Feb-09	*MBE*	0.014	0.014	0.009	0.013	3.32E-04
	R^2	0.950	0.833	0.936	0.961	0.999
	Slope	0.931	0.640	1.084	0.943	1.007
	RMSE	0.014	0.025	0.012	0.014	0.001
Mar-09	*MBE*	0.011	0.012	0.008	0.012	4.08E-04
	R^2	0.958	0.771	0.937	0.958	0.997
	Slope	0.922	0.600	1.037	0.923	1.001
	RMSE	0.019	0.039	0.016	0.019	0.003
Apr-09	*MBE*	0.016	0.015	0.011	0.016	-2.46E-04
	R^2	0.943	0.904	0.947	0.949	0.999
	Slope	0.881	0.674	1.039	0.889	1.000
	RMSE	0.017	0.025	0.014	0.016	0.001
May-09	*MBE*	0.013	0.013	0.010	0.013	1.55E-04
	R^2	0.928	0.867	0.958	0.928	0.997
	Slope	0.858	0.630	0.967	0.859	0.985
	RMSE	0.022	0.038	0.017	0.022	0.003
Jun-09	*MBE*	0.015	0.014	0.013	0.015	-0.002
	R^2	0.961	0.773	0.943	0.961	0.997
	Slope	0.939	0.602	1.044	0.940	0.998
	RMSE	0.021	0.043	0.017	0.021	0.003
Jul-09	*MBE*	0.018	0.017	0.012	0.018	-3.82E-04

Approximately same, but the values of RMSE and MBE of Weibull model were closer to the optimal ones. Lognormal model achieved satisfied statistical parameter values. Since slope, RMSE, and MBE values of lognormal model were better comparing to previous mentioned models ,that means lognormal can perform more effectively than the others in the built up areas. However the performance of D-Weibull model was the best among the all models those were under investigation, since all its figures were the closest to optimal values even the predicted values of mean wind speed were the closest to the observed ones.

Figures (6.5 and 6.6) show the observed wind speed distribution in cumulative format for October-2007 and January-2008, respectively, with the distributions obtained from the cumulative distribution functions.

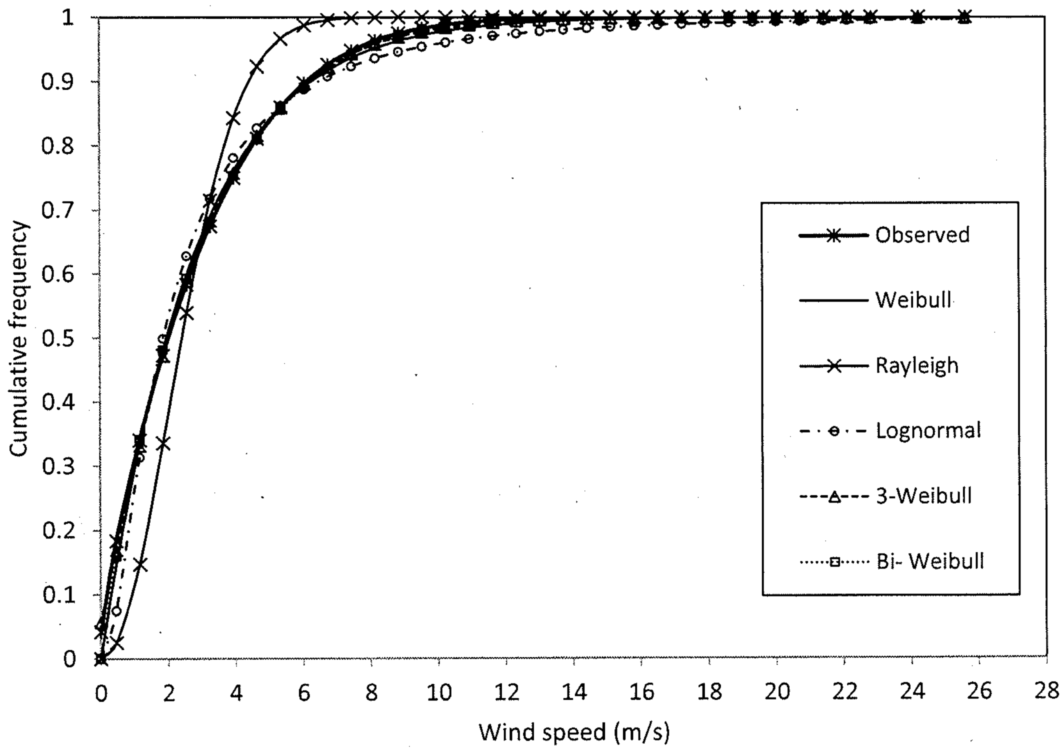

Figure 6.5 Observed cumulative distribution for October-2007 with fitted distributions.

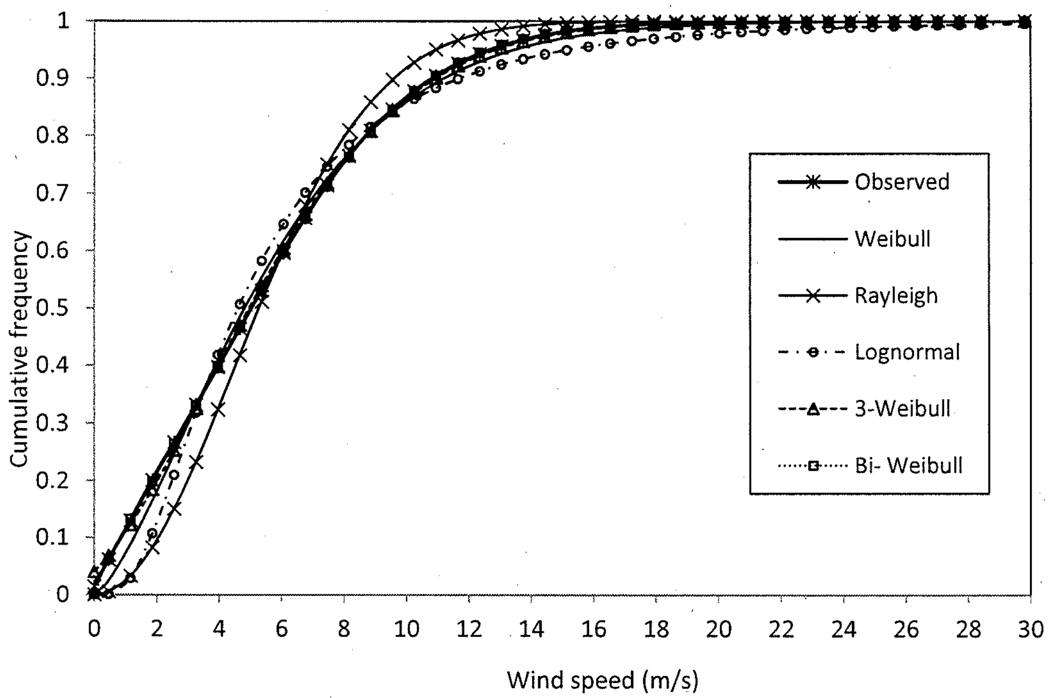

Figure 6.6 Observed cumulative distribution for January-2008 with fitted distributions

Figure 6.5, the Rayleigh model provides an inadequate fit and Lognormal significantly overpredicts the cumulative frequency up to 6 m/s. The remaining functions provide very close values to those of observed values. For the case of January-2008, the Rayleigh function still significantly over and underpredicts the observed cumulative distribution. The parameters of the functions obtained from the fit of cumulative distribution functions to the observed cumulative distributions are given in Table 6.5. From Table 6.5, the Rayleigh parameters of c are now closer to expected $v_m = c\sqrt{\frac{\pi}{4}}$ relationship because the Rayleigh distribution is much more close to the observed cumulative distribution than it was to the observed probability density distribution. Furthermore, they are almost identical to those of the Weibull function. For the three-parameter Weibull function, the γ parameters are distinctly different from zero and interestingly the c and k parameters of it are very close to those of the Weibull function. For the bimodal Weibull cumulative function, unlike the bimodal Weibull probability density function, the ω parameter can have either positive or negative values. Note that, positive ω values are usually around 0.4-0.5 while the negative values are usually less than –1. The mean wind speed values calculated from the probability density distributions obtained from the cumulative distributions are also given in Table 6.5. From this table, it is interesting to note that compared to the mean wind values from the probability density functions those from the cumulative distributions are significantly closer to the observed ones.

Table 6.5 Parameters for cumulative distribution functions and mean wind speed values calculated from them

Month	Rayleigh		Lognormal			Weibull		3-Weibull				bi-Weibull						
	c	v_m	μ	σ	v_m	c	k	v_m	k	c	γ	v_m	c_1	k_1	c_2	k_2	ω	v_m
Aug-07	3.42	3.38	0.86	0.82	3.56	3.33	1.23	3.46	1.39	3.72	-0.33	3.05	8.11	1.64	4.31	1.16	-0.33	3.39
Sep-07	5.40	5.13	1.38	0.74	5.47	5.39	1.40	5.26	1.44	5.54	-0.13	5.34	7.74	1.58	4.37	1.50	0.35	5.33
Oct-07	2.91	2.92	0.62	0.97	3.21	2.79	1.03	3.10	1.16	3.13	-0.27	3.04	8.64	1.21	6.13	0.98	-1.77	2.93
Nov-07	4.07	3.96	1.06	0.79	4.20	4.00	1.29	4.05	1.47	4.50	-0.43	3.99	8.41	1.58	5.32	1.24	-0.51	4.00
Dec-07	3.66	3.59	0.83	1.00	3.90	3.50	1.00	3.84	1.09	3.80	-0.24	3.78	6.69	2.08	2.23	0.91	0.29	3.73
Jan-08	6.32	5.95	1.53	0.73	6.14	6.22	1.42	6.01	1.78	7.64	-1.27	5.88	7.50	2.00	2.98	0.86	0.67	5.87
Feb-08	5.27	5.02	1.25	0.89	5.24	5.07	1.13	5.18	1.29	5.69	-0.50	5.09	7.84	2.15	3.10	0.90	0.39	5.04
Mar-08	4.96	4.75	1.27	0.76	4.95	4.87	1.34	4.82	1.54	5.53	-0.57	4.75	6.01	1.82	2.54	0.94	0.65	4.73
Apr-08	3.23	3.21	0.82	0.83	3.46	3.19	1.23	3.33	1.31	3.38	-0.16	3.30	6.32	1.45	4.80	1.23	-1.22	3.31
May-08	2.73	2.77	0.67	0.77	2.90	2.69	1.32	2.82	1.50	3.02	-0.28	2.78	6.25	1.69	4.19	1.26	-0.85	2.76
Jun-08	3.32	3.29	0.82	0.85	3.43	3.23	1.19	3.39	1.32	3.57	-0.28	3.34	5.33	2.46	2.48	1.07	0.25	3.32
Jul-08	2.80	2.83	0.66	0.84	3.02	2.74	1.21	2.92	1.38	3.10	-0.31	2.86	6.58	1.46	4.64	1.16	-1.19	2.85
Aug-08	2.79	2.82	0.67	0.81	3.01	2.75	1.25	2.90	1.39	3.02	-0.23	2.86	5.97	1.51	4.34	1.23	-1.14	2.87
Sep-08	2.53	2.59	0.53	0.91	2.83	2.48	1.11	2.74	1.18	2.64	-0.13	2.71	5.99	1.30	4.25	1.08	-1.26	2.68
Oct-08	4.63	4.45	1.24	0.69	4.72	4.62	1.50	4.52	1.59	4.88	-0.23	4.49	6.99	1.91	5.79	1.60	-0.97	4.57
Nov-08	4.13	4.01	0.98	0.94	4.12	3.93	1.08	4.13	1.25	4.53	-0.48	4.06	6.52	2.26	2.20	0.88	0.38	4.01
Dec-08	3.07	3.07	0.70	1.01	3.49	3.06	0.98	3.43	0.99	3.10	-0.03	3.42	5.11	2.83	3.32	1.05	-0.11	3.45
Jan-09	4.06	3.94	1.01	0.88	4.24	3.95	1.14	4.11	1.29	4.43	-0.41	4.04	7.11	1.21	5.50	1.11	-1.16	4.06
Feb-09	3.79	3.71	0.98	0.79	3.89	3.72	1.28	3.79	1.47	4.20	-0.42	3.73	4.39	1.67	1.95	0.80	0.69	3.66
Mar-09	4.92	4.08	1.28	0.73	4.91	4.86	1.40	4.13	1.62	5.54	-0.60	4.08	5.42	1.68	1.79	0.73	0.82	4.11
Apr-09	2.97	2.99	0.71	0.85	3.17	2.90	1.20	3.07	1.40	3.37	-0.40	3.01	7.43	1.45	5.22	1.14	-1.29	2.98
May-09	4.21	4.08	1.14	0.70	4.28	4.18	1.49	4.13	1.67	4.63	-0.40	4.08	8.00	1.81	6.14	1.47	-1.15	4.10
Jun-09	2.51	2.58	0.57	0.84	2.81	2.49	1.21	2.68	1.28	2.62	-0.11	2.66	4.37	1.53	3.35	1.27	-0.90	2.71
Jul-09	2.81	2.84	0.66	0.84	2.98	2.74	1.21	2.91	1.42	3.17	-0.37	2.85	7.46	1.48	5.17	1.13	-1.31	2.80

Because the main wind energy related parameters such as mean wind speed or wind power density are calculated from the probability density distributions, the cumulative distribution should be converted to probability density distribution.

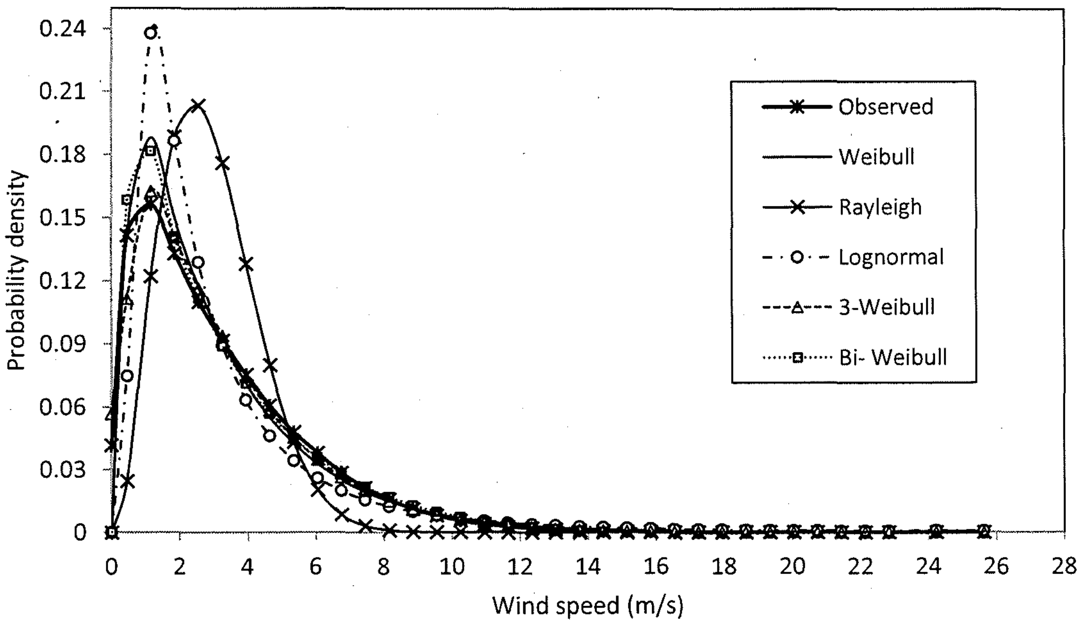

Figure 6.7 Observed probability density distribution for October-2007 with distributions obtained from the cumulative distribution functions.

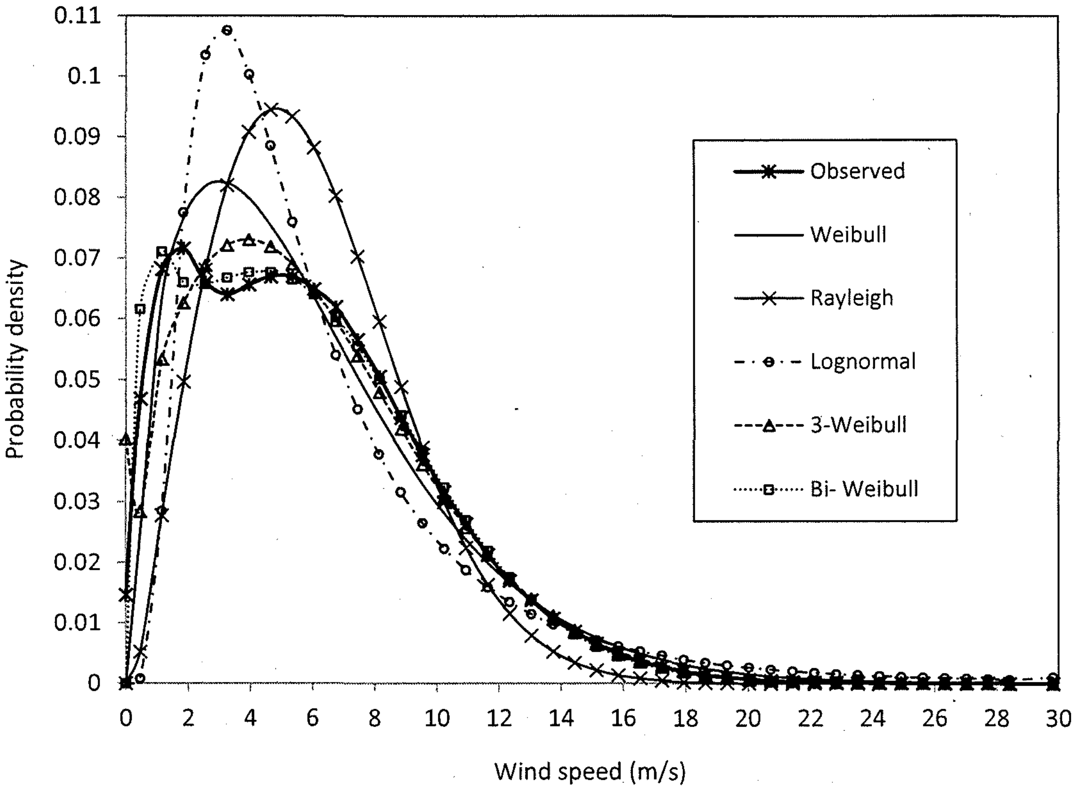

Figure 6.8 Observed probability density distribution for January-2008 with distributions obtained from the cumulative distribution functions.

The probability density distributions obtained from the cumulative distribution are presented in Figure 6.7 for October 2007. The probability density distributions converted from the cumulative ones for January 2008 can be seen in Figure 6.8. As can be seen from Figures. 6.7 and 6.8, the probability density distributions obtained from the cumulative distribution are substantially different from those obtained directly from the probability density functions. The statistical parameters for probability density distributions obtained from the cumulative distribution functions are given in Table 6.6 for some months.

Table 6.6(a) Statistical parameters for probability density distributions obtained from cumulative distribution functions

Month	Var	Weibull	Rayleigh	Lognormal	3-Weibull	bi-Weibull
	R^2	0.999	0.983	0.992	0.991	1.000
	Slope	0.989	0.882	0.978	1.025	0.993
	RMSE	0.011	0.053	0.030	0.029	0.006
Aug-07	*MBE*	-0.004	-0.001	-0.013	-0.005	-6.7E-04
	R^2	0.999	0.992	0.997	0.999	0.999
	Slope	0.986	0.911	0.974	0.984	0.986
	RMSE	0.009	0.037	0.019	0.008	0.008
Sep-07	*MBE*	3.1E-04	0.004	-0.008	-0.002	-0.002
	R^2	0.998	0.968	0.990	1.000	0.999
	Slope	0.979	0.845	0.971	1.003	0.979
	RMSE	0.012	0.062	0.028	0.005	0.009
Oct-07	*MBE*	-0.004	0.003	-0.012	-0.001	-1.7E-03
	R^2	0.999	0.987	0.993	1.000	1.000
	Slope	0.988	0.891	0.976	1.002	0.987
	RMSE	0.009	0.047	0.028	0.004	0.007
Nov-07	*MBE*	-0.003	2.8E-04	-0.012	0.000	-1.5E-03
	R^2	0.998	0.958	0.989	0.999	1.000
	Slope	0.988	0.829	0.980	1.006	0.989
	RMSE	0.012	0.071	0.030	0.009	0.005
Dec-07	*MBE*	-0.005	0.004	-0.013	-0.002	-8.836E-04
	R^2	0.998	0.992	0.990	1.000	1.000
	Slope	0.986	0.902	0.974	1.003	0.997
	RMSE	0.014	0.042	0.034	0.006	0.003
Jan-08	*MBE*	-0.005	-0.003	-0.015	-3.568E-04	-4.909E-04
	R^2	0.997	0.974	0.987	0.998	1.000
	Slope	0.988	0.850	0.977	1.006	0.996
	RMSE	0.015	0.063	0.034	0.012	0.003
Feb-08	*MBE*	-0.005	-9.447E-05	-0.014	-0.002	-0.001
	R^2	0.987	0.973	0.993	0.989	0.988
	Slope	1.003	0.938	0.977	1.014	1.006
	RMSE	0.040	0.057	0.028	0.039	0.040
Mar-08	*MBE*	0.022	0.023	-0.012	0.024	2.224E-02
	R^2	1.000	0.984	0.995	1.000	1.000
	Slope	0.991	0.893	0.979	1.000	0.992
	RMSE	0.005	0.047	0.021	0.001	0.004
Apr-08	*MBE*	-0.001	0.003	-0.009	9.618E-05	-0.001
	R^2	0.999	0.989	0.994	1.000	1.000
	Slope	0.986	0.902	0.975	1.001	0.988
	RMSE	0.009	0.045	0.027	0.002	0.007
May-08	*MBE*	-0.003	2.105E-04	-0.012	-6.381E-05	-1.700E-03
	R^2	0.999	0.980	0.991	1.000	1.000
	Slope	0.989	0.872	0.979	1.005	0.992
	RMSE	0.011	0.058	0.030	0.006	0.004
Jun-08	*MBE*	-0.004	0.001	-0.013	-0.001	-1.059E-03
	R^2	0.999	0.984	0.993	1.000	0.999
	Slope	0.982	0.882	0.970	1.001	0.983
	RMSE	0.010	0.050	0.027	0.003	0.009
Jul-08	*MBE*	-0.003	0.001	-0.011	-3.729E-05	-1.780E-03

Table6.6(b) Statistical parameters for probability density distributions obtained from cumulative distribution functions

Month	Var	Weibull	Rayleigh	Lognormal	3-Weibull	bi-Weibull
	R^2	0.999	0.986	0.994	1.000	1.000
	Slope	0.986	0.894	0.974	1.000	0.988
	RMSE	0.008	0.046	0.025	0.002	0.007
Aug-08	*MBE*	-0.002	0.002	-0.010	1.930E-04	-1.473E-03
	R^2	1.000	0.974	0.994	1.000	1.000
	Slope	0.988	0.869	0.982	1.002	0.988
	RMSE	0.007	0.059	0.024	0.003	0.006
Sep-08	*MBE*	-0.003	0.005	-0.011	-0.001	-0.001
	R^2	1.000	0.994	0.998	1.000	1.000
	Slope	0.996	0.938	0.985	1.001	0.997
	RMSE	0.004	0.029	0.016	0.005	0.002
Oct-08	*MBE*	0.001	0.003	-0.007	0.002	-4.796E-04
	R^2	0.996	0.967	0.984	0.998	1.000
	Slope	0.988	0.836	0.979	1.008	0.994
	RMSE	0.018	0.071	0.037	0.013	0.004
Nov-08	*MBE*	-0.007	-0.001	-0.015	-0.003	-0.001
	R^2	0.999	0.960	0.997	0.999	1.000
	Slope	0.995	0.851	0.988	0.999	0.992
	RMSE	0.007	0.065	0.015	0.006	0.004
Dec-08	*MBE*	-1.242E-04	0.013	-0.008	3.283E-04	-0.001
	R^2	0.999	0.977	0.991	1.000	0.999
	Slope	0.984	0.861	0.972	1.002	0.982
	RMSE	0.011	0.057	0.028	0.004	0.009
Jan-09	*MBE*	-0.004	0.002	-0.012	-0.001	-6.480E-04
	R^2	0.999	0.987	0.992	1.000	1.000
	Slope	0.988	0.890	0.976	1.003	0.989
	RMSE	0.010	0.048	0.029	0.004	0.007
Feb-09	*MBE*	-0.004	8.59E-06	-0.012	-0.001	-0.001
	R^2	0.987	0.993	0.993	0.989	0.988
	Slope	1.003	0.977	0.977	1.014	1.006
	RMSE	0.040	0.028	0.028	0.039	0.040
Mar-09	*MBE*	0.022	-1.23E-02	-0.012	2.37E-02	0.022
	R^2	0.999	0.983	0.991	1.000	0.999
	Slope	0.979	0.874	0.968	1.001	0.981
	RMSE	0.012	0.052	0.030	0.004	0.010
Apr-09	*MBE*	-0.004	0.001	-0.012	-5.65E-05	-0.002
	R^2	1.000	0.995	0.995	1.000	1.000
	Slope	0.990	0.928	0.979	1.000	0.992
	RMSE	0.006	0.032	0.024	0.002	0.005
May-09	*MBE*	-0.002	2.66E-05	-0.010	3.26E-04	-0.001
	R^2	1.000	0.985	0.996	1.000	1.000
	Slope	0.988	0.898	0.977	0.997	0.989
	RMSE	0.006	0.044	0.018	0.005	0.006
Jun-09	*MBE*	-1.08E-04	0.005	-0.008	0.001	-0.001
	R^2	0.999	0.984	0.991	1.000	0.999
	Slope	0.981	0.876	0.970	1.003	0.982
	RMSE	0.013	0.054	0.031	0.004	0.010
Jul-09	*MBE*	-0.005	-3.05E-04	-0.014	-0.001	-0.002

However, it is difficult to independently interpret the individual parameters. Therefore, as a more robust indication of the goodness of different functions, the accuracy score developed earlier is applied to the statistical parameters given in Tables 6.4 and 6.6. The monthly accuracy scores for probability density, cumulative distribution functions and relative distributions obtained from the cumulative distribution functions are presented in Tables 6.7, 6.8 and 6.9, respectively. As can be seen from Table 6.7, the average accuracy score (ψ) changes between 2.55 and 5.83 for the different probability density functions. The highest ψ is provided by the bimodal Weibull function with a significantly large margin, followed by the Lognormal function with ψ value of 4.77. The Rayleigh function is the least accurate model with an overall ψ of 2.38. The Weibull and three-parameter Weibull functions return mediocre ψ, though the former proves a better model than the latter for this particular data set. For the case of relative distributions obtained from the cumulative distribution functions as given in Table 6.9, it is interesting to note that the three-parameter Weibull leads to the highest ψ with a value of 5.52, followed by the Weibull function with a score of 5.46. The bimodal Weibull function achieves an overall score of 5.38. The Rayleigh and Lognormal functions lead to the lowest ψ scores with values of 3.90 and 3.56, respectively. When individual models are compared for their performance in terms of probability density functions and cumulative distribution functions, it is observed that the Rayleigh, Weibull, and the three-parameter Weibull functions perform better when they are fitted to cumulative distributions while the bimodal Weibull and Lognormal functions perform better when the fitting is based on the probability density distributions. The most significant improvement occurs with the three-parameter Weibull function when it is fitted to the cumulative distribution while the Lognormal function deteriorates most when it is fitted to the cumulative distribution.

Table 6.7 Accuracy scores for probability density functions

Month	Rayleigh	Lognormal	Weibull	3-Weibull	bi-Weibull
Aug-07	2.55	4.76	4.34	4.36	5.70
Sep-07	2.84	4.59	3.85	3.86	5.74
Oct-07	2.35	4.91	4.26	4.33	5.94
Nov-07	2.64	4.69	4.29	4.31	5.95
Dec-07	2.09	5.02	4.26	4.37	5.86
Jan-08	2.67	4.57	4.46	4.44	5.82
Feb-08	2.22	4.96	4.47	4.01	5.76
Mar-08	2.65	4.69	4.40	3.16	5.85
Apr-08	2.68	4.75	4.10	4.11	5.83
May-08	2.79	4.62	4.13	4.08	5.95
Jun-08	2.48	4.81	4.38	4.39	5.90
Jul-08	2.66	4.71	4.20	4.23	5.97
Aug-08	2.85	4.78	4.24	3.65	5.92
Sep-08	2.53	4.83	4.18	4.20	5.75
Oct-08	2.96	4.58	3.84	3.83	5.83
Nov-08	2.07	4.99	4.43	4.55	5.70
Dec-08	2.40	4.80	4.04	4.43	5.56
Jan-09	2.40	4.86	4.35	4.59	5.93
Feb-09	2.66	4.71	4.28	4.16	5.92
Mar-09	3.75	5.03	4.78	4.79	5.94
Apr-09	2.62	4.74	4.24	4.24	5.91
May-09	2.94	4.52	3.96	3.97	5.93
Jun-09	2.80	4.55	3.92	3.92	5.76
Jul-09	2.62	4.74	4.28	4.29	5.91
Total average	**2.64**	**4.76**	**4.24**	**4.18**	**5.85**

Table 6.8 Accuracy scores for cumulative distribution functions

Month	Rayleigh	Lognormal	Weibull	3-Weibull	bi-Weibull
Aug-07	4.59	4.37	5.42	4.98	5.81
Sep-07	4.20	4.42	5.68	5.48	5.54
Oct-07	4.26	4.45	5.39	5.82	5.65
Nov-07	4.64	4.33	5.48	5.88	5.69
Dec-07	4.10	4.51	5.40	5.68	5.83
Jan-08	4.48	4.10	5.28	5.82	5.90
Feb-08	4.52	4.38	5.34	5.66	5.87
Mar-08	4.61	4.28	5.45	5.82	5.92
Apr-08	4.28	4.48	5.72	5.96	5.79
May-08	4.68	4.30	5.49	5.94	5.66
Jun-08	4.53	4.41	5.45	5.78	5.82
Jul-08	4.53	4.36	5.45	5.93	5.62
Aug-08	4.48	4.39	5.57	5.93	5.68
Sep-08	4.16	4.54	5.58	5.86	5.77
Oct-08	4.32	4.39	5.72	5.54	5.84
Nov-08	4.43	4.39	5.27	5.62	5.88
Dec-08	3.51	5.15	5.87	5.88	5.85
Jan-09	4.36	4.41	5.46	5.87	5.74
Feb-09	4.66	4.32	5.46	5.86	5.71
Mar-09	5.40	5.40	5.06	4.95	5.03
Apr-09	4.57	4.33	5.38	5.91	5.56
May-09	4.78	4.18	5.59	5.92	5.69
Jun-09	4.04	4.51	5.81	5.73	5.67
Jul-09	4.59	4.33	5.35	5.87	5.60
Total average	**4.45**	**4.45**	**5.49**	**5.74**	**5.71**

Table 6.9 Accuracy scores for probability density distributions obtained from cumulative distribution functions

Month	**Rayleigh**	**Lognormal**	**Weibull**	**3-Weibull**	**bi-Weibull**
Aug-07	3.89	4.45	5.54	3.92	5.66
Sep-07	4.37	3.97	5.13	4.22	5.15
Oct-07	3.56	3.68	5.38	5.80	4.43
Nov-07	4.03	3.33	5.45	5.75	5.52
Dec-07	3.36	3.68	5.51	5.73	5.54
Jan-08	4.19	2.99	5.25	5.52	5.63
Feb-08	3.53	3.31	5.40	5.09	5.63
Mar-08	4.05	3.26	5.47	5.69	5.78
Apr-08	4.07	3.70	5.66	5.91	5.49
May-08	4.13	3.31	5.45	5.83	4.97
Jun-08	3.78	3.47	5.51	5.77	5.66
Jul-08	3.96	3.32	5.38	5.79	4.82
Aug-08	4.07	3.43	5.49	5.83	5.13
Sep-08	3.81	3.83	5.61	5.92	5.29
Oct-08	4.53	3.56	5.74	5.77	5.76
Nov-08	3.32	3.33	5.34	5.49	5.61
Dec-08	3.74	4.15	5.54	5.67	5.65
Jan-09	3.74	3.30	5.39	5.71	5.17
Feb-09	4.00	3.29	5.43	5.74	4.72
Mar-09	4.96	4.20	5.37	5.50	5.31
Apr-09	3.88	3.20	5.27	5.73	4.57
May-09	4.52	3.37	5.54	5.86	5.25
Jun-09	4.15	3.68	5.59	5.82	5.57
Jul-09	3.87	3.23	5.30	5.76	4.66
Total average	**3.98**	**3.54**	**5.45**	**5.58**	**5.29**

6.5 Conclusions

In the present chapter, an inter-comparison of wind speed probability distribution models has been undertaken. Most of the commonly used probability density and cumulative distribution functions used in the literature namely, Rayleigh, Lognormal, Weibull, three-parameter Weibull and bimodal Weibull functions have been included. For the most important aspect of evaluating such functions, a novel statistical tool was presently developed so that an overall accuracy score can be obtained for the models studied. The numerical values of the relevant parameters were obtained from the wind speed data collected at Napier University for a period of twenty four months. The most important results arising from the work undertaken herein are:

- Not any single statistical parameter can adequately be an indication of the goodness of a model. A composite evaluation index for inter-comparing the models was therefore presently developed,

- The question raised in recent years as to the inadequacy of the Weibull function in modelling the wind speed distributions was somewhat substantiated as being correct, thus, alternative more complicated functions are needed to better model wind speed distributions, either unimodal or bimodal,

- Based on the probability density functions, the mean wind speeds calculated from the bimodal Weibull function parameters are closest to the observed ones by a large margin, distantly followed by the Lognormal function. When compared to the mean wind values from the probability density functions, those from the cumulative distributions are significantly closer to the observed ones, the bimodal Weibull function returning the best prediction of mean wind speeds,

- Considering the presently developed accuracy score, ψ changes between 2.64 and 5.85 for the probability density functions. The highest ψ is provided by the bimodal Weibull function, followed by the Lognormal function with value of ψ of 4.76. The Rayleigh function is the least accurate model with an overall ψ of 2.64. It should be noted that the

Lognormal model constitutes a significant alternative to the Weibull model as both of them have two parameters.

- For the case of probability density distributions obtained from the cumulative distribution functions, the three-parameter Weibull leads to the highest ψ with a value of 5.58, followed by the Weibull and bimodal Weibull functions with scores of 5.45 and 5.29, respectively,

When individual models are compared for their performance in terms of their probability density functions and cumulative distribution functions, it is observed that the Rayleigh, Weibull, and the three-parameter Weibull functions perform better when they are fitted to cumulative distributions while the Bimodal and Lognormal functions perform better when the fitting is based on the probability density distributions.

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Chapter 7

Wind Energy Potential for Generating Electricity in Pakistan

7.1 Introduction:

This chapter focuses on exploring the wind energy potential in Pakistan. Data for one of the windiest locations on the southern coast of Pakistan, facing Arabian Sea, i.e. Gharo, near Karachi was obtained by this author through Edinburgh Napier University's contact. One of the aims of this project was to explore the potential for wind energy for Syria. However, it was not possible to acquire any quality data for the country as no systematic measurements have been undertaken to date. Therefore, to circumvent this handicap it was decided to analyse data from locations at latitudes south and north of Syria, and hence to obtain an assessment for Syrian locations by means of interpolation. In this respect reference is made to Figures 7.1 and 7.2. Figure 7.1 provides geographical details of the three locations under discussion, i.e. Syria, Edinburgh (northerly location) and Gharo (southerly location).

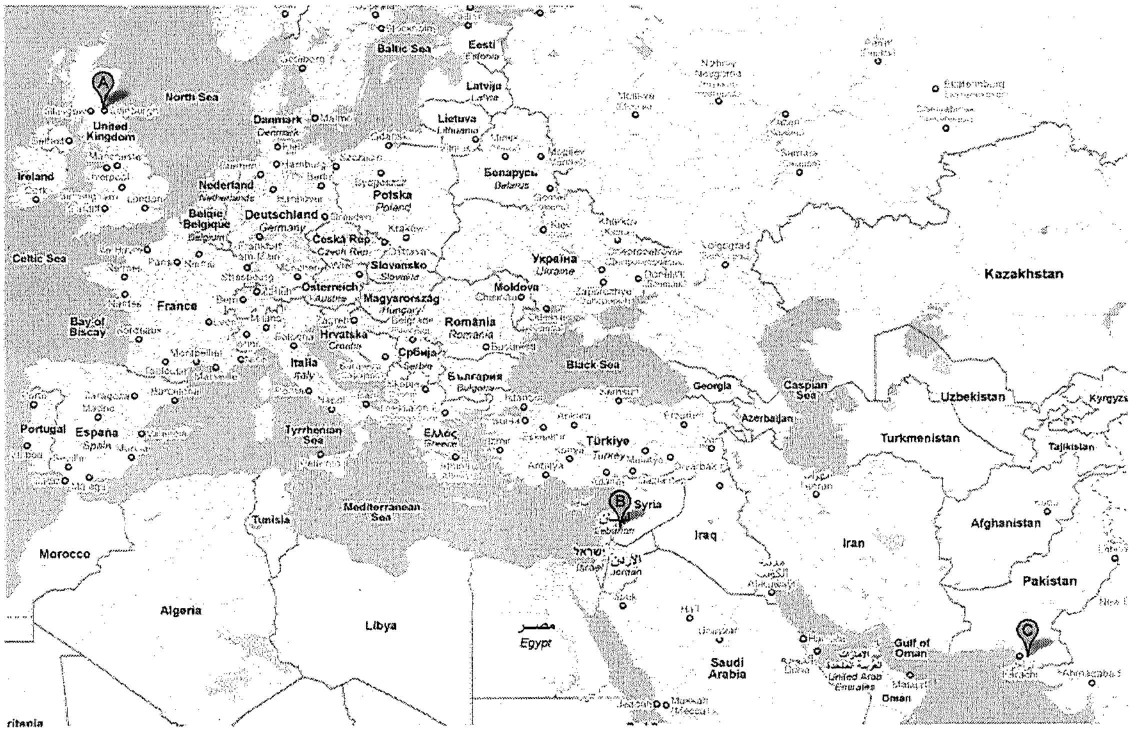


Figure7.1 The geographical positions of the three locations: Scotland (Edinburgh), Syria (Latakia), and Pakistan (Gharo)

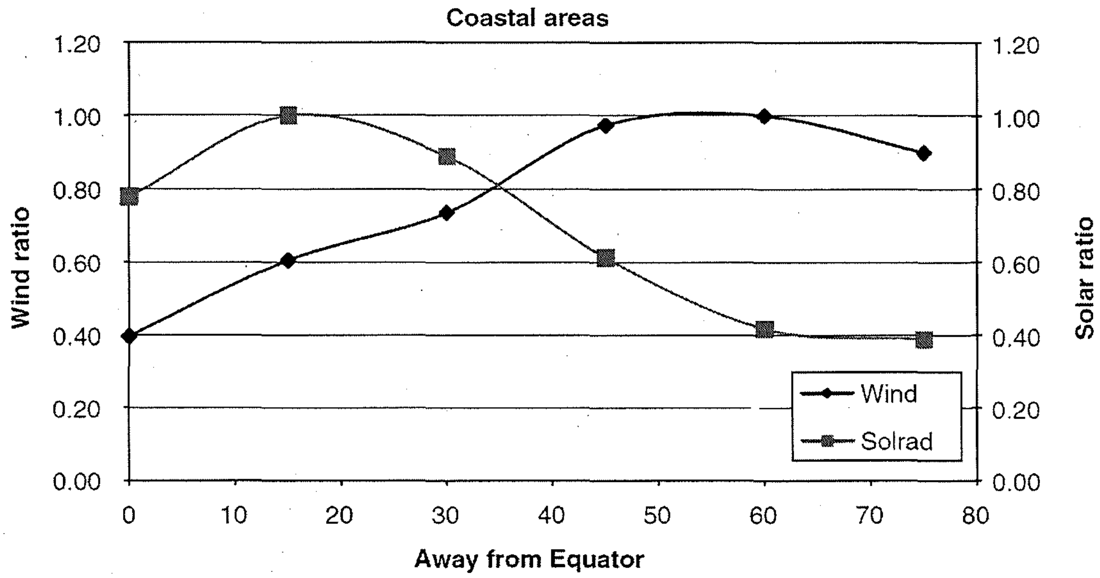


Figure 7.2 Wind energy potential with respect to geographical latitude (Asif and Muneer 2007).

Figure 7.2 shows the distribution of wind energy with respect to latitude. This distribution is the basis of the present argument.

7.2 Need for wind power as alternative energy resource in Pakistan

Within Pakistan the relative ease with which hydrocarbon gas reserves are accessible in Baluchistan has somewhat led to a delay in action on possibility of renewable energy and installation of appropriate important projects. However, with an apparent signal of depleting fossil fuels, the current regime has commenced a key plan of measuring wind speed and installation of large wind farms at locations that have been deemed fit for this purpose. The key force behind the present resurgence of renewable energy activity within Pakistan is the creation of the Alternative Energy Development Board (AEDB), established by the Government of Pakistan in 2003. Under the aegis of AEDB wind speed data have been measured over a period of four years at a minute's frequency for Southern Pakistan at Gharo. The period of measurement was May 2002 – June 2006.

7.3 The objectives behind working on wind data with two different intervals sampling rate

The present work aims to explore the potential for using hourly- as opposed to minute-by-minute data for the design of wind energy systems, the former set being much more widely available for a larger number of locations within the developing world. This work is therefore centred on finding the difference in the wind energy production by using: (a) a measured long-term, minute-by-minute data, and comparing this with (b) a concurrent hourly data set. Furthermore, a comparison of the cumulative frequency of wind speed from the latter data sets has also been carried out. It was found that the difference between the annual energy outputs from the latter two data sets was in close agreement with only a % difference. The two cumulative frequency functions were also found to be closely related. These results may be of use for locations close to the equatorial belt where the wind regime is noted for its stable and seasonal character.

7.5 Data requirements and present datasets

Wind energy is amongst the fastest growing renewable technologies in the world. In the recent past, the annual market for wind has continued to increase at the staggering rate of 32% following the 2009 record year in which the market grew by 39%. Europe is still leading the market with 76,373 MW of installed capacity at the end of 2009, representing 48% of the global total. The countries with the highest total installed capacity are the USA (35,161MW), China (25,805MW) Germany (25,777 MW), Spain (19,149 MW), India (10,926 MW), Denmark (3,480) and UK (4,058 MW). Figure 7.3 provides further details of the global growth of the wind energy see Cumulative installed wind turbine capacity (MW)

Thirteen countries around the world can now be counted among those with over 2000 MW of wind capacity, with Canada reaching this threshold in 2009 (GWEC 2009). UK has recently announced its plans to expand its offshore wind generation capacity to 33GW over the next decade. According to the UK's Energy Secretary, by 2020 UK aims to generate wind energy sufficient to power

25 million homes within UK (Energy Current 2008) (Geoffrey Lean 2007). Wind power is gathering pace not only in the high latitude areas such as Northern and central Europe but also in low latitude areas. By the end of 2009 India, for example, had managed an installation capacity of 10,926 MW.

The starting point of any wind energy project is the resource assessment. It helps to identify suitable sites for wind turbines and also undertake an early economic cost analysis. Due to the rather large capital investment involved with wind energy projects, it is crucial to undertake the resource assessment as precisely as possible. The speed of the wind and its annual frequency are the critical parameters that determine the net output of a wind turbine. Wind speed is a highly fluctuating entity - it varies in a temporal as well as spatial sense. For example, wind speed can gust from 48 to 192 km/hour within three seconds, which is a tremendous change for engineers to design for (Muneer, Asif et al. 2005). Wind speed and direction vary over all measuring periods. Wind speed measurements are logged at pre-defined intervals such as per second, per 5 second, per minute or per hour. The most commonly cited figure is the average wind speed over a year (Gipe 2004). Wind speed measurement and its compilation into reliable datasets is a laborious and expensive task. Often in many parts of the world, in view of the economic constraints, only average hourly data is available.

As mentioned above wind data acquisition, logging and storage is an expensive affair. It is customary for the national metrological office to undertake the above task. Wind turbine installers then approach their local metrological office for purchase of the data sets. The more detailed the data set the higher the price. For example the UK Metrological Office charges 3 UK pence/element/time stamp. This means that a year's minute-by-minute data for wind speed and wind direction would cost the user £31,536 for just one site. This is an excessive cost for wind energy researchers and even small-scale installers. Thus, there are two problems with data acquisition that can be identified: (a) Lack of reliable, measured data sets for a fair number of locations, particularly within the context of developing economies, and (b) The high cost associated with detailed data sets, i.e. wind speed on a minute-by-minute basis.

Pakistan is one of those Asian countries actively seeking to exploit its wind energy potential. In the past in Pakistan the rather ease of availability and exploitation of hydrocarbon gas reserves from Sui, a location in Balochistan had the effect of delaying the work on feasibility of renewable energy and installation of appropriate pilot projects. (Muneer and Asif 2007)

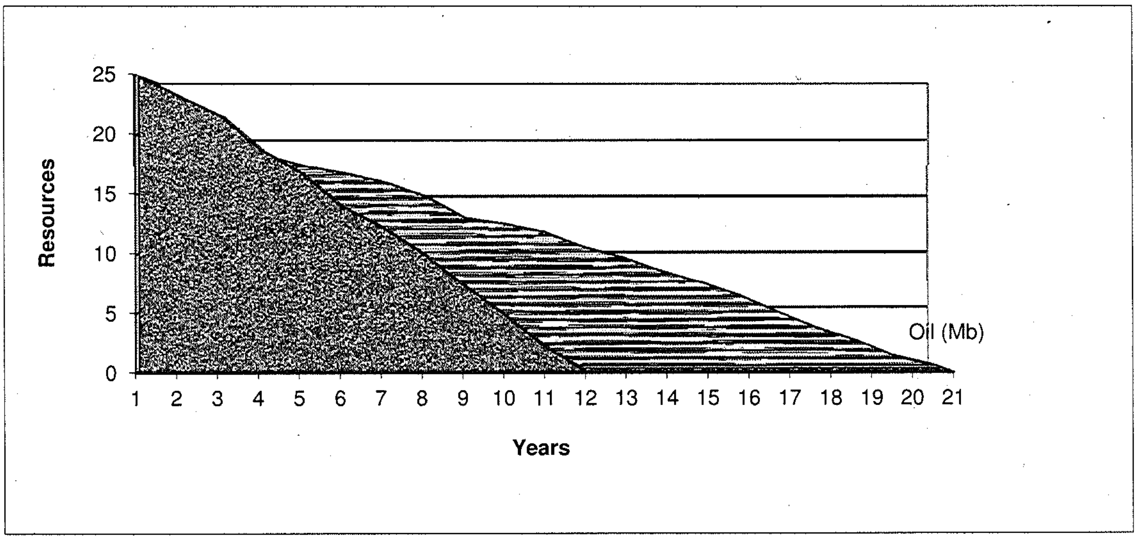


Figure 7.3 Projected oil and gas reserves for Pakistan: oil reserves (million barrels), gas reserves (billion cubic meters). Note: year 1 refers to 2002.

The present government has initiated a major programme of wind speed measurement and installation of large wind farms at locations that have been deemed fit for purpose. Figure 7.5 shows details of those sites with Gharo (24°44'23"N, 67°34'47"E) being identified as the site which will be the recipient of Pakistan's first large wind farm.

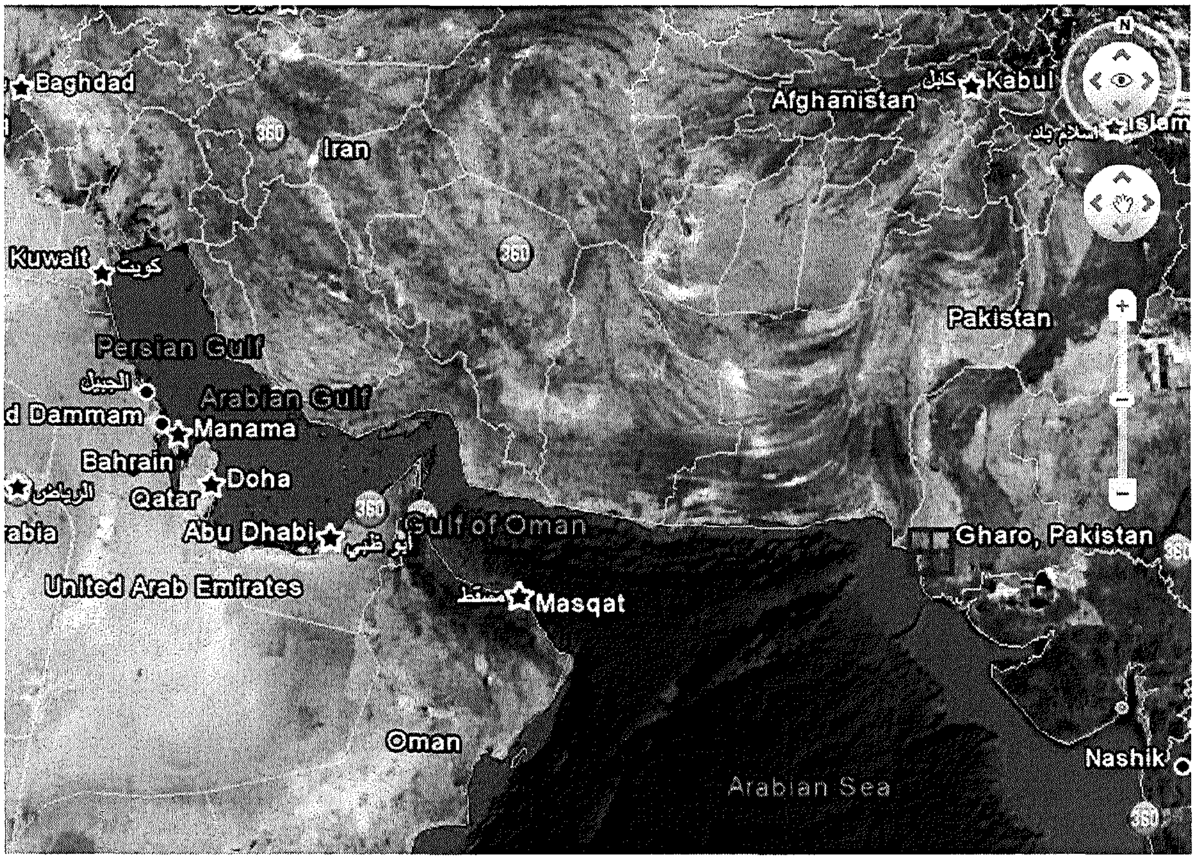


Figure 7.4 Location of Gharo within Pakistan

Table 7.1(a) provides details for some of the candidate sites that have been earmarked for the development of wind farms within Gharo area (UNDP 2007).

Table 7.1(a) Coordinates of wind farm sites in Khuttikun, Gharo (ddd°mm'ss.ss")

Project	Longitude	Latitude
1	67° 26' 28.32" E	24° 39' 00.39" N
2	67° 26' 38.47" E	24° 40' 43.01" N
3	67° 26' 01.50" E	24° 41' 35.05" N
4	67° 24' 42.21" E	24° 42' 19.69" N
5	67° 22' 55.00" E	24° 44' 02.50" N
6	67° 25' 26.53" E	24° 43' 39.63" N
7	67° 27' 42.27" E	24° 43' 37.78" N
8	67° 28' 33.12" E	24° 43' 18.86" N
9	67° 29' 16.52" E	24° 42' 29.37" N
10	67° 29' 53.98" E	24° 41' 02.95" N
11	67° 30' 14.89" E	24° 40' 38.20" N
12	67° 30' 29.88" E	24° 40' 32.45" N
13	67° 30' 27.88" E	24° 39' 34.73" N
14	67° 30' 02.63" E	24° 39' 32.94" N
15	67° 27' 41.98" E	24° 39' 56.18" N
16	67° 27' 39.45" E	24° 40' 18.09" N
17	67° 27' 40.08" E	24° 40' 53.27" N
18	67° 29' 08.98" E	24° 40' 41.44" N
19	67° 28' 55.57" E	24° 41' 02.60" N
20	67° 28' 00.72" E	24° 40' 55.80" N
21	67° 25' 55.21" E	24° 42' 01.06" N
22	67° 28' 33.49" E	24° 42' 08.28" N
23	67° 28' 27.58" E	24° 42' 29.02" N
24	67° 27' 42.99" E	24° 43' 06.69" N
25	67° 26' 55.60" E	24° 42' 51.26" N
26	67° 25' 24.45" E	24° 43' 34.03" N
27	67° 26' 56.41" E	24° 41' 47.80" N

Table 7.1(b) Coordinates of wind farm sites in Jhimpir, near Gharo

Project Name	Longitude	Latitude
ZORLU Wind Farm		
Z1	68° 00' 03,55" E	25° 02' 14,29" N
Z2	68° 00' 20,72" E	25° 02' 44,11" N
Z3	67° 58' 05,64" E	25° 04' 06,90" N
Z4	67° 57' 50,87" E	25° 03 '40,79" N
FFC Wind Farm		
F1	68° 00' 35,19" E	25° 03' 08,76" N
F2	68° 00' 55,22" E	25° 03' 43,74" N
F3	67° 58' 40,12" E	25° 05' 06,50" N
F4	67° 58' 20,31" E	25° 04' 32,17" N
MASTERWIND Wind Farm		
M0	68° 01' 08,99" E	25° 04' 07,20" N
M1	68° 00' 21.36" E	25° 04' 35.87" N
M2	68° 00' 35,48" E	25° 05' 17,94" N
M3	67° 58' 53,18" E	25° 05' 29,64" N

The present work aims to explore the potential for using hourly- as opposed to minute-by-minute data for the design of wind energy systems, the former set being much easier to collect and disseminate at an economical price. For this purpose, the present study uses data measured over a period of four years at a minute's frequency from Gharo. The period of measurement was May 2002 – June 2006. Note that prior to the formation of the Alternative Energy Development Board no such detailed data set for wind speed and direction had been recorded. Note that previously other researchers such as Rehman (Rehman 2004) and Ramirez and Carta (Ramírez and Carta 2005) have undertaken studies that are generically similar. Rehman (Rehman 2004) used hourly data to study the effect of hub height and incorporated a general use of the manufacturers guideline of cut-in speed at least 3.5 m/s. Ramirez and Carta

(Ramírez and Carta 2005) have investigated the influence of the data sampling intervals in the estimation of the parameters of the wind speed probability density functions. In contrast, in the present study the author used actual performance curves of the given wind turbines for achieving the aims highlighted in the above paragraph.

7.5 Previous wind energy related work undertaken within Pakistan:

Pakistan has not yet been able to exploit its wind energy potential. The very first efforts to identify possible exploitation of wind energy for water pumping and aero-generation in Pakistan were made in 1980s. That work has been adequately reviewed by Raja and Abro (Raja and Abro 1994). They also investigated the general potential of wind energy in Pakistan and in this respect wind speed contour maps were also presented. However, they used only cursory, monthly-averaged wind data. More recently, Mirza et al (Mirza, Ahmad et al. 2007) reviewed the developments of wind energy in Pakistan as undertaken by various departments in the country over the last few years. Before AEDB was set up, the department prominently working in this area was Pakistan Council for Renewable Energy Technologies (PCRET) that was established in 2001 by merging National Institute of Silicon Technology (NIST) and Pakistan Council for Appropriate Technologies (PCAT). In the year 2002, 14 small wind turbines, six of 500W each and eight of 300W each, were procured from China and installed by PCRET for demonstration purpose. Out of these, eight were installed in the coastal belt of Balochistan and six in the coastal areas of Sindh (southern Pakistan). That demonstration project has been concluded successfully. It was noted that small wind turbines were both technically and economically viable for electrification of the remote communities. PCRET is now installing 120 small wind turbines within the provinces of Balochistan and Sindh. Efforts are also underway to initiate local manufacture of 500W wind turbines under transfer of technology from China, and 5–10kW turbines under transfer of technology from European countries (Mirza, Ahmad et al. 2007). There have been other sporadic research activities within Pakistan. For example, Ahmed et al (Ahmed.M.A 2006) compared four coastal sites i.e. Karachi, Ormara, Jivani and Pasni to explore the possibilities of using 4kW and 20kW wind turbines. That study used six-year (1995-2000, inclusive) monthly-averaged hourly wind speed data that was measured by Pakistan Meteorological Department at a height of 10m (Ahmed.M.A 2006) . Similarly, Ilyas and Kakac (2006) undertook a study to evaluate the potential of wind power along the coastal areas of Balochistan (Ilyas.S.Z 2006) . That study was also based on five-year monthly-averaged wind speed data, measured at heights of 8-12 meter at 3-h intervals.

The key force behind the present resurgence of wind energy activity within Pakistan is the creation of the Alternative Energy Development Board (AEDB), established by the Government of Pakistan in 2003. The main objectives of the Board include facilitating, promoting and encouraging development of renewable energy in Pakistan. Until the development of AEDB there was no meaningful renewable energy policy in place in the country. Mirza et al (2007) have reviewed the mandate of the AEDB and the relevant policies of the Government of Pakistan i.e. the Medium-Term Development Framework (MTDF) and guidelines for determination of tariff for wind power generation. Lack of availability of sufficient and reliable wind data was also one of the major barriers in exploitation of wind energy. Although, limited daily and monthly wind speed data were available from the local Meteorological Department for different airports of the country, it was not reliable enough to precisely assess the technical and economic viability of wind power projects. It, however, helped identify the potential wind sites in the country. With the help of the data measured by the Pakistan Meteorological Department, coastal areas of Sindh and Balochistan were believed to have exploitable wind potential. With the help of the detailed data made available over the last five years, it is now possible to develop a clearer picture of the wind potential in the country. The Alternate Energy Development Board (AEDB) is currently aiming at producing 650 MW of wind power. The aim is to inject this power within the national grid in the near future (Renewable Energy World 2006). Longer term aims are to (a) Ensure a 10% share of alternative energy in the national grid by year 2015 (AEDB 2010) and,

(b) to develop wind and solar energy to provide a capacity of 9.7GW by 2030 (Daily Times 2006).

7.6 Scope of the present work

In view of excessive costs associated with detailed data sets as pointed out above this work shall concentrate on finding the difference in the wind energy production by using: (a) a measured long-term, minute-by-minute data, and comparing this with (b) a concurrent hourly data set. For this purpose, precisely recorded minute-by-minute wind speed data over a period of four years (May 2002 to June 2006 with the exclusion of September 2005) has been used for one site, in Southern Pakistan. This coastal site, i.e. Gharo has been identified by the Alternate Energy Development Board as being a potential site for the exploitation of wind energy resource within Pakistan (Mustafa 2005).

To enable an appropriate comparison between the above two data sets, i.e. averaged wind speeds recorded at the respective frequencies of one minute and one hour, the following estimates have been prepared for both data sets:

- Cumulative frequency of wind speed
- Energy density of wind speed
- Monthly totals of energy production from wind turbines that are built by two different manufacturers (Suzlon and Vestas)

Note that the performance curves for the respective machine output are provided in Figure 7.6.

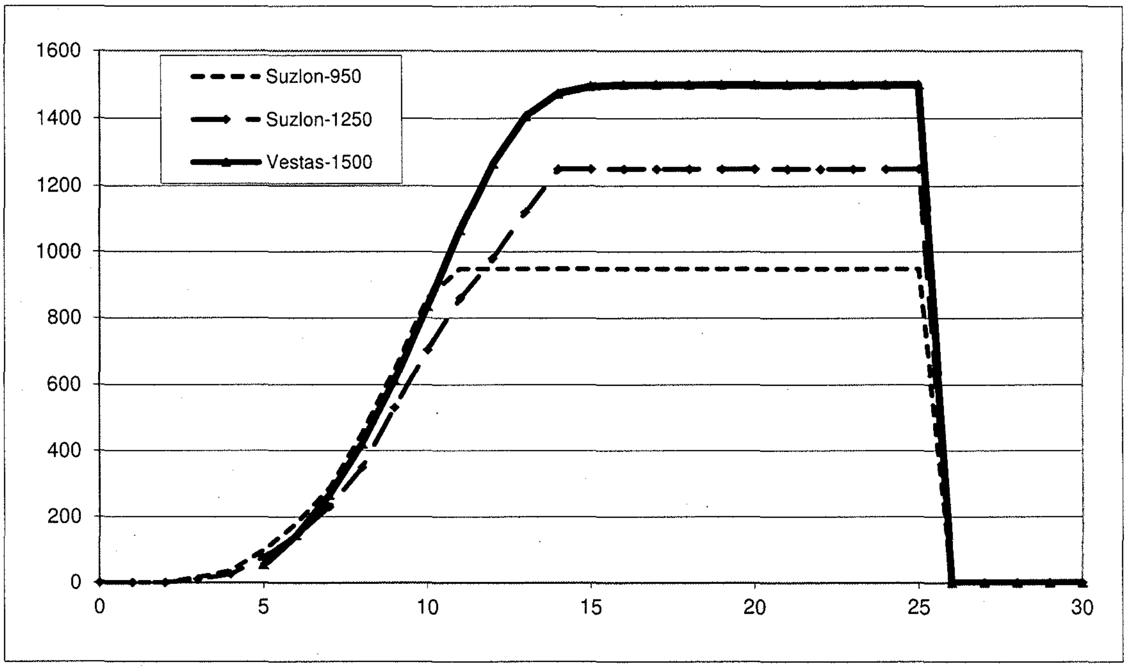


Figure 7.5 Performance curves for the three wind turbines considered in this study

Table 7.2 provides other specifications for the three machines under discussion, including rotors' diameter, their blades' number, hub's height and cut-in and cut-out wind speeds; last two indicating the respective speeds at which the wind turbines will start and cease to generate electricity.

Table 7.2 Wind turbine specifications for the three machines under discussion.

Wind turbine	Rated power	Cut-in wind speed	Rated wind speed	Cut-out wind speed	Hub height	Rotor dia.	No. of Blades
Suzlon-950	950 kW	3 m/s	11 m/s	25 m/s	56 m	64 m	3
Suzlon-1250	1250 kW	3 m/s	14 m/s	25 m/s	56 m	64 m	3
Vestas-1500	1500 kW	4.5 m/s	16 m/s	25 m/s	60 m	63 m	3

Additionally, wind rose diagrams have also been prepared from the one-minute data set for Gharo. This type of information, heretofore unavailable in literature, is useful with respect to siting the wind turbines. Furthermore, machine performance for Suzlon- 950kW, 1250kW and Vestas 1500kW has also been compared.

7.7 Data processing:

Large scale datasets are likely to have some errors. Data errors may be caused by a number of reasons including human mistakes, instrumental malfunctioning and environmental factors. In order to make a given data reliable enough to be used for system design applications it is important to process it to address its errors and shortcomings. The available wind datasets have therefore been processed for quality control.

First of all minute-by-minute data was converted into average hourly format. Secondly, the continuity of the hourly data was checked – any missing links in data were identified. The hours with any missing minute-by-minute readings were discarded. It was found that, after the quality control checks, 99.8 percent of the data over the four year period was available.

7.8 Results and discussion:

The four-year data set for Gharo was used to obtain cumulative frequency curves for the concurrent, detailed per minute and hourly cases. Figure 7.7 shows that plot.

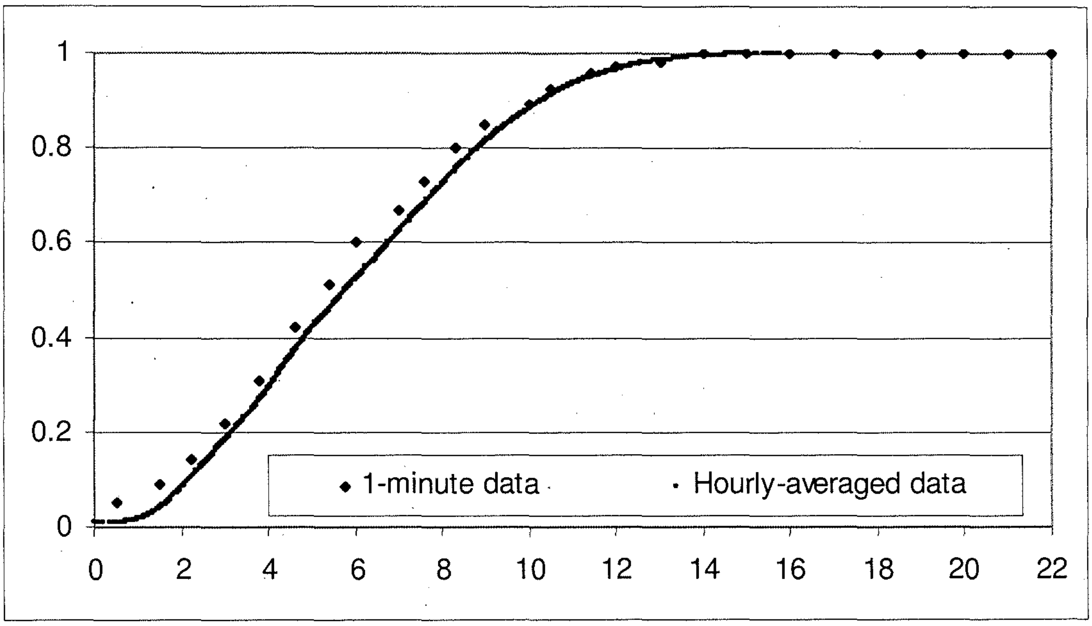


Figure 7.6 Cumulative frequency of wind speed measured at Gharo at 30 m mast

The point of interest here is that barring the 0.5- and 6m/s wind speed regime the hourly and per minute frequency curves closely hug each other, particularly so for speeds that are in excess of 10m/s. It is this range that really matters in terms of serious energy production. This is a very significant result, i.e. that there is only a marginal difference between the cumulative frequencies for the two time samples.

It would thus be possible to use the much reduced (and less expensive to collect) hourly data set for performance prediction of wind turbines without any serious loss of accuracy compared to a more detailed data set such as per minute based sampling. Note that most meteorological sites within the developing countries only report and provide data on an hourly basis and hence the importance of the above findings. It would be safe to say that the validity of the above findings would be true for locations that are in the broader vicinity of Gharo and in general locations that are close to equator, with a fairly stable wind regime. However, for locations closer to the poles, with the potential for frequent gusts, it may or may not be possible to generalize the above findings. More work would therefore be required in that respect.

Figure 7.8 and Table 7.3 respectively provide the energy output for the Suzlon-950kW machine that was computed using the performance curve provided in Figure 7.6, and the two data sets, i.e. hourly and per minute samples of wind speed.

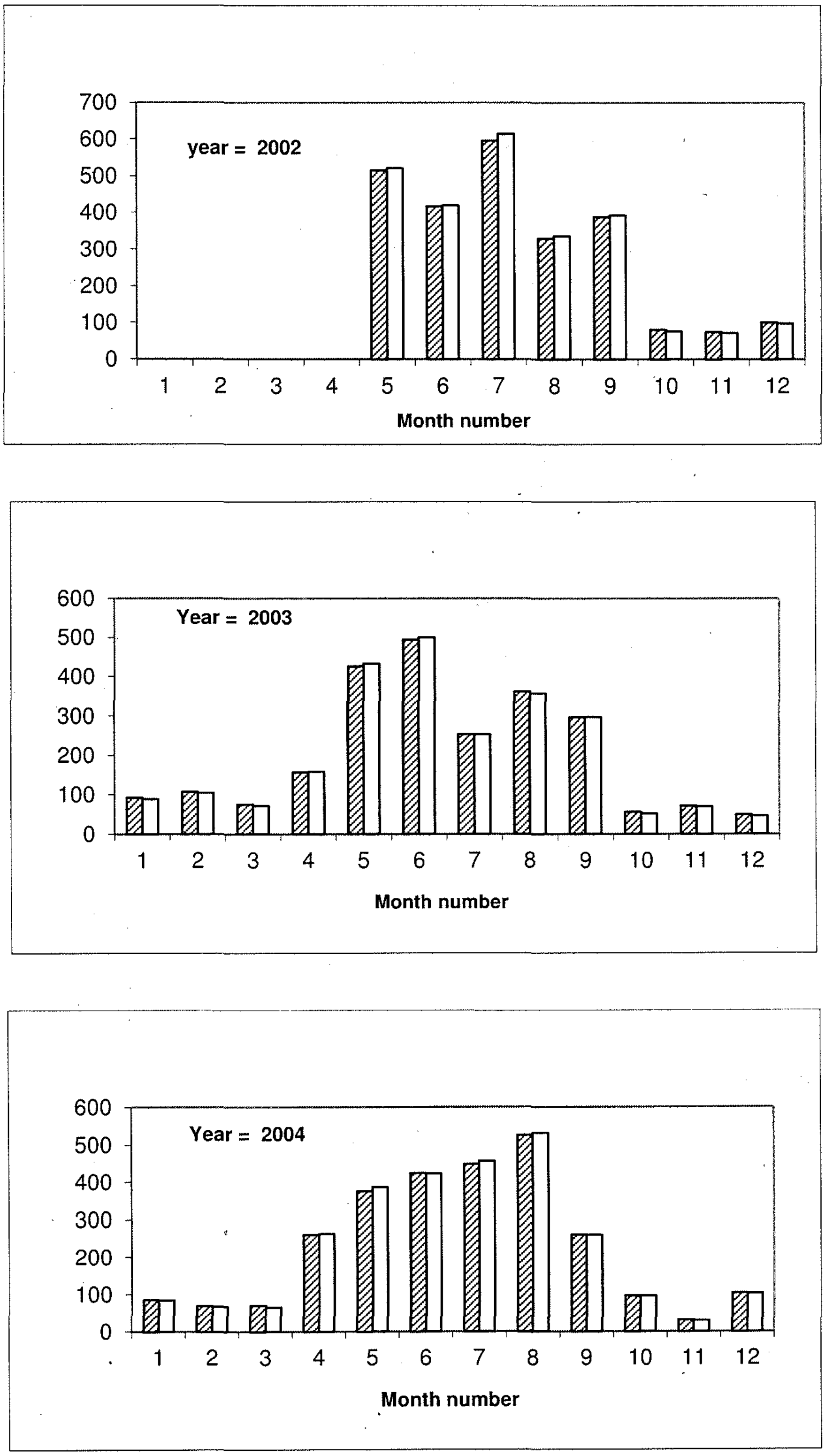
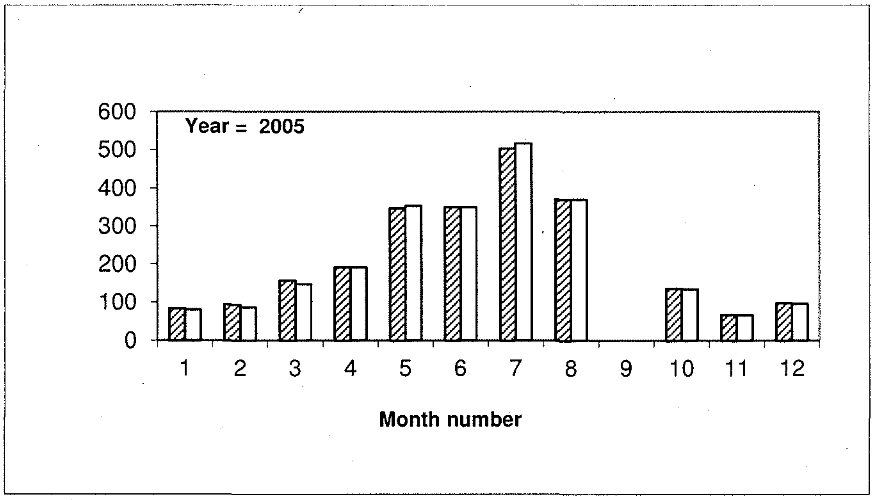


Figure 7.7 Monthly energy output (MWh) of Suzlon-950 kW machine for Gharo. Hatched bars: 1-minute data, blank bars: hourly-averaged data (Year 2002-04).



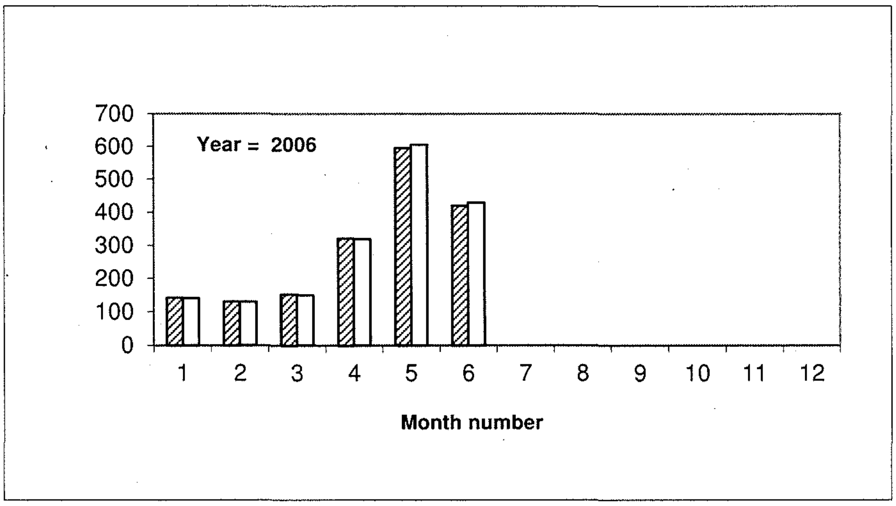


Figure 7.8 Monthly energy output (MWh) of Suzlon-950 kW machine for Gharo. Hatched bars: 1-minute data, blank bars: hourly-averaged data (Year 2005-06).

The energy outputs of the wind turbine Suzlon 950 are so close for the both data sets hourly and 1-minute, as it can be seen in the figures (7.7, 7.8). Consequently, for Location such as Gharo site using hourly data set will be reliable and economical and the accuracy level of results will be highly acceptable, since using smaller sampling intervals (1-minute) will result in 0.45% difference.

Table 7.3 Detailed statistical table for 2003

Year = 2003													Annual
1-minute data	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	
Total number of minutes within the month (T)	44640	40320	44640	43200	44640	43200	44640	44640	43200	44640	43200	44640	
Number of minutes for which data was recorded (R)	44580	40140	34440	26040	44400	43140	44520	44520	43080	44460	43080	44160	
Mean wind speed, m/s	3.8	4.4	3.9	6.6	8.8	9.6	6.4	8	7.3	3.2	3.3	3.3	
Standard deviation of wind speed, m/s	2.9	3.3	2.9	3.3	3.2	3.5	3.4	2.9	2.8	2.5	2.8	2.4	
First quartile of wind speed, m/s	0	2.1	1.2	4.6	7.1	8	4.6	6.3	5.5	0	0	0	
Third quartile of wind speed, m/s	5.5	6.3	6.3	8.8	11.4	12.2	8.8	9.7	8.8	4.7	5.5	4.6	
Interquartile range	5.5	4.2	5.1	4.2	4.2	4.2	4.2	3.4	3.4	4.7	5.5	4.6	
Fraction of the month for which data was recorded (R/T)	0.999	0.996	0.772	0.603	0.995	0.999	0.997	0.997	0.997	0.996	0.997	0.989	
Energy produced via Suzlon 950kW wind turbine, MWh (M)	**92.4**	**107.9**	**76.3**	**156.9**	**426.4**	**494.2**	**254.8**	**362**	**297.2**	**56.4**	**71.8**	**49.8**	**2446.1**
Hourly-averaged data													
Total number of minutes within the month (T)	744	672	744	720	744	720	744	744	720	744	720	744	
Number of minutes for which data was recorded (R)	743	669	574	434	740	719	742	742	718	741	718	737	
Mean wind speed, m/s	3.8	4.4	3.9	6.6	8.8	9.6	6.4	7.9	7.3	3.3	3.4	3.3	
Standard deviation of wind speed, m/s	2.8	3.1	2.8	3.2	3.1	3.3	3.2	2.7	2.7	2.3	2.7	2.2	
First quartile of wind speed, m/s	1.2	2.1	1.4	4.4	6.9	8.2	4.7	6.3	5.6	1.2	0.7	1.3	
Third quartile of wind speed, m/s	5.7	6.3	6	9	11	11.8	8.4	9.7	9.1	4.9	5.2	4.9	
Interquartile range	4.5	4.2	4.6	4.6	4.2	3.6	3.6	3.5	3.5	3.7	4.5	3.6	
Energy produced via Suzlon 950kW wind turbine, MWh (H)	**89.2**	**105.4**	**72.2**	**158.6**	**433**	**500.5**	**254.2**	**357.5**	**298.1**	**52.9**	**69.5**	**46.8**	**2437.9**
Ratio of H/M	0.966	0.977	0.946	1.011	1.016	1.013	0.998	0.987	1.003	0.938	0.967	0.939	

Table7.4 Detailed statistical table for 2004

Year = 2004													Annual
1-minute data	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	
Total number of minutes within the month (T)	44640	41760	44640	43200	44640	43200	44640	44640	43200	44640	43200	44640	
Number of minutes for which data was recorded (R)	44400	41640	44400	43080	44520	43080	44460	44520	43020	44460	43020	44520	
Mean wind speed, m/s	3.9	4.1	4.2	7	8.1	9.2	9.1	10.1	6.9	4.1	3.2	4.5	
Standard deviation of wind speed, m/s	2.7	2.2	2.1	2.6	3.1	3.8	2.5	2.4	3	2.8	1.8	2.5	
First quartile of wind speed, m/s	2.1	2.9	2.9	5.5	5.5	6.3	7.1	8	4.6	2.1	2.1	2.9	
Third quartile of wind speed, m/s	5.5	5.5	5.5	8.8	10.5	12.2	10.5	12.2	8.8	5.5	4.6	6.3	
Interquartile range	3.4	2.5	2.5	3.4	5.1	5.9	3.4	4.2	4.2	3.4	2.5	3.4	
Fraction of the month for which data was recorded (R/T)	0.995	0.997	0.995	0.997	0.997	0.997	0.996	0.997	0.996	0.996	0.996	0.997	
Energy produced via Suzlon 950kW wind turbine, MWh (M)	**86.2**	**69.9**	**70.4**	**260.7**	**376.1**	**424.6**	**448.2**	**525.9**	**260.9**	**96.2**	**31.6**	**103.8**	**2754.6**
Hourly-averaged data													
Total number of minutes within the month (T)	744	696	744	720	744	720	744	744	720	744	720	744	
Number of minutes for which data was recorded (R)	740	694	740	718	742	718	741	742	717	741	717	742	
Mean wind speed, m/s	4	4.2	4.2	7	8.1	9.1	9.1	10	6.9	4.1	3.2	4.5	
Standard deviation of wind speed, m/s	2.6	2	1.9	2.4	2.9	3.7	2.4	2.4	2.9	2.7	1.7	2.4	
First quartile of wind speed, m/s	2.3	2.9	3.1	5.3	5.9	6.3	7.5	8.3	5	2.2	2.1	2.7	
Third quartile of wind speed, m/s	5.4	5.6	5.3	8.6	10.4	11.7	10.8	11.6	8.6	5.5	4.3	6.1	
Interquartile range	3.2	2.7	2.2	3.2	4.4	5.4	3.2	3.3	3.6	3.2	2.2	3.3	
Energy produced via Suzlon 950kW wind turbine, MWh (H)	**84.9**	**67.1**	**66**	**262.6**	**386.7**	**423.1**	**456.8**	**531.3**	**259.4**	**96.4**	**30**	**102.5**	**2766.9**
Ratio of H/M	0.984	0.96	0.938	1.007	1.028	0.996	1.019	1.01	0.994	1.001	0.948	0.988	

Two points are apparent from Figure 7.8, (a) use of the two data sets provides nearly identical energy outputs, and (b) the most productive period is May to September that includes the monsoon season.

Table 7.3 provides numerical and statistical data: apart from providing information on the fraction of the potential data that is available for each month (note that this figure is very high for each of the respective months), information has been given for mean wind speed, standard deviation of wind speed, first- and third quartile of wind speed and inter-quartile range. While the first two of the latter statistic indicate the strength and general variability of the wind resource, the latter three elements give an idea of the consistency and range of the wind speeds. The inter-quartile range provides the range of wind speed encountered for 50% of the time during any given month. At this stage Figure 7.7 can be referred that shows that any meaningful power output is produced once the wind speed is in the vicinity of 5m/s. On examining Table 7.3 it can be noted that from April to September (six months) the figures for first quartile are in the latter range. Analysis such as this may provide important information to characterize the energy production profile. Figures 7.10 and 7.11 respectively show energy rose plots for July to December of the year 2004 and the month of June for all five years.

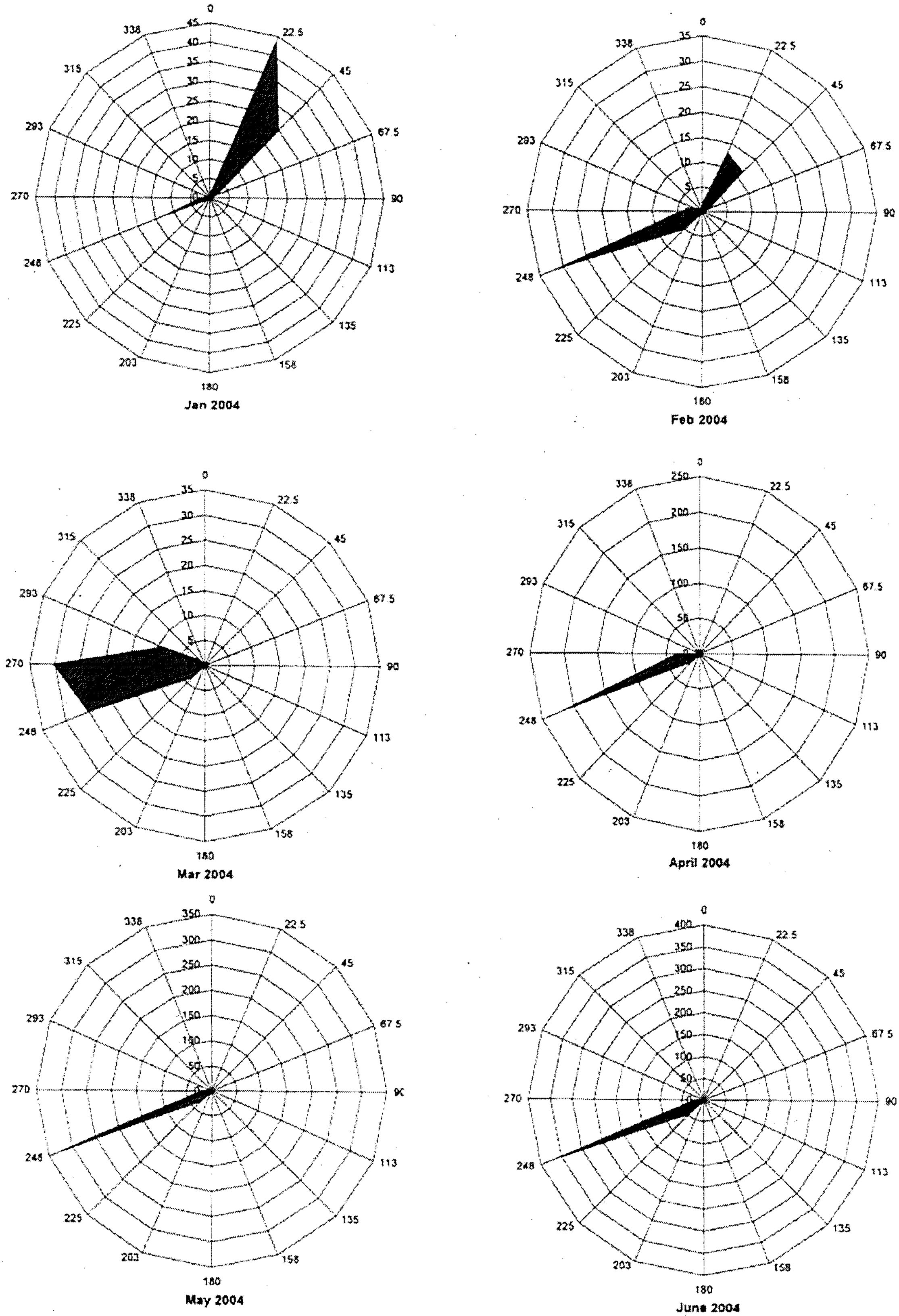


Figure 7.9 (a) Energy roses diagram for Gharo (year 2004). Note: radial scale units are MWh

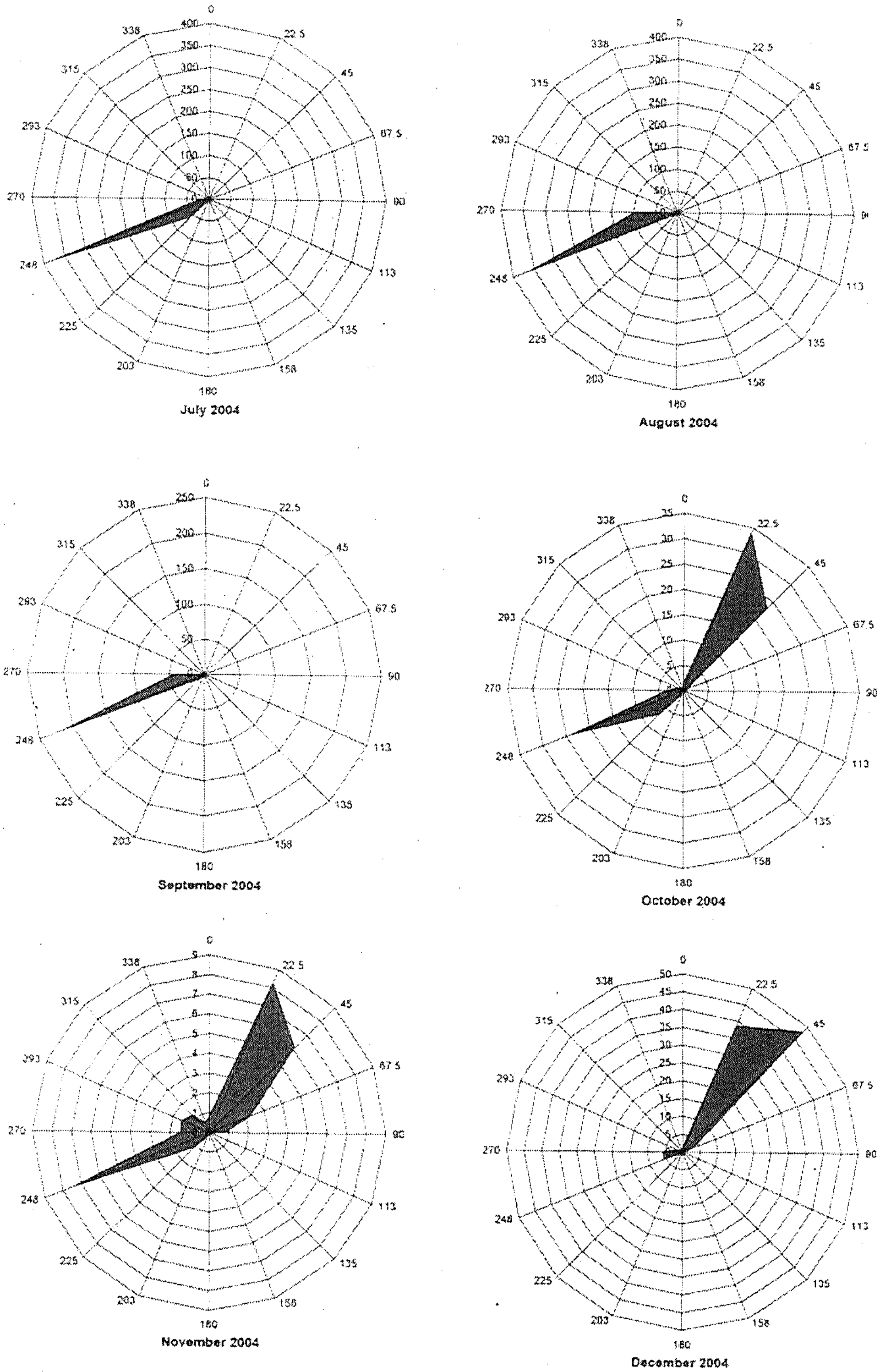


Figure 7.9 (b) Energy roses diagram for Gharo (year 2004). Note: radial scale units are MWh

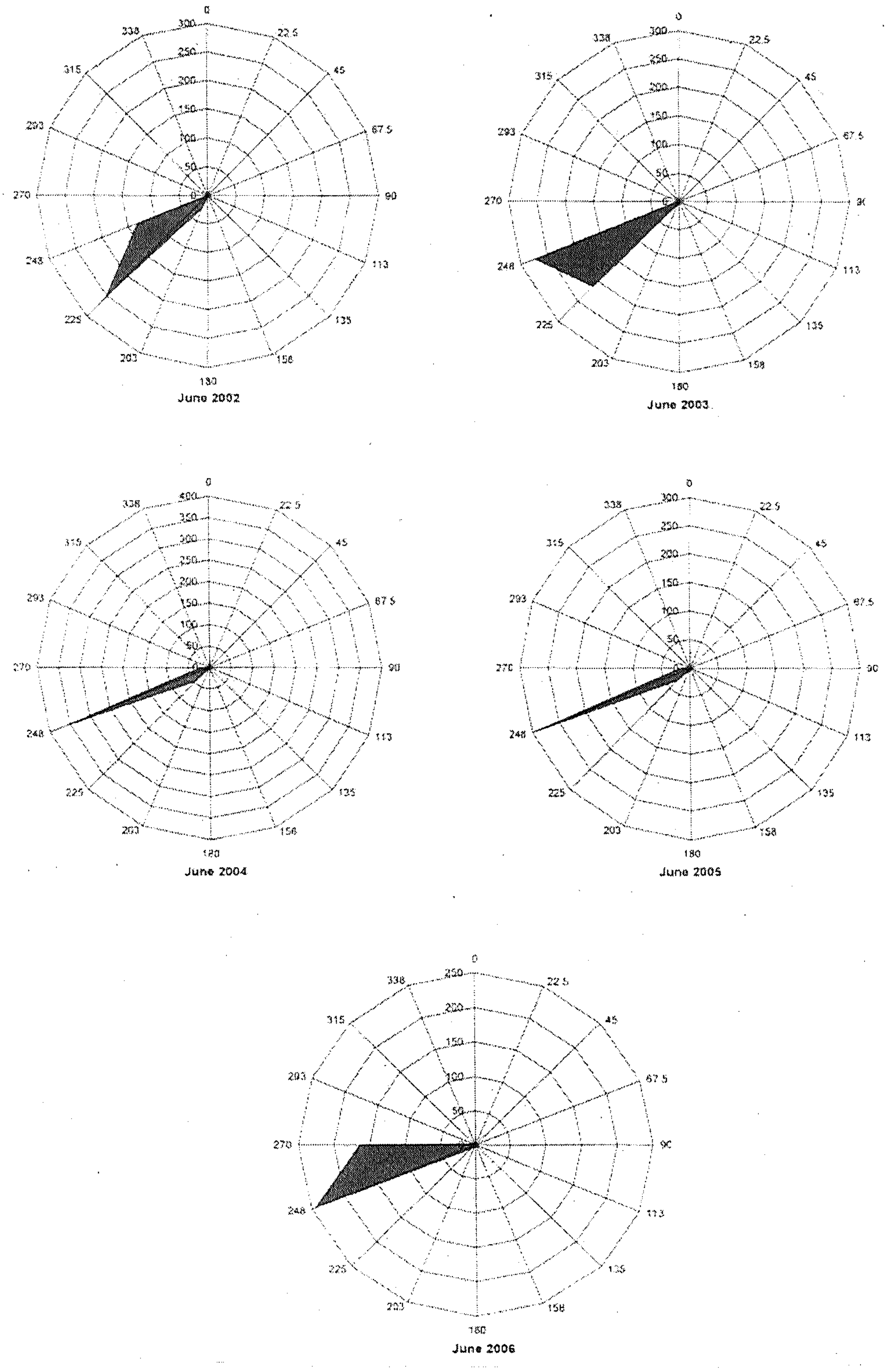


Figure 7.10 Energy roses diagram for Gharo (June 02-06). Note: radial scale units are MWh

From the energy rose diagrams, it is apparent that during the most productive months, i.e. April to September the wind direction is consistently from south-west. Refer to Figure 7.5 that shows Gharo's location. It is well known that sea breeze is the prime source of wind in the monsoon months in that region (the major conurbation of Karachi included). Energy rose plot provides important information on the prevailing direction of the wind resource, which can then be effectively used in the resource's 'preservation' by bureaucratic means to arrest any potential infrastructural projects that may be instigated upstream of onshore wind farms. Figure 7.12 has been prepared with the view to explore the specific energy that is delivered by each of the three wind turbines currently under study.

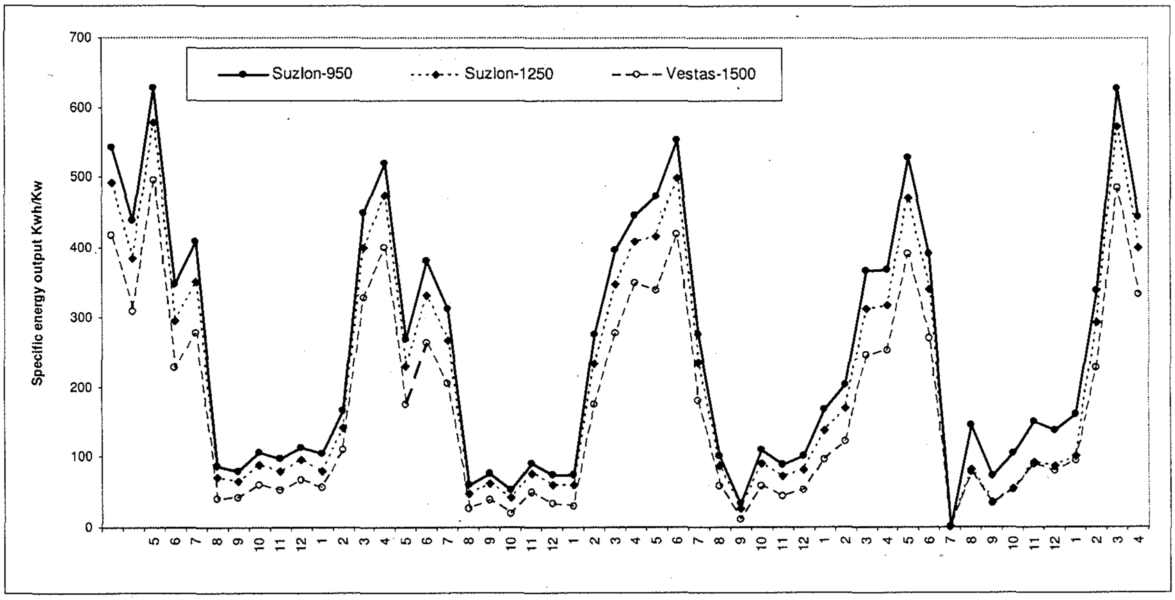


Figure 7.11 Inter-comparison of machine performance for Gharo, May 2002 to June 2006

The plot shows that Suzlon-950kW machine provides the highest specific energy yield. This type of information may further be used by project managers to obtain an optimum cost solution that would include the capital, installation and maintenance cost elements.

7.9 Conclusions

An exploration of the potential for using hourly- as opposed to minute-by-minute data for the design of wind energy systems was undertaken. The former set is much more widely available for a larger number of locations within the developing world. It was found that the difference between the annual energy outputs from the two data sets was in close agreement with only 0.45 % difference. A very similar conclusion was also reported by Celik (Celik 2003) who has quoted the study of Protogeropoulos (Protogeropoulos. C 1992). Protogeropoulos used 5-min and hourly-averaged data for Cardiff in Wales to conclude that the two data sets yield very similar results in terms of energy resource. The above mentioned, hourly and minute-based, cumulative frequency functions were also found to be closely related. These results may be of use for locations close to the equatorial belt where the wind regime is noted for its stable and seasonal character. Although it is a commonly accepted rule that locations near the equator are generally more suited for solar energy exploitation while those closer to the poles for wind energy production, it was found that with careful selection some of the equatorial locations may also be used for effective exploitation of their wind resource. One such location is Gharo in Southern Pakistan. However, it was found that the wind resource was strongly seasonal in character with the monsoon months producing the most significant energy yields.

Chapter 8

Conclusions and Future Work

8.1 Conclusions

The conclusions of the work under taken within this thesis are summarised below:

Micro rooftop wind turbines have received a great deal of attention in recent years. There have been a significant number of manufacturers that were marketing small turbines that were nominally rated around 2kW capacity, and with blade diameters ranging between 1-2 m. The sole purpose being them mounted on the roofs of dwellings and commercial buildings. Manufacturers typically claim that building-mounted turbines can potentially generate 2000kWh annually. Recent reports from users including the author's own publications state that micro rooftop turbines do not deliver their designed energy and power outputs. This thesis investigates the performance of the Zephyr Air-Dolphin rooftop turbine and determines the reason why rooftop turbines do not meet their design performance.

In particular, main issues related to micro-wind turbines have been addressed herein based on author's experience data collection and analysis
The following results have been presented:

1. The preliminary evaluation of micro-wind turbine aerodynamics.
2. The influence of wind speed sampling interval on the wind speed probability distributions,
3. The preliminary evaluation of spatial variation of wind speed. The most important conclusions arising from the present study being:

    a. The recently raised question of the poor performance of micro-wind turbines is substantiated based on the preliminary analyses. Although it is partly due to the turbulent nature of the wind on rooftops, it is believed that the poor aerodynamics of micro-wind turbines is also responsible for this underachievement.
    b. It was shown that different sampling interval; i.e. on a per second or per minute basis, of wind speed has an important bearing on the cumulative frequency curves. This will in turn lead to different computed wind turbine performances based on these data. This is very important particularly for micro-wind turbine systems.

c. Although the wind regime in an uneven terrain over relatively long distances is a complex phenomena, the preliminary analysis show that for Edinburgh the wind speed outside the city limit is stronger- although the average wind speed within the urbanised area was 3.9 m/s the corresponding figure for an outer location was 5 m/s.

d. The wind resource assessment of Merchiston wind site is concluded to have an annual average wind speed of 3.9 m/s, southern west prevailing wind direction with high wind shear and turbulent wind flow which results in low energy production.

4. This thesis also provides an evaluation of the performance of a few micro and larger wind turbines that are at present operating in England and Scotland. It has been shown here that urban, roof-top micro-wind turbines do not offer any good return on their investment and therefore are not serious candidates for future provision of electricity in the building sector. The midi-turbines do perform adequately, but only on rural farms.

5. The present findings concur with many other published works of similar sites throughout the United Kingdom which were monitored by other members of the Warwick Wind Trials (Warwick Wind Trials, 2008). Merchiston wind test site is considered to be a promising location for capturing the wind in the built up areas. The Napier turbine is situated on the roof of five-floor building located on a hill-top within the urban environment. The weather station at this test site is approximately 130 m high above the sea level. The turbine was found to deliver only sixth of the manufacturer acclaimed 2MWh annual energy output. This Low potential of wind energy could be attributed to three issues. Firstly, it can be due to high surface roughness, characteristic of urban locations, which magnifies the wind shear of flowing air stream, in turn, reducing the wind velocity close to the ground or roof surface level. High surface roughness also increases the turbulence of air stream. The second issue is the existence of buildings within the neighbourhood close to the turbines and this induces turbulence. Thirdly, it is believed that poor aerodynamics of micro-wind turbines is also responsible for their underachievement.

6. With regards to micro wind turbine dynamics, the turbine has to be designed to have a very low response time to enable it to react to any changes within the wind regime very rapidly. Due to the high intermittency of the urban wind regime, the power management system used to control the turbine must also have a very high response time to enable any energy generated to be used. Turbines have to be designed very robustly to be able to survive very high turbulent winds. This increased turbidity of winds has been observed at Edinburgh Napier University to cause increased loading and stress on the wind turbines, resulting in damage caused by fatigue. Failure of components has caused both the Air-dolphin and Ampair turbines to stop working during the test survey. These findings are in conformation with those turbines taking part in the Warwick Wind Trials

7. An intercomparison of wind speed probability distribution models has also been undertaken. Most of the commonly used Probability Distribution Function(PDF) and Cumulative Distribution Function(CDF) used in the literature have been included, namely, Rayleigh, lognormal, Weibull, three-parameter Weibull, and bimodal Weibull functions. As a part of evaluating such functions, a novel statistical tool was presently developed so that an overall accuracy score can be obtained for the models studied. The numerical values of the relevant parameters were obtained from the wind speed data collected at Edinburgh Napier University for a period of 24 months. The most important results arising from the current work undertaken are the following:
   a. Not any single statistical parameter can adequately be an indication of the goodness of a model. A composite evaluation index for intercomparing the models was therefore presently developed.
   b. The question raised in recent years as to the inadequacy of the Weibull function in modelling the wind speed distributions was somewhat substantiated as being correct; thus, and alternative, more complicated functions are needed to better model wind speed distributions, either unimodal or bimodal.
   c. Based on the PDFs, the mean wind speeds calculated from the bimodal Weibull function parameters are closest to the observed

ones by a large margin, distantly followed by the lognormal function. When compared to the mean wind values from the PDFs, those from the cumulative distributions are significantly closer to the observed ones, the bimodal Weibull function returning the best prediction of mean wind speeds.

d. Considering the presently developed accuracy score changes between 2.64 and 5.85 for the PDFs. The highest is provided by the bimodal Weibull function, followed by the log-normal function with value of score of 4.76. The Rayleigh function is the least accurate model with an overall score of 2.64. It should be noted that the lognormal model constitutes a significant alternative to the Weibull model as both of them contain two parameters.

e. For the case of probability density distributions obtained from the CDFs, the three-parameter Weibull leads to the highest score with a value of 5.58, followed by the Weibull and bimodal Weibull functions with scores of 5.45 and 5.29, respectively.

f. When individual models are compared for their performance in terms of their PDFs and CDFs, it is observed that the Rayleigh, Weibull, and the three-parameter Weibull functions perform better when they are fitted to cumulative distributions, while the bimodal and lognormal functions perform better when the fitting is based on the probability density distributions.

g. Orography is the study of the physical geography of mountains and mountain ranges. Topography in general is concerned with local detail including vegetative and human-made features. In this study data from one urban site were used to evaluate the strengths and weaknesses of a number of PDF models. It was shown herein that the bimodal Weibull function provides the best estimates of wind speeds. A number of studies such as the present one, undertaken for a variety of topographic and orographic situations, will be needed to develop a more generalized pattern of results. Those results may then be used to specify the suitability of a given model or set of models for a given orography or topography.

h. It is quite possible that the present findings related to the suitability of bimodal distribution to the present database might be due to the presence of nearby buildings and spacing. Thus future researchers working on urban wind speed data may wish to explore this point further.

8. An exploration of the potential for using hourly- as opposed to minute-by-minute data for the design of wind energy systems was undertaken. The former set is much more widely available for a larger number of locations within the developing world. It was found that the difference between the annual energy outputs from the latter two data sets was in close agreement with only 0.45 % difference. A very similar conclusion was also reported by Celik (Celik 2003) who has quoted the study of Protogeropoulos(Protogeropoulos1992). The latter researcher used 5-min and hourly-averaged data for Cardiff in Wales to conclude that the two data sets yield very similar results in terms of energy resource. The above mentioned, hourly and minute-based, cumulative frequency functions were also found to be closely related. These results may be of use for locations close to the equatorial belt where the wind regime is noted for its stable and seasonal character. Although, and as a general rule it is commonly accepted rule that locations near the equator are more suited for solar energy exploitation while those closer to the poles for wind energy production, it was found that with careful selection there may be a case for some of the former locations to exploit the wind resource. One such location is Gharo in Southern Pakistan. However, it was found that the wind resource was strongly seasonal in character with the monsoon months producing the most significant energy yields.

8.2 Future work

In the above main conclusions that were drawn from the present research a number of items of work may be identified that have the potential for further exploration and research. These are mentioned below:

1. More attention has to be given in future researches regarding wind resource assessment in built-up areas. The effects of orographic and topographic features on the potential of wind energy may be undertaken. This may be done by analysing many different wind data sets with

detailed databases for urbanised locations, with disparate structures and landscapes to cover most scenarios.

2. Further research may be carried out by using the presently mentioned probability distribution functions for different sites. An evaluation of fitness and accuracy can be assessed by using the author's statistical methods with a tally of score.

3. Further research may also be carried out on exploring the potential of wind turbine systems using minute by minute against hourly wind data. Many locations with diverse geographical features have to be involved in this future study employing two sampling intervals for every individual location. The results thus obtained can have significant effect on the capital cost related to purchase of data, since minute by minute data set may be up to 60 times more expensive than the hourly data.

4. More research may also be carried out on the analysis of dynamic response of micro wind turbines bearing in mind the turbulent nature of wind flow in urban locations. For such an exercise a per second data would be needed considering the short start time of those machines.

5. The present local authority planning procedures for installing wind turbine in urban areas restrict the height of micro wind turbine above roof level to 2 m. It was shown herein that, that height is not enough for the wind turbine rotor to catch the free-stream wind. Therefore, more research work is required in optimising the wind turbine mast height without ignoring the effects of increased vibrations.

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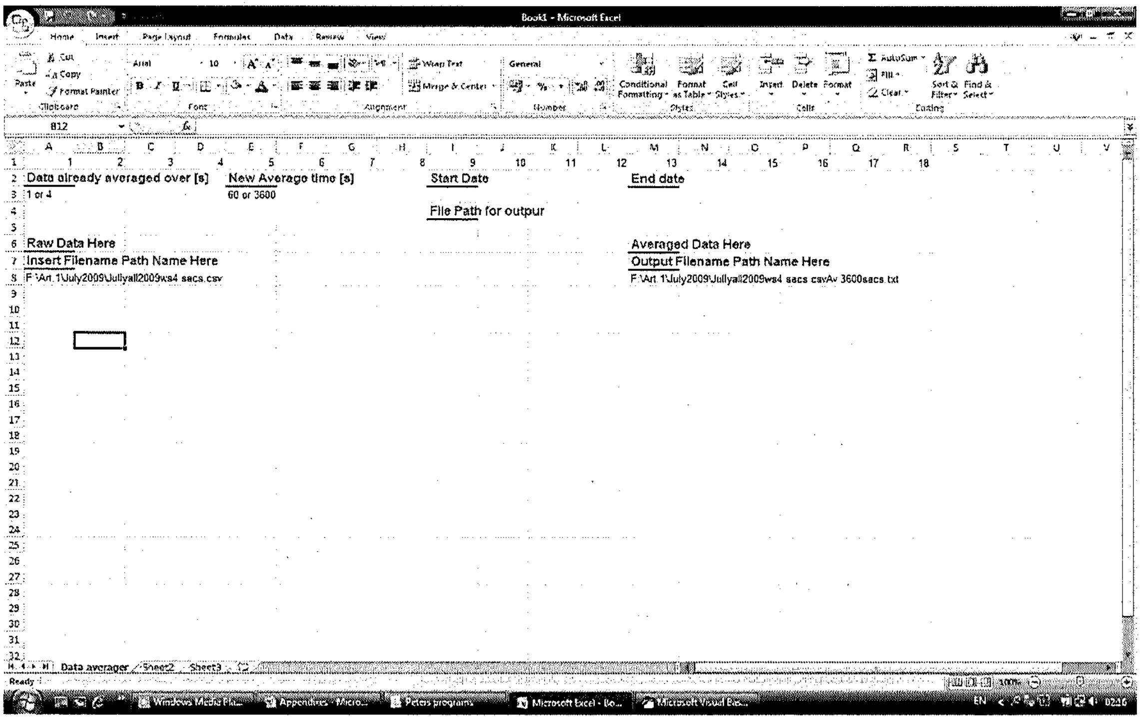
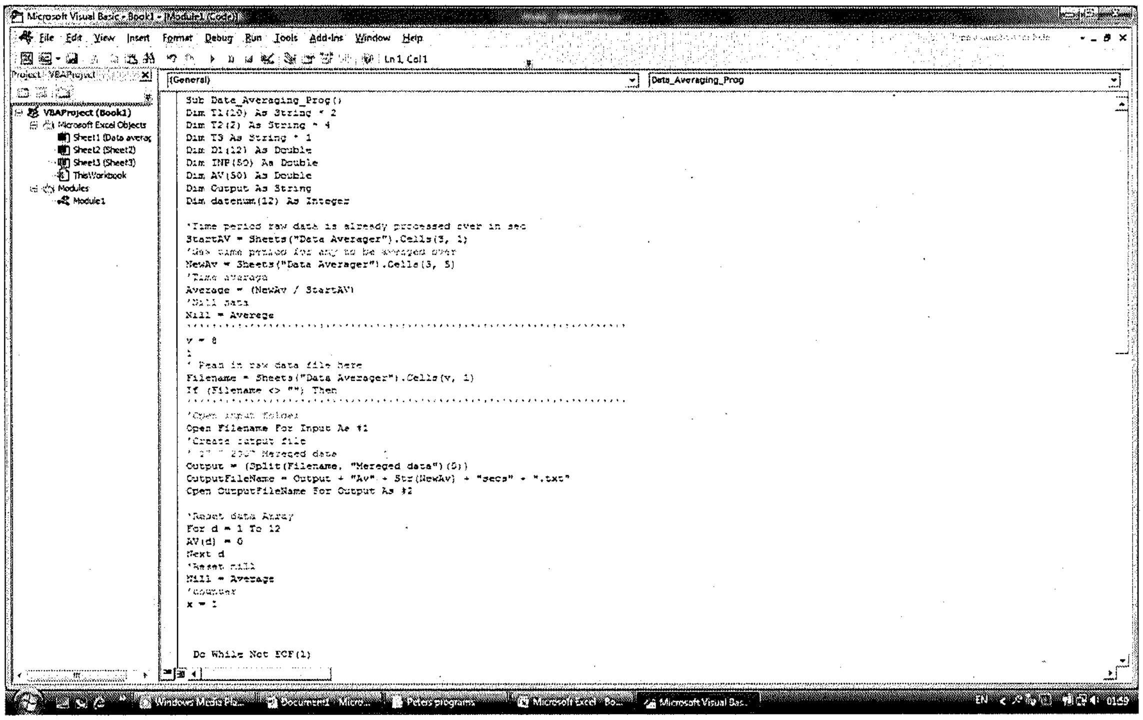
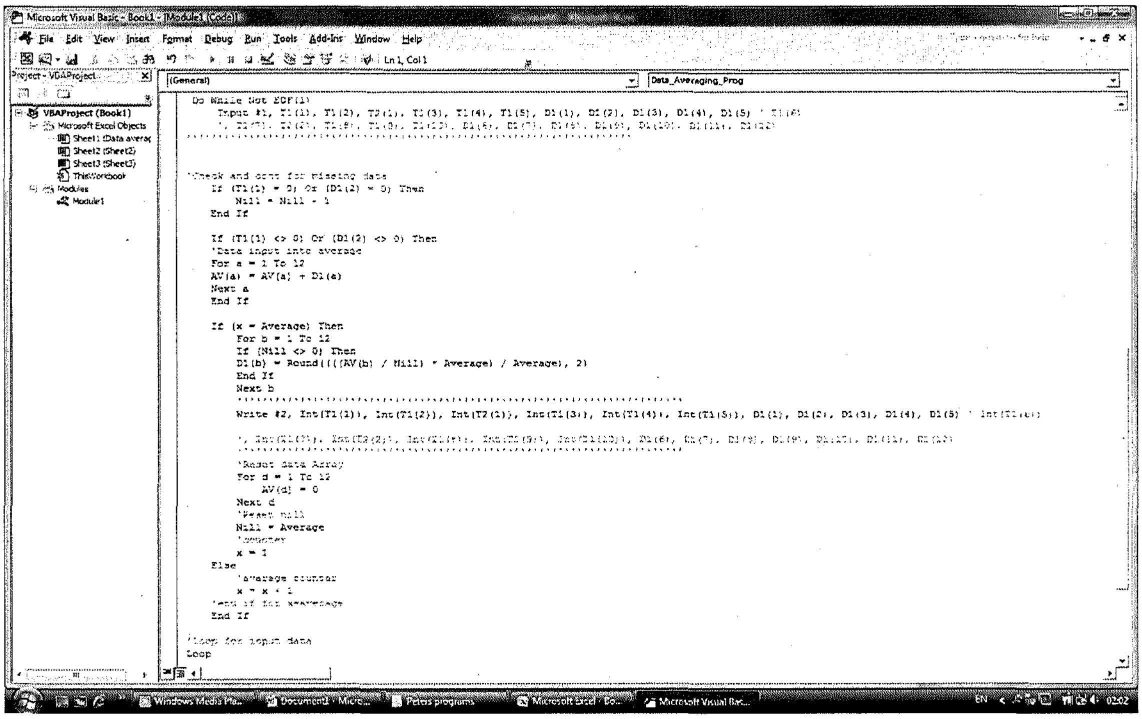
Appendices

Appendix A VBA Codes Developed for Data Processing

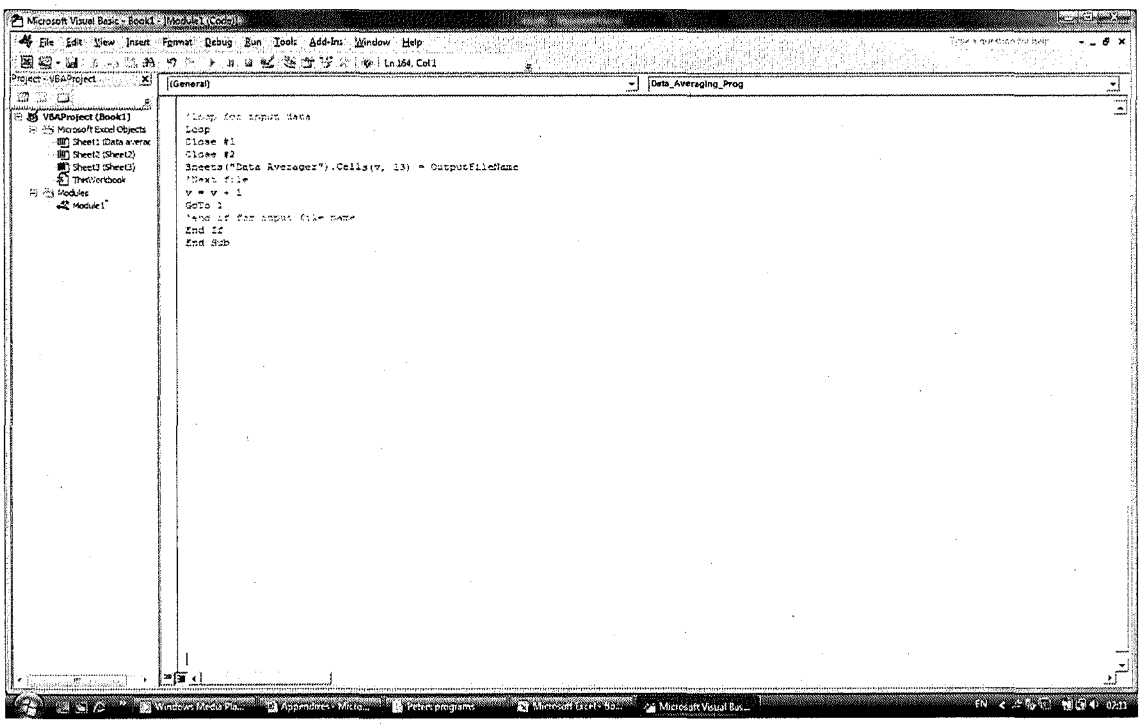
A.1 Data averaging (4sec, Minute, and hourly)





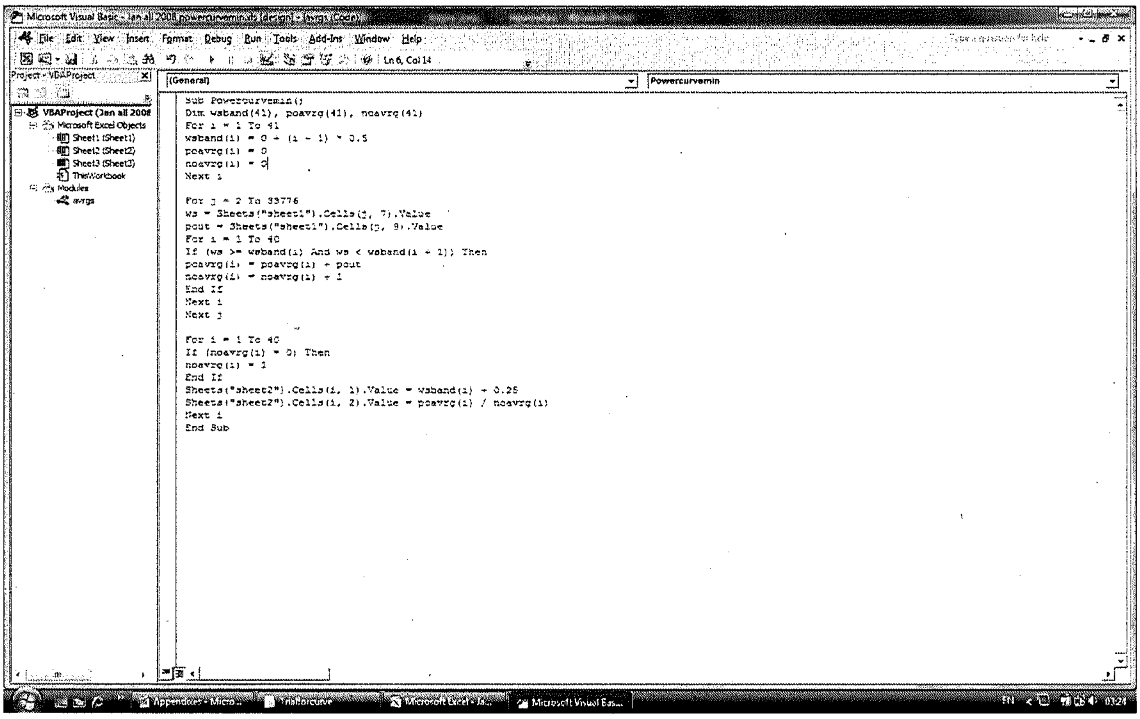


```
Do While Not EOF(1)
    Input #1, T1(1), T1(2), T2(1), T1(3), T1(4), T1(5), D1(1), D1(2), D1(3), D1(4), D1(5) ' T1(6)
    ', T1(7), T2(2), T1(8), T1(9), T1(10), D1(6), D1(7), D1(8), D1(9), D1(10), D1(11), D1(12)
''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''


'Check and cont for missing data
    If (T1(1) = 0) Or (D1(2) = 0) Then
        Nill = Nill - 1
    End If

    If (T1(1) <> 0) Or (D1(2) <> 0) Then
    'Data input into average
    For a = 1 To 12
    AV(a) = AV(a) + D1(a)
    Next a
    End If

    If (x = Average) Then
        For b = 1 To 12
        If (Nill <> 0) Then
        D1(b) = Round((((AV(b) / Nill) * Average) / Average), 2)
        End If
        Next b
        ''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
        Write #2, Int(T1(1)), Int(T1(2)), Int(T2(1)), Int(T1(3)), Int(T1(4)), Int(T1(5)), D1(1), D1(2), D1(3), D1(4), D1(5) ' Int(T1(6))

        ', Int(T1(7)), Int(T2(2)), Int(T1(8)), Int(T1(9)), Int(T1(10)), D1(6), D1(7), D1(8), D1(9), D1(10), D1(11), D1(12)
        ''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
        'Reset data Array
        For d = 1 To 12
            AV(d) = 0
        Next d
        'Reset nill
        Nill = Average
        'counter
        x = 1
    Else
        'average counter
        x = x + 1
    'end if for averaging
    End If

'Loop for input data
Loop
```



```
'Loop for input data
Loop
Close #1
Close #2
Sheets("Data Averager").Cells(v, 13) = OutputFileName
'Next file
v = v + 1
GoTo 1
'end if for input file name
End If
End Sub
```

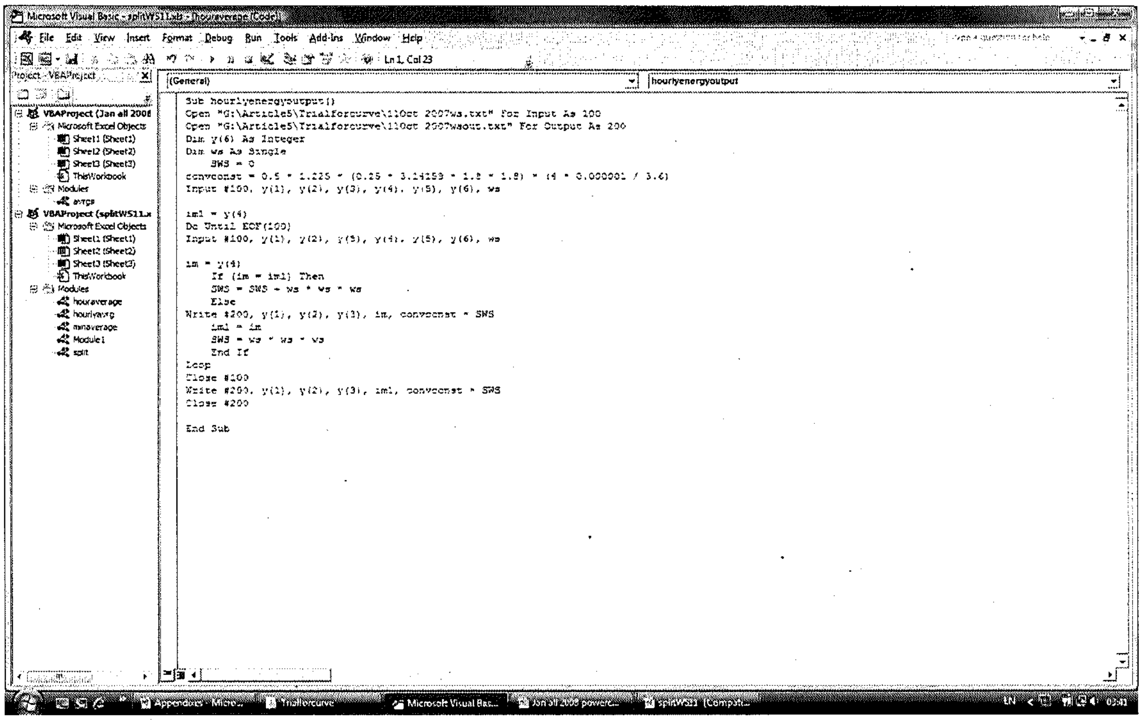
A.2 Power curve code



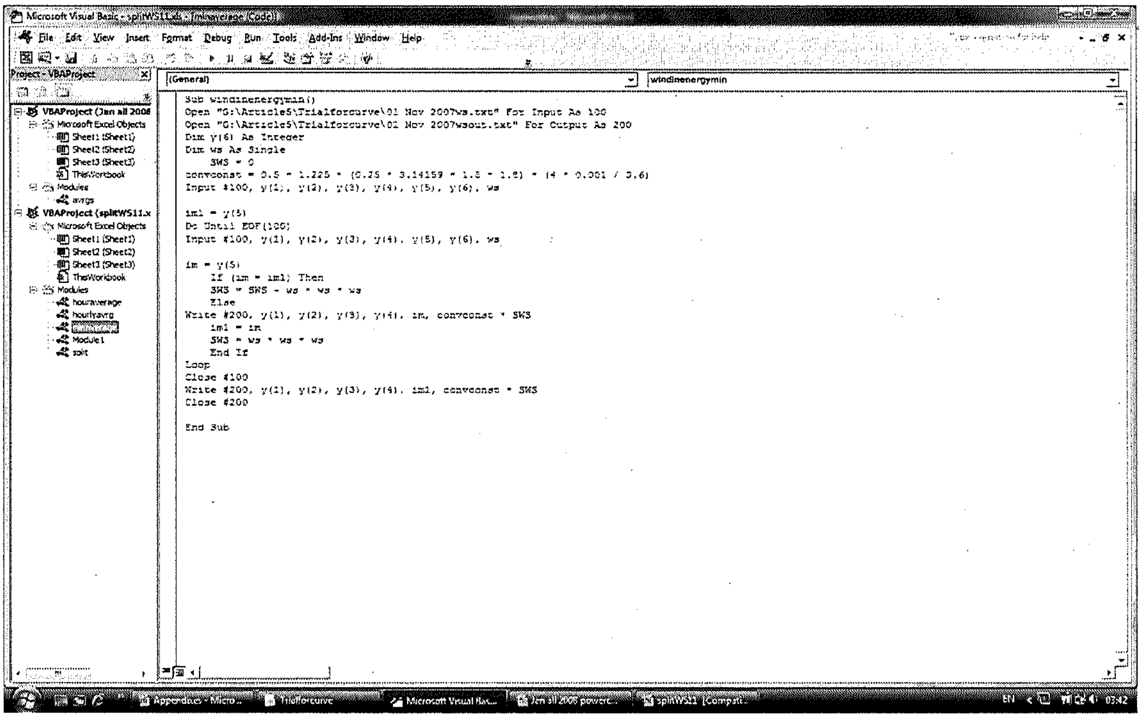
```
Sub Powercurvemin()
Dim wsband(41), poavrg(41), noavrg(41)
For i = 1 To 41
wsband(i) = 0 + (i - 1) * 0.5
poavrg(i) = 0
noavrg(i) = 0
Next i

For j = 2 To 33776
ws = Sheets("sheet1").Cells(j, 7).Value
pout = Sheets("sheet1").Cells(j, 9).Value
For i = 1 To 40
If (ws >= wsband(i) And ws < wsband(i + 1)) Then
poavrg(i) = poavrg(i) + pout
noavrg(i) = noavrg(i) + 1
End If
Next i
Next j

For i = 1 To 40
If (noavrg(i) = 0) Then
noavrg(i) = 1
End If
Sheets("sheet2").Cells(i, 1).Value = wsband(i) + 0.25
Sheets("sheet2").Cells(i, 2).Value = poavrg(i) / noavrg(i)
Next i
End Sub
```

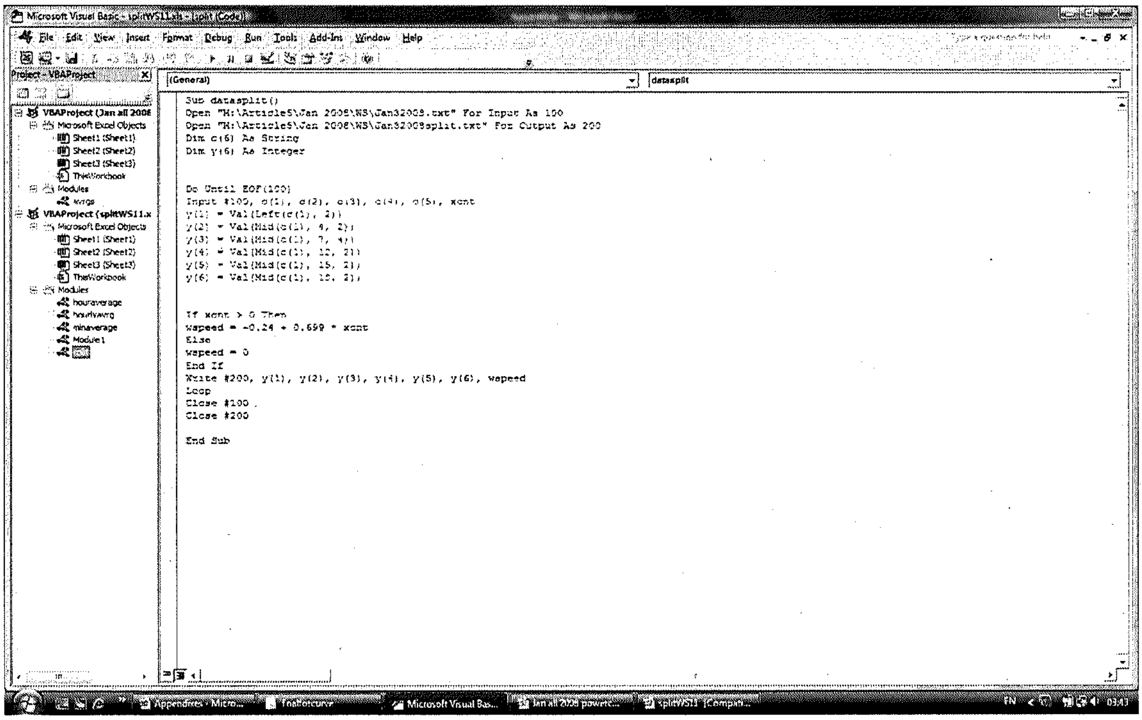
A.3 wind turbine and wind speed data processing codes

A.3.1 Wind speed data code

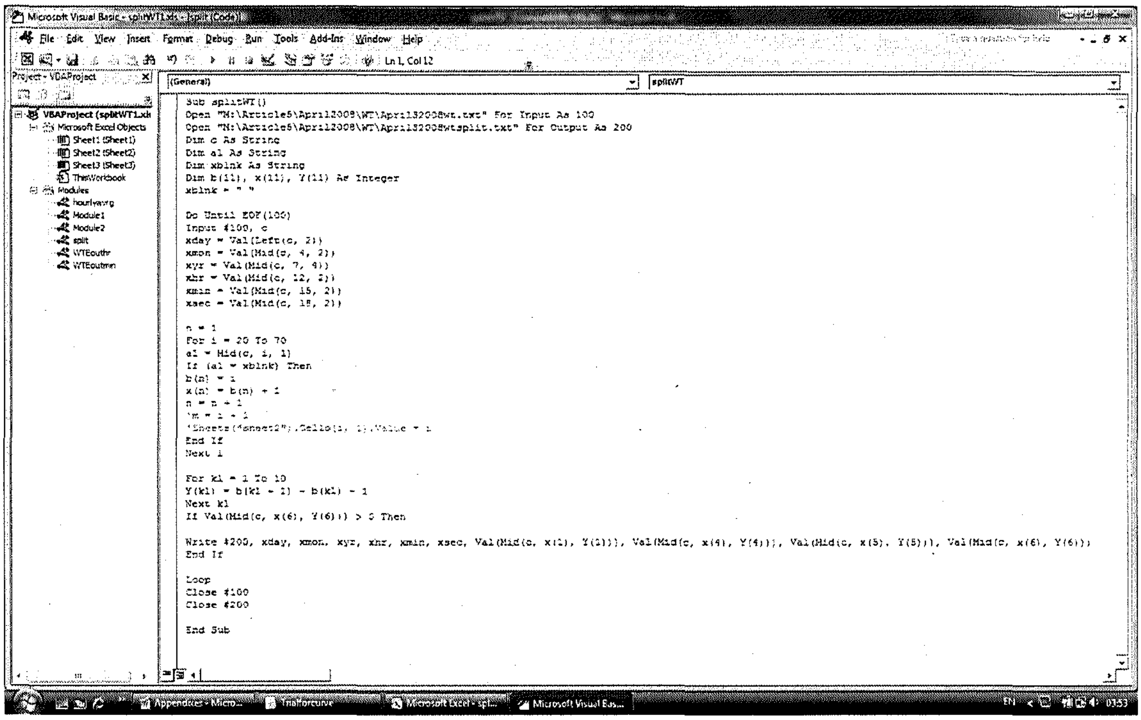


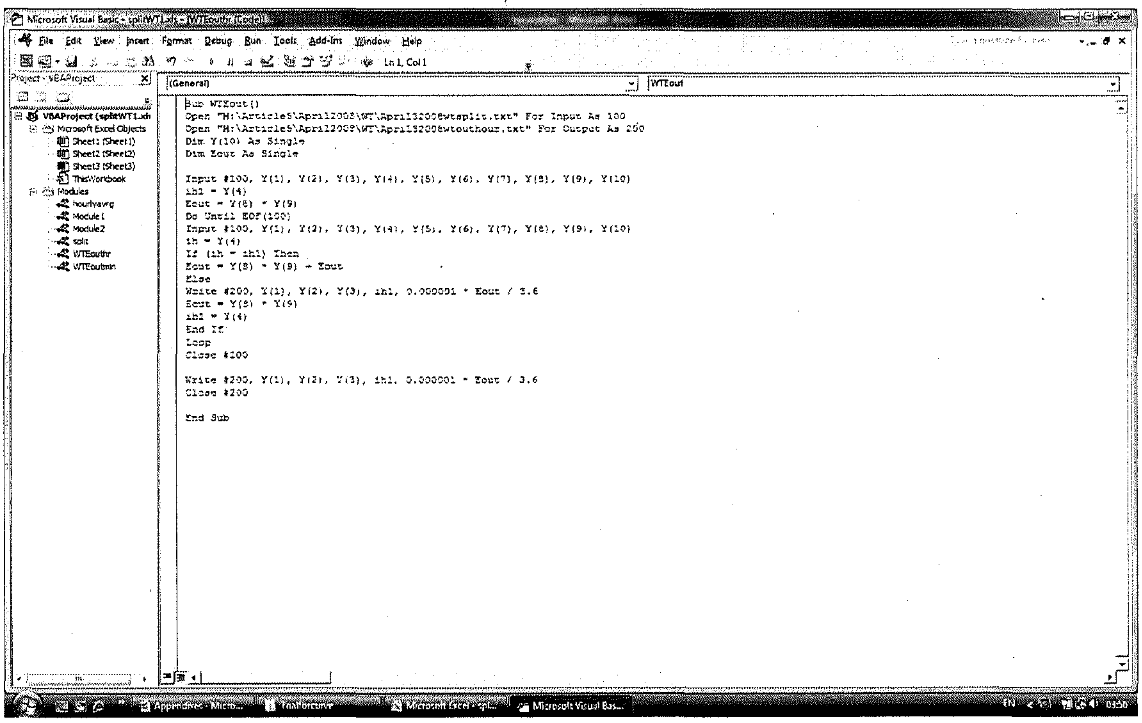
```
Sub hourlyenergyoutput()
Open "G:\Article5\Trialforcurve\11Oct 2007ws.txt" For Input As 100
Open "G:\Article5\Trialforcurve\11Oct 2007wsout.txt" For Output As 200
Dim y(6) As Integer
Dim ws As Single
    SWS = 0
convconst = 0.5 * 1.225 * (0.25 * 3.14159 * 1.8 * 1.8) * (4 * 0.000001 / 3.6)
Input #100, y(1), y(2), y(3), y(4), y(5), y(6), ws

im1 = y(4)
Do Until EOF(100)
Input #100, y(1), y(2), y(3), y(4), y(5), y(6), ws

im = y(4)
    If (im = im1) Then
    SWS = SWS + ws * ws * ws
    Else
Write #200, y(1), y(2), y(3), im, convconst * SWS
    im1 = im
    SWS = ws * ws * ws
    End If
Loop
Close #100
Write #200, y(1), y(2), y(3), im1, convconst * SWS
Close #200

End Sub
```

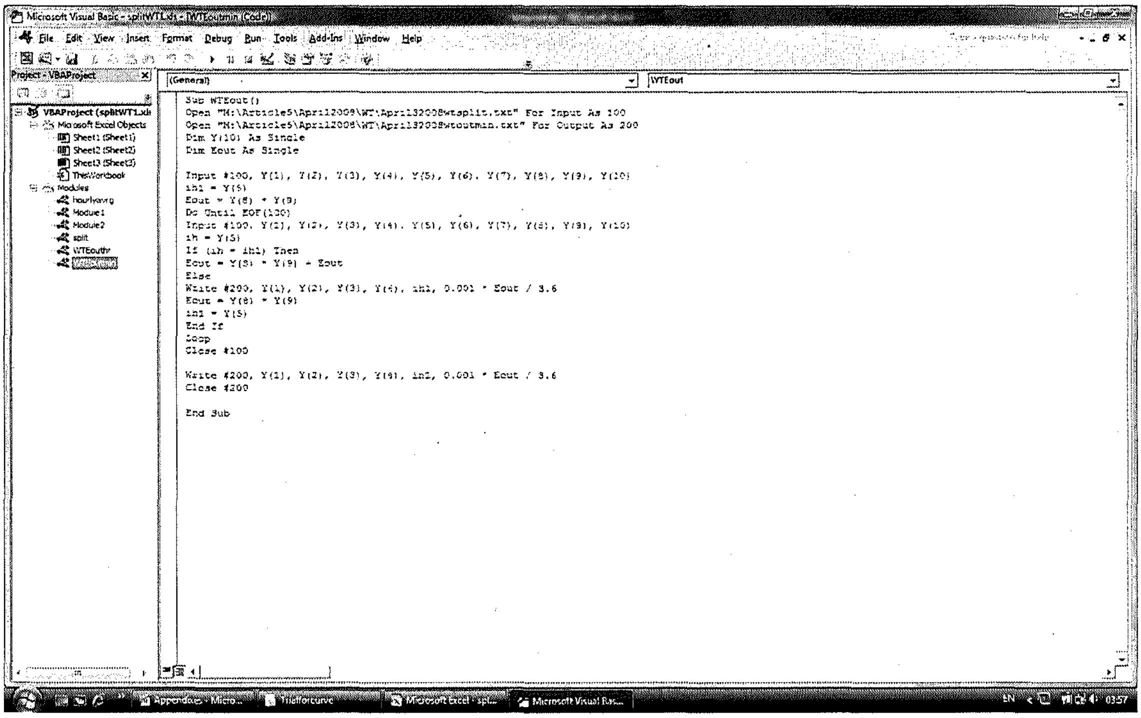

Microsoft Visual Basic - splitWS11.xls - [minaverage (Code)]
(General)
windinenergymin
Sub windinenergymin()
Open "G:\Article5\Trialforcurve\01 Nov 2007ws.txt" For Input As 100
Open "G:\Article5\Trialforcurve\01 Nov 2007wsout.txt" For Output As 200
Dim y(6) As Integer
Dim ws As Single
SWS = 0
convconst = 0.5 * 1.225 * (0.25 * 3.14159 * 1.8 * 1.8) * (4 * 0.001 / 3.6)
Input #100, y(1), y(2), y(3), y(4), y(5), y(6), ws
im1 = y(5)
Do Until EOF(100)
Input #100, y(1), y(2), y(3), y(4), y(5), y(6), ws
im = y(5)
If (im = im1) Then
SWS = SWS + ws * ws * ws
Else
Write #200, y(1), y(2), y(3), y(4), im, convconst * SWS
im1 = im
SWS = ws * ws * ws
End If
Loop
Close #100
Write #200, y(1), y(2), y(3), y(4), im1, convconst * SWS
Close #200
End Sub

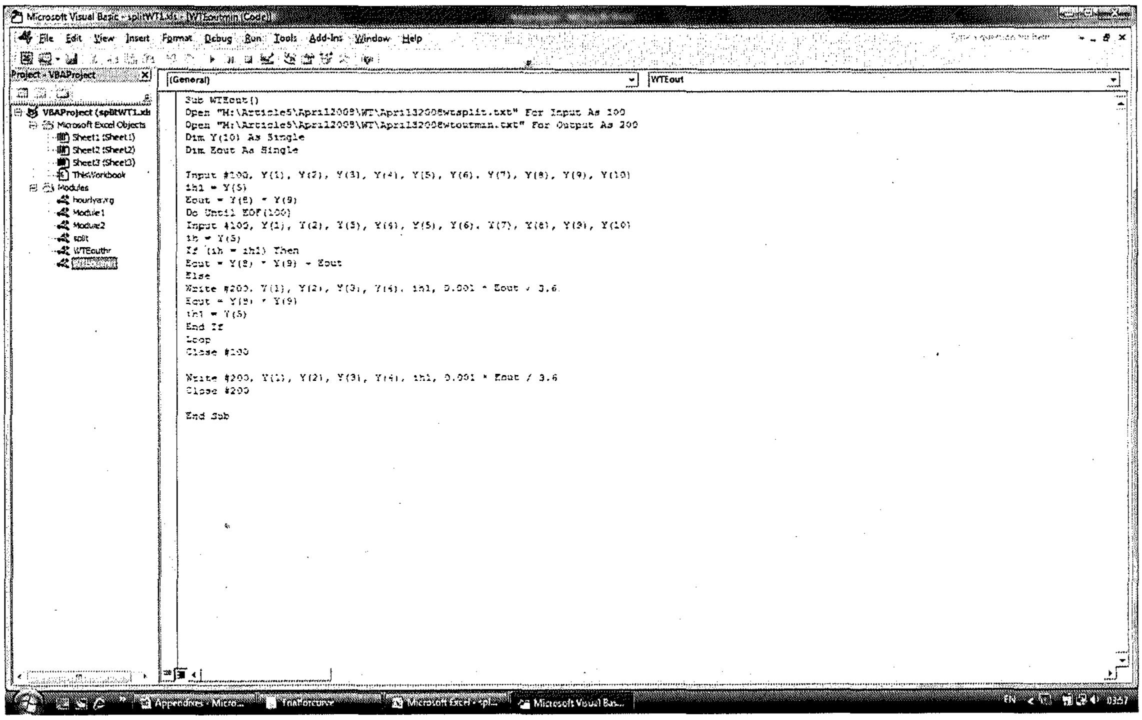

Microsoft Visual Basic - splitWS11.xls - [split (Code)]
(General)
datasplit
Sub datasplit()
Open "H:\Article5\Jan 2008\WS\Jan32008.txt" For Input As 100
Open "H:\Article5\Jan 2008\WS\Jan32008split.txt" For Output As 200
Dim c(6) As String
Dim y(6) As Integer
Do Until EOF(100)
Input #100, c(1), c(2), c(3), c(4), c(5), xcnt
y(1) = Val(Left(c(1), 2))
y(2) = Val(Mid(c(1), 4, 2))
y(3) = Val(Mid(c(1), 7, 4))
y(4) = Val(Mid(c(1), 12, 2))
y(5) = Val(Mid(c(1), 15, 2))
y(6) = Val(Mid(c(1), 18, 2))
If xcnt > 0 Then
wspeed = -0.24 + 0.699 * xcnt
Else
wspeed = 0
End If
Write #200, y(1), y(2), y(3), y(4), y(5), y(6), wspeed
Loop
Close #100
Close #200
End Sub

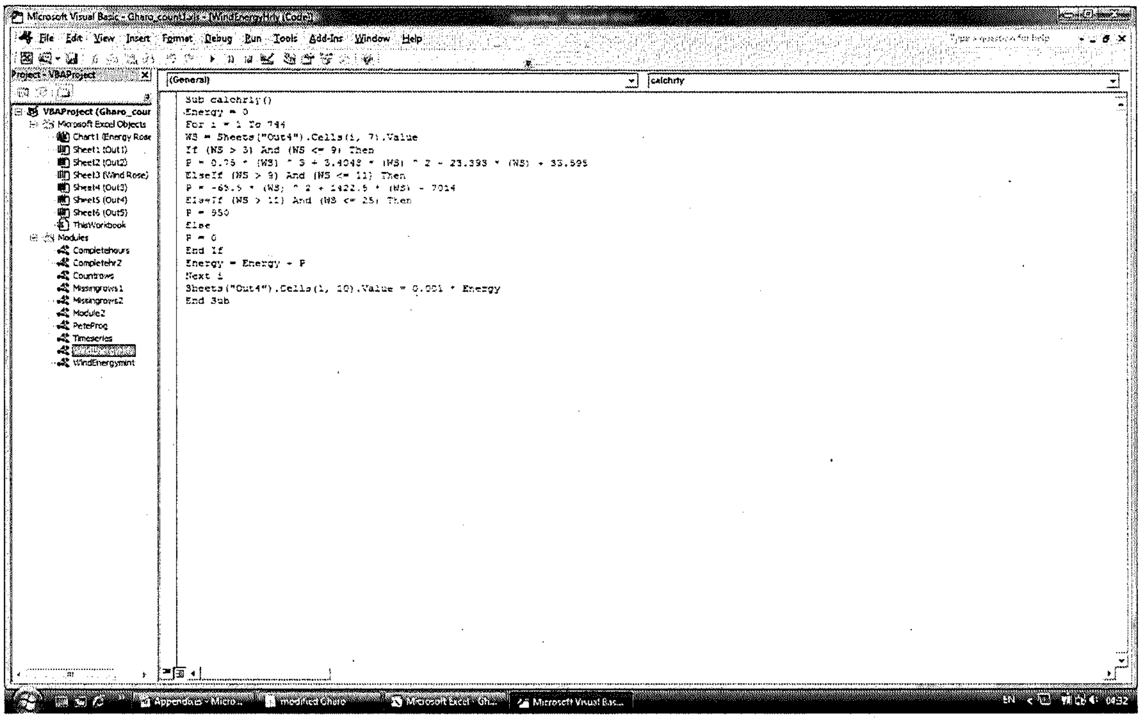
A.3.2 Wind turbine data code

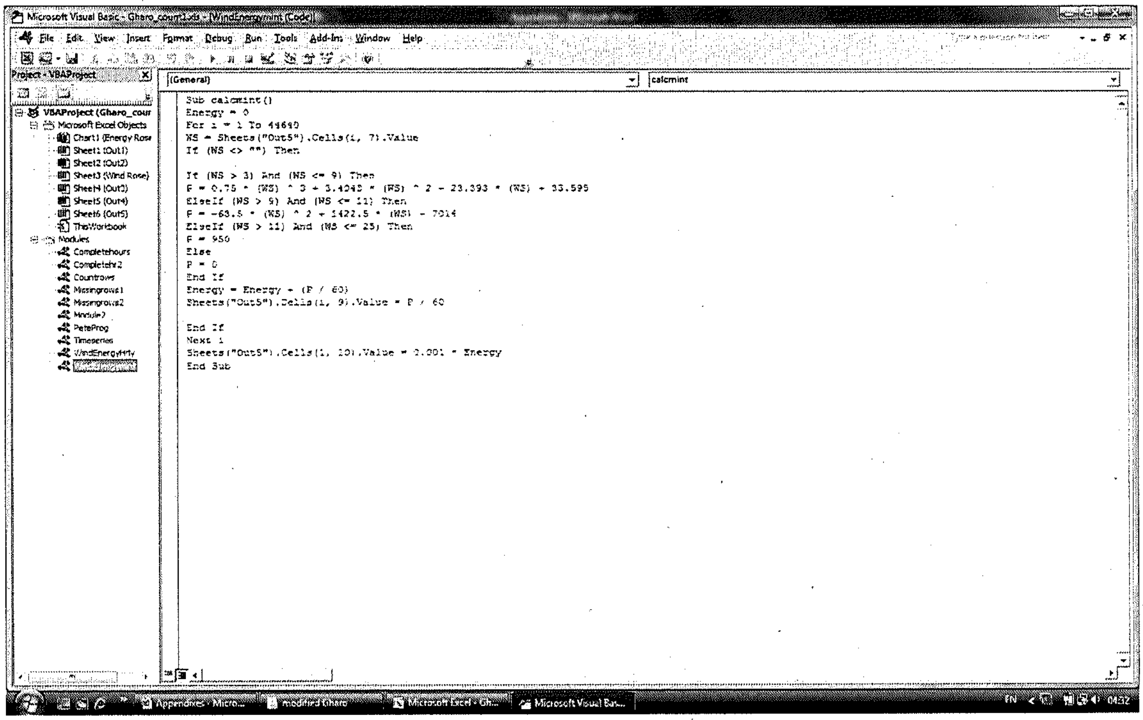


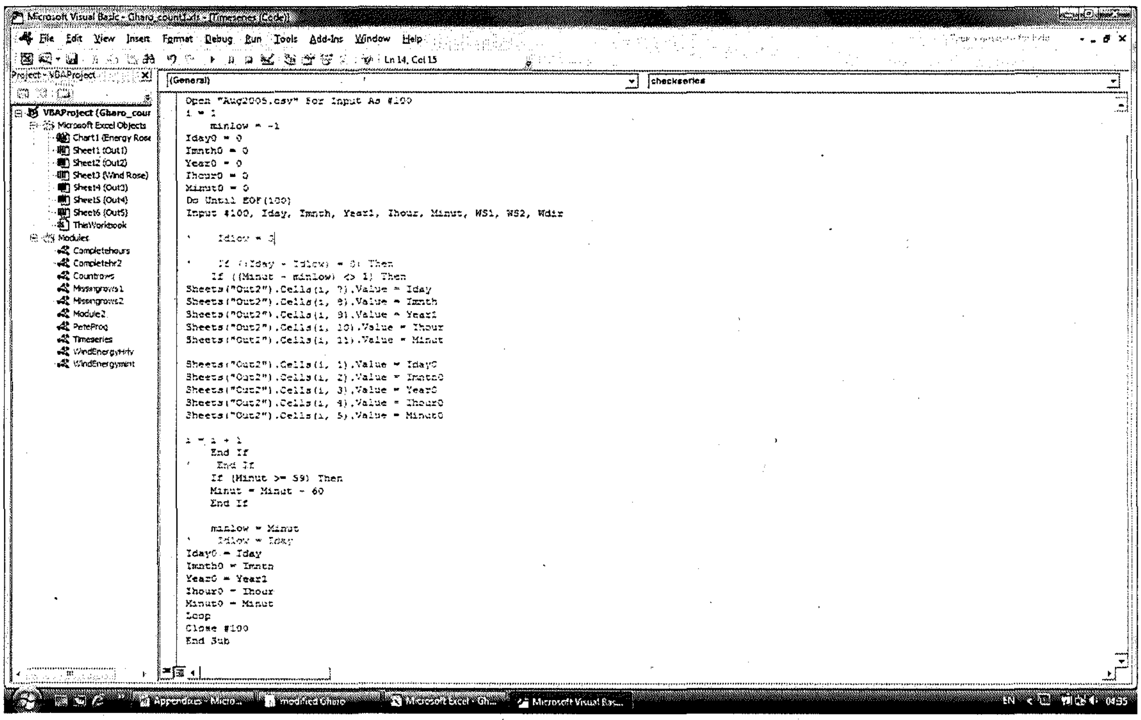


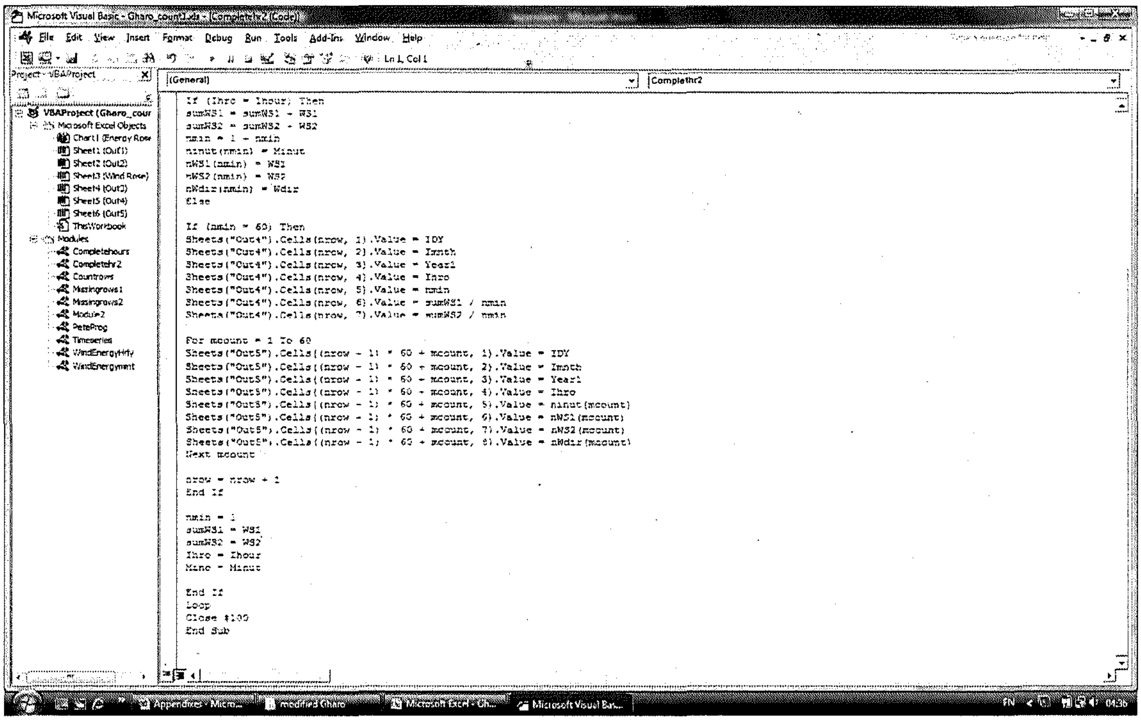

Microsoft Visual Basic - splitWTLxls - [WTEoutmin (Code)]
File Edit View Insert Format Debug Run Tools Add-Ins Window Help
Project - VBAProject
(General)
WTEout
Sub WTEout()
Open "M:\Article5\April2008\WT\April32008wtsplit.txt" For Input As 100
Open "M:\Article5\April2008\WT\April32008wtoutmin.txt" For Output As 200
Dim Y(10) As Single
Dim Eout As Single
Input #100, Y(1), Y(2), Y(3), Y(4), Y(5), Y(6), Y(7), Y(8), Y(9), Y(10)
ih1 = Y(5)
Eout = Y(8) * Y(9)
Do Until EOF(100)
Input #100, Y(1), Y(2), Y(3), Y(4), Y(5), Y(6), Y(7), Y(8), Y(9), Y(10)
ih = Y(5)
If (ih = ih1) Then
Eout = Y(8) * Y(9) + Eout
Else
Write #200, Y(1), Y(2), Y(3), Y(4), ih1, 0.001 * Eout / 3.6
Eout = Y(8) * Y(9)
ih1 = Y(5)
End If
Loop
Close #100
Write #200, Y(1), Y(2), Y(3), Y(4), ih1, 0.001 * Eout / 3.6
Close #200
End Sub

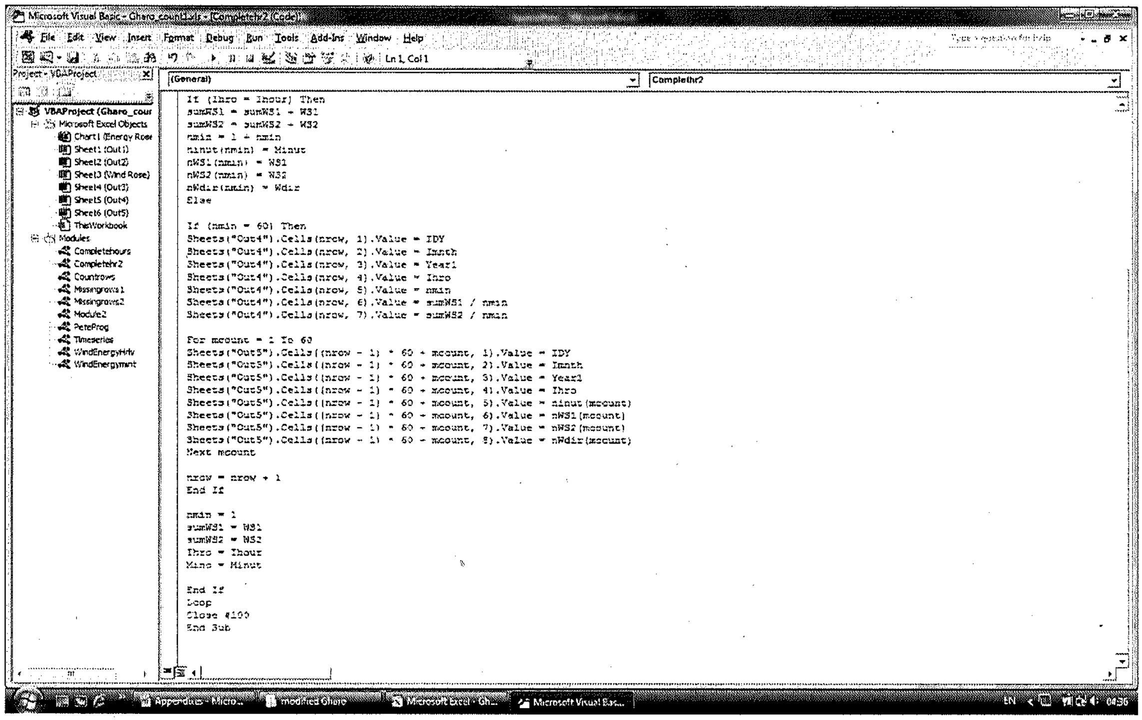

Microsoft Visual Basic - splitWTLxls - [WTEoutmin (Code)]
File Edit View Insert Format Debug Run Tools Add-Ins Window Help
Project - VBAProject
(General)
WTEout
Sub WTEout()
Open "M:\Article5\April2008\WT\April32008wtsplit.txt" For Input As 100
Open "M:\Article5\April2008\WT\April32008wtoutmin.txt" For Output As 200
Dim Y(10) As Single
Dim Eout As Single
Input #100, Y(1), Y(2), Y(3), Y(4), Y(5), Y(6), Y(7), Y(8), Y(9), Y(10)
ih1 = Y(5)
Eout = Y(8) * Y(9)
Do Until EOF(100)
Input #100, Y(1), Y(2), Y(3), Y(4), Y(5), Y(6), Y(7), Y(8), Y(9), Y(10)
ih = Y(5)
If (ih = ih1) Then
Eout = Y(8) * Y(9) + Eout
Else
Write #200, Y(1), Y(2), Y(3), Y(4), ih1, 0.001 * Eout / 3.6
Eout = Y(8) * Y(9)
ih1 = Y(5)
End If
Loop
Close #100
Write #200, Y(1), Y(2), Y(3), Y(4), ih1, 0.001 * Eout / 3.6
Close #200
End Sub


Microsoft Visual Basic - Gharo_count1.xls - [WindEnergyHrly (Code)]
(General)
calchrly
Sub calchrly()
Energy = 0
For i = 1 To 744
WS = Sheets("Out4").Cells(i, 7).Value
If (WS > 3) And (WS <= 9) Then
P = 0.75 * (WS) ^ 3 + 3.4048 * (WS) ^ 2 - 23.393 * (WS) + 33.595
ElseIf (WS > 9) And (WS <= 11) Then
P = -63.5 * (WS) ^ 2 + 1422.5 * (WS) - 7014
ElseIf (WS > 11) And (WS <= 25) Then
P = 950
Else
P = 0
End If
Energy = Energy + P
Next i
Sheets("Out4").Cells(1, 10).Value = 0.001 * Energy
End Sub


Microsoft Visual Basic - Gharo_count1.xls - [WindEnergymint (Code)]
(General)
calcmint
Sub calcmint()
Energy = 0
For i = 1 To 44640
WS = Sheets("Out5").Cells(i, 7).Value
If (WS <> "") Then
If (WS > 3) And (WS <= 9) Then
P = 0.75 * (WS) ^ 3 + 3.4048 * (WS) ^ 2 - 23.393 * (WS) + 33.595
ElseIf (WS > 9) And (WS <= 11) Then
P = -63.5 * (WS) ^ 2 + 1422.5 * (WS) - 7014
ElseIf (WS > 11) And (WS <= 25) Then
P = 950
Else
P = 0
End If
Energy = Energy + (P / 60)
Sheets("Out5").Cells(i, 9).Value = P / 60
End If
Next i
Sheets("Out5").Cells(1, 10).Value = 0.001 * Energy
End Sub


Microsoft Visual Basic - Gharo_count1.xls - [Timeseries (Code)]
(General)
checkseries
Open "Aug2005.csv" For Input As #100
i = 1
minlow = -1
Iday0 = 0
Imnth0 = 0
Year0 = 0
Ihour0 = 0
Minut0 = 0
Do Until EOF(100)
Input #100, Iday, Imnth, Year1, Ihour, Minut, WS1, WS2, Wdir
' Idlow = 0
' If ((Iday - Idlow) = 0) Then
If ((Minut - minlow) <> 1) Then
Sheets("Out2").Cells(i, 7).Value = Iday
Sheets("Out2").Cells(i, 8).Value = Imnth
Sheets("Out2").Cells(i, 9).Value = Year1
Sheets("Out2").Cells(i, 10).Value = Ihour
Sheets("Out2").Cells(i, 11).Value = Minut
Sheets("Out2").Cells(i, 1).Value = Iday0
Sheets("Out2").Cells(i, 2).Value = Imnth0
Sheets("Out2").Cells(i, 3).Value = Year0
Sheets("Out2").Cells(i, 4).Value = Ihour0
Sheets("Out2").Cells(i, 5).Value = Minut0
i = i + 1
End If
' End If
If (Minut >= 59) Then
Minut = Minut - 60
End If
minlow = Minut
' Idlow = Iday
Iday0 = Iday
Imnth0 = Imnth
Year0 = Year1
Ihour0 = Ihour
Minut0 = Minut
Loop
Close #100
End Sub


Microsoft Visual Basic - Gharo_count1.xls - [Completehr2 (Code)]
(General)
Completehr2
If (Ihro = Ihour) Then
sumWS1 = sumWS1 + WS1
sumWS2 = sumWS2 + WS2
nmin = 1 + nmin
ninut(nmin) = Minut
nWS1(nmin) = WS1
nWS2(nmin) = WS2
nWdir(nmin) = Wdir
Else
If (nmin = 60) Then
Sheets("Out4").Cells(nrow, 1).Value = IDY
Sheets("Out4").Cells(nrow, 2).Value = Imnth
Sheets("Out4").Cells(nrow, 3).Value = Year1
Sheets("Out4").Cells(nrow, 4).Value = Ihro
Sheets("Out4").Cells(nrow, 5).Value = nmin
Sheets("Out4").Cells(nrow, 6).Value = sumWS1 / nmin
Sheets("Out4").Cells(nrow, 7).Value = sumWS2 / nmin
For mcount = 1 To 60
Sheets("Out5").Cells((nrow - 1) * 60 + mcount, 1).Value = IDY
Sheets("Out5").Cells((nrow - 1) * 60 + mcount, 2).Value = Imnth
Sheets("Out5").Cells((nrow - 1) * 60 + mcount, 3).Value = Year1
Sheets("Out5").Cells((nrow - 1) * 60 + mcount, 4).Value = Ihro
Sheets("Out5").Cells((nrow - 1) * 60 + mcount, 5).Value = ninut(mcount)
Sheets("Out5").Cells((nrow - 1) * 60 + mcount, 6).Value = nWS1(mcount)
Sheets("Out5").Cells((nrow - 1) * 60 + mcount, 7).Value = nWS2(mcount)
Sheets("Out5").Cells((nrow - 1) * 60 + mcount, 8).Value = nWdir(mcount)
Next mcount
nrow = nrow + 1
End If
nmin = 1
sumWS1 = WS1
sumWS2 = WS2
Ihro = Ihour
Minc = Minut
End If
Loop
Close #100
End Sub


Microsoft Visual Basic - Gharo_count1.xls - [Completehr2 (Code)]
File Edit View Insert Format Debug Run Tools Add-Ins Window Help
Ln 1, Col 1
(General)
Completehr2
If (Ihro = Ihour) Then
sumWS1 = sumWS1 + WS1
sumWS2 = sumWS2 + WS2
nmin = 1 + nmin
minut(nmin) = Minut
nWS1(nmin) = WS1
nWS2(nmin) = WS2
nWdir(nmin) = Wdir
Else
If (nmin = 60) Then
Sheets("Out4").Cells(nrow, 1).Value = IDY
Sheets("Out4").Cells(nrow, 2).Value = Imnth
Sheets("Out4").Cells(nrow, 3).Value = Year1
Sheets("Out4").Cells(nrow, 4).Value = Ihro
Sheets("Out4").Cells(nrow, 5).Value = nmin
Sheets("Out4").Cells(nrow, 6).Value = sumWS1 / nmin
Sheets("Out4").Cells(nrow, 7).Value = sumWS2 / nmin
For mcount = 1 To 60
Sheets("Out5").Cells((nrow - 1) * 60 + mcount, 1).Value = IDY
Sheets("Out5").Cells((nrow - 1) * 60 + mcount, 2).Value = Imnth
Sheets("Out5").Cells((nrow - 1) * 60 + mcount, 3).Value = Year1
Sheets("Out5").Cells((nrow - 1) * 60 + mcount, 4).Value = Ihro
Sheets("Out5").Cells((nrow - 1) * 60 + mcount, 5).Value = minut(mcount)
Sheets("Out5").Cells((nrow - 1) * 60 + mcount, 6).Value = nWS1(mcount)
Sheets("Out5").Cells((nrow - 1) * 60 + mcount, 7).Value = nWS2(mcount)
Sheets("Out5").Cells((nrow - 1) * 60 + mcount, 8).Value = nWdir(mcount)
Next mcount
nrow = nrow + 1
End If
nmin = 1
sumWS1 = WS1
sumWS2 = WS2
Ihro = Ihour
Mins = Minut
End If
Loop
Close #100
End Sub
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Sheet3 (Wind Rose)
Sheet4 (Out3)
Sheet5 (Out4)
Sheet6 (Out5)
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Countrows
Missingrows1
Missingrows2
Module2
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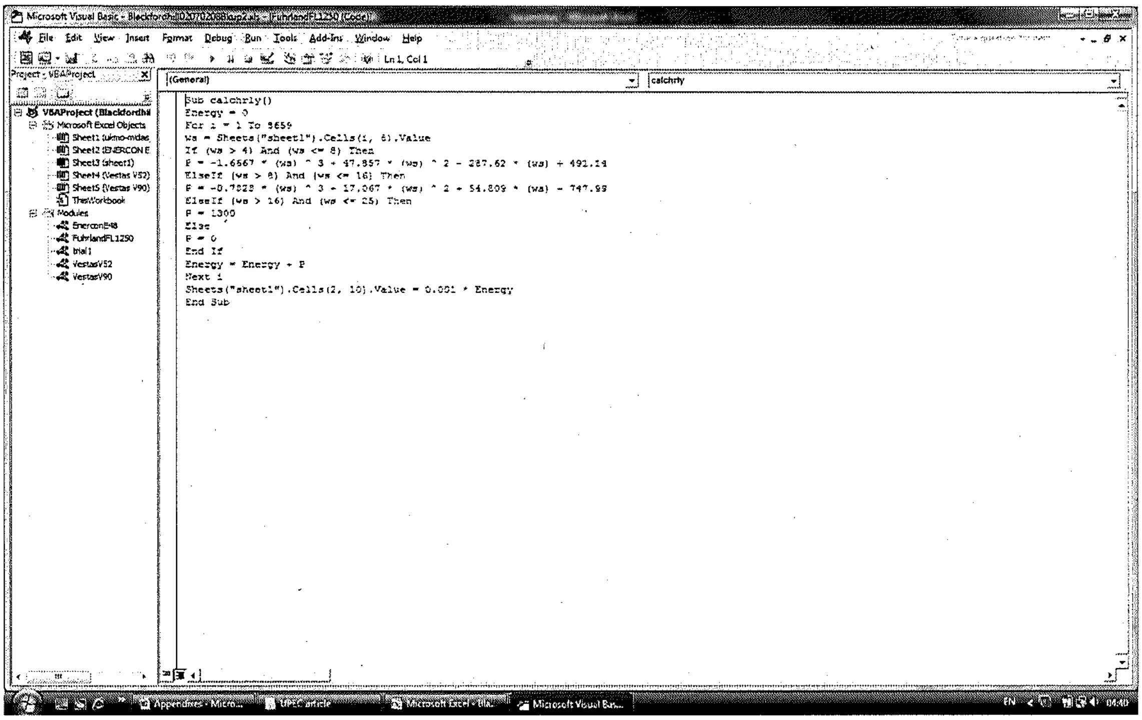
Microsoft Visual Bas...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Ln 1, Col 1
(General)
calchrly
Sub calchrly()
Energy = 0
For i = 1 To 8659
ws = Sheets("sheet1").Cells(i, 6).Value
If (ws > 4) And (ws <= 8) Then
P = -1.6567 * (ws) ^ 3 + 47.857 * (ws) ^ 2 - 287.62 * (ws) + 491.14
ElseIf (ws > 8) And (ws <= 16) Then
P = -0.7823 * (ws) ^ 3 + 17.067 * (ws) ^ 2 + 54.809 * (ws) - 747.99
ElseIf (ws > 16) And (ws <= 25) Then
P = 1300
Else
P = 0
End If
Energy = Energy + P
Next i
Sheets("sheet1").Cells(2, 10).Value = 0.001 * Energy
End Sub
VBAProject (Blackfordhil
Microsoft Excel Objects
Sheet1 (ukmo-midas
Sheet2 (ENERCON E
Sheet3 (sheet1)
Sheet4 (Vestas V52)
Sheet5 (Vestas V90)
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VestasV52
VestasV90
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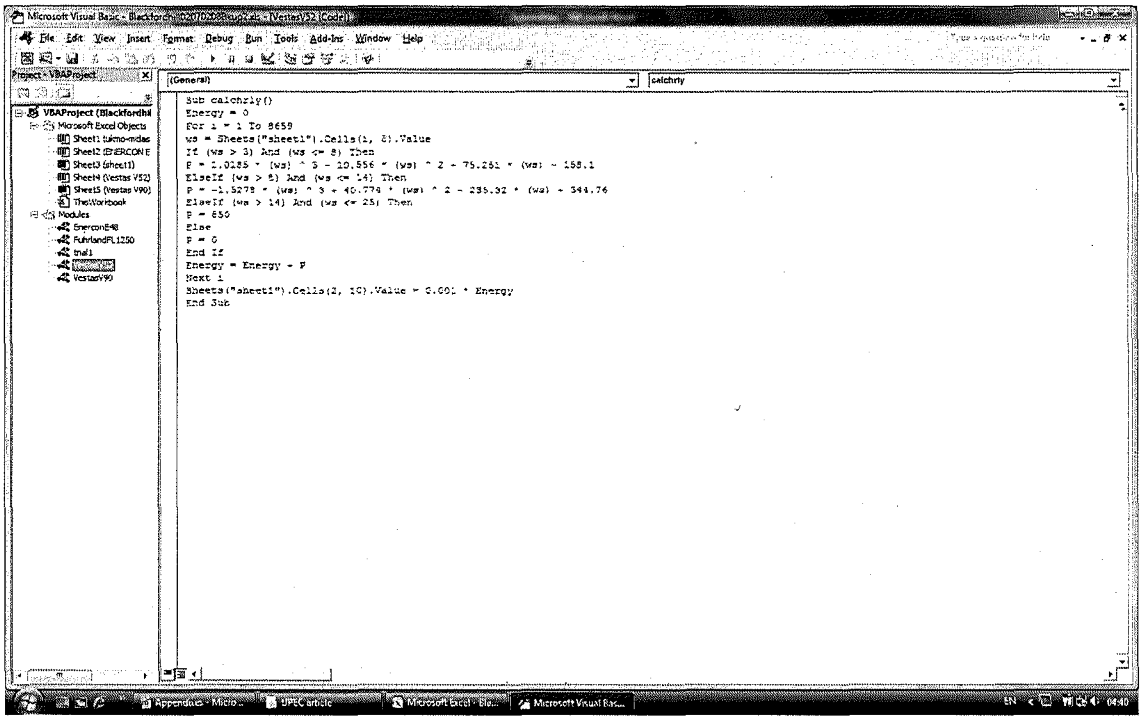
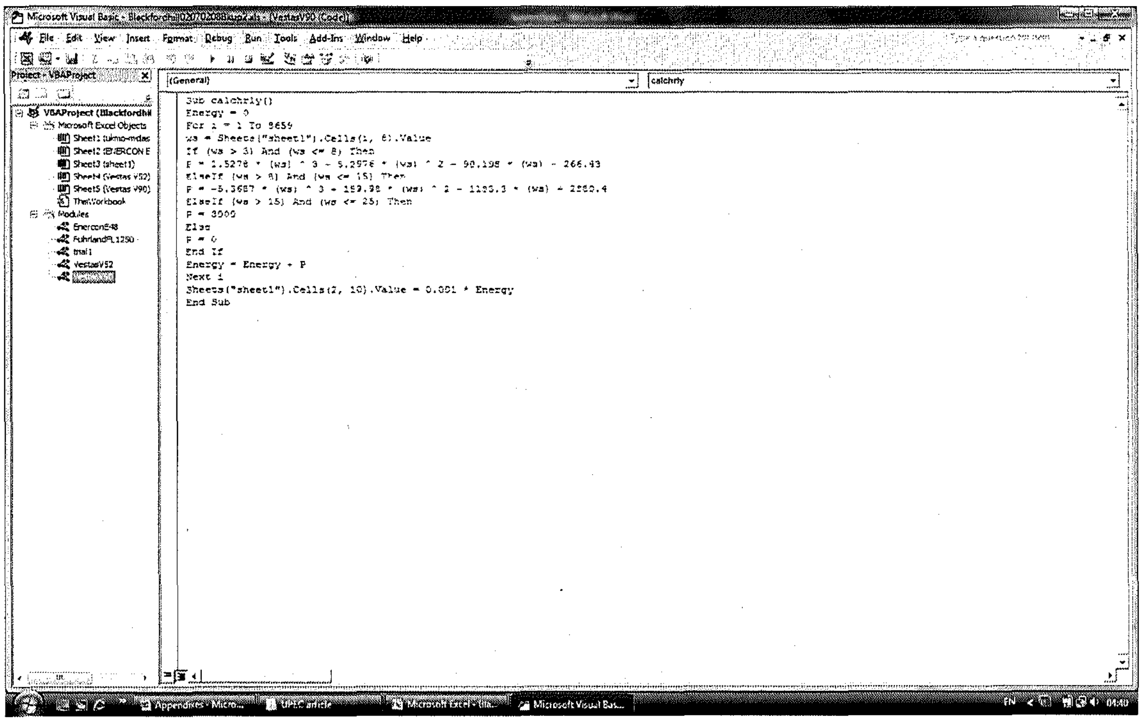
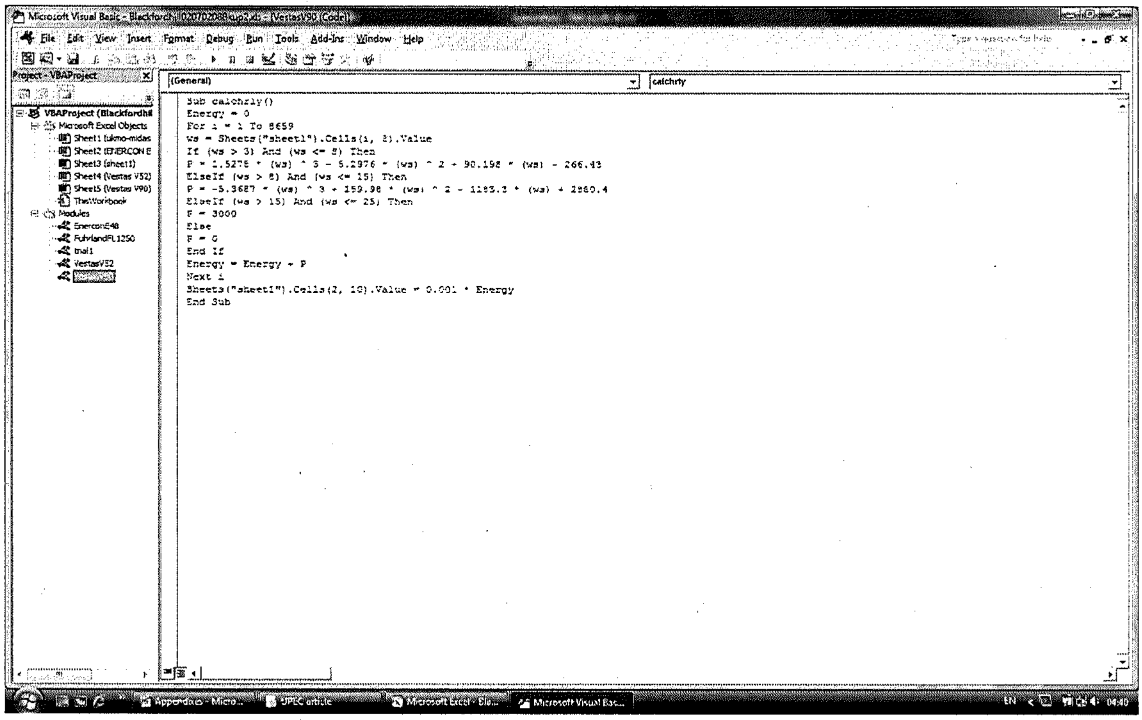
UPEC article
Microsoft Excel - Bla...
Microsoft Visual Bas...


Microsoft Visual Basic - Blackfordhill02070208backup2.xls - [VestasV52 (Code)]
(General)
calchrly
Sub calchrly()
Energy = 0
For i = 1 To 8659
ws = Sheets("sheet1").Cells(i, 8).Value
If (ws > 3) And (ws <= 8) Then
P = 1.0185 * (ws) ^ 3 - 10.556 * (ws) ^ 2 + 75.251 * (ws) - 158.1
ElseIf (ws > 8) And (ws <= 14) Then
P = -1.5278 * (ws) ^ 3 + 40.774 * (ws) ^ 2 - 235.32 * (ws) + 344.76
ElseIf (ws > 14) And (ws <= 25) Then
P = 850
Else
P = 0
End If
Energy = Energy + P
Next i
Sheets("sheet1").Cells(2, 10).Value = 0.001 * Energy
End Sub


Microsoft Visual Basic - Blackfordhill02070208backup2.xls - [VestasV90 (Code)]
(General)
calchrly
Sub calchrly()
Energy = 0
For i = 1 To 8659
ws = Sheets("sheet1").Cells(i, 8).Value
If (ws > 3) And (ws <= 8) Then
P = 1.5278 * (ws) ^ 3 - 5.2976 * (ws) ^ 2 - 90.198 * (ws) - 266.43
ElseIf (ws > 8) And (ws <= 15) Then
P = -5.3687 * (ws) ^ 3 + 159.98 * (ws) ^ 2 - 1193.3 * (ws) + 2260.4
ElseIf (ws > 15) And (ws <= 25) Then
P = 3000
Else
P = 0
End If
Energy = Energy + P
Next i
Sheets("sheet1").Cells(2, 10).Value = 0.001 * Energy
End Sub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FuhrlandFL1250
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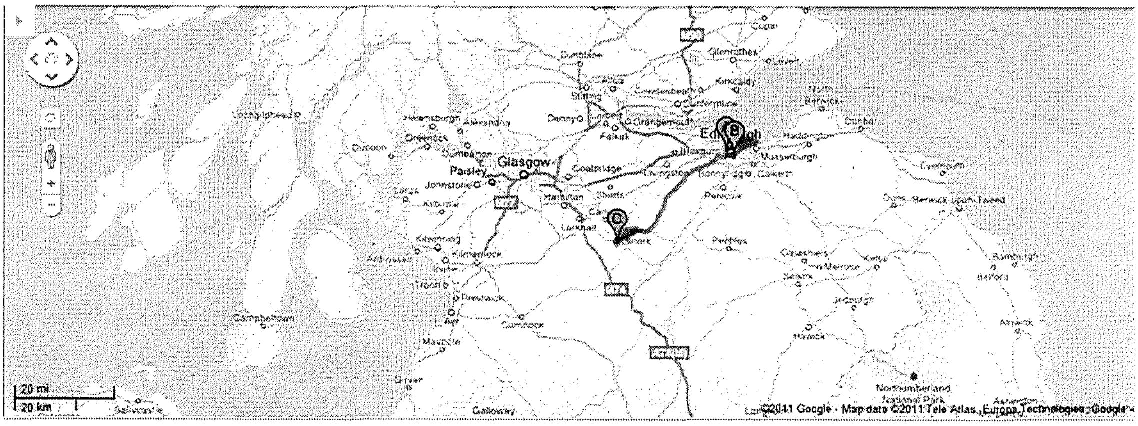
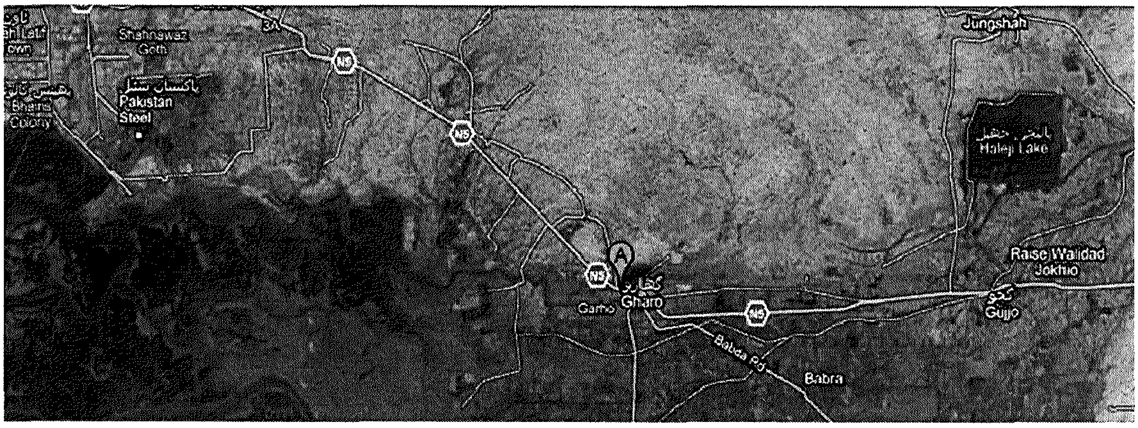
VestasV52
(General)
calchrly
Sub calchrly()
Energy = 0
For i = 1 To 8659
ws = Sheets("sheet1").Cells(i, 2).Value
If (ws > 3) And (ws <= 8) Then
P = 1.5275 * (ws) ^ 3 - 5.2976 * (ws) ^ 2 + 90.198 * (ws) - 266.43
ElseIf (ws > 8) And (ws <= 15) Then
P = -5.3687 * (ws) ^ 3 + 159.98 * (ws) ^ 2 - 1183.3 * (ws) + 2980.4
ElseIf (ws > 15) And (ws <= 25) Then
P = 3000
Else
P = 0
End If
Energy = Energy + P
Next i
Sheets("sheet1").Cells(2, 10).Value = 0.001 * Energy
End Sub
Microsoft Excel
Microsoft Visual Bas...

Appendix B

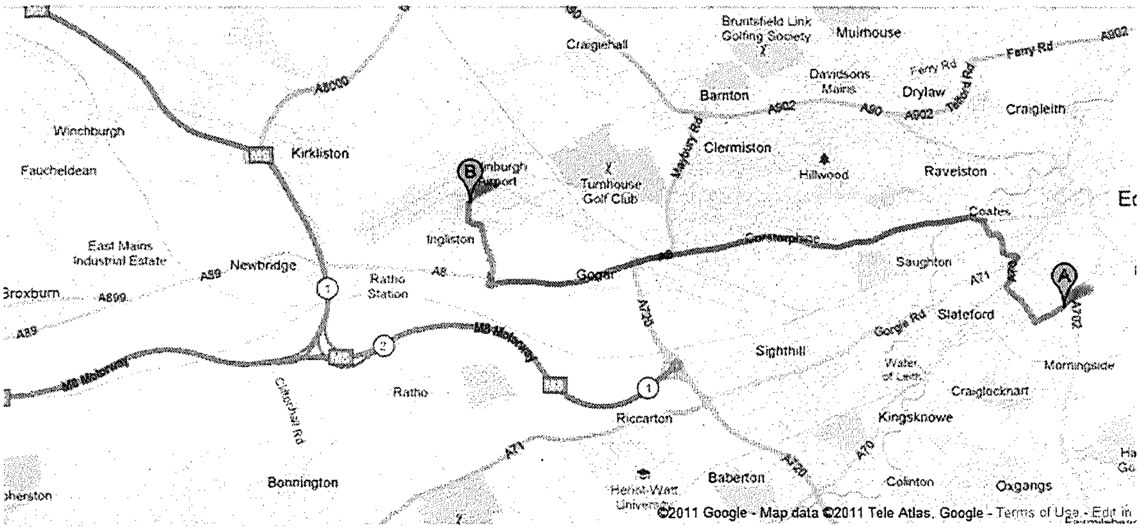
B.1 Map of Edinburgh Napier University, Blackford hill, and Durmalbin locations A, B, C respectively



B.2 Map of Gharo location in Pakistan on Arabian Sea



B.3 Map of Edinburgh Napier University location and Turnhouse Airport location A, and B



Appendix C

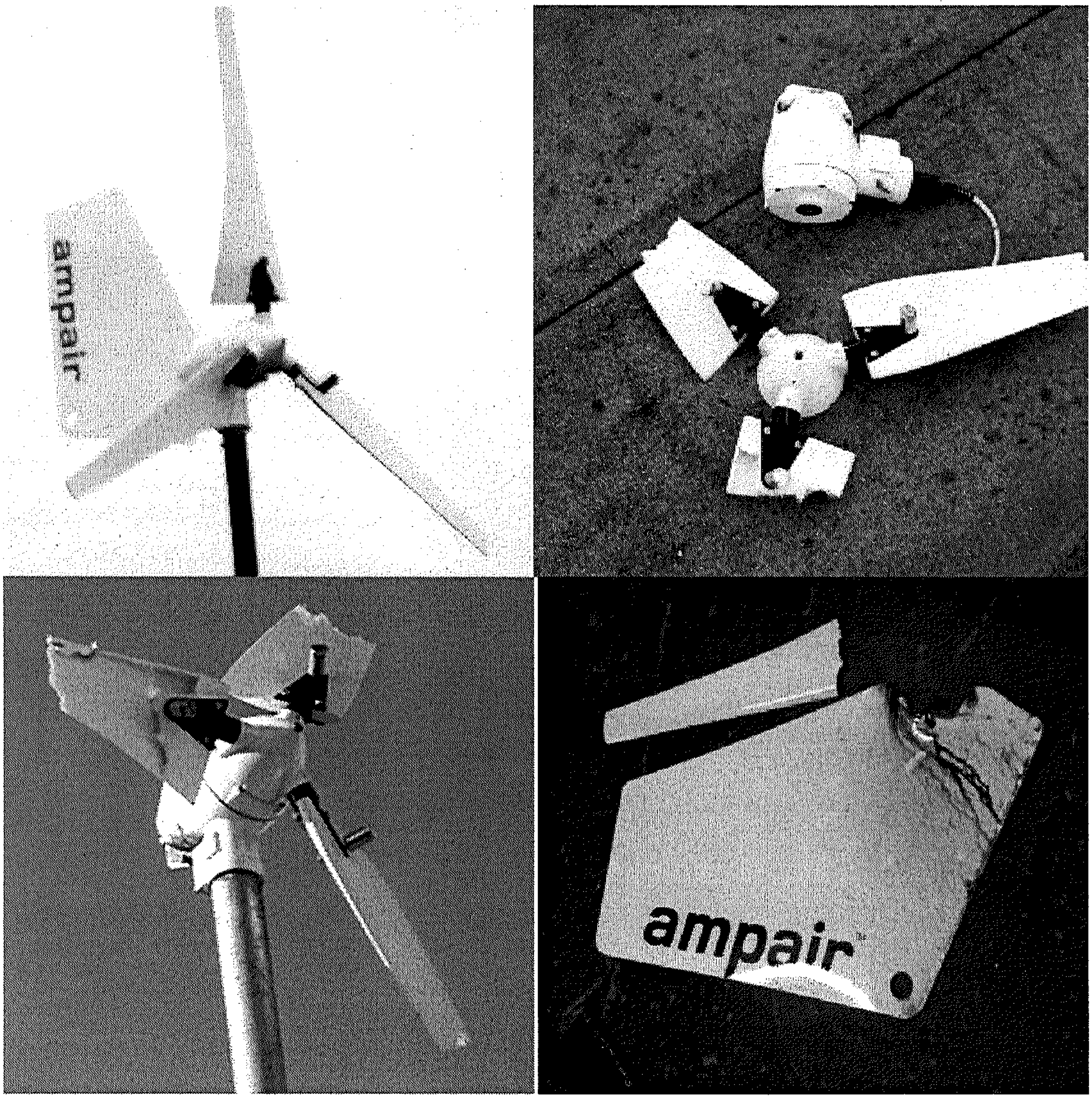


Figure C.1 The Ampair wind turbine is before and after the collapse

Table Appendix C.1 Suzlon-950 wind turbine power curve. It is coloured to distinguish the different areas

Wind speed [m/s]	Power [kW]
0	0
1	0
2	0
3	16
4	37
5	100
6	181
7	287
8	452
9	645
10	861
11	950
12	950
13	950
14	950
15	950
16	950
17	950
18	950
19	950
20	950
21	950
22	950
23	950
24	950
25	950
26	0
27	0
28	0
29	0
30	0

C.3 Steps of downloading data form Squirrel data logger

Downloading the data from data logger into the PC includes the following steps:

1. Disconnect wind speed and wind vane sensors from data logger by choosing from the main menu. The log control then on display will show disarm mode. Next, hold the enter button for a while until arm mode appears. Proceed to download data.
2. Double click on the software icon, choose download button in tools bar.
3. Choose export data mode, and then press download selected files button.

4. Fill in the proper name for the file in dialog box and press save.
5. The software will start to download the data into the selected file on the PC.
6. When the data download is complete, it has to be decoded to required format from export setting window (i.e. date format as in DD/MM/YYYY, where coma ought to separate the variables). Once this is done press next button.
7. When the path of the saved file is all right, and the format is as required press next and then press finish button in the subsequent window.
8. Confirmation message will appear regarding file format; press OK button.
9. Finally, confirmation message appears showing the job has been completed successfully.
10. Delete the data from data logger memory to get more space for the next file.
11. Connect the data logger again to the sensors (in Step1) by pressing on the button, holding it for a while to convert from arm mode to disarm mode and then start recording the data in new file.

Appendix C List of Publications

1. Makkawi A, Gupta N, & Muneer T; Micro, mini or macro? Onshore wind turbine economics for Scotland. Universities Power Engineering Conference, article # 4-27, Padova, 2008.

2. Makkawi A, Celik N A, & Muneer T; Evaluation of micro wind turbine aerodynamics, wind speed sampling interval and its spatial variation. Building Services Engineering Research & Technology, 30, 1, pp7–14, 2009.

3. Makkawi A, Tham Y, Asif M & Muneer T; Analysis and inter-comparison of energy yield of wind turbines in Pakistan using detailed hourly and per

minute recorded dataset. Energy conversion and management, 50, 2340-2350, 2009.

4. Celik A N, Makkawi A & Muneer T; Critical evaluation of wind speed frequency distribution functions. Journal of Renewable Sustainable Energy 2, 013102, pp1-16, 2010.

5. Makkawi A, Gupta N, & Muneer T; Monitoring and modelling the performance of small wind turbines in urban and rural areas in the UK. 16th International Energy & Environment Fair (conference poster paper); Istanbul ,May 2010